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ORBITAL MANEUVERING ENGINE
FEED SYSTEM COUPLED STABILITY INVESTIGATION
COMPUTER USER'S MANUAL

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FOREWORD

This document was prepared by Rocketdyne Division, Rockwell International Corporation, in accordance with Article I and Line Item Nos. 2, 3, and 4 of the Data Requirements List of Contract NAS9-14315 with the National Aeronautics and Space Administration. The contract period of performance was 6 August 1974 to 1 September 1975. The NASA/JSC Technical Monitor was Mr. F. D. Freeburn. The Rocketdyne Program Manager was Mr. R. H. Helsel for the first three months; he was replaced by Mr. R. D. Paster for the remainder of the program. Mr. J. A. Nestlerode served as the Principal Engineer, assisted by Dr. D. R. Kahn.

Several technical people at Rocketdyne performed work or served as consultants regarding specific areas of the various program tasks: Mssrs. J. K. Hunting, R. L. Nelson, and L. E. Sack with respect to the feed system hydrodynamics, Mr. F. R. Linow with respect to combustion dynamics, Mr. M. D. Schuman with respect to combustion dynamics, chamber dynamics, engineering model formulation, and computer programming, and Mr. K. W. Fertig with respect to numerical analysis, computer programming, and checkout.

ABSTRACT

This report is an operating manual for the Feed System Coupled Stability Model. It is submitted as partial fulfillment of an 11-month program designed to develop, verify, and document a digital computer model that can be used to analyze and predict engine/feed system coupled instabilities in pressure-fed storable propellant propulsion systems over a frequency range of 10 to 1000 Hz.

The first section describes the analytical approach to modeling the feed system hydrodynamics, combustion dynamics, chamber dynamics, and overall engineering model structure, and presents the governing equations in each of the technical areas. This is followed by the Program User's Guide, which is a complete description of the structure and operation of the computerized model. Last, appendixes provide an alphabetized FORTRAN symbol table, detailed program logic diagrams, computer code listings, and sample case input and output data listings.

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INTRODUCTION

Historically, during the development of pressure-fed propulsion systems, feed system/engine coupled instabilities have been frequently encountered. Resolution of these problems usually included increasing injector pressure drop to decouple the feed system from the combustor, the result being substantial system weight penalties. A dynamic computer model would be a useful tool in obviating coupled stability problems during the development of the Space Shuttle Orbit Maneuvering System (SS/OMS). A model could be used both as a system design tool to optimize component location and pressure profile (minimize system weight) and a system development tool to define test programs for assessing stability margins of the OMS.

This document is an operating manual for the Feed System Coupled Stability Model (FSCSM) and is submitted as partial fulfillment of an 11-month program conducted by Rocketdyne to develop and verify an engineering digital computer model for the NASA/JSC which can be used to analyze feed system/engine coupled instabilities in pressure-fed, storable propellant, propulsion systems over a frequency range of 10 to 1000 Hz (frequencies lower than the chamber transverse frequencies). The model is sufficiently general so that it may be readily applicable to present and future engine and propulsion programs. For scaling purposes, the baseline configuration chosen is the OMS engine. The model has been written for use on the NASA/JSC Univac 1110, EXEC-8 computer system, and provides NASA a tool which can be used to:

1. Conduct preliminary design tradeoff for feasibility studies prior to propulsion concept selection.

2. Guide the design of propulsion systems to ensure stability at all operating ranges and with minimum penalties.

3. Guide testing programs by predicting the least stable operating regimes thereby reducing the number of stability tests required.

4. Provide stability verification in the event system changes are made and hot-fire verification is impractical.

5. Diagnose problems on existing systems and evaluate potential solutions.

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The work performed in completing the requirements of the program's technical effort is described in a separate companion document, entitled OME Feed System-Coupled Stability Model, Final Report (Ref. 1). This includes the mathematical formulation of the model, development of the model into an overall engineering structure, and verification of the model's operation and capabilities by comparing the model's theoretical predictions with experimental data from an OMS engine and test rig with known feed system/engine chugging history.

The present document contains a detailed description of the structure and operation of the FSCSM. In the first section, the mathematical formulation of the model is reviewed. The analytical approach to modeling the feed system hydrodynamics, combustion dynamics, chamber dynamics, and overall engineering structure is described and the equations utilized by the model in each of the technical areas are presented. The reader may consult Ref. 1 for more details pertaining to the derivation of the equations.

The Program User's Guide section contains the instructions necessary to operate the computer model and interpret the results. First, the structure and logic of the main program and all subroutines are described, followed by a description of the input data required to run FSCSM. The input is divided into four major sections: (1) main control, (2) nozzle admittance control, (3) hydrodynamics control, and (4) combustion dynamics control. The format, content, and description of each input data card is clearly specified for each control section. The output of the FSCSM computer program is then discussed in terms of each tabular page of printout. Finally, additional details on program operation are presented, including program size, overlay structure, computer time, and program input/output data set file information. Appendixes provide an alphabetized FORTRAN symbol table, detailed program logic diagrams, computer code listings, and sample case input and output data listings.
MATHEMATICAL FORMULATION OF MODEL

INTRODUCTION
During certain periods of a rocket engine's operation, conditions within the combustion chamber and feed system are time variant, i.e., the operation is not steady with respect to time. Prime interest of this computer model is focused on abnormal transient operation during unstable combustion, i.e., pressure oscillations in a combustion device which are driven by the feed system and sustained by the combustion process. Start and stop transients are not considered.

The deviations from steady-state combustion which occur during unstable burning depend upon the kind of instability experienced. Liquid rocket instabilities are classified according to their dominant time-varying processes. They may be divided initially into two categories, depending upon whether the instability oscillation wave length is long or short compared with the chamber dimensions.

If the instability wave length is considerably longer than the chamber length and diameter, pressure disturbances propagate rapidly through the combustion space compared with rates of change due to the instability. As a result, wave motion in the chamber may be neglected and chamber pressure can be considered to vary only with time but not to vary spatially (i.e., $P_C$ is a lumped parameter). These instabilities depend upon a fluid mechanical coupling between the propellant feed system(s) dynamics (fluctuating injection rates), the propellant combustion rates (delay times), and the combustion gas exhaust rates (pressure relaxation). Such instabilities can be further subdivided into various categories depending on the extent of wave motion in the feed system.

The breakpoint at which chamber wave motion becomes important is not abrupt. In reality, chamber wave motion is always present and, in effect, lumped chamber instabilities are really "zero order mode" limits of more general wave motion instabilities. In practice, it is found that the chamber gases
can be considered to act as a lump until the frequency of oscillation exceeds roughly one-fourth of the frequency of the lowest chamber acoustic resonance mode. At and above such frequencies wave motion becomes important and cannot be neglected in analysis. Chamber wave motion instabilities are characterized by the wavelength of the oscillatory motion being comparable to the chamber dimensions. As with lumped chamber instabilities, the driving energy comes from oscillatory spray combustion. With wave motion instabilities, however, in addition to the effects of injection rate fluctuations, there is the combustion response of burning propellant sprays as they are disturbed by passage of a pressure wave through them. Wave motion may increase local burning rates by any of several mechanisms: (1) a pressure effect on the drop vapor gas phase burning rates; (2) enhanced mixing between gases and between sprays and gases; and (3) increased spray gasification rates. Increased spray gasification may be due to transient increases in convective flow velocities, to increased temperature or concentration gradients, and/or spray droplet shattering. The instability amplitude depends upon the magnitude of the response, and vice versa; typically, the interacting processes are driven to a limit represented by abrupt, essentially complete consumption of the propellant sprays. This direct response can be so great that injection rate fluctuations may be of secondary importance. As a result this class of instability can also be further subdivided as to the importance of feed system coupling. In the absence of feed system coupling, the instability is referred to as "classical acoustic instability." Only longitudinal chamber modes with feed system coupled instabilities are considered in this program.
FEED SYSTEM DYNAMICS

Development of the Waterhammer Equations

Consider the differential control volume of a fluid element in a duct shown in Fig. 1.

\[
\begin{align*}
\frac{\partial p}{\partial t} &= -\rho \frac{\partial v}{\partial x} = -c^2 \rho \frac{\partial v}{\partial x} \quad (1) \\
\frac{\partial p}{\partial x} &= -\rho \frac{\partial v}{\partial t} = -\frac{\beta}{c^2} \frac{\partial v}{\partial t} \quad , \quad (2)
\end{align*}
\]

where
\[
\begin{align*}
p &= \text{fluid pressure} \\
v &= \text{fluid velocity} \\
\beta &= \text{fluid bulk modulus} \\
\rho &= \text{fluid density} \\
c &= \text{acoustic velocity} = (\beta/\rho)^{\frac{1}{2}}
\end{align*}
\]

There are several ways in which to solve these equations. The solution method presented here follows that of Ezekiel (Ref. 2). The general form of the solution that satisfies either of equations (1) and (2) is
\[
p = F_1 (t + \frac{x}{c}) + F_2 (t - \frac{x}{c}) \quad (3)
\]

where \( F_1 \) and \( F_2 \) are arbitrary functions.
Taking the partial derivative of \( p \) with respect to \( x \) and \( t \) separately and substituting the results in equations (1) and (2) gives:

\[
\frac{\partial v}{\partial x} = -\frac{1}{c} \frac{\partial p}{\partial t} = -\frac{1}{\beta} \left[ \frac{F_1'(t + \frac{x}{c}) + F_2'(t - \frac{x}{c})}{c} \right] \tag{4}
\]

\[
\frac{\partial v}{\partial t} = -\frac{1}{\rho} \frac{\partial p}{\partial x} = -\frac{1}{\rho c} \left[ F_1'(t + \frac{x}{c}) - F_2'(t - \frac{x}{c}) \right] \tag{5}
\]

where

\[
F'(\xi) = \frac{\partial F(\xi)}{\partial \xi}.
\]

The expression for \( v \) is obtained from either equation (4) or (5):

\[
v = -F_1(t + \frac{x}{c}) + F_2(t - \frac{x}{c}) \tag{6}
\]

where

\[
z \equiv (\rho \beta)^{\frac{1}{2}}.
\]

Letting the subscript \( o \) denote \( x=0 \), the upstream position, and the subscript \( L \) denote \( x=L \), the downstream position, and defining \( \tau = L/c \) as the signal propagation time between the two positions, equations (3) and (6) become

\[
p_0 = F_1(t) + F_2(t) \tag{8}
\]

\[
p_L = F_1(t+\tau) + F_2(t-\tau) \tag{9}
\]

\[
zv_0 = -F_1(t) + F_2(t) \tag{10}
\]

\[
zv_L = -F_1(t+\tau) + F_2(t-\tau) \tag{11}
\]

Combining Eqs. (8) and (10), and Eqs. (9) and (11) separately, yields four additional relations:

\[
p_0 + zv_0 = 2F_2(t) \tag{12}
\]

\[
p_0 - zv_0 = 2F_1(t) \tag{13}
\]
\[ \begin{align*}
    p_L + zv_L &= 2 F_2(t-\tau) \\
    p_L - zv_L &= 2 F_1(t+\tau). 
\end{align*} \tag{14} \tag{15} \]

Eliminating the functions \( F_1 \) and \( F_2 \) gives the final result as:

\[ \begin{align*}
    [p_0 + zv_0]_{t=\tau} &= p_L + zv_L \tag{16} \\
    [p_L - zv_L]_{t=\tau} &= p_0 - zv_0 \tag{17} 
\end{align*} \]

Consider now Fig. 2, which depicts a generalized line segment forming a portion of a feed system with many such segments.

The equations which describe the pressure and flows as functions of time and of each other for the generalized line segment are obtained from Eqs. (16) and (17):

\[ \begin{align*}
    p_n - \left( \frac{v_n}{A_n g} \right) w_n &= \left[ p_{n+1}' - \left( \frac{v_n}{A_n g} \right) w_{n+1} \right]_{t=\tau_n} \\
    p_{n+1}' + \left( \frac{v_n}{A_n g} \right) w_{n+1} &= \left[ p_n + \left( \frac{v_n}{A_n g} \right) w_n \right]_{t=\tau_n} 
\end{align*} \tag{18} \tag{19} \]
The expression, $t - \tau_n$, indicates values at $\tau_n$ seconds before, and

$$p_{n+1}' = p_{n+1} + R_n|\dot{w}_n|\dot{w}_n$$  \hspace{1cm} (20)

$$\dot{w}_n = \rho_n A_n v_n.$$  \hspace{1cm} (21)

Equations (18) and (19) are solutions of the wave equation, and equation (20) is the flow through a nonlinear fluid resistance. Letting

$$\alpha_n = \frac{v_n}{A_n g}$$  \hspace{1cm} (22)

these equations can be combined to give:

$$p_n - \alpha_n \dot{w}_n = \left[p_{n+1} + R_n|\dot{w}_{n+1}|(\dot{w}_{n+1} - \alpha_n)\right]_{(t-\tau_n)}$$  \hspace{1cm} (23)

$$p_n + R_{n-1}|\dot{w}_n|\dot{w}_n + \alpha_{n-1} \dot{w}_n = \left[p_{n-1} + \alpha_{n-1} \dot{w}_{n-1}\right]_{(t-\tau_{n-1})}.$$  \hspace{1cm} (24)

Eliminating $p_n$ and rearranging into quadratic form results in

$$R_{n-1} \dot{w}_n^2 + (\alpha_{n-1} + \alpha_n) \dot{w}_n - \left[p_{n-1} + \alpha_{n-1} \dot{w}_{n-1}\right]_{(t-\tau_{n-1})}$$

$$+ \left[p_{n+1} + R_n|\dot{w}_{n+1}|(\dot{w}_{n+1} - \alpha_n)\right]_{(t-\tau_{n+1})} = 0$$  \hspace{1cm} (25)

which can be solved for the appropriate solution using the quadratic formula. The tank end parameters are obtained using a solution of Eq. (23) only. The injector end solution is obtained using the quadratic formula for equation (25).

The linear model incorporated in the Hydrodynamics subprogram utilizes the same basic equations, (23) and (24), but in the following linearized form:
\[(\delta p_n) - \alpha_n (\delta \dot{w}_n) = \left[ (\delta p_{n+1}') - \alpha_n (\delta \dot{w}_{n+1}) \right]_{(t-\tau_n)} \]  

\[-(\delta p_{n+1}') + \alpha_n (\delta \dot{w}_{n+1}) = \left[ (\delta p_n) + \alpha_n (\delta \dot{w}_n) \right]_{(t-\tau_n)}, \]

where

\[(\delta p_{n+1}') = (\delta p_{n+1}) + 2R_n \dot{\bar{w}}_{n+1} (\delta \dot{w}_{n+1}). \]

These equations are then combined, resulting in

\[\alpha_n (\delta \dot{w}_n) - (\delta p_n) + \left[ (\delta p_{n+1}) + (\bar{R}_n - \alpha_n) (\delta \dot{w}_{n+1}) \right]_{(t-\tau_n)} = 0 \]  

\[\left( \bar{R}_n + \alpha_n \right) (\delta \dot{w}_{n+1}) + (\delta p_{n+1}) - \left[ (\delta p_n) + \alpha_n (\delta \dot{w}_n) \right]_{(t-\tau_n)} = 0 , \]

where

\[\bar{R} = 2 R_n \dot{\bar{w}}_{n+1} \]

At the tank end, the term \(\delta p_n\) is zero for constant tank pressure. At the injector end, \(\delta p_{n+1}\) is the independent variable.
Injector Dynamics

The injector dynamics are included by treating the injector as a lumped compressible volume as shown in the figure below.

\[
\frac{dp_I}{dt} = \frac{c_I^2}{V_I g} (\dot{w}_n - \dot{w}_I)
\]

where \( V_I \) is the injector volume and \( c_I \) is the fluid sonic velocity.

The injectors flow is controlled by the differential pressure across the injector as well as by the resistance and inertia of the injector orifices. Thus,

\[
p_I - p_C = R_I \dot{w}_I + \frac{\xi}{Ag} \frac{d}{dt} \dot{w}_I,
\]

where \( p_C \) is the thrust chamber pressure, \( R_I \) is the injector hydraulic resistance and \( \xi/Ag \) is the equivalent inertance of all the injector orifices combined, i.e.,

\[
\frac{1}{\xi/Ag} = g \sum_{i=1}^{n} \frac{1}{\xi_i/A_i}
\]
In the preceding equation, $l_i$ and $A_i$ are the length and area, respectively, of an individual injector orifice.

An additional factor which can have a significant effect on the response of the feed system to chamber pressure oscillations is injector face flexibility. This effect can be expressed as a change in injector volume proportional to a change in injector pressure drop:

$$\frac{dV_I}{dt} = K \left( \frac{dp_I}{dt} - \frac{dp_c}{dt} \right)$$  \hspace{1cm} (35)

Also,

$$\frac{dp}{dt} = \frac{c^2}{g} \frac{d}{dt} \left( \frac{\dot{m}}{V} \right),$$  \hspace{1cm} (36)

which can be rewritten as

$$\frac{dp}{dt} = \frac{c^2}{V g} \dot{\omega} - \frac{c^2 \rho}{V g} \dot{V}.$$  \hspace{1cm} (37)

Combining Eqs. (35) and (37) gives

$$\frac{dp_I}{dt} = \frac{c^2}{V_I g} (\dot{W}_n - \dot{W}_I) - \frac{c^2 \rho I}{V_I g} \left[ K \left( \frac{dp_I}{dt} - \frac{dp_c}{dt} \right) \right],$$  \hspace{1cm} (38)

which can be rewritten as

$$\left( 1 + \frac{c^2 \rho I K}{V_I g} \right) \frac{dp_I}{dt} = \frac{c^2}{V_I g} (\dot{W}_n - \dot{W}_I) + \frac{c^2 \rho I K}{V_I g} \frac{dp_c}{dt}$$  \hspace{1cm} (39)

This expression reduces to Eq. (32) if no injector flexibility exists ($K = 0$).
Two-Phase Flow Acoustic Velocity

In the waterhammer equations the acoustic velocity, c, of the fluid appears in two places; (1) directly in the constant relating flow to pressure, and (2) indirectly in the time delay value, \( \tau \), which equals \( \ell/c \) seconds, where \( \ell \) is the pipe segment length. The acoustic velocity of a fluid is a property of that fluid. However, its effective value can be reduced by the elastic walls of the flow passage or by the entrainment of gas and vapor in the liquid (two phase flow).

Gas in the liquid can appear from two sources. One source is direct entrainment from mixing of gas and liquid in the propellant tank, while the other can result from the evolution of dissolved gas as the pressure drops along the feed system.

Given the steady-state pressure at each point in the feed system and data on the solubility of the pressurant gas in the propellant as a function of pressure and temperature, the amount of gas in the fluid can be determined for each feed system segment. Then, knowing the amount of gas in the liquid, the effective acoustic velocity of the mixture may be calculated.

Assuming isentropic compression of the gas, the change in volume of the gas is

\[
dV_g = -\frac{V_g}{K_p} dp,
\]

and for the liquid

\[
dV_l = \frac{V_l}{\beta} dp
\]

Defining a constant, \( \alpha = \frac{V_g}{V_l} \)

the following relation is obtained:

\[
\frac{dV_t}{V_t} = \frac{-dp}{[\frac{1}{\beta} + \frac{\alpha}{K_p}]_{\frac{1}{\beta} + \frac{\alpha}{K_p}}}
\]
The bracketed term is the compressibility of the mixture. The density of the mixture can be shown to be

$$\rho_m = \frac{\alpha \rho_g + \rho_l}{(1 + \alpha)} \quad (43)$$

The acoustic velocity of a liquid in an elastic pipe is

$$c = \sqrt{\frac{1}{\rho g \left( \frac{1}{\beta} + \frac{Dcf}{Ee} \right)}} \quad (44)$$

Using the above expressions for density and compressibility, the acoustic velocity, can be written as

$$c = \left[ \frac{\rho_m}{1 + \alpha} \left( \frac{\alpha}{\rho_l c_l^2} + \frac{1}{\rho_g c_g^2} + \frac{1 + \alpha}{g} \frac{Dcf}{Ee} \right) \right]^{\frac{1}{2}} \quad (45)$$

This expression can be used to define the acoustic velocity of a feed system segment with two phase flow. For an all liquid system, $\alpha = 0$ and the same equation can be used.

In the Hydrodynamics subprogram the effect of the wall compressibility term, $\frac{Dcf}{Ee}$, on the fluid acoustic velocity is handled automatically (assuming input values of $\frac{Dcf}{Ee}$ are provided for each feed system segment). However, the program does not compute the effects of two-phase flow. If such flow occurs in the feed system being modeled, an effective fluid acoustic velocity must be pre-calculated for each affected segment. Equation (45) above, with the $\frac{Dcf}{Ee}$ term set equal to zero can be used for this calculation.

**Simulation of Branch Lines**

In the Hydrodynamics subprogram, branched lines are handled by assuming that each branch has zero internal volume and that its flows are incompressible. Thus, the pressures at the end of all segments which meet at a branch are set equal. The continuity of flow is then used to provide the additional equations in combination with the waterhammer equations to solve for the overall feed system dynamic response.
Generalized Feed System Model

A schematic of the generalized feed system which is modeled by the hydrodynamics subprogram is shown in Fig. 4. The configuration chosen is based on design and operating mode data for the OMS, PBK, and RCS feed systems obtained from McDonnell Douglas/St. Louis. The system is comprised of 30 individual line segments, each denoted in Fig. 4, as the lines between the black dots. A continuous parameter representation of each line segment is obtained through the use of separate sets of waterhammer equations. Each line segment can have a different line length, area, wall compliance, fluid acoustic velocity and resistance, and hence can model a wide variety of feed system components by merely choosing the appropriate values from these parameters. Also included in the generalized model are lumped parameter descriptions of two injectors (designated "0" and "F" on Fig. 4). Parameters for the injectors are volume, resistance, inertance, fluid acoustic velocity and face flexibility.

The system of 57 equations describing the generalized Fig. 4 feed system is listed in Table 1. The equations are shown in the linearized, LaPlace transformed format required by the frequency response subroutine.
Figure 4. Generalized OME Feed System Schematic
### TABLE 1. HYDRODYNAMIC EQUATIONS

1-1: \[ P_1 + (R_1 + a_1) \dot{w}_1 + [P_1 + (R_1 - a_1) \dot{w}_1] e^{-2T_{1S}} = 0 \]

1-2: \[ P_1 - a_3 \dot{w}_3 - [P_2 + (R_3 - a_3) \dot{w}_4] e^{-T_{3S}} = 0 \]

1-3: \[ P_2 + (R_3 + a_3) \dot{w}_4 - [P_1 + a_3 \dot{w}_3] e^{-T_{3S}} = 0 \]

1-4: \[ P_1 - (R_2 + a_2) (\dot{w}_1 - \dot{w}_3) - [P_1 - (R_2 - a_2) (\dot{w}_1 - \dot{w}_3)] e^{-2T_{2S}} = 0 \]

1-5: \[ P_2 - a_5 \dot{w}_6 - [P_3 + (R_5 - a_5) \dot{w}_7] e^{-T_{5S}} = 0 \]

1-6: \[ P_2 - a_4 (\dot{w}_4 - \dot{w}_6) - [P_8 + (R_4 - a_4) \dot{w}_{15}] e^{-T_{4S}} = 0 \]

1-7: \[ P_8 + (R_4 + a_4) \dot{w}_{15} - [P_2 + a_4 (\dot{w}_4 - \dot{w}_6)] e^{-T_{4S}} = 0 \]

1-8: \[ P_3 + (R_5 + a_5) \dot{w}_7 - [P_2 + a_5 \dot{w}_6] e^{-T_{5S}} = 0 \]

1-9: \[ P_3 - a_6 \dot{w}_7 - [P_4 + (R_6 - a_6) \dot{w}_8] e^{-T_{6S}} = 0 \]

1-10: \[ P_4 - (R_7 + a_7) (\dot{w}_8 - \dot{w}_{10}) - [P_4 - (R_7 - a_7) (\dot{w}_8 - \dot{w}_{10})] e^{-2T_{7S}} = 0 \]

1-11: \[ P_4 - a_8 \dot{w}_{10} - [P_5 + (R_8 - a_8) \dot{w}_{11}] e^{-T_{8S}} = 0 \]

1-12: \[ P_5 (R_8 + a_8) \dot{w}_{11} - [P_4 + a_8 \dot{w}_{10}] e^{-T_{8S}} = 0 \]

1-13: \[ P_5 - a_9 \dot{w}_{12} - [P_6 + (R_9 - a_9) \dot{w}_{12}] e^{-T_{9S}} = 0 \]

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TABLE 1. (Continued)

\[ P_6 + (R_9 + a_9) \dot{w}_{12} - [P_5 + a_9 \dot{w}_{11}] e^{-T_9s} = 0 \]  \hspace{1cm} 1-14

\[ P_6 - a_{10} \dot{w}_{12} - [P_7 + (R_{10} - a_{10}) \dot{w}_{13}] e^{-T_{10s}} = 0 \]  \hspace{1cm} 1-15

\[ P_7 + (R_{10} + a_{10}) \dot{w}_{13} - [P_6 + a_{10} \dot{w}_{12}] e^{-T_{10s}} = 0 \]  \hspace{1cm} 1-16

\[ P_7 - Z_0 s \dot{w}_{14} - R_0 \dot{w}_{14} = P_0 \]  \hspace{1cm} 1-17

\[ sP_7 - \left( \frac{c^2}{gV} \right)_0 \dot{w}_{13} + \left( \frac{c^2}{gV} \right)_0 \dot{w}_{14} + \left( \frac{c^2}{gV} \right)_0 K_0 sP_7 = \left( \frac{c^2}{gV} \right)_0 K_0 sP_0 \]  \hspace{1cm} 1-18

\[ P_8 + a_{14} \dot{w}_{17} - [P_{12} - (R_{14} - a_{14}) \dot{w}_{24}] e^{-T_{14s}} = 0 \]  \hspace{1cm} 1-19

\[ P_{12} - (R_{14} + a_{14}) \dot{w}_{24} - [P_8 - a_{14} \dot{w}_{17}] e^{-T_{14s}} = 0 \]  \hspace{1cm} 1-20

\[ P_8 - a_{11} (\dot{w}_{15} + \dot{w}_{17}) - [P_9 + (R_{11} - a_{11}) \dot{w}_{18}] e^{-T_{11s}} = 0 \]  \hspace{1cm} 1-21

\[ P_9 + (R_{11} + a_{11}) \dot{w}_{18} - [P_8 + a_{11} (\dot{w}_{15} + \dot{w}_{17})] e^{-T_{11s}} = 0 \]  \hspace{1cm} 1-22

\[ P_9 - (R_{13} + a_{13}) (\dot{w}_{18} - \dot{w}_{19}) - [P_9 - (R_{13} - a_{13}) (\dot{w}_{18} - \dot{w}_{19})] e^{-2T_{13s}} = 0 \]  \hspace{1cm} 1-23

\[ P_9 - a_{12} \dot{w}_{19} - [X + R_{12} - a_{12}] \dot{w}_{20}] e^{-T_{12s}} = 0 \]  \hspace{1cm} 1-24

\[ P_{11} + (R_{15} + a_{15}) \dot{w}_{22} + [P_{11} + (R_{15} - a_{15}) \dot{w}_{22}] e^{-2T_{15s}} = 0 \]  \hspace{1cm} 1-25

\[ P_{11} - a_{16} \dot{w}_{22} - [P_{12} + (R_{16} - a_{16}) (\dot{w}_{24} + \dot{w}_{25})] e^{-T_{16s}} = 0 \]  \hspace{1cm} 1-26
TABLE I. (Continued)

\[ P_{12} + (R_{16} + a_{16}) (\dot{w}_{24} + \dot{w}_{25}) - [P_{11} + a_{16} \dot{w}_{22}] e^{-T_{16}^S} = 0 \] 1-27

\[ P_{13} + (R_{22} + a_{22}) \dot{w}_{34} + [P_{13} + (R_{22} - a_{22}) \dot{w}_{34}] e^{-2T_{22}^S} = 0 \] 1-28

\[ P_{13} - a_{24} \dot{w}_{36} - [P_{17} + (R_{24} - a_{24}) \dot{w}_{37}] e^{-T_{24}^S} = 0 \] 1-29

\[ P_{13} - (R_{23} + a_{23}) (\dot{w}_{34} - \dot{w}_{36}) - [P_{13} - (R_{23} - a_{23}) (\dot{w}_{34} - \dot{w}_{36})] e^{-2T_{23}^S} = 0 \] 1-30

\[ P_{12} - (R_{17} + a_{17}) \dot{w}_{25} - [P_{14} - a_{17} \dot{w}_{26}] e^{-T_{17}^S} = 0 \] 1-31

\[ P_{14} + a_{17} \dot{w}_{26} - [P_{12} - (R_{17} - a_{17}) \dot{w}_{25}] e^{-T_{17}^S} = 0 \] 1-32

\[ P_{17} - a_{21} (\dot{w}_{37} - \dot{w}_{38}) - [P_{14} + (R_{21} - a_{21}) \dot{w}_{27}] e^{-T_{21}^S} = 0 \] 1-33

\[ P_{14} + (R_{21} + a_{21}) \dot{w}_{27} - [P_{17} + a_{21} (\dot{w}_{37} - \dot{w}_{38})] e^{-T_{21}^S} = 0 \] 1-34

\[ P_{14} - a_{18} (\dot{w}_{26} + \dot{w}_{27}) - [P_{15} + (R_{18} - a_{18}) \dot{w}_{29}] e^{-T_{18}^S} = 0 \] 1-35

\[ P_{15} + (R_{18} + a_{18}) \dot{w}_{29} - [P_{14} + a_{18} (\dot{w}_{26} + \dot{w}_{27})] e^{-T_{18}^S} = 0 \] 1-36

\[ P_{15} - (R_{19} + a_{19}) (\dot{w}_{29} - \dot{w}_{31}) - [P_{15} - (R_{19} - a_{19}) (\dot{w}_{29} - \dot{w}_{31})] e^{-2T_{19}^S} = 0 \] 1-37

\[ P_{15} - a_{20} \dot{w}_{31} - [Y + (R_{20} - a_{20}) \dot{w}_{32}] e^{-T_{20}^S} = 0 \] 1-38

\[ P_{16} + (R_{20} + a_{20}) \dot{w}_{32} - [P_{15} + a_{20} \dot{w}_{31}] e^{-T_{20}^S} = 0 \] 1-39

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### TABLE 1. (Continued)

\[
\begin{align*}
    P_{17} - a_{25} \dot{w}_{38} - [P_{18} + (R_{25} - a_{25}) \dot{w}_{39}] e^{-T_{25}s} &= 0 \\
    P_{18} + (R_{25} + a_{25}) \dot{w}_{39} - [P_{17} + a_{25} \dot{w}_{38}] e^{-T_{25}s} &= 0 \\
    P_{18} - a_{26} \dot{w}_{39} - [P_{19} + (R_{26} - a_{26}) \dot{w}_{40}] e^{-T_{26}s} &= 0 \\
    P_{19} + (R_{26} + a_{26}) \dot{w}_{40} - [P_{18} + a_{26} \dot{w}_{39}] e^{-T_{26}s} &= 0 \\
    P_{19} - (R_{27} + a_{27})(\dot{w}_{40} - \dot{w}_{42}) - [P_{19} - (R_{27} - a_{27})(\dot{w}_{40} - \dot{w}_{42})] e^{-2T_{27}s} &= 0 \\
    P_{19} - a_{28} \dot{w}_{42} - [P_{20} + (R_{28} - a_{28}) \dot{w}_{43}] e^{-T_{28}s} &= 0 \\
    P_{20} + (R_{28} + a_{28}) \dot{w}_{43} - [P_{19} + a_{28} \dot{w}_{42}] e^{-T_{28}s} &= 0 \\
    P_{20} - a_{29} \dot{w}_{43} - [P_{21} + (R_{29} - a_{29}) \dot{w}_{44}] e^{-T_{29}s} &= 0 \\
    P_{21} + (R_{29} + a_{29}) \dot{w}_{44} - [P_{20} + a_{29} \dot{w}_{43}] e^{-T_{29}s} &= 0 \\
    P_{21} - a_{30} \dot{w}_{44} - [P_{22} + (R_{30} - a_{30}) \dot{w}_{45}] e^{-T_{30}s} &= 0 \\
    P_{22} + (R_{30} + a_{30}) \dot{w}_{45} - [P_{21} + a_{30} \dot{w}_{44}] e^{-T_{30}s} &= 0 \\
    P_{22} - Z_{F}^{s} \dot{w}_{46} - R_{F} \dot{w}_{46} &= P_{F} \\
    s P_{22} - \left( \frac{c^2}{gV} \right)_{F} (\dot{w}_{45} - \dot{w}_{46}) + \left( \frac{c^2}{gV} \right)_{F} K_{F} s P_{22} = \left( \frac{c^2}{gV} \right)_{F} K_{F} s P_{F}^{P} 
\end{align*}
\]

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TABLE 1. (Concluded)

\[ P_4 + (R_6 + a_6) \dot{w}_8 - [P_3 + a_6 \dot{w}_7] e^{-T_{6s}} = 0 \]  
1-53

\[ P_{10} + (R_{12} + a_{12}) \dot{w}_{20} - [P_{9} + a_{12} \dot{w}_{19}] e^{-T_{12s}} = 0 \]  
1-54

\[ P_{17} + (R_{24} + a_{24}) \dot{w}_{37} - [P_{13} + a_{24} \dot{w}_{36}] e^{-T_{24s}} = 0 \]  
1-55

\[ X = P_{10} \]  
1-56

\[ Y = P_{16} \]  
1-57

\textbf{NOTE:} \quad a_n = \frac{c_n}{A_{ng}}
It should be noted that the hydrodynamics subprogram solves the complete system of 57 equations (describing the complete Fig. 4 feed system) each time it is called. Thus the frequency response of the entire system is calculated each time. It has been shown, however, that simpler feed systems, representing only a portion of the Fig. 4 schematic, can be modeled by merely assigning values to the parameters of the unneeded line segments which will exclude them from any effect on the system frequency response. This is accomplished automatically by the hydrodynamics subprogram via the assignment of very large resistances and very short lengths to all line segments for which no data is entered.
COMBUSTION DYNAMICS

Analytical Approach

In the past, the combustion response has been modeled with a simple time delay(s) (Ref. 3 through 9). This time delay represents the time required for the propellants to travel at their injected velocity from the point where they are injected to another point where they burn, and implies the burning is concentrated at a fixed plane some arbitrary distance from the injector face. The procedure outlined above is obviously an oversimplification of the burning process which is distributed in some fashion throughout the combustion chamber.

Steady-state combustion models (Ref. 10 and 11 for example) provide insight to determine the droplet burning distribution as well as additional information required to relate the distribution to a combustion response as a function of frequency. Combustion models are designed to march incrementally down the combustion chamber from a set of specified initial conditions. In so doing, the model calculates the rate at which the propellants are consumed as a function of the axial position in the combustion chamber (burning rate profile).

The analytical technique selected to describe the combustion dynamics is based on employing the mathematical expressions used in the steady-state combustion models (in particular the JANNAF DER program, Ref. 11). These mathematical expressions are expanded into time average and oscillatory components and are described in the following sections.

Atomization Process

A very essential part of the combustion field initialization is the assignment of propellant spray droplet sizes and flowrates. Analytical descriptions of the atomization process are not available but empirical correlations that relate droplet diameter to injector geometry and flow conditions are available (Refs. 12, 13, and 14). For like-doublets, one empirical relationship is (Ref. 12).

\[ D_d = 4.85 \times 10^4 \ v_j^{-0.75} \ (p_c/p_j)^{-0.52} \ d_j^{0.57} \]  

(46)
where $v_j$ is the liquid jet velocity and $d_j$ is the liquid jet diameter at the atomization plane. (For steady-state analysis, the velocity is the injection velocity and the diameter is the orifice diameter.)

For purposes of the current analysis, the atomization process is described by:

$$D_d = K(d_j)^a (v_j)^b x=x_{imp}$$

where $x_{imp}$ is the location of the atomization plane or the impingement point. Expanding Eq. 47 into time-averaged and oscillatory parts, yields the oscillatory droplet diameter

$$\frac{\partial \tilde{D}_d}{\partial t} = a \left( \frac{\partial \tilde{d}_j}{\partial t} \right)_{x=x_{imp}} + b \left( \frac{\tilde{v}_j}{v_j} \right)_{x=x_{imp}}$$

In order to evaluate the oscillatory droplet diameter, the oscillatory liquid jet diameter and velocity (and therefore the jet flowrate) are required at the atomization plane. Therefore, the dynamics of the fluid from the injector to the atomization plane is required and outlined in the following section.

**Klystron Effect**

The dynamics of the liquid propellant jet from the injector face to any location in the chamber are described by the continuity and momentum equations:

$$\frac{\partial}{\partial t} (A_j \rho_j) + \frac{\partial}{\partial x} (A_j \rho_j v_j) = 0$$

$$\frac{\partial}{\partial t} (A_j \rho_j v_j) + \frac{\partial}{\partial x} \left( A_j \rho_j v_j^2 \right) = -A_j \frac{\partial p}{\partial x}$$

Assuming

$$\rho_j = \text{constant}$$

$$\frac{\partial p}{\partial x} = 0$$

$$\phi = \phi + \phi$$ (\phi any variable),

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where
\[ \phi = f(x) \] (time average value) \hspace{1cm} (54)
\[ \phi' = g(x), \] (oscillatory value) \hspace{1cm} (55)
\[ \phi'' = h(x), \] (time average value) \hspace{1cm} (56)

the preceding equations can be expanded into time average and oscillatory parts and integrated between the injector face and any location in the chamber to yield:

\[
\left( \frac{\bar{v}_j}{v_j} \right) = e^{i\omega x/v_j} \left( \frac{\bar{m}_j}{\bar{m}_j} \right)_{inj} \hspace{1cm} (57)
\]

\[
\left( \frac{\bar{A}_j}{A_j} \right) = \frac{-i\omega x}{v_j} \left( \frac{\bar{m}_j}{\bar{m}_j} \right)_{inj} \hspace{1cm} (58)
\]

\[
\left( \frac{\bar{m}_j}{\bar{m}_j} \right) = e^{i\omega x/v_j} \left[ 1 - \frac{i\omega x}{v_j} \right] \left( \frac{\bar{m}_j}{\bar{m}_j} \right)_{inj} \hspace{1cm} (59)
\]

where \( \omega \) is the angular frequency and the oscillatory injection rate, \( (\bar{m}_j)_{inj} \), is determined by the feed system dynamics. Equation 59 is the oscillatory jet flowrate at \( x \) and is usually referred to as the Klystron effect (Ref. 15). The Klystron time delay, \( \tau_K \), is therefore given by

\[
\tau_K = \frac{x_K}{v_j} \hspace{1cm} (60)
\]

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Considerable amplification of the injector face flow oscillations are possible when the Klystron effect is present and could explain the periodic burst of acoustic resonances called resurging and the steep-fronted waves seen in low and intermediate frequency instabilities.

**Droplet Vaporization**

Theories of droplet combustion (Refs. 10, 16, 17) are available which may be used to evaluate the extent of coupling between droplet burning rate and local pressure and velocity fluctuations. In general, droplet burning is enhanced by increased turbulence levels or by periodic directional variations in velocity, because droplets are relatively heavy and resist following gas streamlines.

Calculation of the spray heating and vaporization is usually accomplished through specification of the corresponding individual droplet processes and summation over all the droplets that constitute the spray(s) being analyzed. The calculation of single droplet evaporation is usually based on a spherically symmetric model of simultaneous heat transfer and mass transfer across the gas side boundary, or film, separating the liquid droplet from the surrounding hot combustion gas. Forced convection and resultant nonspherical transfer processes are accounted for through empirical Nusselt number correlations for both heat and mass transfer.

For the fuel or oxidizer spray, the droplet continuity equation is

\[
\frac{d}{dx} (A_k v_k) = -A_k N_k \dot{m}_{vap_k} \tag{61}
\]

and the vaporization rate is (Ref. 10)

\[
\dot{m}_{vap_k} = \frac{\pi D_k k_{f_k} N_{u_k} Z_k}{C_{p_k}} \tag{62}
\]

where \( p_k \) is the spray density (mass of spray per unit chamber volume), \( N_k \) is the number of droplets per unit chamber volume, and
\[ Z_k = \frac{c_p v_k N_k m_k p M W_{v_k}}{k_f k k_f N_k R T_{f_k} v_k} \ln \left( \frac{p}{p - p_{v_k}} \right) \]  
Equation (63)

Noting that
\[ \rho_k = N_k m_k = N_k \rho_{z_k} \frac{4D_k^3}{3} \]  
Equation (64)

the droplet number flowrate can be written as
\[ \dot{N}_k = v_k A N_k = \frac{A v_k \rho_k}{m_k} \]  
Equation (65)

Therefore, Eq. 61 can be written as
\[ \frac{d}{dx} (m_k \dot{N}_k) = -\frac{\dot{N}_k}{v_k} m_{vap_k} \]  
Equation (66)

For steady-state combustion models, the preceding equation (along with Eq. 62) is numerically integrated allowing the droplet diameter, \( D_k \), to vary along the length of the combustion and maintaining constant droplet number flowrate (\( \dot{N}_k \)). Combs (Ref. 18) has shown that changing from a variable droplet diameter to a variable droplet number flowrate yields approximately the same results for steady-state vaporization. Therefore, in order to simplify the integration for stability analysis, the droplet diameter was held constant and the droplet number flowrate was assumed to vary.

Summing Eq. 61 over all fuel or oxidizer droplet size groups yields
\[ \sum_k \frac{d}{dx} (A \rho_k v_k) = -A \sum_k \rho_k \frac{m_{vap_k}}{m_k} = -A \sum_k \frac{\rho_k (6) Z_k k_f k N_k}{\rho_{z_k} D_k^2 c_{p v_k}} \]  
Equation (67)
which can be written as

\[
\frac{d}{dx} \left( A_p v_s \right) = - \frac{A_p}{\tau_s} = - A \dot{m}_{\text{vap}}
\]  

(68)

where

\[
\rho_s = \sum_k \rho_k
\]  

(69)

\[
v_s = \frac{1}{\rho_s} \sum_k (\rho_k v_k)
\]  

(70)

\[
\frac{1}{\tau_s} = \frac{1}{\rho_s} \sum_k \left( \frac{\rho_k (6) Z_k}{\rho_s} \right) \frac{k_f}{k_c \rho_{v_k}} \frac{\text{Nu}_k}{k_c}
\]  

(71)

Letting \(Z_k, k_f, \rho_{v_k}\) be independent of \(k\) and assuming

\[\tau_s = f(t)\]

(72)

yields:

\[
\tau_s = \frac{\rho_s c_{v_s} D_s^2}{(6) Z_s k_f \text{Nu}_s}
\]  

(73)

where

\[
D_s^2 = \left( \dot{m}_s \right)_{\text{inj}} \sqrt{\sum_k \left( \frac{m_k}{D_k^2} \right)_{\text{inj}}}
\]  

(74)

From Eq. 68

\[
\frac{d(A_p v_s)}{A_p v_s} = \frac{dx}{\tau_s v_s}
\]  

(75)
Integrating Eq. 75 between \( x_0 \), the start of vaporization plane, and any location \( x \) yields

\[
A_T V_s = (m_s)_{x=x_0} \exp \left[ - \int_{x_0}^{x} \frac{dx}{\tau_S V_s} \right]
\]  

(76)

substituting Eq. 76 into Eq. 68 yields the fuel or oxidizer spray vaporization rate:

\[
m_{\text{vap}} = \frac{(m_s)_{x=x_0}}{A_T V_s} \exp \left[ - \int_{x_0}^{x} \frac{dx}{\tau_S V_s} \right]
\]  

(77)

Using perturbation techniques, the time average vaporization rate can be written as

\[
m_{\text{vap}} = \frac{(m_s)_{x=x_0}}{A_T V_s} \exp \left[ - \left( \frac{x-x_0}{\tau_S V_s} \right) \right]
\]  

(78)

and the oscillatory vaporization rate can be written as

\[
m_{\text{vap}} = \frac{(m_s)_{x=x_0}}{A_T V_s} \left\{ \frac{\tilde{V_s}}{V_s} + \left( \frac{\tau_S}{\tau_s} - \frac{\tilde{V_s}}{V_s} \right) \right\}
\]  

(79)

Assuming

\[
V_s \approx (V_s)_{x=x_k}
\]  

(80)

yields

\[
\frac{\tilde{V_s}}{V_s} \approx \frac{V_s}{V_s} \left( \frac{(V_s)}{V_s} \right)_{x=x_k}
\]  

(81)
Letting \( \rho_s, c_p, k_f \) be constant, the oscillatory time delay can therefore be expressed as

\[
\frac{\tilde{\tau}_S}{\tau_S} = 2 \frac{\tilde{D}_S}{D_s} - \frac{\tilde{Z}_S}{Z_s} - \frac{\tilde{\text{Nu}}_H_S}{\text{Nu}_H_S} + \left( \frac{\partial T_S}{\partial \text{MR}} \right) \frac{\tilde{\text{MR}}}{\tau_S}
\]  

(82)

The oscillatory spray droplet diameter (\( D_s \)) is given by Eq. 48 and the oscillatory flowrate is given by Eq. 59. The above formulation results in a linear oscillatory vaporization model similar to, but more realistic than Crocco's n-t model (Ref. 4). The formulation includes the effects of: (1) distributed energy release, (2) oscillations in the injection rate, (3) oscillations in droplet diameter, (4) oscillations in droplet temperature, (5) gas pressure and velocity oscillations, and (6) oscillations in the local mixture ratio.

**Nusselt Number.** It may be observed that one of the dominant terms in both the expressions for the average and oscillatory time delay is the Nusselt number. The Nusselt number, for longitudinal modes, is (Ref. 19).

\[
\text{Nu}_H_S = 2.0 + 0.6 \frac{\rho D_s}{\mu} \left\{ \sqrt{\frac{\rho D_s}{\mu}} \left| v - v_s \right| \right\}^{1/2}
\]  

(83)

In order to evaluate the oscillatory Nusselt number, the oscillatory droplet spray velocity is required. The droplet spray velocity can be obtained from the drag equation.

\[
m_s \frac{dv_s}{dt} = \frac{\pi}{8} \rho D_s^2 \left| v - v_s \right| (v - v_s) C_D
\]  

(84)
Letting
\[
\tau_{\text{drag}} = \frac{\rho_s D_s^2}{\alpha_s \mu}
\]  
\[\text{(85)}\]

where
\[
\alpha_s = \frac{C_D}{24} \left( \frac{D_s \rho}{\mu} |v - v_s| \right)
\]  
\[\text{(86)}\]

the oscillatory droplet spray velocity can be written as
\[
\tilde{v}_s = \left[ \frac{1 + i \omega \tau_{\text{drag}}}{1 + (\omega \tau_{\text{drag}})^2} \right] \tilde{v} = \rho v_s \tilde{v}
\]  
\[\text{(87)}\]

Defining
\[
F_\rho = \left( \frac{\rho_s}{\rho} \right), \quad F_{v_s} = \left[ \frac{|v - v_s|}{\Delta M_s} \right]^{1/2}
\]  
\[\text{(88)}\]

where
\[
\Delta M_s = \left[ \frac{|v - v_s|}{c} \right]^{\text{steady state}}
\]  
\[\text{(89)}\]

the Nusselt number can be written as
\[
Nu_{H_s} = 2.0 + 0.6 \left( Pr_s \right)^{1/3} \left[ \frac{\rho_s D_s}{\mu} c \Delta M_s \right]^{1/2} F_\rho F_{v_s} \left( \frac{D_s}{\bar{D}_s} \right)^{1/2}
\]  
\[\text{(90)}\]

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Expanding the preceding equation into time average and oscillatory parts yields

\[
\overline{\text{Nu}}_{H_S} = 2.0 + 0.6 \text{Pr}_S^{1/3} \left[ \frac{\overline{\rho D_s}}{\mu \text{c}} \right]^{1/3} \frac{1}{F_p F_v} \]  
(91)

\[
\frac{\tilde{\text{Nu}}_{H_S}}{\overline{\text{Nu}}_{H_S}} = \left( \frac{\text{Nu}_{H_S}}{\overline{\text{Nu}}_{H_S}} - 2 \right) \left[ \frac{1}{2} \left( \frac{\tilde{D}_s}{D_s} \right) + \frac{\tilde{F}_t}{F_t} + \frac{\tilde{F}_v}{F_v} \right] \]  
(92)

Letting

\[
\frac{\tilde{F}_v}{F_v} = R_F \frac{\tilde{v}}{\bar{c}} , \text{ and} \]  
(93)

\[
\frac{\tilde{F}_t}{F_t} = R_F \frac{\tilde{\rho}}{\bar{\rho}} , \]  
(94)

the oscillatory Nusselt number is

\[
\frac{\tilde{\text{Nu}}_{H_S}}{\overline{\text{Nu}}_{H_S}} = \frac{\text{Nu}_{H_S}^{2}}{\overline{\text{Nu}}_{H_S}} \left[ \frac{1}{2} \left( \frac{\tilde{D}_s}{D_s} \right) + R_F \frac{\tilde{\rho}}{\bar{\rho}} + R_F \frac{\tilde{v}}{\bar{c}} \right] \]  
(95)

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For small perturbations in the pressure, the linear response factors and the time average values for $F_P$ and $F_V$ are

$$F_P = 1, F_V = 1$$

$$R_{F_P} = \frac{1}{2}, R_{F_V} = \frac{1}{2} \left( \frac{1 - R_V}{\Delta M_s} \right)$$

(96) (97)

Calculations have been made which indicate that, for large droplet diameters, the average and oscillatory Nusselt numbers are quite sensitive to pressure and velocity oscillations. Therefore, the Nusselt number can have a significant effect on engine stability.

**Droplet Heat Transfer Blockage Term.** The oscillatory combustion time delay given by Eq. 82 requires the evaluation of the heat transfer blockage term ($Z_s$) which is related to the combustion gas and liquid vapor properties by Eq. 63. Because the vapor pressure ($P_{Vs}$) at the droplet surface is related to the droplet temperature, the blockage term also depends on the oscillatory droplet surface temperature inside the droplet which is given by:

$$\frac{\partial}{\partial t} \left( \rho \, c_v \, T_s \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \, k_{eff} \, \frac{\partial T_s}{\partial r} \right)$$

(98)

Therefore, the oscillatory heat transfer rate to the droplet can be related to the oscillatory droplet surface temperature by

$$\dot{Q}_s = R_{T_s} \, \dot{T}_s$$

(99)

The droplet heating rate can also be written as (Ref. 10)

$$Q_s = Z_s \, k_{f_s} \, N_{H_s} \left[ \frac{(T - T_s)}{Z_s} - \frac{\Delta H_{\text{Vad}}}{c_{p_{Vs}}} \right] \left( \pi D_s \right)$$

(100)

Assuming that

$$\left( \frac{dT_s}{dt} \right) = 0$$

(droplet at "wet bulb" temperature)

(101)

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and
\[
\frac{\tilde{p}_V}{p_V} = R_p \frac{\tilde{p}}{p}
\]

etc. for the other variables, the response factor for the heat transfer blockage term can be related to droplet and gas properties and flow conditions.

Examination of the response factor for the heat transfer blockage term indicates that this term is not important at low frequencies (also see Ref. 20 and 21). Therefore, the oscillatory heat blockage term has not been included in the computer program. Detailed equations for this term are presented in Appendix B of Ref. 1.

Generalized Vaporization Rate Expression

In order to maintain generality in representing the combustor dynamics, the spray vaporization rates (fuel and oxidizer) were written as:

\[
\dot{m}_{\text{vap}} = \dot{m}_{\text{vap}} \left[ c_1 \left( \frac{n}{R} \right) + c_2 \left( \frac{\tilde{p}}{p} \right) + c_3 \left( \frac{\tilde{p}}{p} \right) \right. \\
+ c_4 \left( \frac{\tilde{p}}{p} \right) + c_5 (MR)_{x=0} + c_6 (MR) \\
+ c_7 \left( \frac{\tilde{p}}{p} \right) + c_8 \left( \frac{\tilde{p}}{c} \right) + \int_{x=0}^{x} \left[ c_9 \left( \frac{\tilde{p}}{p} \right) \right. \\
+ c_{10} \left( \frac{\tilde{p}}{p} \right) + c_{11} \left( \frac{\tilde{p}}{c} \right)_{x=0} + c_{12} (\tilde{p}) + c_{13} (MR)_{x=0} \\
+ c_{14} (MR) + c_{15} (\tilde{p}) + c_{16} (\tilde{p} \frac{c}{c})_{x=0} + c_{17} (\tilde{p} \frac{c}{c}) \left. \right] \frac{dx}{\tau_s \tilde{V}_s}
\]

Combining the expressions of the preceding sections with this generalized vaporization rate expression yielded the combustion coefficients:

\[
c_1 = R_n - R_v - 2 R_D + \left( \frac{Nu_s - 2}{Nu_s} \right) \frac{R_D}{2}
\]

\[
c_4 = R_F \left( \frac{Nu_s - 2}{Nu_s} \right)
\]

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\[ c_{6s} = -\left(\frac{a}{3MR}\right) \frac{1}{\tau_s} \]  
\[ c_{8s} = R_{FV_s}\left(\frac{Nu_s - 2}{Nu_s}\right) \]  
\[ c_{9s} = 2R_{D_s} - \left(\frac{Nu_s - 2}{Nu_s}\right) \frac{R_{D_s}}{2} + R_{V_s} \]  
\[ c_{12s} = -c_{4s} \]  
\[ c_{14s} = -c_{6s} \]  
\[ c_{16s} = -c_{8s} \]  
\[ c_2 = c_3 = c_5 = c_7 = c_{10} = c_{11} = c_{13} = c_{15} = 0 \]

where the subscript \( s \) denotes the fuel or oxidizer and

\[ R_{m_s} = G_{inj_s} \left(1 - \frac{i\omega x_{ks}}{v_s}\right) \]  
\[ R_{u_s} = G_{inj_s} \]  
\[ R_{D_s} = \left[b_s - a_s \frac{i\omega x_{imp_s}}{v_s}\right] G_{inj_s} \]

In the above expressions \( G_{inj_s} \) is the oscillatory injection rate divided by the oscillatory pressure at the injector face and is calculated by the hydrodynamics subprogram.

The main function of the combustion dynamics subprogram is the calculation of the combustion coefficients. The general spray vaporization rate expressions are used in the chamber dynamic subprogram which is discussed in the following section.
CHAMBER DYNAMICS

Analytical Approach

Two methods of approach were considered for solving the chamber dynamics. The first method used a linear lump chamber coefficient. This method is valid only at low frequencies (less than 500 Hz) and results in a set of nonlinear algebraic equations to be solved.

The second method employed a first-order perturbation model to define the chamber frequency and growth coefficient along with the oscillatory pressure distribution in the chamber. This method is valid for all frequencies of interest in the present program (10 to 1000 Hz). For the oscillatory variables, solutions of the form \( \phi = \phi' e^{-i\omega t} \), where \( \omega \) is the complex frequency, were assumed. These forms yielded a set of nonlinear differential equations which were numerically integrated between the injector face and the nozzle inlet plane. Using iteration techniques and the requisite boundary conditions at the injector and nozzle inlet plane, the chamber frequency and growth coefficient are obtained.

Consideration of the degree of complexity in solving the governing equations by each of the above methods as well as the range of validity of each approach resulted in choosing the first-order perturbation models as the best method for describing the chamber dynamics. In the following paragraphs, the derivation and solution to the first-order perturbation model stability equations are presented.

First-Order Perturbation Model

In this section, chamber model equations are stated without showing their detail derivations. Complete derivation of the basic equations is presented in Ref. 1. Assumptions used in the derivation of the basic equations are: (1) ideal gas flow is a valid state equation; (2) dilute sprays occupy a negligible fraction of chamber volume; (3) the spray can be represented by a finite number of dropsize groups; each dropsize group contains a large number of locally identical drops; and, each size group constitutes a separate liquid phase and exchange terms between liquid phases are not included; (4) drag contributes only kinetic energy to the spray energy equation; (5) secondary "shear" breakup of...
drops is not included; (6) negligible coupling between diffusion and thermal gradients; and (7) no body forces.

The following equations can be formulated for the gas phase:

**Gas Continuity**

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = \sum_n \sum_j \left( N_j^n \cdot \mathbf{n} \right)
\]

\[ \text{Equation (116)} \]

**Gas Momentum**

\[
\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\mathbf{p} + \nabla \cdot \mathbf{t}
\]

\[ \sum_n \sum_j \left[ N_j^n \left( F_j^n - m_{\text{vap}_j} \mathbf{u}_j^n \right) \right] \]

\[ \text{Equation (117)} \]

**Equation of State**

\[ p = \rho RT \]

\[ \text{Equation (118)} \]

**Shear Stress**

\[ \mathbf{t} = -\nu_{\text{eff}} \left[ \mathbf{v} \mathbf{u} + (\mathbf{v} \mathbf{u})^T - \frac{2}{3} (\nabla \cdot \mathbf{u}) \mathbf{I} \right] \]

\[ \text{Equation (119)} \]

**Gas Energy**

\[
\frac{\partial}{\partial t} \left[ \rho \left( h + \frac{u^2}{2} \right) \right] + \nabla \cdot \left[ \rho \mathbf{u} \left( h + \frac{u^2}{2} \right) \right]
\]

\[ = -\mathbf{v} \cdot \mathbf{q} + \mathbf{v} \cdot (\mathbf{u} \mathbf{u}) + \frac{\partial p}{\partial t} \]

\[ + \sum_n \sum_j \left\{ N_j^n \left[ m_{\text{vap}_j} \left( h_j + \frac{(u_j^n)^2}{2} \right) \right] \right\} \]

\[ - Q_j^n - u_j^n \cdot \mathbf{f}_j^n \}

\[ \text{Equation (120)} \]
Gas Mixture Ratio

\[
\frac{\partial}{\partial t} (\rho \text{MR}) + \nabla \cdot (\rho \underline{u} \text{MR}) = \]

\[
- \rho \frac{\phi}{\text{eff}} \left[ v^2 \text{MR} - \frac{2|v| \text{MR}^2}{\text{MR} + 1} \right] \]

\[
- (\nabla \text{MR}) \cdot \nabla (\rho \frac{\phi}{\text{eff}}) = \]

\[
(2 \text{MR} + 1) \left[ \sum_{n} \sum_{j} N_j n_{\text{m}_{\text{vap},j}} \right] \]

\[
- (\text{MR})^2 \left[ \sum_{n} \sum_{j} N_j n_{\text{m}_{\text{vap},j}} \right] \]

Heat Transfer Rate

\[
\dot{q} = -k_{\text{eff}} \nabla T - \sum_{i} (\rho \frac{\phi}{\text{eff}}) h_i \nabla y_i \]

Drag Force

\[
\vec{F}_j = \frac{\pi}{8} \left\{ \rho \left( D_j \right)^2 \left| \vec{u} - \vec{u}_j \right| \left( \vec{u} - \vec{u}_j \right) \right\} \]

Assuming

(1) Diffuser, thermal and viscous gradients are negligible,
(2) Droplet drag forces and heat transfer to the droplets are negligible,
(3) Droplet velocities are approximately equal to the gas velocity,

and letting

\[
h = \left( \frac{C_p}{R} \right) \phi \text{RT} + (h_{\text{ref}}) + \left( \frac{\partial h}{\partial \text{MR}} \right) \phi (\text{MR} - \text{MR}_\phi), \]

\[
-C_p R \phi = \frac{\gamma_{\phi}}{\left( \gamma_{\phi} - 1 \right)}, \]

\[
R = R_{\phi} + \left( \frac{\partial R}{\partial \text{MR}} \right) \phi (\text{MR} - \text{MR}_\phi), \]

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\[ \dot{m}_{\text{vap}_\text{ox}} = \sum_n \sum_j N_j^n \dot{m}_{\text{vap}_j} \quad (127) \]

\[ \dot{m}_{\text{vap}_\text{fu}} = \sum_n \sum_j N_j^n \dot{m}_{\text{vap}_j} \quad (128) \]

where the subscript \( \phi \) denotes that the properties are evaluated based on the overall injection mixture ratio during steady-state operation, the preceding equations can be simplified for longitudinal modes to

**Gas Continuity**

\[ \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} (\rho \gamma v) = A (\dot{m}_{\text{vap}_\text{ox}} + \dot{m}_{\text{vap}_\text{fu}}) \quad (129) \]

**Gas Momentum**

\[ \rho \frac{\partial v}{\partial t} + \rho v \frac{\partial v}{\partial x} = 0 \quad (130) \]

**Equation of State**

\[ p = \rho T \left[ R_\phi + \left( \frac{\partial R}{\partial \text{MR}^\phi} \right)_\rho (\text{MR} - \text{MR}^\phi) \right] \quad (131) \]

**Gas Energy**

\[ \frac{\partial \rho}{\partial t} + A v \frac{\partial}{\partial x} \rho + \frac{\partial}{\partial x} (\rho v) (Av) = \]

\[ (\gamma - 1) A \left\{ \dot{m}_{\text{vap}_\text{ox}} \left[ \Delta h_{\text{ox}} - \left( \frac{\partial h}{\partial \text{MR}^\phi} \right)_\phi (2 \text{MR} + 1) \right] + \dot{m}_{\text{vap}_\text{fu}} \left[ \Delta h_{\text{fu}} + \left( \frac{\partial h}{\partial \text{MR}^\phi} \right)_\phi (\text{MR})^2 \right] \right\} \quad (132) \]

**Gas Mixture Ratio**

\[ \rho \frac{\partial \text{MR}}{\partial t} + \rho v \frac{\partial \text{MR}}{\partial x} = \rho_0 (\text{MR} + 1) \left[ \dot{m}_{\text{vap}_\text{ox}} - (\text{MR}) \dot{m}_{\text{vap}_\text{fu}} \right] \quad (133) \]
Because of the complexity in solving nonlinear partial differential equations, perturbation techniques were used to simplify the governing dynamic equations. Assuming

\[ \phi = \phi + \tilde{\phi} \quad (\phi \text{ any variable}), \quad (134) \]

where

\[ \phi = f(x) \quad (135) \]

and

\[ \tilde{\phi} = g(x, t), \quad (136) \]

each perturbation quantity was taken to be of order \( \varepsilon \), where \( \varepsilon \) is a small ordering parameter that is a measure of the wave amplitude. The perturbation expressions for each of the independent variables were substituted back into the nonlinear partial differential equations, where all terms of the order \( \varepsilon^2 \) or higher were neglected. The resulting time-averaged equations were solved for the time-averaged variables and the oscillatory equations were solved by assuming solutions of the form

\[ \tilde{\phi} = \phi' e^{-i\omega t} \quad (137) \]

where \( \phi' = f(x) \) and \( \omega \) is the complex frequency. The resulting equations form a system of ordinary differential equations in terms of the variables \( \phi' \) and can be numerically integrated by employing boundary conditions and iteration techniques.

Following this approach the perturbation equations were expressed as:

\[ \rho = \rho' \left[ 1 + \rho' e^{-i\omega t} \right] \quad (138) \]
\[ v = v' \left[ 1 + v' e^{-i\omega t} \right] \quad (139) \]
\[ T = T' \left[ 1 + T' e^{-i\omega t} \right] \quad (140) \]

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\[ p = \bar{p} \left[ 1 + p' e^{-i\omega t} \right] \quad (141) \]
\[ MR = \bar{MR} + MR' e^{-i\omega t} \quad (142) \]
\[ \dot{m}_{vap_{ox}} = \bar{\dot{m}}_{vap_{ox}} + \dot{m}'_{vap_{ox}} e^{-i\omega t} \quad (143) \]
\[ \dot{m}_{vap_{fu}} = \bar{\dot{m}}_{vap_{fu}} + \dot{m}'_{vap_{fu}} e^{-i\omega t} \quad (144) \]

The time-averaged equations were determined to be:

(a) Gas Continuity
\[ \frac{d}{dx} \left( A \bar{\rho} \bar{v} \right) = A \left( \bar{\dot{m}}_{vap_{ox}} + \bar{\dot{m}}_{vap_{fu}} \right) \quad (145) \]

(b) Gas Momentum
\[ \bar{\rho} \bar{v} \frac{d\bar{v}}{dx} + \frac{d\bar{p}}{dx} = 0 \quad (146) \]

(c) Equation of State
\[ \bar{p} = \bar{\rho} R \bar{T} \left[ 1 + \frac{1}{\bar{\rho}} \left( \frac{\partial R}{\partial MR} \right) (MR - MR) \right] \quad (147) \]

(d) Gas Energy
\[ A \bar{v} \frac{d\bar{p}}{dx} + \gamma \bar{\rho} \frac{d}{dx} (A \bar{v}) = \]
\[ (\gamma - 1) A \left\{ \bar{\dot{m}}_{vap_{ox}} \left[ \Delta h_{ox} - \left( \frac{\partial h}{\partial MR} \right) (2MR + 1) \right] \right. \]
\[ + \bar{\dot{m}}_{vap_{fu}} \left[ \Delta h_{fu} + \left( \frac{\partial h}{\partial MR} \right) (MR) \right] \}
\[ (148) \]

(e) Gas Mixture Ratio
\[ \bar{\rho} \bar{v} \frac{dMR}{dx} = (MR + 1) \left[ \bar{\dot{m}}_{vap_{ox}} - MR \bar{\dot{m}}_{vap_{fu}} \right] \quad (149) \]
and the oscillatory equations were determined to be:

(a) Gas Continuity

\[
\rho' \left(-i\omega \frac{\partial}{\partial \phi}\right) + \frac{\partial v' \rho'}{\partial x} + \frac{v' \rho'}{\rho'} \frac{\partial (A\rho)}{\partial x} + \frac{\partial \rho'}{\partial x} \frac{\partial (A\rho \cdot v)}{\partial x} = \frac{(m_{vap_{ox}} + m_{vap_{fu}})}{\rho \rho'} \tag{150}
\]

(b) Gas Momentum

\[
v' \left(-i\omega \frac{\partial}{\partial \phi}\right) + \frac{\partial v' \partial v}{\partial x} + \frac{\partial v' \rho}{\partial x} \frac{\partial v}{\partial x} + \frac{\partial \rho'}{\partial x} \frac{\partial \rho}{\partial x} = 0 \tag{151}
\]

(c) Equation of State

\[p' = \rho' + T' + \frac{\rho T}{p} \left(\frac{\partial R}{\partial MR}\right) \phi \tag{152}
\]

(d) Gas Energy

\[
p' \left(-i\omega \frac{\partial}{\partial \phi}\right) + \frac{\partial v' \rho'}{\partial x} \left[\frac{\partial \rho'}{\partial x} + \frac{\partial \rho}{\partial x} \frac{\partial p}{\partial x}\right] + \frac{\partial v' \rho}{\partial x} \left[\frac{\partial v}{\partial x} + \frac{\partial v}{A} \frac{\partial A}{\partial x}\right] + \frac{\partial \rho'}{\partial x} \frac{\phi}{A} \frac{\partial A}{\partial x} (A \cdot v) = \frac{(\gamma - 1)}{\rho} \frac{\partial G}{\partial \phi} \left\{m_{vap_{ox}} \Delta h_{ox}\right\}
\]
\[- \left( \frac{\partial h}{\partial MR} \right)_\phi \left( 2MR + 1 \right) \right] + \dot{m}_{\text{vap}} + \\Delta h_{\text{fu}} \]
\[+ \left( \frac{\partial h}{\partial MR} \right)_\phi \left( MR \right)^2 - 2 \dot{m}_{\text{vap}} \left( \frac{\partial h}{\partial MR} \right)_\phi MR' \]
\[+ 2 \dot{m}_{\text{vap}} \left( \frac{\partial h}{\partial MR} \right)_\phi \left( \frac{\partial h}{\partial MR} \right)_\phi MR' \right) \]
\[(153)\]

\[\text{(e) Gas Mixture Ratio} \]
\[MR' \left( \frac{-i\omega}{c} \right) + \left( \frac{\nu}{c} \right)_\phi \frac{dMR'}{dx} + \left[ \left( \frac{\nu}{c} \right)_\phi \rho' + \nu' \right] \frac{dMR}{dx} \]
\[= \left( \frac{MR + 1}{\rho c} \right) \left[ \dot{m}'_{\text{vapox}} - MR \dot{m}'_{\text{vapfu}} \right] \]
\[+ \frac{1}{\rho c} \left[ \dot{m}'_{\text{vapox}} - (2MR + 1) \dot{m}'_{\text{vapfu}} \right] (MR') \]
\[(154)\]

In the computer model, the preceding set of ordinary differential equations are numerically integrated between the injector face and the nozzle inlet plane. The method of calculating the complex frequency for the perturbation model, based on nozzle admittances calculated from upstream and downstream variables, is discussed in the Engineering Model section.

Steady-State Solution

The boundary conditions for the steady-state differential equations are

\[x = x_0 \quad (155)\]
\[p = p_c \quad (156)\]
\[\nu_x = \nu_x = 0 \quad (157)\]
\[MR_x = MR_x = 0 \quad (if \nu_x = 0 \neq 0) \quad (158)\]
\[\left( A_\nu \nu_x \right)_x = (m)_x = 0 \quad (if \nu_x = 0 \neq 0) \quad (159)\]
Assuming small Mach numbers, i.e., \( M^2 \ll 1 \), the steady-state differential equations can be integrated between the start plane for vaporization \( (x_0) \) and any location \( (x) \) to yield

\[
\bar{p} = \text{constant} = p_c
\]

\[
\bar{M} = \frac{\left( \frac{\bar{M}}{1+\bar{M}} \right)}{\left( \frac{1}{1+\bar{M}} \right)} \left( A\bar{\rho} \bar{v} \right)_{x=0} + (\bar{m}_{\text{o}_x})_{\text{inj}} (1 - \phi_{\text{o}_x})
\]

\[
\bar{V} = \frac{(A\bar{v})_{x=0}}{A} + \left( \frac{\gamma - 1}{\gamma \bar{p} A} \right) \left\{ (\bar{m}_{\text{o}_x})_{\text{inj}} (1 - \phi_{\text{o}_x}) \Delta h_{\text{o}_x} + (\bar{m}_{\text{fu}})_{\text{inj}} (1 - \phi_{\text{fu}}) \Delta h_{\text{fu}} + (A\bar{\rho} \bar{v} \bar{M})_{x=0} \left( \frac{\partial h}{\partial (\bar{M}/\bar{p})} \right) 
\]

\[
- \bar{M}R \left( \frac{\partial h}{\partial \bar{M}} \right) \left[ (A\bar{\rho} \bar{v})_{x=0} + (\bar{m}_{\text{o}_x})_{\text{inj}} (1 - \phi_{\text{o}_x}) + (\bar{m}_{\text{fu}})_{\text{inj}} (1 - \phi_{\text{fu}}) \right] \}
\]

\[
\bar{\rho} = \frac{1}{A \bar{v}} \left\{ (A\bar{\rho} \bar{v})_{x=0} + (\bar{m}_{\text{o}_x})_{\text{inj}} (1 - \phi_{\text{o}_x}) + (\bar{m}_{\text{fu}})_{\text{inj}} (1 - \phi_{\text{fu}}) \right\}
\]

\[
\bar{T} = \frac{\bar{p}}{\bar{p} R_\phi \left[ 1 + \frac{1}{R_\phi} \left( \frac{\partial R}{\partial (\bar{M}/\bar{p})} \right) (\bar{M} - \bar{M}_0) \right]}
\]

where

\[
\phi_s = e^{-(x-x_0)/\tau_s} v_s
\]

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If the gaseous injection velocity is equal to zero \( (\overline{v}_{x=0} = 0) \), the steady-state mixture ratio and density at \( x = x_0 \) are determined by

\[
\overline{\text{MR}}_{x_0} = \left( \frac{\overline{m}_{\text{ox}}}{\overline{m}_{\text{fu inj}}} \right) \left( \frac{\overline{\tau}_{fu}}{\overline{\tau}_{ox}} \frac{\overline{v}_{fu}}{\overline{v}_{ox}} \right)
\]

(166)

\[
(\overline{\rho})_{x_0} \left( \frac{\gamma_\phi - 1}{\gamma_\phi} \right) \left\{ \overline{\text{MR}}_{x_0} \left[ \Delta h_{\text{ox}} - \frac{\partial h}{\partial \overline{\text{MR}}_{x_0}} \right] + \Delta h_{fu} - \frac{\partial h}{\partial \overline{\text{MR}}_{x_0}} \right\} = \overline{\text{MR}}_{x_0} + 1
\]

(167)

These equations were developed by taking the limit as \( x \to x_0 \) from a downstream distance.

**Oscillatory Solution**

The boundary conditions for the oscillatory differential equations are

\[
\theta \quad x = 0
\]

(168)

\[
p' = \Delta p
\]

(169)

\[
v' = (v')_{x=0}
\]

(170)

From these boundary conditions and the oscillatory differential equations, the oscillatory conditions at the start plane for vaporization \( (x_0) \) can be determined and are:

\[
p'_{x_0} = \left[ \Delta p \cos \left( \frac{\omega x_0}{c_\rho} \right) + i \gamma_\phi \eta (v')_{x=0} \sin \left( \frac{\omega x_0}{c_\rho} \right) \right] e^{-\frac{i \omega}{c_\rho} \eta^2 \overline{v}_{x=0} \frac{x_0}{c_\rho}}
\]

(171)
\[ v'_{x_0} = \left[ \frac{i}{\gamma \rho} \frac{\Delta P}{\eta} \sin \left( \frac{\omega x_0}{c_\phi} \right) \right] + \]

\[ (v')_{x=0} \cos \left( \frac{\omega x_0}{c_\phi} \right) e^{-\frac{i \omega}{c_\phi} n} 2 \frac{v_{x=0}}{c_\phi} x_0 \]  

(172)

\[ \rho'_{x_0} = \frac{P_{x_0}}{\gamma \rho} \]  

(173)

\[ (MR')_{x_0} = (MR)_{x=0} e^{\left( \frac{i \omega}{c_\phi} \frac{1}{v_{x=0}} \right) x_0} \]  

(174)

\[ T'_{x_0} = p'_{x_0} - \rho'_{x_0} - \frac{1}{R_{x_0}} \left( \frac{\partial P}{\partial MR} \right)_\rho (MR'_{x_0}) \]  

(175)

where

\[ n = \sqrt{\frac{-\rho_{x_0} c_\phi^2}{\gamma \rho \rho}} \]  

(176)

If the gaseous injection velocity is equal to zero \((v_{x=0} = 0)\), the oscillatory mixture ratio at \(x_0\) is determined by

\[ MR'_{x_0} = \left[ \left( \frac{\overline{m}_{fu}}{\overline{M} x_0} \right) \text{inj} \left( 1 + \overline{MR} x_0 \right) - \frac{i \omega}{c_\phi} \left( \overline{\tau}_{fu} - v_{fu} \right) \right] \]

\[ = \frac{(MR)_{x_0} + 1}{A \overline{\rho}_{x_0}} \left( \frac{\overline{m}_{fu}}{\overline{M} x_0} \right) \text{inj} \overline{MR}_{x_0} \left( \frac{\overline{m}_{vapox}}{\overline{m}_{vapox}} + \frac{\overline{m}_{vapfu}}{\overline{M} x_0} \right) \]

\[ - \frac{(v')_{x_0}}{MR_{x_0} x_0} \frac{(MR)_{x_0} + 1}{(MR)_{x_0} + 2} \left( 1 - \frac{MR}{MR_{\text{inj}}} \right) \]  

(177)

This equation was developed by taking the limit of the mixture ratio equation as \(x \to x_0\) from a downstream distance.
The ordinary differential equations describing the oscillatory solution are solved using a second order implicit finite difference method. This method has the advantage of being simple to implement and modify, as well as being unconditionally stable for systems of equations which do not have exponentially growing solutions. The method as applied to the first order system

\[ Y' = AY + g \]  

where \( Y \) and \( g \) are \( n \times 1 \) vectors and \( A \) is an \( n \times n \) matrix is as follows:

\[ y_{i+1} = y_i + \frac{\Delta x}{2} A_{i+\frac{1}{2}} (y_i + y_{i+1}) + g_{i+\frac{1}{2}} \]  

Here, the subscript \( i \) refers to the \( i \)'th mesh point in the finite difference scheme, e.g., \( x_i = x_0 + i\Delta x \). The \( y_i \) approximate the \( Y \) vector at \( x_i \). That is \( y_i = Y(x_i) \). The subscript \( i+\frac{1}{2} \) refers to evaluation at \( x_i + \Delta x/2 \); e.g., \( A_{i+\frac{1}{2}} = A(x_i + \frac{\Delta x}{2}) \).

That the above method leads to a second order approximation (error is proportional to \( \Delta x^3 \)) can be shown as follows:

Solving for \( y_{i+1} \) yields

\[ y_{i+1} = (I - \frac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} (I + \frac{\Delta x}{2} A_{i+\frac{1}{2}}) y_i + \Delta x (I - \frac{\Delta x}{2} A_{i+\frac{1}{2}})^{-1} g_{i+\frac{1}{2}} \]  

Without loss of generality, assume \( i = 0 \).

From the two expansions

\[ Y_1 = Y_{1/2} + \frac{\Delta x}{2} Y'_{1/2} + \frac{\Delta x^2}{8} Y''_{1/2} + o(\Delta x^3) \]  
\[ Y_0 = Y_{1/2} - \frac{\Delta x}{2} Y'_{1/2} + \frac{\Delta x^2}{8} Y''_{1/2} + o(\Delta x^3) \]

the following are obtained

\[ Y_1 = Y_0 + \Delta x Y'_{1/2} + o(\Delta x^3) \]  

and

\[ Y_{1/2} = \frac{Y_0 + Y_1}{2} + o(\Delta x^2) \]
Let \( y_0 = Y_0 \); it is necessary to show \( y_1 = Y_1 + o(\Delta x^3) \) in order to demonstrate second-order accuracy.

From the differential equation

\[
\begin{align*}
\frac{d}{d \tau} y_1 &= Y_1 - A y_1,
\end{align*}
\]

(185)

Substituting (185) into (180) and noting \( y_0 = Y_0 \),

\[
y_1 = \left( I - \frac{\Delta x}{2} A \right)^{-1} \left( I + \frac{\Delta x}{2} A \right) Y_0 + \Delta x \left( I - \frac{\Delta x}{2} A \right)^{-1} \left( \frac{d}{d \tau} - A \right) Y_0 + \Delta x \left( I - \frac{\Delta x}{2} A \right)^{-1} \left( \frac{d}{d \tau} A \right) Y_0
\]

(186)

Using (183) and (184), gives the result

\[
y_1 = Y_1 + \left( I - \frac{\Delta x}{2} A \right)^{-1} o(\Delta x^3)
\]

(187)

Consider now the stability of the finite difference formula (179) for systems which do not have exponentially increasing solutions; that is, the real part of each of the eigenvalues of \( A \) is negative. To prove that they are stable for this situation, define the error \( \epsilon_i = Y_i - y_i \) and consider the two equations given by (179) and

\[
Y_{i+1} = \left( I - \frac{\Delta x}{2} A \right) Y_i + \Delta x \left( I - \frac{\Delta x}{2} A \right) g_{i+1} + o(\Delta x^3)
\]

(188)

the latter resulting from (187). Subtracting (179) from (188)

\[
\epsilon_{i+1} = \left( I - \frac{\Delta x}{2} A \right) \epsilon_i + o(\Delta x^3)
\]

(189)
Let $B = \frac{\Delta x}{2} A \frac{\Delta y}{2}$. The method is stable if and only if the matrix $(I-B)^{-1}(I+B)$ has a spectral radius less than one, for this would produce (Ref. 22)

$$\lim_{n \to \infty} [(I-B)^{-1}(I+B)]^n = 0$$  \hspace{1cm} (190)

Since the eigenvalues of $(I-B)^{-1}(I+B)$ are just equal to $(1+\beta)/(1-\beta)$, where $\beta$ is an eigenvalue of $B$, the spectral radius of $(I-B)^{-1}(I+B)$ is just

$$\max_{\beta} \left| \frac{1+\beta}{1-\beta} \right|$$  \hspace{1cm} (191)

For this to be less than one,

$$|1+\beta| < |1-\beta|$$  \hspace{1cm} (192)

for all $\beta$. This implies

$$1+\beta + \overline{\beta} + \beta \overline{\beta} < 1-\beta-\overline{\beta} + \beta \overline{\beta}$$  \hspace{1cm} (193)

or

$$\beta + \overline{\beta} < -(\beta + \overline{\beta})$$  \hspace{1cm} (194)

Real $\beta < 0$  \hspace{1cm} (195)

Since $\beta = \frac{\Delta x}{2\alpha}$, where $\alpha$ is an eigenvalue of $A$, the method will be stable if all the eigenvalues of $A$ have real parts less than zero, that is, the solutions to (178) are not exponentially increasing.
Nozzle Admittance

The nozzle admittance based on downstream conditions is calculated based on the following analysis.

The gas flowrate of the nozzle inlet plane is

\[ \dot{m} = \frac{p A_c g}{c^*} = A p \nu \quad (196) \]

where the characteristic velocity is

\[ c^* = \sqrt{\frac{g \gamma RT}{\gamma \left[ \frac{2}{(y+1)/(y-1)} \right]}} \quad (197) \]

For short nozzles, the oscillatory mass flowrate can be written as

\[ \frac{\dot{m}'}{\dot{m}} = \frac{\rho'}{\rho} + \frac{v'}{v} = \frac{p'}{\rho} - \frac{1}{2} \frac{T'}{T} - \left( \frac{\rho c^*}{\rho MR} \right) \frac{MR'}{c^*} \quad (198) \]

Assuming

\[ \frac{\rho'}{\rho} = \frac{1}{\gamma} \frac{p'}{\rho} , \quad \frac{T'}{T} = \left( \frac{\gamma-1}{\gamma} \right) \frac{p'}{\rho} \quad (199) \]

the nozzle admittance for a short nozzle can be written as

\[ A_{N_s} = \frac{\rho \ c \ \nu}{2Y} \left[ \frac{(\gamma-1)}{2Y} \frac{\rho c^*}{\rho MR} \frac{MR'}{c^* \ p'} \right] \quad (200) \]
Assuming

\[ A_{N_D} = A_{N_S} \left( \frac{A_{N_D}}{A_{N_S}} \right) \text{ MR = constant} \]  

(201)

the nozzle admittance based on downstream conditions becomes

\[ A_{N_D} = \left[ 1 - \left( \frac{c^*}{\text{MR}} \right) \frac{\text{MR}'}{c^*} \frac{p'}{p} \left( \frac{2\gamma}{\gamma-1} \right) \right] A_{N_{MR}} = \text{constant} \]  

(202)

where \( A_{N_{MR}} = \text{constant} \) is calculated using the admittance program developed by Bell (Ref. 23).

The nozzle admittance based on upstream conditions is

\[ A_{N_U} = \gamma \phi \left( \frac{v'}{p'} \right)_{x=\lambda} \]  

(203)

where \( (v'/p')_{x=\lambda} \) is calculated from the oscillatory solution. For solutions to the chamber dynamic equations, the nozzle admittance based on upstream and downstream conditions must be equal. The method of calculating the complex frequency which satisfies this condition is discussed in the Engineering Model section which follows.
ENGINEERING MODEL

Analytical Approach

The overall model structure had the greatest variety of factors influencing its nature. Some of these factors were related to the overall confidence in the success of the effort. Factors relating to cost included the solution time and numerical stability, which bears on the number of runs which will be required for a solution. Still other factors were related to the JSC Univac 1110 capabilities. The remaining factors concerning the overall model structure reflect on its conversion cost applicability to the resolution of propulsion system problems. Its accuracy has direct bearing on the design margins involved. The type of impact and the obtainability of characterization parameters could not limit the accuracy and useability. The type and useability of the output was also given due consideration as well as the degree of generalization such that the model can be applied to a range of systems.

The structure of the Engineering Program was based on a trade-off of setup time, storage capabilities, and solution time. General input data to the program includes geometric factors, engine operating conditions and propellant properties. An equilibrium gas properties program similar to NASA ODE computer program, and the DER combustion model program are executed external to the stability program. The control program then executes the nozzle admittance and hydrodynamics programs to calculate the admittance and oscillatory injector flowrate as a function of frequency and stores the results on tapes. Steady-state distributed combustion parameters calculated from the DER Model are inputs to the combustion dynamics subprogram which are iterated with the chamber dynamic subprogram until the nozzle and injection admittance conditions are satisfied. The solution method for obtaining solutions for the complex frequency is outlined in the following section.
Determination of Complex Frequency

The complex frequency, $\omega$, is determined such that the boundary condition in the nozzle is satisfied. Specifically, the admittance is required to be continuous across the interface between the combustion zone and the zone immediately downstream of the combustion zone. In the downstream zone, the nozzle admittance, $A_{ND}$, is computed from a nozzle admittance program. In the upstream combustion zone, the nozzle admittance, $A_{NU}$, is computed from the oscillatory flow parameters determined by the chamber dynamics. The complex frequency must be such that

$$A_{NU} = A_{ND}$$  \hspace{1cm} (204)

Let $\omega = x + iy$ and $F = A_{NU} - A_{ND} = u + iv$. The numerical problem is to find $x$ and $y$ such that

$$u(x,y) = 0$$  \hspace{1cm} (205)

$$v(x,y) = 0$$  \hspace{1cm} (206)

Several methods were considered for solving this system of equations. Because $F$ is not an analytic function of $\omega$, the complex form of the Newton-Raphson method may not always work. On the other hand, one could use the two-dimensional form of Newton-Raphson (Ref. 24), but since the derivatives of $u$ and $v$ with respect to $x$ and $y$ must be computed numerically, the two-dimensional Newton-Raphson method will require three functional evaluations of $F$ at each $\omega$, i.e., $(x,y), (x+\Delta x,y), \text{and} (x,y+\Delta y)$. Alternatively, a far more efficient method is to use the two-dimensional form of the secant method (Ref. 24) since this does not require the evaluation of any derivatives. Specifically, this method approximates the $u$ and $v$ surfaces with linear functions $u_L$ and $v_L$ (planes) based on three previous guesses for $\omega$, $(x_1,y_1), (x_2,y_2), (x_3,y_3)$. The next guess for $\omega$, $(x_4,y_4)$, is determined from the equations $u_L(x_4,y_4) = v_L(x_4,y_4) = 0$. The new value of $\omega$ then replaces one of the previous three values, normally the one with the largest error as measured by the absolute value of $F(x_j,y_j)$, and the iteration

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is continued until convergence is reached. The actual equations for the above process take the following form. Let \( w_j = x_j + iy_j, u_j = u(x_j, y_j), \) and \( v_j = v(x_j, y_j) \) for \( j = 1, 2, 3. \)

1. Determine \( \pi_j, j = 1, 2, 3, \) such that
   \[
   \pi_1 + \pi_2 + \pi_3 = 1
   \]  
   \[
   \pi_1 u_3 + \pi_2 u_2 + \pi_3 u_1 = 0
   \]  
   \[
   \pi_1 v_3 + \pi_2 v_2 + \pi_3 v_1 = 0
   \]

2. Compute \( \omega_4 = \pi_1 \omega_3 + \pi_2 \omega_2 + \pi_3 \omega_1. \)

3. Compute \( u_4 \) and \( v_4 \) based on \( x_4 \) and \( y_4. \)

4. Test for convergence, i.e., require that \( \min |\omega_j - \omega_4|/|\omega_4| < \epsilon_1 \) and \( |F_4| < \epsilon_2. \)
   If the process has not converged, continue with steps 5, 6, and 7.

5. Determine the \( j \) between 1 and 3 such that \( u_j^2 + v_j^2 \) is maximum.

6. Replace \( \omega_j, u_j, \) and \( v_j \) by \( \omega_4, u_4, \) and \( v_4, \) respectively.

7. Go to 1.

Operationally, steps 4 and 5 may be altered to replace the \( \omega \)'s cyclically, i.e., \( \omega_i + \omega_{i-1}, u_i + u_{i-1}, v_i + v_{i-1}. \) In fact the computer program as written alternates between these two procedures every three iterations in order to avoid any possible cycling that may occur.

The above algorithm has been found to be very efficient when the first three guesses are relatively near an actual solution. The difficult problem was to develop a searching algorithm which determines the regions in the \( \omega \) plane where solutions exist.

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One possible procedure would be to utilize the fact that the surface $u^2 + v^2$ has an absolute minimum at each solution. Using any reasonable value of $\omega$ as a first guess, one might be tempted to employ a gradient, or modified gradient, method to march along the surface until one comes near a relative minimum. Unfortunately, this procedure fails because the surface $u^2 + v^2$ has many relative minima which are not actual solutions. The reason for the large number of relative minima (and maxima) for this surface is undoubtedly due to the coupling between the combustion processes and the feed system oscillation in conjunction with the very rapid change of the feed system response as a function of frequency. The searching algorithm must be able to discriminate between those relative minima that are not solutions and those that are. Such a procedure was developed for this program. It takes advantage of the fact that a large portion of the computations required are only a function of the real part of $\omega$, i.e., they use $x$ as an independent variable and do not depend upon $y$. Thus, $y$ may be changed without having to redo many of the calculations within the program.

Intuitively, the idea is to increment $x$ through a range of values, while determining $y$ at each $x$ according to the criterion mentioned below, until it is determined that a solution has been crossed. This determination employs the use of a test function which changes sign when a root is crossed in the same manner that a single equation in one unknown changes sign as it goes through a zero. The task of developing a defining criterion for $y$ and a test function for $x$ would be easy if, for example, $v$ were a strong function of $y$ and $u$ were a strong function of $x$. Then, each $x$, $y$ could be chosen such that $v(x,y) = 0$ and, as $x$ is incremented, a solution would be crossed when $u(x,y(x))$ changes sign. Unfortunately, neither $u$ nor $v$ behaves this way.

To develop functions that do behave this way, the following procedure was developed. First, for each $x$, choose $y$ such that the absolute value of $F$ is minimized. This can be done in several ways. The program uses a method that always guarantees finding a value if one exists. Essentially, the absolute
value of $F$ squared and its gradients are computed. The value of $y$ is altered in the direction indicated by the gradient until either the gradient changes sign or is so close to zero that convergence has been reached. Once the gradient changes sign, Muller's method (Ref. 25) is used to converge on the root. This is essentially a bisection method followed by inverse parabolic interpolation. For this searching process, it is not necessary to make the convergence criteria very tight, since only rough estimates are eventually needed in order to start the two-dimensional secant method described earlier.

Now that a criterion for $y$ has been established, it is only necessary to find a test function that will change sign when a solution is crossed while incrementing $x$. Such a function is given by

$$ uu_x + vv_x $$

(211)

This function acts as a very good test function because it represents the coordinate direction in the $u,v$ plane along which the vector $(u,v)$ changes most with $x$. When this coordinate changes sign as one goes from, say, $x_1$ to $x_2$ with $y_1$ and $y_2$ chosen so that the length of the vector $(u,v)$ is minimized, then it is very likely that a solution has been crossed. Exceptions to this rule occur when one is near relative minima of the surface $u^2 + v^2$ that are not zero. To see this, consider the actual equations that are being solved. In order that the vector $(u,v)$ is minimum for each $y$, it is necessary that $\partial(u^2 + v^2)/\partial y = 0$. That is $uu_y + vv_y = 0$. Combining this with the above equation, we see we are finding an $x$ and $y$ such that the matrix equation

$$
\begin{pmatrix}
  u_x & v_x \\
  u_y & v_y \\
\end{pmatrix}
\begin{pmatrix}
  u \\
  v \\
\end{pmatrix}
= \begin{pmatrix}
  0 \\
  0 \\
\end{pmatrix}
$$

(212)
is satisfied. The matrix is just the transpose of Jacobian of $u$ and $v$ with respect to $x$ and $y$.

This equation can be satisfied if either $u$ and $v$ are zero, or the Jacobian is singular. The Jacobian is necessarily singular at all relative minima of the surface $u^2 + v^2$ except those at $u = v = 0$. In order to differentiate between those solutions to (212) that are due to singularities of the Jacobian and those that are due to $u$ and $v$ vanishing, we employ two different tests. First of all, when a singularity point is crossed, the determinant of the Jacobian should change sign. If this occurs, then the program rejects this point as a possible solution. Sometimes, however, the determinant does not change sign because either the convergence criterion used in the searching algorithm is too loose or because the singularity has a double root. In either case, the procedure is to test the condition number* of the transpose of the Jacobian matrix in the region near the suspected solution. If the condition number does not exceed a given input limit (e.g., around 80), then the point in question is usually a solution.

Once it is determined that a potential solution has been crossed between $x_1$ and $x_2$, for example, the procedure is to (a) determine $x_3$ based on the method of false position using the test function given in (211), (b) determine $y_3$ to minimize $|F|$, and (c) use $(x_1, y_1), (x_2, y_2),$ and $(x_3, y_3)$ as the required first three guesses for the two-dimensional secant method.

The above procedure has been found to be most satisfactory for the conditions tested in this program. The search algorithm described above has several salient features. First, as mentioned earlier, the search method takes advantage of the fact that many of the computations are not a function of the imaginary part of $\omega$, namely $y$: This allows the minimization of $|F|$ with respect to $y$ to proceed with high efficiency. Secondly, and more importantly,

*The condition number of a matrix, $A$, is a measure of how sensitive a solution to the system $Ab=c$ is to perturbations in $c$. It is equal to the square root ratio of the absolute value of the largest eigenvalue of $A'A$ to the smallest eigenvalue of $A'A$. For singular matrices, the condition number is infinite. For matrices that are nearly singular, the condition number will be quite large.

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the procedure has been automated to the extent that the user only has to specify a frequency range and a maximum number of roots desired in that range. The algorithm will start at the lower end of the frequency range and will increment through it until either the maximum number of roots are found or the upper end of the frequency range is reached. This is a very powerful property since it does not require the user to have a clear knowledge of the location of any of the roots in the $\omega$ plane.
FSCSM MAIN PROGRAM

The main program for the FSCSM computer model performs much of the input/output activity of the model and controls the sequencing through the various major subprogram blocks of the model. After writing the header page (Fig. 5), the main program reads in and writes out the data described in Table 2 of the input section of this report under the heading Main Control Section Input. The program then computes the area profiles through a call to subroutine AREA. It then begins its main do loop controlling the number of solutions to the nozzle admittance boundary equation that are desired. During the iterations for each solution to be found, the main program proceeds with successive calls to subroutines NØZADM, HYDRDY, ÇOMBDY, and SØLVW in order to compute the downstream nozzle admittance factor, the feed system response parameters, the combustion dynamics coefficients, and performance calculations necessary to solve the nozzle admittance boundary equations respectively. Subroutine SØLVW also causes a call to subroutine CHAMDY which computes the oscillatory profiles. Further, during the first iteration in the do loop for the main program for the first solution, the main program also calls subroutine STEADY in order to obtain the steady-state profiles.

The variable ISCNT is the FORTRAN variable set by the main program and altered in SØLVW which controls the type of iteration being performed. When ISCNT equals one or four, the search algorithm described on pages 54-56 is called out. This is the initial condition at the beginning of each set of iterations to solve the nozzle admittance boundary equation. When ISCNT equals five, the two-dimensional secant method is being performed in SØLVW.
Figure 5. Logic Diagram for FSCSM Main Program
The variable KWHERE, which is set by subroutine SØLVW, controls the logical flow in the main program subsequent to a call to SØLVW. When ISCNT equals one or four and KWHERE equals one, the control is returned to that portion of the main program which starts the calculation for the next value of \( \omega \) being tried by the search algorithm. When KWHERE equals two and ISCNT equals one or four, control is passed to that portion which will perform calculations for a perturbed \( \omega \) in order to compute the derivative of \( A_{NU} - A_{ND} \) with respect to \( \omega_R \). When ISCNT equals 5 and convergence has not been reached, the normal exit from SØLVW also sets KWHERE equal to two. For this case however, no derivatives are calculated. The program will just proceed with successive calls to NØZADM, HYDRDY, and CØMBDY in order to compute the downstream nozzle admittance factor, the feed system response, and the combustion dynamic coefficients, respectively. It then proceeds to SØLVW in order to obtain an updated estimate of \( \omega \) using the two-dimensional secant method.

When KWHERE equals three or four, convergence on a solution to the nozzle admittance boundary equation has been attained. For this case, control is passed to that portion of the main program which prints the final results for that solution.

When KWHERE equals five, control is passed to the end of the main do loop in the main program. The output portion is bypassed. This only occurs when an error was detected by subroutine SØLVW.
SØLVW

This subroutine performs many of the calculations and controls most of the logical flow required to match the downstream boundary condition on the nozzle admittance. The FORTRAN variable ISCNT controls the logical flow within subroutine SØLVW (Fig. 6). If ISCNT equals one, then that portion of the subroutine used for searching the ω-plane for possible solutions to the nozzle admittance boundary equation is used. Two calls to SØLVW are used for this purpose. During the first call, the imaginary part of ω is determined so that the absolute value of the upstream nozzle admittance minus the downstream nozzle admittance is minimized. The second call is made in order to complete the computation of the Jacobian of this difference with respect to the real portion of ω. (The derivatives of the difference with respect to the imaginary part of ω are computed during the first call.) When ISCNT equals one, tests are also made to determine if a solution is nearby. The actual test function and the logic employed is described on pages 54-56.

Once it is determined that a possible solution is bracketed by two successive frequencies, the variable ISCNT is set equal to four. Subroutine SØLVW performs the same calculations for this value of the variable ISCNT as it does when ISCNT equals one. The only difference occurs at the end of the second call to SØLVW. At that point, checks are made to ensure that the potential solution is in fact an actual solution and not due to a singularity in the Jacobian. If the error passes certain criteria and at least three iterations have been performed with ISCNT equal to four, then ISCNT is set equal to five for subsequent calls to SØLVW. Between each iteration for ISCNT equal to four, as well as for the first iteration for ISCNT equal to four, the real part of the frequency is modified using the method of false position or the bisection method, depending upon the value of the iteration counter, KSCNT4.

When ISCNT equals five, no derivatives are computed. For this situation, subroutine SØLVW only computes the difference between the upstream and downstream nozzle admittances based on the current value of ω. It then checks to determine whether convergence has been obtained. If not, the
CALLS CHAMDY TO COMPUTE OSCILLATORY PROFILES. COMPUTES $A_N^U$ AND $A_N^D$. IF 
ISLP=1 AND ISCNT=1 OR 4, 
COMPUTES $3(A_N^U-A_N^D)/3\omega_I$ 
AND $3|A_N^U-A_N^D|/2/3\omega_I$

IF ISCNT=5 

1 OR 4
ISLP ≠ 0

RESTORE $\omega_1$ AND 
FINISH COMPUTATION OF JACOBIAN, J.

COMPUTE DETERMINANT AND 
CONDITION NUMBER OF J.

ISLP ?

MINIMIZE $|A_N^U-A_N^D|$ WITH 
RESPECT TO $\omega_1$. 
SAVE $3(A_N^U-A_N^D)3\omega_I$

ISLP = 0

INCREMENT $\omega_0$ BY $\Delta\omega$ TO 
COMPUTE JACOBIAN 
ON NEXT CALL TO SØLVW

UPDATE $\omega$ USING 2-D SECANT METHOD

WRITE ERROR MESSAGE

REQUEST 2

CONVERGED?
NO

ITERATION 
COUNTER TOO 
LARGE?

YES

WRITE ERROR 
MESSAGE

KWHERE = 5

ISLP = 0

KWHERE = 2

KWHERE = 3

RETURN

KWHERE = 2

RETURN

A

B

YES

ISCNT=4

Figure 6. Logic Diagram for Subroutine SØLVW

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ORIGINAL PAGE IS
OF POOR QUALITY
Figure 6. (Concluded)

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value of \( \omega \) is updated according to the two-dimensional secant method described on page 53.

The variable which controls the flow in the main program subsequent to a call to SOLVW is \textsc{KWHERE} and is described in the section of this report dealing with the main program.

\textbf{CHAMDY}

This subprogram is called by XIMAGF in order to compute the oscillatory pressure, temperature, velocity, mixture ratio, and density profiles. From these quantities (Fig. 7), it determines the upstream nozzle admittance. It solves for the oscillatory profiles by solving the linearized set of differential equations presented on pages 41 and 42. This is done using a second order implicit finite difference scheme. Those integrals appearing in the vaporization expression which cannot be integrated analytically are numerically integrated using the trapezoidal rule.

Because the differential equations represent a linear initial value problem, the finite difference equations are also linear and one can "march off" the solution from the initial plane. Since the four differential equations are coupled, replacing them at each axial position by their finite difference approximation results in a four by four system of complex linear equations. Because of the nature of the differential equations, the resulting matrix equations are essentially diagonally dominant and can therefore be solved very quickly using Gaussian elimination with the diagonal element used for pivoting.

\textbf{XIMAGF}

This subroutine is called by SOLVW and \textsc{Zero}. Its main function is to compute the difference between the upstream and downstream nozzle admittances (Fig. 8). When the program is still performing the search algorithm, this routine computes the derivative of this difference with respect to the imaginary part of \( \omega \) as well as the derivative of the absolute value of this difference squared with respect to the imaginary part of \( \omega \).
Figure 7. Logic Diagram for Subroutine CHAMDY
CALCULATE \( A_{ND} \) FROM OSCILLATORY PROFILES AND DOWNSTREAM NOZZLE ADMITTANCE FACTOR

\[
FN = A_{NU} - A_{ND} \\
HN = |F_N|
\]

ISCNT = 1 OR 4 AND ISLP = 1

yes

no

COMPUTE \( a(FN)/a \omega \)

\( a|HN|^2/a \omega \)

RETURN

Figure 8. Logic Diagram for Subroutine XIMAGF
This routine is called by CHAMDY and calculates certain parameters necessary for determining the coefficients used in CHAMDY.

**CÔMMAT**

This routine solves the four by four complex system of linear equations discussed in the section describing subroutine CHAMDY. It uses Gaussian elimination with pivoting on the diagonal.

**ZERO**

This routine is called by subroutine CHAMDY. Its function is to find the zero of a given functional when that zero is bracketed both above and below. The functional in this case is the derivative with respect to the imaginary part of \( \omega \) of the absolute value squared of the difference between the upstream and downstream nozzle admittances. Finding the zero of this functional is done in order to minimize the error in the difference between the nozzle admittances with respect to the imaginary part of \( \omega \). The method used by subroutine ZERO is due to Muller (Ref. 25). It essentially involves a bisection step followed by inverse parabolic interpolation to determine the next guess.

**STEADY**

This routine (Fig. 9) is called by the main program to determine the time independent solution to the set of differential equations given on page 40. These equations have been analytically integrated on pages 42-44. This subroutine uses these latter equations to determine the steady state profiles. Also, several parameters which are a function of these steady state variables are computed and saved for subsequent use by the chamber dynamics subprogram, CHAMDY. If the FORTRAN variable IPRSTE is greater than zero, a printout of the steady state profiles will be given.

**COMBDY**

This subprogram (Fig. 10) calculates the fuel and oxidizer combustion coupling coefficients required for the determination of the time oscillatory vaporization rates needed to solve the chamber dynamics. The equations for these parameters
Figure 9. Logic Diagram for Subroutine STEADY
Figure 10. Logic Diagram for Subprogram COMBDY

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are given on pages 33-34. During the first pass into this program, the combus-
tion dynamic input variables are read in from input device 5 and written
out onto device 6. A discussion of these variables is given in the Model
Input Section. The logical flow in COMBNOY is controlled by the FGRTRAN
variable INPCOM. If this variable is less than or equal to one, the combus-
tion coefficients are computed for the current frequency only. If INPCOM
is greater than one, these coefficients are computed for the entire fre-
quency table, FREQT (e.g., from 10 to 1000 Hz), and saved on tape/disk
ITAPE for subsequent use by the main program.

AREA

This subroutine is called by the main program. It computes the area pro-
files and axial distance profiles necessary for solution of the steady-state
and transient profiles.

LOCFAC

This routine is used to determine the subscript, I, within an ordered array,
TX, such that the input argument, X, is in the interval TX(I), TX(I+1).
This routine also returns the interpolating factor FX = (X-TX(I))/(TX(I+1)-
TX(I)) for subsequent use in linear interpolation.

HEAD

This subroutine is called by the main program to print the heading page which
gives the title of the program, by whom and where it was developed, and the
program sponsor.

HYDRDY

Subroutine HYDRDY (Fig. 11) is called by the main program to calculate the
frequency domain characteristics of the feed system. Functions performed
by HYDRDY are (1) reading of input data describing the physical attributes
Figure 11. Logic Diagram for Subprogram HYDRDY
of the feed system components, (2) generation of a matrix of linear differential equations representing the complete feed system, (3) solution of the feed system equations to yield the amplitude and phase response of all feed system pressures and flowrates as a function of chamber pressure oscillation amplitude and frequency, and (4) generation of tabulated output of injector flowrate frequency response for use by the main program.

A basic assumption of subroutine HYDRDY is that the feed system being modeled can be represented by the generalized schematic of Fig. 4 (or by some portion of this schematic). This assumption is necessary because HYDRDY sets up and solves the complete set of simultaneous equations representing the Fig. 4 schematic. By assigning very high resistance and very short length attributes to any of the 30 numbered line segments of the generalized schematic, whose segment can effectively be excluded from having any effect on the frequency response characteristics of the rest of the system. With this approach a wide variety of feed systems can be modeled with no changes to the program other than the input data.

Figure 11 shows the functional block diagram for subroutine HYDRDY. When called, the subroutine initially zeroes the values of all of the elements of the coefficient and time delay matrices C and TD in labeled common block F. The values of various fixed input arguments required by the frequency response subroutine (FRESP) are then initialized.

Input argument IR directs the reading of subroutine HYDRDY input data. If IR is zero or less, the program assumes that all required data has previously been read and the data read function is bypassed. If IR = 1, the program assumes that no hydrodynamic data has been read and proceeds to initialize all hydrodynamic input variables to values which will exclude all 30 line segments and both injectors of the generalized Fig. 4 feed system schematic. Control is then passed to statement 45 for reading of input data. If
IR = 2, the assumption is made that most input data is already set up (such as from a previous case during the same program run). Control is passed directly to statement 45 for reading any changes to the input data.

Input data reading for HYDRDY is in the NAMELIST format (NAMELIST name HYD) and is normally in the form of card input on logical unit number 5. However, if the program is run in a timesharing environment, an option is provided for reading data from a timesharing terminal. This option is controlled by variables IRFLAG and ITERM. Both of these variables are stored in labeled common block/F/ and can be changed by input to NAMELIST HYD. Variable IRFLAG is tested in statement 45 and if non-zero specifies reading NAMELIST HYD data from unit 5. If timesharing terminal input is desired, variable ITERM is set (by input data read or block data initialization of labeled common block/F/) to the logical unit number to the timesharing terminal. If variable ITERM is non-zero, statement 46 sets IRFLAG to 1. Thus, once terminal data input has been specified, all subsequent data reads will default to the terminal. Card input can be respecified (for a subsequent data case) by entering IRFLAG = 0 in the terminal data input.

Input variables for subroutine HYDRDY are described in detail in the Hydrodynamic Input Section. The variables include the length (L), cross-sectional area (A), propellant sonic velocity (V), propellant density (RHOL), hydraulic resistance (R), and wall compliance (CW) for each of the 30 numbered waterhammer segments in the generalized Fig. 4 feed system schematic. Input variables for the left ("o") injector of Fig. 4 are resistance (Rφ), inertia (Zφ), volume (VOLφ), propellant sonic velocity (Vφ), and injector deflection constant (Kφ). The corresponding input variables for the right ("F") injector are RF, ZF, VφF, VF and KF. The designation of the two injectors as "o" and "F" is a notational convenience for cases in which the feed system being modeled has only one injector and sufficiently simple flow paths so that both oxidizer and fuel systems can simultaneously be laid out on the Fig. 4 schematic. Such cases have the advantage of reduced computer time because the
frequency response of both fuel and oxidizer feed systems is obtained with a single call to subroutine HYDRDY. Of the fuel and oxidizer feed systems overlap when laid out on the Fig. 4 schematic, subroutine HYDRDY must be called twice - once for each feed system.

When data input is complete, a value of 2 (or greater) for variable IWRITE specifies a printout of all input data on logical unit 6. IWRITE = 0 is the default and specifies no printout of input data.

Next, control is passed to the D0 loop at statement 100 in which the input values for propellant density, propellant acoustic velocity and segment wall compliance for each of the 30 waterhammer segments of the Fig. 4 schematic are combined to yield an effective acoustic velocity for each segment. The subsequent statements, up to statement 400, combine the input variables as required to yield the constant coefficients of the 57 linear waterhammer and injector equations describing the complete Fig. 4 feed system. Simultaneous solution of these 57 equations, at each specified input frequency, yields the oscillatory amplitude and phase response of all pressures and flowrates in the feed system to inputs via chamber pressure oscillations at that frequency.

At statement 500 a call to subroutine FRESP is made to obtain the frequency response solution of the feed system equations. Initially, however, at statement 400 the value of input argument INPHYD is tested to determine the desired output from FRESP. If INPHYD is greater than 1, HYDRDY will call FRESP to calculate the feed system frequency response for each of the frequencies in array FREQT. The total number of frequencies is given by variable NFREQT and may range from 1 to 100. Both the variable, NFREQT, and the array, FREQT are in labeled common block/COMTAP/. If the value of INPHYD is less than or equal to 1 HYDRDY will call FRESP to calculate the feed system frequency response for the single frequency given by input argument, FRE.

Output data from subroutine HYDRDY consists of a pair of complex numbers for each specified input frequency. If INPHYD was specified as < 1 then the output numbers GINJFX and GINJFU are returned in labeled common block/F/ and also in the HYDRDY argument list as GINJFX and GINJFU. The real
and imaginary parts of complex number GINJΩX (GINφ) represent the amplitude and phase angle respectively of \( \frac{\Delta \Omega}{\Delta P_C} \) at frequency FREQ (FRE). Similarly, the complex number GINJFU (GINF) represents the amplitude and phase angle of \( \frac{\Delta \Omega}{\Delta P_C} \) at frequency FREQ (FRE), \( \Phi_{\text{FIN}} \), WFIN and PCIN are the input normal values for the oxidizer injector flowrate, fuel injector flowrate and chamber pressure, respectively, from the HYDRDY argument list.

If INPHYD was specified as >1, then rather than a single pair of complex numbers representing oscillatory injection flowrates, HYDRDY returns two arrays, GINJΩT and GINJFT, containing the oscillatory injection flowrate amplitude and phase data for each of the NFREQT frequencies in array FREQT. The output arrays GINJΩT and GINJFT are stored in labeled common block/CΩMTAP/ and are also written out on the output device whose logical unit number is designated by variable ITAPH in labeled common block/CΩMTAP/. The order of storage on the output device is GINJΩT(I), GINJFT(I), for I values from 1 through NFREQT. After writing the GINJΩT and GINJFT arrays on the output device HYDRDY sets the value of variable INPHYD to 3. Also, before returning control to the main program, HYDRDY tests the value of variable IWRITE. If IWRITE is non-zero, each specified frequency and the corresponding value of GINJΩT and GINJFT are written out on logical unit 6. If only one frequency was specified (INPHYD < 1), then only the single point values of FREQ, GINJΩX and GINJFU are written out.

It should be noted that although output from a single call to HYDRDY contains values for both "oxidizer" and "fuel" oscillatory injection flowrates (at one or more frequencies), the output values actually refer to the "Ω" and "Φ" injectors of the Fig. 4 schematic. Thus, unless both oxidizer and fuel feed systems can simultaneously be modeled with the Fig. 4 layout, it is necessary to call HYDRDY twice - once for the oxidizer feed system and once for the fuel feed system.

FRESP

Subroutine FRESP (Fig. 12) is used to obtain the frequency domain characteristics of the feed system indirectly from input data that describes the physical
Figure 12. Logic Diagram for Subroutine FRESP
characteristics of the feed system. (The actual input to FRESP is
generated by the subroutine HYDRDY which orders the physical character-
istics of the system into specific matrices of coefficients that FRESP
can use as input data.)

FRESP merely solves for the variables \( X_i \) in the following relation-
ship:

\[
C \{X\} = a Y
\]

where \( Y \) is a single input variable that represents a unit value of
the injector end combustion chamber pressures. The matrix \( a \) then
relates the specific pressure input to each applicable equation that
contains combustion chamber pressure (\( a \) may contain both static and
dynamic terms.) The matrix \( C \) is simply the coefficients of the linear
differential equations that represent the physical system. The values
of the coefficients for the \( a \) and \( C \) matrices are computed by the
subroutine HYDRDY.

The FRESP matrices can be expressed as:

\[
C_{ijk} \cdot s^{k-1} \cdot \{X_j\} = a_{ik} \cdot s^{k-1} \cdot Y
\]

with the differential operator defined as \( S = J \omega \), where \( J = \sqrt{-1} \) and
\( \omega \) is the frequency. The matrices may be broken down to provide real
matrices and imaginary matrices.

\[
C_{ij1} - C_{ij3} \omega^2 + C_{ij5} \omega^4 - \ldots + J \cdot C_{ij2} \omega - C_{ij4} \omega^3 + \ldots
\]

\[
X_j = a_{i1} - a_{i3} \omega^2 + \ldots + J \cdot a_{i2} \omega - a_{i4} - A_{i4} \omega^3 + \ldots \cdot Y \quad (213)
\]

Since the time delay coefficients used in the differential equations are
of the form \( e^{-\tau S} \cdot X \), which is equivalent to \( e^{-\tau J \omega} \cdot X \), and since \( e^{-jy} =
\cos(y) + j \sin(y) \), these terms may be added to the previously formed
real and imaginary matrices to give:
\[
\begin{align*}
\left[ \begin{array}{c}
C_{ij1} - C_{ij3} \omega^2 + \ldots + \cos (\tau_{ij} \omega) \\
+ J \left( C_{ij2} \omega - C_{ij4} \omega^3 + \ldots + \sin (\tau_{ij} \omega) \right)
\end{array} \right] \cdot \left[ \begin{array}{c}
X_j
\end{array} \right] &= \\
\left[ \begin{array}{c}
\cos (\tau_{ij} \omega) \\
\sin (\tau_{ij} \omega)
\end{array} \right] = \\
\left[ \begin{array}{c}
a_{i1} \omega^2 + \ldots + \cos (\tau_i \omega) \\
+ J \left( a_{i2} \omega - a_{i4} \omega^3 + \ldots + \sin (\tau_i \omega) \right)
\end{array} \right] \cdot Y
\end{align*}
\]

and solved for \([ X_i ]\):

\[
\begin{align*}
\left[ X_i \right] &= \left[ \begin{array}{c}
C_{ij1} - C_{ij3} \omega^2 + \ldots + \cos (\tau_{ij} \omega) \\
+ J \left( C_{ij2} \omega - C_{ij4} \omega^3 + \ldots + \sin (\tau_{ij} \omega) \right)
\end{array} \right] \\
&\quad \cdot \left[ \begin{array}{c}
a_{i1} \omega^2 + \ldots + \cos (\tau_i \omega) \\
+ J \left( a_{i2} \omega - a_{i4} \omega^3 + \ldots + \sin (\tau) \omega \right)
\end{array} \right]
\end{align*}
\] (214)

The matrices are multiplied and then solved for \([ X_i ]\) in the subroutine C\&G\&E\&L which employs the standard Gaussian elimination procedure for solving linear equations. The \([ X_i ]\) solution is still separated into real and imaginary components, and are simply combined to form a vector for each variable. The procedure is repeated for each frequency being considered.

R-9808/79
This subroutine is called by the hydrodynamic frequency response subroutine, FRESP, to triangularize the complex matrix of feed system equations. Back substitution into the triangular system of equations is subsequently performed by subroutine FRESP to yield the real and imaginary portions of each feed system variable.

The conventional method of Gaussian elimination is employed by C0GAEL to triangularize the system of equations. The reduction process proceeds in column order from left to right. First the complex element with the largest absolute value in the current ("pivot") column at or below the diagonal is located. Then the rows are interchanged if required to move this maximum element (pivot element) to the diagonal. The row interchange serves to minimize the round-off errors from the subsequent reduction process. The pivot row (row containing the pivot element) is then divided by the pivot element yielding 1.0 from the pivot element. Finally, the elements in the pivot column below the diagonal are eliminated by subtracting the appropriate multiple of the pivot row from each row below it. The subtraction is not actually performed on the elements below the diagonal since these elements do not enter into the subsequent back substitution process performed by subroutine FRESP.

It should be noted that the above discussion refers to the complex matrix as if the elements were single numbers. The actual elements are stored as two numbers in each row, the real portion to the left of the constant term, and the imaginary portion on the right. This distinction does not alter the elimination process except that two separate numbers must be operated on at each step.

If the value of ICRT is greater than 0 this subroutine is called by the frequency response routine FRESP to generate CRT plots of the gain and phase of the output variables as a function of frequency.
The input arguments to TDPLT are, \( W \), an array of up to 101 frequencies; \( Y \), an array of gain or phase values; NFP, the number of data points in arrays \( W \) and \( Y \); TL, the lowest desired frequency grid line; XR, the highest desired frequency grid line; and LL, a flag indicating a gain plot if 1 or a phase plot if 2.

Initially TDPLT scans the \( Y \) array for the maximum and minimum values and generates values for the \( Y \) axis grid scaling. The first value of \( Y \) is not included in this scan. This allows an initial very low value of frequency to be used to approximate the system DC frequency response without upsetting the plot frequency scaling. TDPLT uses the standard graphics package routines for the SC-4020 to generate the plot grids and plot the data points. If the value of LL is 1 the CRT frame is advanced and a plot of \( Y(I) \) versus \( W(I) \) is made on the bottom half of the page. If LL is 2, the frame is not advanced and the plot is made on the top half of the page.

In addition to the plots, TDPLT prints the numeric value of the first \( Y \) array element immediately above the corresponding plot. This element typically corresponds to a very low frequency value (default value of .001 cps in subroutine FRESP) which is well below the frequency range desired for the plot and approximates the DC value of the output variable.

TDPLT does not generate any titles or identifying information on the plots.
This routine and its support routines, is called by the main program to determine the nozzle admittance based on downstream conditions. The programs were developed and programmed by Georgia Institute of Technology and the user is referred to Ref. 23 for a complete description of these routines. The main nozzle admittance program was modified by Rocketdyne so that input data could be read if required and also the nozzle admittance saved on a tape unit ITAPN (Fig. 13).
FSCSM COMPUTER MODEL INPUT

This section, and the Hydrodynamic Input section, describes the input necessary to run the FSCSM computer model. The input is broken up into four major control sections. These are the main control section input, the nozzle admittance control section input, the hydrodynamics control section input, and the combustion dynamics control section input. Table 2 lists all the variables that are to be input for each control section. This input is in the usual 80 character card form. Listed in Table 2 for each control section are each card's number and format, the variable names appearing on each card, and a brief description of each variable appearing in the list.

The main control section requires either eight or nine cards depending upon the input value of INPN0Z. (If INPN0Z is less than or equal to three, the last card in this section should be input). The first two cards, cards 1 and 2, should contain title and case identification information. These are read in alphanumeric format and printed at the top of almost every page of output to identify the case being considered.

The third card contains control information for various run options, file numbers for the auxiliary storage of datasets used by the program, print codes, and the number of mesh points to be used in the analysis. The control flags are INPHYD, INPCOM, and INPN0Z. These flags allow the user to save the results from the current case or use the results from a previous case for the current case. It is recommended that these datasets be set up as permanent files in order to use them for subsequent job submittals.

The first of these flags, INPHYD, controls the hydrodynamics feed system dataset. If it is input as one, no action will be taken with respect to saving or reading information on or from a dataset. The hydrodynamics coupling terms will be recomputed each time the frequency changes. If INPHYD is input as two, a table of hydrodynamic coupling terms will be generated for the frequency range specified by the input variables NFREQ, FREQMI, and FREQMX. This table will be saved on file ITAPH (also input on this card) and used to linearly interpolate in each time the frequency changes. If INPHYD is input as three, the program assumes a
<table>
<thead>
<tr>
<th>CONTROL SECTION</th>
<th>CARD NO./ FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Program Input</td>
<td>1,2 (18A4)</td>
<td>TITLE(I,J), I=1,18, J=1,2</td>
<td>Title information is input on the first two cards in the input dataset. These should be used to identify the case being run.</td>
</tr>
<tr>
<td></td>
<td>3 (12I6)</td>
<td>INPHYD</td>
<td>Code used for hydrodynamic calculations. 1: Hydrodynamic coupling terms (HCT) will be computed each time the frequency changes. 2: A table of HCT's will be computed using frequency table, FREQT, and saved on file ITAPH. Each time the frequency changes in trying to satisfy the nozzle admittance boundary condition, the HCT will be interpolated for in that table. 3: Table of HCT's already resides on file ITAPH from an earlier run. When the frequency changes, the HCT will be interpolated for in that table.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INPCOM</td>
<td>Code used for the combustion dynamics coefficients (CDC). It can take on values from one to three. It has the same meaning with respect to the CDC as INPHYD does with respect to the HCT. The tables are saved on file ITAPC.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>INPNoz</td>
<td>Code used for the downstream nozzle admittance term (DNAT). 1: The DNAT is computed each time the frequency changes. 2: A table of DNT's versus frequency using frequency table, FREQT, is computed and saved internally. Each time the frequency changes in trying to satisfy the nozzle admittance boundary condition, the DNT will be interpolated for in that table.</td>
</tr>
<tr>
<td>CONTROL SECTION</td>
<td>CARD NO./ FORMAT</td>
<td>VARIABLE NAME</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------</td>
<td>---------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Main Program Input (Cont.)</td>
<td></td>
<td>ITAPH</td>
<td>File used to save hydrodynamic coupling term table. Must be specified if INPHYD&gt;2.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ITAPC</td>
<td>File used to save combustion coefficients table. Must be specified if INPCQOM&gt;3.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ITAPN</td>
<td>File used to save nozzle admittance terms table. Must be specified if INPNQZ&gt;3.</td>
</tr>
</tbody>
</table>
| | | IPRHYD | Code used for hydrodynamics coupling term table printout.  

0: Table will not be printed. 

1: Table will be printed. |
| | | IPRCQOM | Code used for combustion coupling coefficients printout  

0: Coefficients will not be printed. 

1: Coefficients will be printed at each frequency found to satisfy the nozzle admittance boundary condition. |
| | | IPRNQZ | Code used for the downstream nozzle admittance terms table printout.  

0: Table will not be printed. 

1: Table will be printed. |
| | | IPRCHM | Code used for the oscillatory profiles printout.  

0: Profiles will not be printed. 

1: Profiles will be printed at each frequency found to satisfy the nozzle admittance boundary condition. |

3: Same as 2, but the table is also saved on file ITAPN. 

4: A table of DNT's versus frequency already resides on file ITAPN (from a previous run). Interpolation is the same as 2 and 3.
<table>
<thead>
<tr>
<th>CONTROL SECTION</th>
<th>CARD NO./FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
</table>
| Main Program Input (Cont.) | | IPRSTE | Code used for the steady-state profiles printout.  
0: Profiles will not be printed.  
1: Profiles will be printed. |
| | | NXP | Number of axial positions to be used between the XO plane (start of vaporization) and the nozzle inlet plane. (Both the XO and nozzle inlet planes must be counted.) |
| | 4 (6E12.8) | XO | Axial coordinate of start of vaporization plane, inches. |
| | | XNZ | Nozzle inlet plane, inches |
| | | RINJ | Radius of combustion chamber at injector face, inches. |
| | | GAMØ | Ratio of specific heats of combustion gas \( (C_p/C_v) \) evaluated at overall mixture ratio, unitless. |
| | | Ø | Sonic velocity evaluated at overall mixture ratio, ft/sec. |
| | | DELP | Oscillatory non-dimensional pressure amplitude at injector face, unitless. |
| | 5 (616) | NRØÐT | Absolute value of this variable is the number of frequency solutions that will be searched for starting at the frequency specified by the real part of \( \Omega \)EGA and ending at FROMAX. This variable may be input as either positive or negative. (See input of \( \Omega \)EGAR for explanation.) |
| | | IWRT | Intermediate output dump code used to write the oscillatory profiles solved for in CHAMDY for each iteration.  
0: Oscillatory profiles will not be printed out between iterations.  
1: Oscillatory profiles will be printed for each iteration. |
<table>
<thead>
<tr>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
</table>
| IWSKP         | Intermediate output dump code used in subroutine SØLVW.  
0: No intermediate output will be printed from SØLVW during iterations.  
1: Limited intermediate output will be printed by SØLVW.  
2: Extended intermediate output will be printed by SØLVW. |
<p>| KNTMX         | Maximum number of iterations allowed to minimize the error in the nozzle admittance boundary equation with respect to the imaginary part of ω. |
| KNTRMX        | Maximum number of times the frequency will be allowed to be changed by DELFRQ during the searching algorithm between each solution. |
| KNTSMX        | Maximum number of iterations allowed for the convergence of the two-dimensional secant method used in SØLVW. |
| ØMEGAR        | Starting value for the real part of complex frequency of NROOT&gt;0. This should be input in units of Hertz times $2\pi$. If NROOT&lt;0, this should be input in Hertz. |
| ØMEGAI        | Starting value for the imaginary part of complex frequency. This should be input as the growth coefficient if NROOT&gt;0. It should be input as the decrement if NROOT&lt;0. |
| FRQMAX        | Maximum frequency above which no solutions to the nozzle admittance boundary equation will be sought, Hertz. |
| DELFRQ        | Increment used to adjust the frequency during the searching portion of the algorithm to solve the nozzle admittance boundary equation, Hertz. |</p>
<table>
<thead>
<tr>
<th>CONTROL SECTION</th>
<th>CARD NO./ FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input (Cont.)</td>
<td>7 (4E12.8)</td>
<td>DELMX</td>
<td>Maximum allowable change in the growth coefficient between two successive iterations in the portion of the program that minimizes the error in the nozzle boundary condition equation with respect to the growth coefficient, sec⁻¹.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CTEST</td>
<td>Upper bound on the condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to the complex frequency. If the condition number of that matrix exceeds CTEST for a given frequency, then it is assumed the Jacobian is singular near that frequency and hence a solution will not be sought at that point. Unitless.</td>
</tr>
</tbody>
</table>
|                 |                 | EPSF          | Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, \( \omega_I \). To obtain convergence, it is necessary that 
\[
\frac{\partial |HN|}{\partial \omega_I} \left/ \frac{\partial N_D}{\partial \omega_I} \right| \leq EPSF.
\]
Unitless. |
|                 |                 | EPSX          | Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, HN, in the nozzle admittance boundary equation with respect to the growth coefficient, \( \omega_I \). To obtain convergence, it is necessary that 
\[
\frac{|\omega_{I1} - \omega_{I2}|}{|\omega_{I2}|} \leq EPSX
\]
where the subscripts 1 and 2 refer to two successive iterations. Unitless. |
<table>
<thead>
<tr>
<th>CONTROL SECTION</th>
<th>CARD NO./ FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Program Input (Cont.)</td>
<td></td>
<td>EPSFS</td>
<td>Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that</td>
</tr>
</tbody>
</table>
| | | | \[
| A_{NU} - A_{ND} | | A_{ND} \quad < EPSFS |
| | | | Unitless. |
| | | EPSXS | Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that |
| | | | \[
| \omega_1 - \omega_2 | | \omega_2 \quad < EPSXS |
| | | | where the subscripts 1 and 2 refer to successive iterations. Unitless. |
| | 8 | (3E12.8) | PC | Steady-state chamber pressure, psia. |
| | | | MBØXI | Oxidizer injection flowrate, lbm/sec |
| | | | MBFUI | Fuel injection flowrate, lbm/sec |
| | | | | INPUT THIS CARD ONLY IF INPNØZ\leq3 |
| | 9 | (112,2E12.8) | NFREQT | Number of points in frequency table. |
| | | | FREOMI | Minimum frequency in frequency table, Hertz. |
| | | | FREQMX | Maximum frequency in frequency table, Hertz. |
### CONTROL SECTION

<table>
<thead>
<tr>
<th>CARD NO./FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT THE CARD IN THIS CONTROL SECTION ONLY IF INPNZ ≤ 3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Nozzle Admittance Program

1. **RCCX**
   - Ratio of the radius of curvature at the nozzle inlet to the chamber radius at nozzle inlet, unitless (see Fig. 15).

2. **RCTX**
   - Ratio of the radius of curvature upstream of the throat to the chamber radius at nozzle inlet, unitless (see Fig. 15).

3. **ANGLEX**
   - Nozzle convergence half angle, degrees, (see Fig. 15).

4. **CRR**
   - Contraction ratio, cross-sectional area of chamber/throat area, unitless (see Fig. 15).

#### Hydrodynamics Program

This control section reads in its input data in NameList format. The NameList name is /HYD/. Input this data only if INPHYD < 2.

- **&HYD**
  - Input these characters starting in column two of the first card of the input.

- **NAMELIST Variables in any order**
  - See Table 3 for a listing of the NAMELIST data input names. The accompanying text describes the meaning of these variables.

- **&END**
  - Character string denoting the end of the NAMELIST input block.

*For Univac 1110 systems, use $HYD$ and $END*
<table>
<thead>
<tr>
<th>CONTROL SECTION</th>
<th>CARD NO./FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion Dynamics Program</td>
<td>1 (6E12.8)</td>
<td>XKØX</td>
<td>Klystron constant for oxidizer jet, inches.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TAUBØX</td>
<td>Steady-state oxidizer vaporization time delay, sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VBØX</td>
<td>Steady-state oxidizer injection velocity, ft/sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DELHØX</td>
<td>Pseudo energy term for oxidizer, Btu/lbm.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TDRAGØ</td>
<td>Steady-state oxidizer drag time delay, sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ADVØX</td>
<td>Velocity exponent for the oxidizer atomization process, unitless.</td>
</tr>
<tr>
<td></td>
<td>2 (5E12.8)</td>
<td>ADDØX</td>
<td>Oxidizer liquid jet diameter exponent, unitless.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DELVØX</td>
<td>Steady-state velocity difference between oxidizer droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NUBØX</td>
<td>Steady-state oxidizer Nusselt number used in vaporization expression, unitless.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DTØXDM</td>
<td>Partial derivative of oxidizer vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, drop diameter, and Nusselt number constant, sec.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>XIMPØX</td>
<td>Oxidizer jet impingement point, inches.</td>
</tr>
<tr>
<td></td>
<td>3 (6E12.8)</td>
<td>XKFU</td>
<td>Klystron constant for fuel jet, inches.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>TAUBFU</td>
<td>Steady-state vaporization time delay, sec</td>
</tr>
<tr>
<td></td>
<td></td>
<td>VBFU</td>
<td>Steady-state fuel injection velocity, ft/sec.</td>
</tr>
</tbody>
</table>

INPUT THE CARDS IN THIS CONTROL SECTION ONLY IF INPCOM<2

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<table>
<thead>
<tr>
<th>CARD NO./FORMAT</th>
<th>VARIABLE NAME</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 (5E12.8)</td>
<td>DELHFU</td>
<td>Pseudo energy term for fuel, Btu/lbm.</td>
</tr>
<tr>
<td></td>
<td>TDRAGF</td>
<td>Steady-state fuel drag time delay, sec.</td>
</tr>
<tr>
<td></td>
<td>ADVFU</td>
<td>Velocity exponent for fuel atomization process, unitless.</td>
</tr>
<tr>
<td></td>
<td>ADDFU</td>
<td>Fuel liquid jet diameter exponent, unitless.</td>
</tr>
<tr>
<td></td>
<td>DELVFU</td>
<td>Steady-state velocity difference between fuel droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless.</td>
</tr>
<tr>
<td></td>
<td>NUBFU</td>
<td>Average steady-state fuel Nusselt number used in vaporization expression, unitless.</td>
</tr>
<tr>
<td></td>
<td>DTFUDM</td>
<td>Partial derivative of fuel vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, droplet diameter, and Nusselt number constant, sec.</td>
</tr>
<tr>
<td></td>
<td>XIMPFU</td>
<td>Fuel jet injection impingement point, inches.</td>
</tr>
<tr>
<td>5 (5E12.8)</td>
<td>MWG</td>
<td>Steady-state molecular weight of the gas at the overall mixture ratio, lbm/lbm-mole.</td>
</tr>
<tr>
<td></td>
<td>CS</td>
<td>Characteristic velocity at the overall mixture ratio, ft/sec.</td>
</tr>
<tr>
<td></td>
<td>DRGDMR</td>
<td>Partial derivative of gas constant with respect to mixture ratio evaluated at the overall mixture ratio, ft-lb/lb/**R.</td>
</tr>
<tr>
<td></td>
<td>DCSDMR</td>
<td>Partial derivative of characteristic velocity with respect to mixture ratio evaluated at the overall mixture ratio, ft/sec.</td>
</tr>
<tr>
<td></td>
<td>DHDMR</td>
<td>Partial derivative of gas reference enthalpy with respect to mixture ratio averaged over the mixture range during steady-state operation, Btu/lbm.</td>
</tr>
</tbody>
</table>
table of hydrodynamic coupling terms versus frequency already resides on file ITAPH in the format used during generation of such a table when INPHYD is input as two. The program will interpolate in this table in order to obtain the hydrodynamic coupling terms each time the frequency changes. The use of interpolation, once a table has been generated, substantially reduces the computer run time for each case run.

The other two control flags input on the third card control the datasets for the combustion dynamics coefficients and the nozzle admittance factors. These flags are similar to INPHYD. Their description is given in Table 2.

Also input on the third card of the main control section input are the file numbers of the datasets discussed above and print control flags for the various forms of output one can obtain. These are all self-explanatory. The user need only refer to Table 2 in order to determine the values that should be input for the case being considered.

The final entry on the third card is for the variable NXP, the number of points to be used for the axial distance and area arrays. This controls the step size that will be taken during the integration of the chamber dynamics equations; i.e., step size = \((XN\delta Z - XO)_{NXP-1}\) where \(XO\) is the axial location of the start of vaporization plane and \(XN\delta Z\) is the axial location of the nozzle inlet plane. The values of \(XO\) and \(XN\delta Z\) are both input on the very next card read in (card 4 in Table 2).

The start of vaporization plane \((XO)\) is calculated by plotting the percent unburned of both fuel and oxidizer that is calculated by the DER program (or equivalent steady-state combustion model) as a function of distance from the injector face (Fig. 14). These plots are then extrapolated back to 100% unburned and the axial location of this point is \(XO\).

Also input on card 4 are the radius of the combustion chamber at the injector face, \(R_{INJ}\), the ratio of specific heats \((C_p/C_v)\), \(GAM\delta\), the sonic velocity, \(C\delta\), and the oscillatory non-dimensional pressure amplitude desired at the injector face \((\Delta P/P)\), DELP. The variables \(GAM\delta\) and \(C\delta\) should be evaluated at the overall
TEST #12  FUEL

... OXIDIZER

\[ T_x = 2.318 \text{ IN.} \ (0.059 \text{ m}) \]
\[ T_{x_{\text{fuel}}} = 1.952 \text{ IN.} \ (0.049 \text{ m}) \]
\[ \gamma_{\text{ox}} = 0.00669 \text{ SEC} \]
\[ \gamma_{\text{fuel}} = 0.00463 \text{ SEC} \]

Figure 14. Percent Unburned Propellant as a Function of Distance from Injector Face

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mixture ratio. The variable DELP will scale the amplitude of the oscillatory waves solved for in subroutine CHAMDY. A value of 0.1 is recommended.

The first variable input on the fifth card of the MAIN program control section input is NRØDT. The absolute value of this variable controls the maximum number of frequency solutions the program will try to find. The program begins its search at the frequency implied by the input variable ØMEGAR. It will stop looking once it has found \(|NRØDT|\) solutions or if the frequency is above FRQMAX. The variables IWRT and IWSKP are the next two variables input on this card. They control the amount of intermediate output one desires. Their exact function is described in the Program Operation Section of this manual.

The last three variables input on the fifth card are KNTMX, KNTRMX, and KNTSMX. Their meaning is explained in Table 2. Recommended values for these variables are 50, 100, and 20 respectively.

The sixth card of the MAIN program control section input contains the variables ØMEGAR, ØMEGAI, FRQMAX, DELFRQ, DELMX, and CTEST. The first two of these variables specify the starting guess in the \(\omega\) plane for solution. No solutions will be sought below the frequency implied by ØMEGAR. Note that ØMEGAR and ØMEGAI can be input as the frequency in Hertz times \(2\pi\) and the growth coefficient or the frequency in Hertz and the decrement depending upon whether NROOT was input as positive or negative. The variable FRQMAX, as mentioned earlier, is the maximum frequency allowed for the search algorithm to find solutions. The variable DELFRQ specifies the "stepsize" used by the search algorithm. Since there are sometimes many areas in the \(\omega\) plane which contain solutions, a fairly small stepsize is recommended, e.g., 5 Hz. The variable DELMX controls the maximum allowable change in the growth coefficient during successive iterations to minimize the error in the nozzle admittance boundary condition as a function of the imaginary part of \(\omega\). A recommended value for this variable is 50 sec\(^{-1}\). The last variable on this card, CTEST, is the upper bound on the condition number of the transposed Jacobian used to solve the nozzle admittance boundary condition. If the calculated condition number exceeds CTEST, then the search algorithm assumes that there is a singularity near the current value of \(\omega\) and hence, does not proceed further in that area to try and find a solution. A value of 50 to 80 is recommended.
The seventh card of the MAIN Program Control Section input contains error tolerances used in solving the nozzle admittance boundary condition. The first two, EPSF and EPSX, are used during the search algorithm and should be fairly large, e.g. 0.01 to 0.05 (1% to 5% error). The last two, EPSFS and EPSXS, control the final stages of iteration and should be fairly tight, e.g. 0.0005 (0.05%).

The eighth card of this control section contains the variables PC, MBØXI, and MBFUI. The first is the steady state chamber pressure, in PSIA, and the next two are the oxidizer and fuel injection flowrates, respectively (lbm/sec).

The last card, card number 9, in the MAIN Program Control Section input should be input only if the variable INPNØZ is less than or equal to three. If this is the case, the program needs to know the size and range of the frequency table it will use to generate tables for linear interpolation as discussed in the section describing the input variables INPHYD, INPCØM, and INPNØZ. The input variables on this ninth card are NFREQT, FREQMI, and FREQMX. Their meaning is described in Table 2.

The next control section to read data after the MAIN program is the Nozzle Admittance Program. The data for this control section should be input only if INPNØZ ≤ 3. Otherwise, the information is not needed since the nozzle admittance information will be on tape ITAPN. Even when INPNØZ ≤ 3, there is only one card input. This card contains information describing the nozzle geometry. Refer to Table 2 to determine the meaning of the variables on this card. Figure 15 shows exactly what portion of the nozzle each variable is applicable to.

The next control section that requires data is the Hydrodynamics Program section. This control section uses namelist input. The data for this control section are only input if INPHYD ≤ 2. Otherwise, the hydrodynamics information will be on tape ITAPH. The Hydrodynamic Input section (page 102) describes the meaning of the variables to be input for the control section.

The last control section to require input data is the Combustion Dynamics Program. This input is contained on five cards. It should be omitted if INPCØM is greater than or equal to three, since then the combustion dynamics information will reside on tape ITAPC.
Figure 15. Chamber and Nozzle Geometry
The first two cards for this section contain information specific to the oxidizer; the next two cards contain information specific to the fuel; the last card contains information specific to the combustion gas. Much of the information required in this section is obtainable from the output of the DER program (Ref. 11). This program solves for the steady state behavior of the chamber under consideration. The single stream tube option of the DER program is sufficient for this application.

As mentioned above, the variables input on the first two cards of the Combustion Dynamics Program control section are applicable to the oxidizer. These variables are \( \text{XK}_\text{OX} \), \( \text{TAUB}_\text{OX} \), \( \text{VB}_\text{OX} \), \( \text{DELH}_\text{OX} \), \( \text{TDRAG}_\text{OX} \), \( \text{ADV}_\text{OX} \), \( \text{ADD}_\text{OX} \), \( \text{DELVOX} \), \( \text{NUB}_\text{OX} \), \( \text{DTXDM} \), and \( \text{XIMP}_\text{OX} \). The first variable \( \text{XK}_\text{OX} \), is the Klystron constant for the oxidizer jet. This variable controls the distance downstream from the injector face that the Klystron effect will be allowed to occur. The exact method of calculating \( \text{XK}_\text{OX} \) has not been determined but it is recommended that a distance corresponding to approximately 45% of the oxidizer vaporized be used.

The next variable, \( \text{TAUB}_\text{OX} \), is the steady state oxidizer vaporization time delay. Figure 14 gives the percent unburned for the sample input case of liquid oxidizer and fuel remaining in the chamber as a function of axial distance plotted on semi log graph paper. This output was derived from a DER computer run. The reciprocal of the average slope of the oxidizer curve during the initial burning phases should be taken as the oxidizer vaporization distance delay. For Figure 14, this is 2.318 inches. The time delay is obtained by dividing this by the average injector velocity, which, for the sample case presented in Figure 14 is 28.859 ft/sec. The result is 0.00669 seconds. The next variable, \( \text{VB}_\text{OX} \), is the average oxidizer injection velocity. This is also given by the DER program from injector orifice and steady state \( \Delta P \) considerations.

The variable \( \text{DELH}_\text{OX} \) is the pseudo energy of the oxidizer droplets and is discussed at the end of this section. The variable \( \text{TDRAG}_\text{OX} \) is the steady-state oxidizer drag time delay and a value of zero is currently recommended. If this variable is different from zero, the computed pressure and velocity profiles calculated in the chamber are unrealistic (see Conclusions and Recommendations in Ref. 1).
ADV\(_{OX}\) and ADD\(_{OX}\) are the velocity and orifice diameter exponents for the oxidizer atomization process, i.e.,

\[
\bar{D}_{ox} = V^{ADV_{OX}} \cdot D_{orif}^{ADD_{OX}}
\] (216)

These variables are obtained from cold flow tests and for like-doublets -0.75 and 0.57 are recommended. It should be noted that these variables are on different input cards. The next input variable is DELV\(_{OX}\) which is the steady-state velocity difference between the oxidizer droplets and the combustion gas stream normalized to the sonic velocity. Since the vaporization rate is highest near the injector face, this variable should be evaluated near the injector face. Because the gas and the droplet velocities are approximately equal to each other at this location, a value of 0.01 is recommended based on turbulence levels in a rocket chamber (Ref. 26).

The next variable, NUB\(_{OX}\), is the steady state oxidizer Nusselt number used in the vaporization expression. This variable should be computed from the relation

\[
N_{u_{OX}} = \frac{8}{6} \frac{\bar{D}_{ox}^2}{k_{ox}' T_{ox}}
\] (217)

where \(\bar{D}_{ox}\) is the average oxidizer droplet diameter near the injector face, \(k_{ox}'\) is the vaporization coefficient used in the \(k'\)-model evaluated at a mixture ratio near the injector face and \(T_{ox}\) is the oxidizer time delay. Both \(\bar{D}_{ox}\) and \(k_{ox}'\) are obtainable from a DER computer run. For the sample case input, "near the injector face" was taken as the first axial step printed by the DER program.

The variable DT\(OX_{DM}\) is the change in the oxidizer vaporization time delay with respect to mixture ratio. At the present time, a value of zero is recommended based on model verification cases (Ref. 1).

The last oxidizer variable input is XIMP\(_{OX}\). This is the impingement point in inches for the oxidizer jets.
The next two cards contain data for the fuel. These data are obtained the same way as they were for the oxidizer and are input in the same order.

The last card for this control section contains combustion gas data. The first variable input on this card, MWG, is the steady state molecular weight evaluated at the overall mixture ratio. This may be obtained from tables of molecular weight versus mixture ratio printed by the DER program. The next variable, CS, is the characteristic velocity evaluated at the overall mixture ratio. This is also obtainable from DER table output. The last three variables on this card are DRGDMR, DCSDMR, and DHDMR. These are the partial derivatives with respect to mixture ratio of the gas constant, the characteristic velocity, and the reference enthalpy respectively. DRGDMR and DCSDMR can be calculated from equilibrium calculations but a value of zero is recommended for DCSDMR based on model verification cases (Ref. 1).

The variable DHDMR, and also the variables DELHØX and DELHFU, is calculated by curvfitting the steady-state energy equation with stagnation temperature/mixture ratio data calculated by an equilibrium program. The steady-state energy equation can be written as

\[
\left( \frac{\gamma_\phi}{\gamma_\phi - 1} \right) R_\phi \left\{ T \left[ 1 + \frac{1}{R_\phi} \left( \frac{\partial R}{\partial MR} \right)_\phi (MR - MR_\phi) \right] (1 + MR) \right.
\]

\[
- (1 + MR_\phi) T_\phi \left\{ \frac{1}{MR} - \frac{1}{(1 + MR_\phi)} \right\} = (MR - MR_\phi) (\Delta h_{\text{ox}})
\]

\[
- \left[ MR (1 + MR) - MR_\phi (1 + MR_\phi) \right] \left( \frac{\partial h}{\partial MR} \right)_\phi
\]

where

\[
(\Delta h_{\text{fu}}) = \left( \frac{\gamma_\phi}{\gamma_\phi - 1} \right) (1 + MR_\phi) R_\phi T_\phi - MR_\phi (\Delta h_{\text{ox}})
\]

\[
+ (MR_\phi)(1 + MR_\phi) \left( \frac{\partial h}{\partial MR} \right)_\phi
\]

and the subscript \( \phi \) indicates that the variable is to be evaluated based on the overall mixture ratio.
HYDRODYNAMIC INPUT

This section describes data needed by the hydrodynamics subroutine, HYDRDY, to simulate the various feed system components. It is assumed that the feed system being modeled has been laid out on the generalized feed system schematic of Fig. 4 with an appropriate segment number assigned to each feed system component (or combination of components).

Basic Feed-System Data
To describe the basic feed system it is necessary to know the length, area, resistance and wall compliance of each of the numbered segments of Fig. 4 which are being used. Also, the acoustic velocity and density of the fluid in each segment must be known. If there is dissolved an entrained gas in the system, then a preliminary calculation must be made for each feed system section to account for the effect of the gas on the fluid acoustic velocity.

Specific parameters required for the numbered segments are:

- **A** - Segment cross-sectional area - in.$^2$
- **CW** - Segment wall compliance ($\Delta V/\Delta P/V$ - in.$^2$/lb)
- **L** - Segment length - in.
- **R** - Segment linearized hydraulic resistance ($\Delta P/\dot{Q}$) - sec/in.$^2$
- **V** - Segment fluid acoustic velocity - in./sec
- **RH0L** - Segment fluid density - lb/in.$^3$

Valves, Fittings, Orifices, Screens, Flowmeters, etc.
These components can each be described in the model simply as lumped resistance at the end of a line segment. Rather than using all the attributes of one of the numbered segments (length, area, wall compliance, etc.) for one of these "resistance only" components, it is suggested that its resistance merely be added to that of the adjacent upstream pipe segment. The combination can then be entered as one of the numbered segments with the length, area and wall compliance values being primarily those of the pipe segment.
Accumulators
A feed system accumulator can be represented as one of the side branch lines of the Fig. 4 schematic by specifying an appropriate length, area, acoustic velocity and fluid density for the fluid volume of the accumulator and also specifying an appropriate connecting resistance. The spring rate of the accumulator piston can be specified in terms of the segment wall compliance value.

Propellant Tanks
A large tank will have the effect of constant fluid pressure at its outlet and can be represented simply as the input to segment number 1, 15, or 22. No descriptive parameters are required for these inputs. Small tanks can be represented as one of the side branch lines in a manner similar to an accumulator. Ullage volume in a small tank is represented by a reduced value for the segment acoustic velocity.

Cavitating Venturis
The steady-state effect of a cavitating venturi is to have constant flow through the venturi as a function of variations in downstream pressure. For an oscillatory system, the vapor bubble downstream of the venturi throat makes the venturi look like a constant pressure boundary for small amplitude oscillations. To simulate this effect the effective acoustic velocity for the segment downstream of the cavitating venturi should be made very small (=10 inches/sec would be appropriate). The steady-state hydraulic resistance of the cavitating venturi can be lumped with that of the upstream pipe segment as described above for valves, fittings, etc.

Regeneratively-Cooled Thrust Chamber
Regeneratively-cooled thrust chamber jackets can be represented as one or more of the numbered Fig. 4 segments. Because in most thrust chambers the coolant flow area changes continuously with length, as many segments as possible should be devoted to the jacket so as to improve the simulation
accuracy. The fluid temperature also may change significantly along the chamber length thereby necessitating the use of several segments with different acoustic velocities to achieve accurate simulation.

**Lines, Ducts, Bends, Bellows, and Flex Lines**

These components are described in the model in terms of the basic numbered segment input parameters of length, area, fluid acoustic velocity, fluid density, wall compliance and linearized hydraulic resistance. For a duct or line of constant diameter, D, wall thickness, h, and wall material bulk modulus, E, the program input wall compliance value, CW, is simply D/LE. For a bellows or flux line of volume, V, the wall compliance value, CW, may be calculated from ΔV/ΔP/V where ΔV/ΔP is the volume change per psi at the operating pressure.

**Injectors**

The hydrodynamics subprogram employs a separate set of equations to describe the hydrodynamic characteristics of the two injectors in the Fig. 4 generalized feed system schematic. The specific input parameters for the two injectors are the volume, linearized hydraulic resistance, orifice inertance (1/Ag), fluid acoustic velocity, and a structural parameter defining the change in injector volume per psi of injector ΔP. In terms of the program variable names the required injector parameters are:

- **RF** - Linearized hydraulic resistance for the "F" injector, 
  $$(2 \Delta P/\dot{W}) \text{ sec/in.}^2$$
- **RØ** - Linearized hydraulic resistance for the "Ø" injector, 
  $$(2 \Delta P/\dot{W}) \text{ sec/in.}^2$$
- **VOLF** - Volume of the "F" injector - in.$^3$
- **VOLØ** - Volume of the "Ø" injector - in.$^3$
- **VF** - Fluid acoustic velocity of the "F" injector - in./sec
- **VØ** - Fluid acoustic velocity of the "Ø" injector - in./sec
- **ZF** - Inertance of the "F" injector orifices (1/Ag) - sec$^2$/in.$^2$
- **ZØ** - Inertance of the "Ø" injector orifices, (1/Ag) - sec$^2$/in.$^2$
- **KF** - "F" injector deflection constant, (ΔV/ΔP) - in.$^5$/lb
- **KØ** - "Ø" injector deflection constant, (ΔV/ΔP) - in.$^5$/lb

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Tees, Splitters and Capped Lines

No provision is made in the model for completely generalized input of tees and branched lines. However, a system of considerable complexity can be modeled by laying out an appropriate flow path on the generalized Fig. 4 schematic. For example, a feed system with up to seven side branch lines can be simulated by choosing the main flow path through segments 1, 3, 4, 14, 17, 21, 25, 26, 28, 29, 30 and the "F" injector in series.

Input Variables

Data input to the hydrodynamics subprogram is from three sources: (1) Via the argument list in the CALL HYDRDY statement, (2) Through labeled common block/C_NTAP/ and (3) By use of the NAMELIST data read routine.

The argument list variables, in order, are:

IR - Data read flag - dimensionless
INPHYD - Program function flag - dimensionless
FRE - Single frequency for feed system frequency response calculation - Hz
GINØ - Output value of oscillatory oxidizer injector flowrate for input frequency FRE - dimensionless
GINF - Output value of oscillatory fuel injector flowrate for input frequency FRE - dimensionless
PCIN - Injector end thrust chamber pressure - psia
W_OKIN - Steady-state oxidizer injector flowrate - lb/sec
W_FIN - Steady-state fuel injector flowrate - lb/sec

Several HYDRDY input variables are transmitted via labeled common block/C_NTAP/. ITAPH is the logical unit number of the output device on which subroutine HYDRY tabulates output values of oscillatory injection flowrates for the specific frequencies (up to 100 separate values) given in the array FREQT in common block/CONTAP/. The value of the FREQT in common block/C_NTAP/is the total number of frequencies stored in the array FREQT.

All other data required by HYDRDY, including all the feed system descriptive data, is read in by use of the NAMELIST routine. The local rules for using this routine should be checked to verify that the correct card or terminal format is being used. Table 3 shows a list of allowable FORTRAN names, the maximum values of subscripts, and a definition of the names. The name of the NAMELIST block is HYD.
TABLE 3. NAME LIST/HYD/DATA INPUT NAMES

<table>
<thead>
<tr>
<th>NAME</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(30)</td>
<td>Array containing segment cross-sectional area values</td>
</tr>
<tr>
<td>CW(30)</td>
<td>Array containing segment wall compliance values</td>
</tr>
<tr>
<td>FREQ</td>
<td>Frequency at which HYDRDY will compute feed system frequency response if INPHYD ≤ 1</td>
</tr>
<tr>
<td>FREQT(100)</td>
<td>Array containing frequencies at which HYDRDY will compute feed system frequency response of INPHYD &gt; 1.</td>
</tr>
<tr>
<td>ICRT</td>
<td>ICRT = 1; injector flowrate gain and phase will be plotted vs frequency. ICRT = 0; no plot (default)</td>
</tr>
<tr>
<td>ID</td>
<td>Dummy name to allow for data card sequence numbers</td>
</tr>
<tr>
<td>IH(126)</td>
<td>Array containing control flags used by subroutine FREQD. Can be used to obtain printouts and plots of feed system frequency response for other variables in addition to the injector flowrates.</td>
</tr>
<tr>
<td>IRFLAG</td>
<td>IRFLAG = 0; read data from unit 5 (default)</td>
</tr>
<tr>
<td></td>
<td>IRFLAG ≠ 0; read data from unit ITERM</td>
</tr>
<tr>
<td>ITERM</td>
<td>ITERM = 0; no terminal data input (default)</td>
</tr>
<tr>
<td></td>
<td>ITERM &gt; 0; read data from terminal (unit ITERM)</td>
</tr>
<tr>
<td>ITYPE</td>
<td>ITYPE = 1; both oxidizer and fuel feed systems are modeled simultaneously (default)</td>
</tr>
<tr>
<td></td>
<td>ITYPE = 2; oxidizer feed system modeled on first pass of frequency response routine; fuel feed system modeled on second pass.</td>
</tr>
<tr>
<td>IWRITE</td>
<td>IWRITE = 0; HYDRDY input printed on unit 6 (default)</td>
</tr>
<tr>
<td></td>
<td>IWRITE = 2; extensive printout of all HYDRDY input, intermediate output and final output on unit 6</td>
</tr>
<tr>
<td></td>
<td>IWRITE = 1; printout of HYDRDY input and final output on unit 6</td>
</tr>
<tr>
<td>KF</td>
<td>Injector face flexibility constant for &quot;F&quot; injector</td>
</tr>
<tr>
<td>KΦ</td>
<td>Injector face flexibility constant for &quot;Φ&quot; injector.</td>
</tr>
<tr>
<td>L(30)</td>
<td>Array containing segment length values</td>
</tr>
</tbody>
</table>
TABLE 3. (Concluded)

<table>
<thead>
<tr>
<th>NAME</th>
<th>DEFINITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>φMI</td>
<td>Lowest frequency for injector flowrate gain/phase plot; default to FREQT(1) if not entered</td>
</tr>
<tr>
<td>φMFL</td>
<td>Highest frequency for injector flowrate gain/phase plot; default to FREQT(NFREQT) if not entered</td>
</tr>
<tr>
<td>R(30)</td>
<td>Array containing segment hydraulic resistance values</td>
</tr>
<tr>
<td>RF</td>
<td>Hydraulic resistance for &quot;F&quot; injector</td>
</tr>
<tr>
<td>RHØL(30)</td>
<td>Array containing segment propellant density values</td>
</tr>
<tr>
<td>RØ</td>
<td>Hydraulic resistance for &quot;Ø&quot; injector</td>
</tr>
<tr>
<td>V(30)</td>
<td>Array containing segment acoustic velocity values</td>
</tr>
<tr>
<td>VF</td>
<td>Acoustic velocity for &quot;F&quot; injector</td>
</tr>
<tr>
<td>VØ</td>
<td>Acoustic velocity for &quot;Ø&quot; injector</td>
</tr>
<tr>
<td>VØLF</td>
<td>Volume of &quot;F&quot; injector</td>
</tr>
<tr>
<td>VØLØ</td>
<td>Volume of &quot;Ø&quot; injector</td>
</tr>
<tr>
<td>ZF</td>
<td>Inertance of &quot;F&quot; injector</td>
</tr>
<tr>
<td>ZØ</td>
<td>Inertance of &quot;Ø&quot; injector</td>
</tr>
</tbody>
</table>
Required input in the NAMELIST/HYD/data is a value of A, CW, L, R, RH, L, and V (see Table 3 for descriptions) for each numbered segment being included in the feed system. Values of KF and/or KØ, RF and/or RØ, VF and/or VØ, VØLF and/or VØLØ and ZF and/or ZØ are also required. It should be noted that, when possible, both oxidizer and fuel feed systems should simultaneously be laid out on the Fig. 4 schematic with the injector labeled "Ø" being used for the oxidizer side (data values KØ, RØ, VØ, VØLØ and ZØ) and the injector labeled "F" being used for the fuel side (data values, KF, RF, VF, VØLF and ZF). If this can be done, a single call to subroutine FRESP will generate frequency response data for both oxidizer and fuel feed systems. If feed system complexity requires that the oxidizer and fuel feed systems be laid out separately on the Fig. 4 schematic, then two sets of input data must be read and subroutine HYDRDY must call FRESP twice - first for the oxidizer feed system calculations and second for the fuel feed system calculations. To specify this option, variable ITYPE must be set equal to 2.

Variable INPHY in the HYDRDY argument list controls the HYDRDY calculation process. If INPHY < 1 the oscillation injection flowrates are calculated for a single frequency, specified by variable FRE in the HYDRDY argument list. If INPHY > 1, HYDRDY calculates oscillatory injector flowrates for the number of frequencies, NFREQT, which are contained in array FREQT. Both NFREQT and the array FREQT are stored in labeled common block/CBMTAP/ prior to calling HYDRDY.

NAMELIST variable ICRT controls the option for generating CRT plots of the oscillatory injection flowrate gains and phase values as a function of frequency. If ICRT = 0 (the default value) no plots are made. If ICRT > 1 plot output is written to the output file named SYSCRT.

NAMELIST variable, ID, is a dummy name which can be used on each input card to provide an identification number field without violating the NAMELIST restriction that the entire card is read as data. For example, ID = 00000010 could be in columns 70-80 of a HYDRDY data card and ID = 00000020 in columns 70-80 of the next card. The NAMELIST routine would then interpret each card's sequence number as a new value for the dummy variable, ID. The value of ID is not used in any way by subroutine HYDRDY.

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NAMELIST variable, ITYPE, is used to indicate to HYDRDY the format of the feed system modeling. If ITYPE = 1 (the default value) it is assumed that both oxidizer and fuel feed systems are modeled simultaneously with only one set of HYDRDY input values (for the 30 segments and 2 injectors of the Fig. 4 schematic). If ITYPE = 2, HYDRDY will send two consecutive sets of input data; the first set will be assigned to the oxidizer feed system and the second set to the fuel feed system. For either value of ITYPE the program will assume that the injector labeled "O" on Fig. 4 is the oxidizer flow outlet and the injector labeled "F" is the fuel flow outlet. Therefore, this convention must be followed when laying out the feed system model.

NAMELIST variables IRFLAG and ITERM are optional HYDRDY inputs which indicate that data input will be provided from a timesharing terminal. If IRFLAG = 0 (the default value), input data will be read only from FORTRAN logic unit number, ITERM. It should be noted that the default values for IRFLAG and ITERM are set up so that the initial data input will always be card input on unit 5.

After reading the initial NAMELIST data on unit 5, HYDRDY checks the value of ITERM and, if non-zero, proceeds to read additional first case data from the terminal on unit ITERM. Thus, the first case card NAMELIST input could consist of the single item ITERM = N, where N is the terminal logical unit number. If terminal input only is desired, block data program/F/ can be recompiled with the IRFLAG default value changed from 0 to 1 and the ITERM default value changed from 0 to the desired unit number.

NAMELIST variable IWRITE (main program control variable IPRHYD) controls the printed output from HYDRDY. If IWRITE = 0 (the default value), only the NAMELIST input to HYDRDY is printed on logical unit 6. If IWRITE < 0 the NAMELIST input is printed and the normal HYDRDY output is printed as well as being saved on an output device in binary form. If IWRITE = 1 both HYDRY input and normal output are printed. If IWRITE > 1 extensive print-outs of subroutine FRESP intermediate calculations are printed in addition to the normal HYDRDY input and output.
PROGRAM OUTPUT

The output of the FSCSM computer program is provided as the usual tabular printout. A sample case is included in Appendix E which corresponds to the input dataset listed in Appendix D. As is also mentioned in the Program Operation section of this manual, the input case listed in Appendix D consists of two cases being run back to back. The output from the first case is given in Appendix E from pages E-2 through E-14. The first page of output consists of a title page identifying the current version of the FSCSM computer program. The input data are printed out as they are read in. This permits both a full documentation of the computer run conditions for later analysis as well as a convenient method to check for input errors if unusual results are calculated. Page E-3 of the listing in Appendix E gives the two alphanumeric cards identifying the case at the top of the page right under the program title. Subsequent to these two cards, the information on the cards read in by the main control section and the nozzle admittance control section are printed out. After reading and writing these cards, and since INPN02 = 3, the program proceeds to the nozzle admittance table calculations. Information pertinent to these calculations is printed on page E-4. The frequency table goes from 150 Hz to 400 Hz as specified by the input variables FREQMI and FREQMX.

Since INPHYD = 2, the program proceeds to the hydrodynamic subroutines right after the nozzle admittance calculations. Input for this routine is in the form of NAMELIST data. The NAMELIST is output on pages E-5 and E-6. A printout of the feed system response table computed by subroutine HYDRDY and saved on file ITAPH is given on page E-7.

The next set of input required is used in subroutine C0MBOY and STEADY. This is output on page E-8. The steady-state profiles are then computed and printed on pages E-9 and E-10.
The program then begins its search for solutions to the nozzle admittance boundary condition. The first one it finds is at 210.42 Hz. The program then outputs the combustion dynamic coefficients, the frequency and decrement, and the feed system response for this solution on page E-14. On page E-12, the oscillatory profiles correspond to this solution are given. The program then proceeds to the next case.

Since the second case does not generate the data on files ITAPN and ITAPH (it only reads this information), these tables are not printed. The first page of output, page E-15, in Appendix E, consists entirely of the data read by the Main Control Section and the Combustion Dynamics Control Section. Since the STEADY Control Section print code is zero (IPRSTE = 0), the program skips over the steady-state output (although of course, it still computes it) and proceeds directly to the section which solves the nozzle admittance boundary condition. The first root it finds above the input frequency of 265 Hz (given by the variable $\omega_{MEGAR}$), is at 280.62 Hz. It prints out the frequency, decrement, nozzle admittances, and feed system response for this solution. Output of the combustion coefficients and oscillatory profiles is bypassed because the input flags IPRCQM and IPRCHM were set to zero.

The final page of output is the title page. This indicates normal termination of the job.
PROGRAM OPERATION

The FSCSM computer program is designed to read in an input case sequentially, perform the calculations for that case, and output the results. The program then transfers back to its beginning to read in the next case. In this manner, running jobs back-to-back is quite straightforward. The sample input case listed in Appendix D provides an example of two such cases run back to back. The first case, given by the first 24 cards, is run with no prior information residing on the hydrodynamic feed system, the combustion dynamics, or the nozzle admittance datasets. Since INPHYD = 2 and INPNZ = 3, this case generates tables of the hydrodynamic feed system response and nozzle admittance versus frequency and saves them on files ITAPH and ITAPN, respectively. The subsequent case (the last 13 cards in Appendix D) will use the information stored on these datasets. Although these two cases were run back to back, this was by no means necessary. The second case is self-contained and could be submitted separately. Of course, if this were the situation, the user must be sure there are datasets on files ITAPH and ITAPN which are applicable to that second case.

For the sample dataset run, the two input cases found solutions to the nozzle admittance boundary equation at 210.42 Hz and 280.62 Hz, respectively. If there are no other solutions between these two frequencies, the same effect could have been obtained by setting the input variable NRZT equal to -2 for the first case instead of -1. The program would have then looked for the first two roots above the input frequency 190 Hz (ΩEGR) and found both solutions automatically. The second case would not be input for this situation.
Program Size, Overlay Structure, and Timing

Without overlay, the FSCSM computer program load module requires 262.4 K Bytes of computer storage on the IBM 370 Model 165 computer. This storage does not count the buffers needed for input/output. If one allocates a 1 K Byte of buffer size for each of the three date sets used to store the feed system, combustion dynamic, and nozzle admittance data (which are all unformatted input/output), uses two buffers for each data set, and adds in the buffer requirements for his card input, printed output, and CRT output, then the total buffer space should be well under 10 K bytes on a 370/165 computer. With the overlay structure specified in Fig. 16, the total program requirement is 220 K bytes of storage on an IBM 370/165 computer, including two buffers for each of the three unformatted datasets at 1K bytes each.

Computer run time has only been checked for an IBM 370/165 computer where the subroutines were compiled using the IBM procedure AFORTRAN with the optimizing parameter, OPT, equal to one. For this situation, each iteration during the search algorithm portion of the program (when ISCNT equals one or four) averaged 3.7 CPU seconds. When ISCNT=5, each iteration is about twice as fast. For the cases run during model verification a five Hz step size for the search algorithm was used (DELFRO=5). For these cases, each solution to the nozzle admittance boundary equations averaged 0.85 minutes of CPU.

Program Input/Output Dataset File Information

The case input dataset file number used by the FSCSM computer program is 5. The printed output dataset file number is 6. There are three auxiliary files used by the program. These are specified by the input parameters, ITAPC, ITAPH, and ITAPN, corresponding to the combustion dynamics, hydrodynamic feed system, and nozzle admittance datasets. Control of the reading from or writing on to these respective datasets is specified by the three input flags INPCOM, INPHYD, and INPN0Z. The

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program uses unformatted input/output statements for transmitting information to and from these datasets. A convenient blocksize to use is 1K bytes.

<table>
<thead>
<tr>
<th>FSCSM MAIN</th>
<th>HEAD</th>
<th>AREA</th>
<th>LØCFAC</th>
<th>SØLVW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HY/</td>
<td></td>
<td>/CØMCM/</td>
<td>/CØNSTS/</td>
</tr>
<tr>
<td></td>
<td>/CØMCM/</td>
<td>/CØMCHM/</td>
<td>/CØMARE/</td>
<td>/CØMNØZ/</td>
</tr>
<tr>
<td></td>
<td>/FZERØ/</td>
<td>/DUMP/</td>
<td>/SØLVE/</td>
<td>/CØNTAP/</td>
</tr>
<tr>
<td></td>
<td>/ADARND/</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
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<th>ORIGIN A</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NØZADM</td>
<td>ZERØ</td>
<td>CØMBDY</td>
<td>HYDRDY</td>
<td></td>
</tr>
<tr>
<td>TADAMS</td>
<td>CHAMDY</td>
<td>STEADY</td>
<td>FRESP</td>
<td></td>
</tr>
<tr>
<td>ZADAMS</td>
<td>XIMAGF</td>
<td></td>
<td>TDPLØT</td>
<td></td>
</tr>
<tr>
<td>RKIDIF</td>
<td>CHMCØN</td>
<td></td>
<td>CØGAEL</td>
<td></td>
</tr>
<tr>
<td>RKZDIF</td>
<td>CØMMAT</td>
<td></td>
<td></td>
<td>/F/</td>
</tr>
<tr>
<td>RKTZ</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/X1/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/X2/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/X3/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>/X4/</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 16. FSCSM Program Overlay Structure
Diagnostics

The Feed System Coupled Stability Model computer program has been designed to operate as straightforward as possible with a minimum amount of user interaction for each case being run. There may be times however, when the program's results appear questionable or the algorithm used to find solutions in the frequency space to the nozzle admittance boundary equation runs into difficulty or does not find solutions that were expected. Many diagnostic messages are coded into the program to warn the user of such problems. Also, there are certain dump codes which enable the user to obtain intermediate output in order to debug most problems that may arise.

One of these dump codes is the variable IWSKP. When this is set to zero, no intermediate output is obtained. When it equals one, a certain amount of limited output will be generated. This output comes in two forms depending upon whether or not the program is within its search algorithm portion or its two-dimensional secant portion. For the first case, the variable ISCNT has the value of one or four. In the second case it has the value 5. When ISCNT equals one or four and IWSKP equals one, subroutine SOLVW will print the following variables in the order given: the iteration counter (KNTR), the control flag (ISCNT), the counter (KSCNT4), the current values of omega (ω), the upstream and downstream nozzle admittances (CNZA and NZA), the absolute value of the error in the nozzle admittance equation (HN), the value of the test function (FTST2), and the determinant and condition number of the transposed Jacobian (DET2 and CND2). This printing will be performed every time the real part of ω is incremented by 2π*DELFREQ right after the imaginary part of ω has been chosen to minimize |F|, the absolute value of the error in the nozzle admittance boundary equation. The user can employ this output to determine if there is a region in the ω-plane where a possible solution may have existed (e.g., the error became small but the test function did not change sign). He can then rerun his case while taking smaller frequency steps through the narrowed range where he suspects a solution may exist. Also, the program may jump over a solution if there is a singularity within DELFRQ of that solution. If this is the case, the program will sense the singularity and not proceed any further in its search in that range. Rerunning the case with a smaller value of DELFRQ will solve this problem.

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When ISCNT equals five and IWSKP equals one, subroutine S\textsubscript{LVW} prints after each two-dimensional secant method, these variables in the following order: ISCNT, KNTS, \( \Omega \)EGA, CN\textsubscript{ZA}, N\textsubscript{ZA}, and HN. Although it did not happen for any of the cases performed during the checkout of the computer model, the two-dimensional secant method may diverge. The above computer output would be useful in determining the cause of the problem.

When the variable IWSKP equals two, all the above output is printed plus the following:

1. When ISCNT equals one or four, intermediate output is obtained during the iterations to minimize |FN| with respect to Imag (\( \omega \)). For this case, one obtains the variables KNT, IER, X1, X2, F1, F2, \( \Omega \)EGA, FN, GN, and HN. These are all described in Appendix A. This output may be useful in seeing how the error is changing as a function of the decrement when the real part of the frequency is held fixed. Further, when ISCNT equals one or four, the variables FN, DFRDX, DFIDX, DFRDY, and DFIDY are printed along with the output obtained when IWSKP = 1.

2. When ISCNT equals five and IWSKP equals two, one obtains the output for the case IWSKP equals one for the two-dimensional secant method plus the following variables in order: XR1, XI1, FR1, FI1, XR2, XI2, FR2, FI2, XR3, XI3, FR3, FI3, XR4, XI4, FR4, FI4, and FN. These variables correspond to the current values of \( \omega \) and FN being used by the two-dimensional secant method. They can be used to trace which points the algorithm is replacing as the iteration proceeds as well as how the error is behaving.

Another input variable which controls intermediate output is the FORTRAN variable IWRT. This variable is input as zero, no intermediate output is obtained. If this variable is input as a positive number, then intermediate output from subroutine CHAMDY is obtained. This output consists of the oscillatory profiles for the variables P (pressure), RH\( \Omega \) (density), MR (mixture...
ratio), and T (temperature) along with the current value of the complex frequency, \( \omega \). This output is printed everytime subroutine CHAMDY is entered.

The diagnostic messages that are coded within the FSCSM computer program may be printed for several reasons.

Within subroutine S\_LVW, there are three diagnostic messages coded which will appear when certain iteration counters are exceeded. The first is

```
WARNING, POSSIBLE ROOT IN FREQUENCY RANGE: --
```

When this message appears, it means that a potential root was bracketed but the error did not decrease sufficiently within ten additional iterations to warrant the program proceeding further with its search in that range. Moreover, the determinant did not change sign and the condition number remained less than CTEST in that range. Rerunning the case over the specified frequency range given in the message with IWSKP equal to one or two may prove beneficial if the user suspects there may be an actual solution in that range.

The second diagnostic message printed by subroutine S\_LVW is

```
**** UNABLE TØ FIND RØOT FØR IMAG PART ØF F ****
```

Along with this message, the variables X1, F1, K2, F2, X3, F3, ANS, FANS, KNT, IER, and ØMEGA are printed in the order listed. When this message appears, it means the algorithm to minimize |FN| with respect to \( \text{Imag} \left( \omega \right) \) has failed. If this message appears, it usually means something is wrong with the input parameters. The only occurrence that the programmers are aware of when this is not the case is when the error attains a minimum as |\text{Imag} \left( \omega \right)| \rightarrow \infty. Since this happens only in the most extraordinary situations, the procedure should be to rerun the case and not include the frequency range where that anomaly is occurring.
The third diagnostic produced by subroutine SOLLVW is

**** EXCEEDED CONVERGENCE LIMIT ****

Along with this message, the variables IER, KNTS, KNTR, ISCNT, XRI, XI1, FRI, FI1, ......, XR4, XI4, FR4, FI4, are printed.

This message will appear if KNTR is greater than KNTRMX or KNTS is greater than KNTRSMX. In the former case, the usual error is that the user input too small a DELFRO to cover the range between solutions to the nozzle admittance boundary equation in KNTRMX steps or too small a KNTRMX to allow that range to be covered in steps of length DELFRO.

In the case where KNTS is greater than KNTRSMX, it would probably mean that the two-dimensional secant method is diverging. The job should be rerun with IWSKP equal to one or two to obtain more information concerning the problem.

There is also a diagnostic message printed from subroutine CMAT. This is the subroutine that solves the four by four system of linear equations for subroutine CHAMDY. If any of the diagonal elements of the associated matrix are zero, then the message

***** DIVIDE CHECK IN CMAT *****

will appear along with a printout of the row number of the zero diagonal as well as the complex matrix being solved. If this error message appears, then there must be something very wrong with the case being run, e.g., the input data is in error, or a dimension has been exceeded. One should recheck his input carefully and then, if necessary, rerun the case with IWRT equal to one and IWSKP equal to one or two.

Two similar messages as the one above are printed by subroutine CGAEL. The first of these messages is

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****ERROR IN CÔGAEL SUBROUTINE, J AND JMAX EQUAL, RESPECTIVELY****

and the second is

****MATRIX IS SINGULAR, EXIT FROM CÔGAEL. THE PIVOT ELEMENTS ARE...****

The reasons for these errors are similar to the CÔMMAT error message.

Conversion to UNIVAC

The following cards must be changed to execute the FSCSM program on a UNIVAC computer (see Appendix C for code listing):

1. Change CÔMPLEX*16...to CÔMPLEX....

<table>
<thead>
<tr>
<th>Routine</th>
<th>Card Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHAMDY</td>
<td>80</td>
</tr>
<tr>
<td>CÔMMAT</td>
<td>150</td>
</tr>
</tbody>
</table>

2. In subroutine CÔMMAT, change CDABS to CA_S on card No. 24.

3. In subroutine TDPLØT, replace card 11310 with

   31 CONTINUE.....0011310

4. In subroutine NØZADM, replace card 1730 with

   8 NØZA = CMPLX(SYR, SYI)....00001730

5. In the main program, change ATAND( ) to 57.296*ATAN( ) on card numbers 3370, 3410, 3450, and 3490.
REFERENCES


APPENDIX A

FORTRAN SYMBOL TABLE
<table>
<thead>
<tr>
<th>FORTRAN VARIABLE NAME</th>
<th>ENGINEERING VARIABLE SYMBOL</th>
<th>TYPE</th>
<th>CONTROL SECTION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A(IO0)</td>
<td>A</td>
<td>R</td>
<td>CØMARE</td>
<td>Axial distance array, (X(1) = X_0 + (X-1)* ) DELX, m</td>
</tr>
<tr>
<td>ADDFU</td>
<td>(a_{fu})</td>
<td>R</td>
<td>CØMCBM</td>
<td>Fuel liquid jet diameter exponent, unitless</td>
</tr>
<tr>
<td>ADDØX</td>
<td>(a_{\phi x})</td>
<td>R</td>
<td>CØMCBM</td>
<td>Oxidizer liquid jet diameter exponent, unitless</td>
</tr>
<tr>
<td>ADVFU</td>
<td>(b_{fu})</td>
<td>R</td>
<td>CØMCBM</td>
<td>Velocity exponent for fuel atomization process, unitless</td>
</tr>
<tr>
<td>ADVØX</td>
<td>(b_{\phi x})</td>
<td>R</td>
<td>CØMCBM</td>
<td>Velocity exponent for the oxidizer atomization</td>
</tr>
<tr>
<td>AINJ</td>
<td>(A_{inj})</td>
<td>R</td>
<td>CØMARE</td>
<td>Cross sectional area at injector face, (m^2)</td>
</tr>
<tr>
<td>AMA(4,5)</td>
<td>--</td>
<td>C</td>
<td>CHAMDY</td>
<td>Array used to store coefficients of finite difference equations approximating the oscillatory differential equations</td>
</tr>
<tr>
<td>ANGLEX</td>
<td>--</td>
<td>R</td>
<td>CØMNØZ</td>
<td>Nozzle convergence half angle, degrees (see Fig. 15)</td>
</tr>
<tr>
<td>ANS</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Solution to minimization of error in nozzle admittance boundary equations. Returned to SØLVW from subroutine ZERØ.</td>
</tr>
<tr>
<td>CFU1,...</td>
<td>(c_{1fu})</td>
<td>C</td>
<td>CØMCBM</td>
<td>Fuel combustion coefficients, unitless</td>
</tr>
<tr>
<td>CFU16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMA(4)</td>
<td>(c_{16fu})</td>
<td>C</td>
<td>CHAMDY</td>
<td>Right hand side of finite difference equation approximating the oscillatory differential equations. In equivalence with CMA(1,5).</td>
</tr>
<tr>
<td>CNØZA</td>
<td>(A_{hu})</td>
<td>C</td>
<td>CØMCHM</td>
<td>Upstream nozzle admittance</td>
</tr>
<tr>
<td>CØ</td>
<td>(c_{\phi})</td>
<td>R</td>
<td>CØMCBM</td>
<td>Sonic velocity evaluated at overall mixture ratio, (m/sec (ft/sec))</td>
</tr>
<tr>
<td>CØND1</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to (\omega).</td>
</tr>
</tbody>
</table>

R-9808/A-2
<table>
<thead>
<tr>
<th>FORTRAN VARIABLE NAME</th>
<th>ENGINEERING VARIABLE SYMBOL</th>
<th>TYPE</th>
<th>CONTROL SECTION</th>
<th>DESCRIPTION</th>
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</thead>
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<tr>
<td>C0ND2</td>
<td>--</td>
<td>R</td>
<td>S0LVW</td>
<td>Condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ( \omega ).</td>
</tr>
<tr>
<td>C0X1,..., C0X16</td>
<td>( c_i ), ( c_{ox} )</td>
<td>C</td>
<td>C0MCBM</td>
<td>Oxidizer combustion coefficients, unitless</td>
</tr>
<tr>
<td>CRR</td>
<td></td>
<td>R</td>
<td>C0MN0Z</td>
<td>Contraction ratio, cross-sectional area of chamber/throat area, unitless (see Fig. 15)</td>
</tr>
<tr>
<td>CS</td>
<td>( c^* )</td>
<td>R</td>
<td>C0MCBM</td>
<td>Characteristic velocity evaluated at the overall mixture ratio, ( \text{m/sec (ft/sec)} )</td>
</tr>
<tr>
<td>CTEST</td>
<td>--</td>
<td>R</td>
<td>S0LVE</td>
<td>Upper bound on the condition number of the transpose of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to the complex frequency. If the condition number of that matrix exceeds CTEST for a given frequency, then it is assumed that Jacobian is singular near that frequency and hence a solution will not be sought at that point, unitless.</td>
</tr>
<tr>
<td>DA(100) ( \partial A/\partial x )</td>
<td>R</td>
<td>C0MARE</td>
<td></td>
<td>Slope of area of chamber at XM(I), ( \text{m} )</td>
</tr>
<tr>
<td>DCSDMR ( \partial c^*/\partial MR )</td>
<td>R</td>
<td>C0MCBM</td>
<td></td>
<td>Partial derivative of the characteristic velocity with respect to mixture ratio holding, ( \text{m/sec} )</td>
</tr>
<tr>
<td>DELFRQ</td>
<td>--</td>
<td>R</td>
<td>S0LVE</td>
<td>Frequency increment used during the search procedure to solve the nozzle admittance boundary equation, Hz.</td>
</tr>
<tr>
<td>DELHFU ( \Delta h_{fu} )</td>
<td>R</td>
<td>C0MCBM</td>
<td></td>
<td>Pseudo energy term for fuel, ( \text{J/kg (Btu/lbm)} )</td>
</tr>
<tr>
<td>DELHOX ( \Delta h_{ox} )</td>
<td>R</td>
<td>C0MCBM</td>
<td></td>
<td>Pseudo energy term for oxidizer, ( \text{J/kg (Btu/lbm)} )</td>
</tr>
<tr>
<td>DELMX</td>
<td>--</td>
<td>R</td>
<td>S0LVE</td>
<td>Maximum change in ( \omega ) allowed between iterations</td>
</tr>
<tr>
<td>DELP ( \Delta P )</td>
<td></td>
<td>R</td>
<td>C0MCHM</td>
<td>Oscillatory pressure at injector face, dimensionless</td>
</tr>
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</table>

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<table>
<thead>
<tr>
<th>FORTRAN VARIABLE NAME</th>
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<th>TYPE</th>
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<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>DELVFU</td>
<td>--</td>
<td>R</td>
<td>COMCBM</td>
<td>Steady-state velocity difference between fuel droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless</td>
</tr>
<tr>
<td>DELVØX</td>
<td>--</td>
<td>R</td>
<td>COMCBM</td>
<td>Steady-state velocity difference between oxidizer droplets and gas stream normalized to the sonic velocity at the overall mixture ratio, unitless</td>
</tr>
<tr>
<td>DELX</td>
<td>Δx</td>
<td>R</td>
<td>COMARE</td>
<td>Axial distance between successive X(I), m</td>
</tr>
<tr>
<td>DET1</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Determinant of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.</td>
</tr>
<tr>
<td>DET2</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Determinant of the Jacobian of the difference between the upstream and downstream nozzle admittances with respect to ω.</td>
</tr>
<tr>
<td>DFIDX</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Derivative of Imag (FN) with respect to real (ω).</td>
</tr>
<tr>
<td>DFIDY</td>
<td>--</td>
<td>R</td>
<td>SØLVW</td>
<td>Derivative of real (FN) with respect to real (ω).</td>
</tr>
<tr>
<td>DHDMR</td>
<td>$(\partial h/\partial MR)_b$</td>
<td>R</td>
<td>COMCBM</td>
<td>Partial derivative of gas reference enthalpy with respect to mixture ratio averaged over the mixture ratio range during steady-state operation, J/kg (Btu/lbm).</td>
</tr>
<tr>
<td>DM1</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equations approximating the oscillatory differential equations.</td>
</tr>
<tr>
<td>DM2</td>
<td>--</td>
<td>R</td>
<td>ADARND</td>
<td>Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equation approximating the oscillatory differential equations.</td>
</tr>
<tr>
<td>FORTRAN VARIABLE NAME</td>
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</tr>
<tr>
<td>DM3</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Used to store intermediate values needed to compute boundary conditions and coefficients of finite difference equations approximating the oscillatory differential equations.</td>
</tr>
<tr>
<td>DM4</td>
<td>--</td>
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</tr>
<tr>
<td>DM5</td>
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<td>DM6</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM7FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM7OX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
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<tr>
<td>DM8FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM8OX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM9FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM9OX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DM22</td>
<td>--</td>
<td>R</td>
<td>ADARND</td>
<td></td>
</tr>
<tr>
<td>DMRB(100)</td>
<td>$\theta_{MR}/x$</td>
<td>R</td>
<td>CONSTANTS</td>
<td>Derivative of steady-state mixture ratio with respect to distance, $m^{-1}$</td>
</tr>
<tr>
<td>DRGDMR</td>
<td>$\theta R/\theta x$</td>
<td>R</td>
<td>constants</td>
<td>Partial derivative of gas constant with respect to mixture ratio evaluated at the overall mixture ratio, $J$/kmole/$^\circ K$ (ft-lb/lb/$^\circ R$)</td>
</tr>
<tr>
<td>DRHQB(100)</td>
<td>$\theta d/\theta x$</td>
<td>R</td>
<td>Constants</td>
<td>Derivative of steady-state density with respect to distance, $kg/m^3/m$</td>
</tr>
<tr>
<td>DTFUDM</td>
<td>$\theta_{fu}/\theta MR$</td>
<td>R</td>
<td>constants</td>
<td>Partial derivative of fuel vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, droplet diameter, and Nusselt number constant, sec</td>
</tr>
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</table>

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<table>
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<th>FORTRAN VARIABLE NAME</th>
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<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>DT@XDM</td>
<td>$\frac{\partial \tau_{ox}}{\partial MR}$</td>
<td>R</td>
<td>C@MCBM</td>
<td>Partial derivative of oxidizer vaporization time delay with respect to mixture ratio, holding the vaporization blockage term, drop diameter, and Nusselt number constant, sec</td>
</tr>
<tr>
<td>EPSF</td>
<td>--</td>
<td>R</td>
<td>S@OLVE</td>
<td>Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, $H_N$, in the nozzle admittance boundary equation with respect to the growth coefficient, $\omega_1$. To obtain convergence, it is necessary that $\frac{\partial</td>
</tr>
<tr>
<td>EPSFS</td>
<td>--</td>
<td>R</td>
<td>S@OLVE</td>
<td>Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that $</td>
</tr>
<tr>
<td>EPSX</td>
<td>--</td>
<td>R</td>
<td>S@OLVE</td>
<td>Relative error criterion used during the search algorithm for the portion of the program that minimizes the error, $H_N$, in the nozzle admittance boundary equation with respect to the growth coefficient, $\omega_1$. To obtain convergence, it is necessary that $</td>
</tr>
</tbody>
</table>

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<tr>
<th>FORTRAN VARIABLE NAME</th>
<th>ENGINEERING VARIABLE SYMBOL</th>
<th>TYPE</th>
<th>CONTROL SECTION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
</table>
| EPSXS                  | --                          | R    | SØLVW           | Tightened relative error criterion used to determine if convergence has been obtained while iterating to solve the nozzle admittance boundary equation. To obtain convergence, it is necessary that

$$\frac{\omega_1 - \omega_2}{|\omega_2|} < \text{EPSXS}$$

where the subscripts 1 and 2 refer to successive iterations, unitless. |
| F1                     | --                          | R    | SØLVW           | Derivatives of absolute value squared of the difference between the upstream and downstream nozzle admittances with respect to Imag (ω) corresponding to X1, X2, and X3. |
| F2                     | --                          | R    | SØLVW           | Derivative of squared error in nozzle admittance boundary equation at ANS. |
| F3                     | --                          | R    | SØLVW           | Interpolating factor used in the main program. |
| FANS                   | --                          | R    | SØLVW           | Used to store successive values of Imag (FN) during the 2-dimensional secant method. |
| FI                     | --                          | R    | MAIN            | |
| FI1                    | --                          | R    | SØLVW           | |
| FI2                    | --                          | R    | SØLVW           | |
| FI3                    | --                          | R    | SØLVW           | |
| FI4                    | --                          | R    | SØLVW           | |
| FN                     | --                          | C    | FZERØ           | Difference between the upstream and downstream nozzle admittances. |
| FNF                    | --                          | R    | FZERØ           | Imaginary (FN) |
| FNR                    | --                          | R    | FZERØ           | Real (FN) |
| FR1                    | --                          | R    | SØLVW           | Used to store successive values of Real (FN) during the 2-dimensional secant method. |

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<table>
<thead>
<tr>
<th>FORTRAN VARIABLE NAME</th>
<th>ENGINEERING VARIABLE SYMBOL</th>
<th>TYPE</th>
<th>CONTROL SECTION</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>FR2</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Used to store successive values of Real (FN) during the 2-dimensional secant method.</td>
</tr>
<tr>
<td>FR3</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Frequency, i.e., real (ω), Hz</td>
</tr>
<tr>
<td>FR4</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Frequency, i.e., real (ω), Hz</td>
</tr>
<tr>
<td>FREQ</td>
<td>2\pi ω R</td>
<td>R</td>
<td>SOLW</td>
<td>Frequency, i.e., real (ω), Hz</td>
</tr>
<tr>
<td>FREQMI</td>
<td>--</td>
<td>R</td>
<td>CMN0Z</td>
<td>Minimum frequency, used for generation of frequency table FREQT, Hz</td>
</tr>
<tr>
<td>FREQMX</td>
<td>--</td>
<td>R</td>
<td>CMN0Z</td>
<td>Maximum frequency used for generation of frequency table FREQT, Hz</td>
</tr>
<tr>
<td>FREQT(100)</td>
<td>--</td>
<td>R</td>
<td>CMTAP</td>
<td>Table of terms used for computation of downstream nozzle admittance.</td>
</tr>
<tr>
<td>FRQMAX</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Maximum frequency above which no solutions to the nozzle admittance boundary equation will be sought, Hz</td>
</tr>
<tr>
<td>FTST1</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Test function used to determine if a solution to the nozzle admittance boundary equation has been bracketed.</td>
</tr>
<tr>
<td>FTST2</td>
<td>--</td>
<td>R</td>
<td>SOLW</td>
<td>Test function used to determine if a solution to the nozzle admittance boundary equation has been bracketed.</td>
</tr>
<tr>
<td>G1FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory pressure in fuel oscillatory vaporization expression.</td>
</tr>
<tr>
<td>G1OX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory pressure in oxidizer oscillating vaporization expression.</td>
</tr>
<tr>
<td>G2FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory density in fuel oscillatory vaporization expression.</td>
</tr>
<tr>
<td>G2OX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory density in oxidizer oscillating vaporization expression.</td>
</tr>
<tr>
<td>FORTRAN VARIABLE NAME</td>
<td>ENGINEERING VARIABLE SYMBOL</td>
<td>TYPE</td>
<td>CONTROL SECTION</td>
<td>DESCRIPTION</td>
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<tr>
<td>-----------------------</td>
<td>-----------------------------</td>
<td>------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>G3FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory mixture ratio in fuel oscillatory vaporization expression.</td>
</tr>
<tr>
<td>G3ΩX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory mixture ratio in oxidizer oscillating vaporization expression.</td>
</tr>
<tr>
<td>G4FU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory velocity in fuel oscillatory vaporization expression.</td>
</tr>
<tr>
<td>G4ΩX</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Coefficient of oscillatory velocity in oxidizer oscillating vaporization expression.</td>
</tr>
<tr>
<td>GAMØ</td>
<td>Ψ</td>
<td>R</td>
<td>CØMCBM</td>
<td>Specific heat ratio evaluated at the overall mixture ratio, unitless.</td>
</tr>
<tr>
<td>GINJFT(100) Ginjfu</td>
<td></td>
<td>C</td>
<td>CØMTAP</td>
<td>Fuel feed system response table. Real (GINJFT) is the amplitude of the response and Imag (GINJFT) is the phase angle of the response.</td>
</tr>
<tr>
<td>GINJOT(100) Ginjox</td>
<td></td>
<td>C</td>
<td>CØMTAP</td>
<td>Oxidizer feed system response table. Real (GINJOT) is the amplitude of the response and Imag (GINJOT) is the phase angle of the response.</td>
</tr>
<tr>
<td>GN</td>
<td>--</td>
<td>C</td>
<td>FZERØ</td>
<td>Variable used to store the value of the derivative of CNØZA-NØZA with respect to ω₁ or the value of CNØZA-NØZA itself.</td>
</tr>
<tr>
<td>HN</td>
<td>--</td>
<td>R</td>
<td>FZERØ</td>
<td>FN*FN</td>
</tr>
<tr>
<td>I</td>
<td>--</td>
<td>I</td>
<td>--</td>
<td>Used throughout the program as a do loop index.</td>
</tr>
<tr>
<td>INPNØZ</td>
<td>--</td>
<td>I</td>
<td>CØMNØZ</td>
<td>Code used for the downstream nozzle admittance term calculation.</td>
</tr>
<tr>
<td>INRT</td>
<td>--</td>
<td>I</td>
<td>DUMP</td>
<td>Code used to determine whether or not intermediate output from CHAMDY is desired.</td>
</tr>
<tr>
<td>IPASS</td>
<td>--</td>
<td>I</td>
<td>SØLVE</td>
<td>Internal code no longer in use.</td>
</tr>
<tr>
<td>FORTRAN VARIABLE NAME</td>
<td>ENGINEERING VARIABLE SYMBOL</td>
<td>TYPE</td>
<td>CONTROL SECTION</td>
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<td>-----------------------------</td>
<td>------</td>
<td>----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>IPRNØZ</td>
<td>--</td>
<td>R</td>
<td>CØMNØZ</td>
<td>Code used for downstream nozzle admittance term printout</td>
</tr>
<tr>
<td>IR</td>
<td>--</td>
<td>I</td>
<td>MAIN</td>
<td>Flag set by MAIN program to indicate the first pass through it. After reading in a new case.</td>
</tr>
<tr>
<td>ISCNT</td>
<td>--</td>
<td>I</td>
<td>FZERØ</td>
<td>Code used to determine logical flow in subroutine SOLVW.</td>
</tr>
<tr>
<td>ISLP</td>
<td>--</td>
<td>I</td>
<td>FZERØ</td>
<td>Code used to determine whether or not the derivative of FN with respect to Imag (ω) is needed.</td>
</tr>
<tr>
<td>ISTRT</td>
<td>--</td>
<td>I</td>
<td>SOLVE</td>
<td>Code used to indicate the first iteration after a solution to the nozzle boundary equation.</td>
</tr>
<tr>
<td>II</td>
<td>C</td>
<td>ADARND</td>
<td>The imaginary number i.</td>
<td></td>
</tr>
<tr>
<td>ITAPC</td>
<td>--</td>
<td>I</td>
<td>CØMTAP</td>
<td>File number used to save combustion coefficients table.</td>
</tr>
<tr>
<td>ITAPH</td>
<td>--</td>
<td>I</td>
<td>CØMTAP</td>
<td>File number used to save hydrodynamic coupling term table.</td>
</tr>
<tr>
<td>ITAPN</td>
<td>--</td>
<td>I</td>
<td>CØMTAP</td>
<td>File number used to save nozzle admittance term table.</td>
</tr>
<tr>
<td>IWSKP</td>
<td>--</td>
<td>I</td>
<td>SOLVE</td>
<td>Intermediate output dump code used in subroutine SOLVW.</td>
</tr>
<tr>
<td>J</td>
<td>--</td>
<td>I</td>
<td></td>
<td>Used throughout the program as a do loop index.</td>
</tr>
<tr>
<td>KNTMX</td>
<td>--</td>
<td>I</td>
<td>SOLVE</td>
<td>Maximum number of iterations allowed to minimize the error in the nozzle admittance boundary equation with respect to the imaginary part of ω.</td>
</tr>
<tr>
<td>KNTR</td>
<td>--</td>
<td>I</td>
<td>SOLVE</td>
<td>Counter used to control the number of iterations used during the search algorithm between solutions.</td>
</tr>
<tr>
<td>KNTRMX</td>
<td>--</td>
<td>I</td>
<td>SOLVE</td>
<td>Maximum number of times the frequency will be allowed to be changed by DELFRQ during the searching algorithm between each solution.</td>
</tr>
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<table>
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<tr>
<th>FORTRAN VARIABLE NAME</th>
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</thead>
<tbody>
<tr>
<td>KNTSMX</td>
<td>--</td>
<td>I</td>
<td>SØLVE</td>
<td>Maximum number of iterations allowed for the convergence of the two-dimensional secant method used in SØLVW.</td>
</tr>
<tr>
<td>KSCNT4</td>
<td>--</td>
<td>I</td>
<td>SØLVE</td>
<td>Counter used to control the number of iterations used when ISCNT = 4.</td>
</tr>
<tr>
<td>KWHERE</td>
<td>--</td>
<td>I</td>
<td>MAIN</td>
<td>Flag to control logical flow in the MAIN program after a call to subroutine SØLVW.</td>
</tr>
<tr>
<td>MBFUI ((\dot{m}<em>{fu})</em>{inj})</td>
<td>R</td>
<td>CØMCBM</td>
<td>SØLVE</td>
<td>Fuel injection mass flowrate, kg/sec (lb/sec).</td>
</tr>
<tr>
<td>MB(\dot{Ox}) ((\dot{m}<em>{ox})</em>{inj})</td>
<td>R</td>
<td>CØMCBM</td>
<td>SØLVE</td>
<td>Oxidizer injection mass flowrate, kg/sec (lb/sec).</td>
</tr>
<tr>
<td>MGI (\dot{m}_{inj})</td>
<td>R</td>
<td>CØNSTS</td>
<td></td>
<td>Steady-state gas flowrate at injector face, kg/sec.</td>
</tr>
<tr>
<td>MR(100) (MR_{o})</td>
<td>R</td>
<td>CØMCBM</td>
<td>SØLVE</td>
<td>Oscillatory mixture ratio, dimensionless.</td>
</tr>
<tr>
<td>MRB(100) (MR_{r})</td>
<td>R</td>
<td>CØNSTS</td>
<td></td>
<td>Steady-state mixture ratio, unitless.</td>
</tr>
<tr>
<td>MRGI (MR_{inj})</td>
<td>R</td>
<td>CØNSTS</td>
<td></td>
<td>Steady-state gas mixture ratio at injector face, unitless.</td>
</tr>
<tr>
<td>MRNTFU</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Mixture ratio integral in fuel oscillatory vaporization expression.</td>
</tr>
<tr>
<td>MRNT(Ox)</td>
<td>--</td>
<td>C</td>
<td>ADARND</td>
<td>Mixture ratio integral in oxidizer oscillatory vaporization expression.</td>
</tr>
<tr>
<td>MWG (M_{\theta})</td>
<td>R</td>
<td>CØMCBM</td>
<td></td>
<td>Molecular weight of the gas evaluated at the overall mixture ratio, kg/kmole (Ibm/lb-mole).</td>
</tr>
<tr>
<td>NFREQT</td>
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<tr>
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<td>--</td>
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<td>COMCBM</td>
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<tr>
<td>RCTX</td>
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<td>COMNØZ</td>
<td>Ratio of the radius of curvature upstream of the throat to the chamber radius at nozzle inlet, unitless (see Fig. 15).</td>
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<td>CØMCBM</td>
<td>Steady-state fuel liquid injection velocity, m/sec (ft/sec).</td>
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<td>C</td>
<td>CØMCHM</td>
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<td>CØMARE</td>
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<td>SØLVW</td>
<td></td>
</tr>
<tr>
<td>XIMPFU</td>
<td>( ximp_{fu} )</td>
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<td>CØMCBM</td>
<td>Fuel jet injection impingement point, m (in.).</td>
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<td>CØMCBM</td>
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<td>Axial distance midpoints, XM(I) = (X(I) + X(I-1))/2, m.</td>
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<tr>
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<td>COMARE</td>
<td>Nozzle inlet point, m.</td>
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## APPENDIX 3

### PROGRAM FLOW CHARTS

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<td>AREA</td>
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MAIN CONTROL PROGRAM FOR THE FEED SYSTEM COUPLED STABILITY MODEL
PROGRAM DEVELOPED BY RODIETONE, A DIVISION OF ROCKWELL INTERNATIONAL, CANDIA PARK, CALIF 91304
PROGRAMMED BY R. D. BOYD, RODIETONE, MAY 1975

ORIGINAL PAGE IS
OF POOR QUALITY
SUBPROGRAM CALCULATES AXIAL STRESS AND STRAIN
PROGRAMMED BY .
REVISION: AUG 1975

01
INPUT = NIP - 1
DELS = INOC - HST/100001
X11 = X0
A11 = A11
DA11 = 0.0

NOTE 01
BEGIN DO LOOP
0 1 = 2, NIP

03
X11 = X0
DELPHI = 11
A11 = A11
DA11 = 0.0

10
END OF DO LOOP
YES

NOTE 05
BEGIN DO LOOP
2 0 = 1, NIP

06
X11 = X11
DELPHI = 0
A11 = A11
DA11 = 0.0

20
END OF DO LOOP
YES

08
DELHNP = DELPHI + DELX
A11NP = A11NP
DA11NP = 0.0

09
EXIT
DIMENSION A(12,12)
12 FORMAT (4E12.6)
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SUBROUTINE TO CALCULATE THE CONVOLUTION COEFFICIENTS ASSIGNED BY M. O. R. H. JUNE, 1975.

NOTE 01
DR: L.E. 0

NOTE 02
THIS IS FIRST PASS FOR THIS CASE. READ INPUT DATA.

NOTE 03
READ FROM DEV 9 VIA FORMAT INTO THE LIST

NOTE 04
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 05
LIST = WORK, TAURUS, SIGMA, DELTA, TO, XIX, DOPH, NARSI, DOPH, XIX

NOTE 06
WORK = XIXD, GEAR, DOPH, TO, XIX, DOPH, NARSI, DOPH, XIX

NOTE 07
READ FROM DEV 9 VIA FORMAT INTO THE LIST

NOTE 08
LIST = WORK, TAURUS, SIGMA, DELTA, TO, XIX, DOPH, NARSI, DOPH, XIX

NOTE 09
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 10
LIST = FRE, FRE, FRE, FRE, FRE, FRE, FRE, FRE, FRE

NOTE 11
INPUT = XIXFNG, DELTA, TO, XIX, DOPH, NARSI, DOPH, XIX

NOTE 12
EXTERNAL FORMAT FROM THE LIST

NOTE 13
LIST = FRE, CS, SIS, SIGMA, OMEGA

NOTE 14
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 15
LIST = HAPS, CS, OMEGA, SIGMA, OMEGA

NOTE 16
CS = CS, 0: 0: 0: 0: 0: 0: 0: 0: 0: 0

NOTE 17
DOPH = DOPH, 0: 0: 0: 0: 0: 0: 0: 0: 0: 0

NOTE 18
READING 1+TAP

NOTE 19
CONTINUE

NOTE 20
IF INPUT LE. 1, COMPUTE CORRELATION COEFFICIENTS FOR INPUT FREQUENCY-PEAKED. IF INPUT CORRELATION COEFFICIENTS FOR ENTIRE FREQUENCY-PEAKED AND SAVE ON ITAP.

NOTE 21
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 22
PRE = FRE

NOTE 23
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 24
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 25
LIST = FRE, FRE, FRE, FRE, FRE, FRE, FRE, FRE, FRE

NOTE 26
READ FROM DEV 9 VIA FORMAT INTO THE LIST

NOTE 27
INPUT = XIXFNG, DELTA, TO, XIX, DOPH, NARSI, DOPH, XIX

NOTE 28
EXTERNAL FORMAT FROM THE LIST

NOTE 29
LIST = FRE, CS, SIS, SIGMA, OMEGA

NOTE 30
WRITE TO DEV 9 VIA FORMAT FROM THE LIST

NOTE 31
LIST = HAPS, CS, OMEGA, SIGMA, OMEGA

NOTE 32
CS = CS, 0: 0: 0: 0: 0: 0: 0: 0: 0: 0

NOTE 33
DOPH = DOPH, 0: 0: 0: 0: 0: 0: 0: 0: 0: 0

NOTE 34
READING 1+TAP

NOTE 35
CONTINUE

NOTE 36
IF INPUT LE. 1, COMPUTE CORRELATION COEFFICIENTS FOR INPUT FREQUENCY-PEAKED. IF INPUT CORRELATION COEFFICIENTS FOR ENTIRE FREQUENCY-PEAKED AND SAVE ON ITAP.
COMPLEX GROSS, GIBFU, DME, MGAT, GMAT, GMAFT.
CO1, CO2, CO3, CO4, CON, CON, CON, CONT, CONB, CONB,
CON1, CON2, CON3, CON4, CON5, CON6, 
CF1, CF2, CF3, CF4, CF5, CF6, CF7, CF8, 
CF9, CF10, CF11, CF12, CF13, CF14, CF15, 
CF16, CF17, CF18, CF19, CF20, CF21, CF22, CF23, CF24.

REAL MWD, MFD, MG, MGDF, MGDF.

COMMON /COMPANY/ VREDH, VOETD, MGAT1, MGAT2, 
SCHLFT1, TAMP, STAP, TAPC.

COMMON /COMP/ VREDH, MGDF, MG, MGDF, TAMP, TAMP, MGDF.

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ROUTINE SOLVES AX = B. MX = A & B ARE COMPLEX MATRICES.
COMPLEX VECTOR IT IS STORED IN A ( )
A = B, T
ANSWER IS RETURNED IN
Mx I. THE NUMBER OF THE RECURSION
STATEMENT FOR
A ROUTINE IN THE
CALLING PROGRAM.

A.X. AND B ARE ALL
COMPLEX.

PROGRAMMED BY K. W. FOTTG. 1970

NOTE 08
WRITE TO DEV
EXIT
COMPLEX=1B A100A,10.H
9000 FORMAT(' IINN DIVIDE CHECK IN CONVAT', i, 10)'

IF ( ,10) = '1'
(S=20,PR(1,6),",",PR(2,6))
CHART TITLE - SUBROUTINE WRITE (WRITE, 191)

ORIGINAL PAGE IS OF POOR QUALITY
DIMENSION OH(101),OW(101),OM(101),OP(101),OB(101),OD(101)
DIMENSION LX(101),LY(101),Z(101),C(101),A(101),DF(101,63),DF(126)
DIMENSION AM(101),AN(101),ML(101),ML(101),MN(101),MAH(101),FACE(101)
DIMENSION V(101),W(101),X(101),Y(101),Z(101),DF(101),DF(101,63)
DIMENSION AT(101,101),DF(101,101)
COMMON/UNIT,AH,AN,ML,ML,ML,ML,ML,ML,ML,ML
COMMON/MOD,MOD,MOD,MOD,MOD,MOD,MOD
COMMON/MOD,MOD,MOD,MOD,MOD,MOD,MOD

STATEMENT FUNCTION DEFINITION: 
DELTA(000FL) = 1.0 -ABS(000FL) / ABS(000FL) + 1.0

STATEMENT FUNCTION DEFINITION: \( N(000FL) = 2 \times \) \( \text{SIGN}(000FL) \times \text{SIGN}(000FL) \)

STATEMENT FUNCTION DEFINITION: \( \text{SIGN}(000FL) \)

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122 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
121 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
51 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
124 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
115 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
117 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
50 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
13 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
99 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
112 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
310 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
115 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
52 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
1001 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
1002 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
312 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
1003 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
53 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
94 FORMAT(112,13,19,13,19,F2.0,132,F12.0)
COMMON / ICP, IFLAG, ISTEP, ITYPE, ITMAX, ITL, JL, L, PH0, P1.
W, VO, V0I, VOLO, Z, Z0, OSAVE (OSAVE), ISAVE (ISAVE).
REAL A (301), CM (301), CF, X, X0, X (301), PH0 (301), V (301).
DATA JCP / ICP / 1, IFLAG / 1, ISTEP / 0, ITYPE / 1, LMAX / 0.

R-5062/B-54
ORIGINAL PAGE IS OF POOR QUALITY
COMMON / CRT, IFLAG, ITERM, TYPE, WRITE, YEAR, DAY, HOUR, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, VOL, 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00  FORMAT (NH, x, ERROR IN TABLE)

02  FORMAT (NH, x) transfer to subroutine LOGIC //

06  XX(NH) = X(NH) / nh with = REC(NH) / X(1) REC(NH) //

180  FORMAT (NH, XHE R, NO R = EXTRAPOLATION OF TABLE IS BEYOND R
         REASONABLE LIMITS //

R-5000/8-64
AUTOFLOW CHART SET - FSCOM COMPUTER PROGRAM

CHART TITLE - NON-PROCEDURAL STATEMENTS

IMPLICIT REAL(A-H,I-L,0-Z)
COMMON /XV/ANG,X,Y,Z,ARC,DEC./RZ/ ,AX,AT,AB,AR,AC,AP
DIMENSION 9(51),Q(51)


ORIGINAL PAGE IS OF POOR QUALITY.
IMPLICIT REAL(A-H, I-O, Q-Z)
COMMON A, B, C, D, E, F
DIMENSION U(1), V(1), W(1), X(1), Y(1), Z(1)
1000 FORMAT (66, 1X, 10.5, 3X, 10.5)
IMPLICIT REAL(A-H,O-Z)
COMMON /X1,Y1,M1,N1,ANG,X,DA,DA1,DA2,DA3,
/33/25.71)
DIMENSION 0(5),10(5)
16 FORMAT(X,2X,PRINTING FROM CASE 5000:1.3X:AM:1.8,
3X,N1+1,15.8,SM,MT+1,15.8)
SUBROUTINE SOLNFSH

SUBPROGRAM SOLVES FOR THE COMPLEX FREQUENCY BASED ON THE UPSTREAM AND DOWNSTREAM MUSCLE ANGULAR VELocities BY W. W. PORTIS, BECTON, MAY 1976

WHEN ISONT = 1, 4, OR 5, THIS PROGRAM
COMPUTES DETAILED FOR \( S \) \( \omega \)
DOWNSTREAM. WHEN
ISONT = 1 OR 4, THIS
OUTLINE ALSO CHANGING
PERIODIC MUSCLE-MUSCLE
KEEPING REAL(DETAILED) CONSTANT

FURTHER, WHEN ISONT = 4, TESTING IS
COMPLETED TO DETERMINE IF A ROOT IS NEARBY.

\[ X1 = \text{ATAN}(\text{DETAILED}) \]

XTHASF COMPUTES FROM (3.11) REAL(MUSCLE), AVCHIC(MUSCLE), WHEN ISONT = 1 OR 4, AND ISF = 1; XTHASF/COMPUTS (3.11)

\[ F = \text{XTHASF}(F); X1 = XN \]

IF (K1 = 0.0) TRUE

IF (K1 = 0.0) TRUE

IF (K1 = 0.0) FALSE

IF (K1 = 0.0) FALSE

IF (K1 = 0.0) THEN

\[ \text{COMPUTE}_1 \]

\[ \text{COMPUTE}_2 \]

\[ \text{COMPUTE}_3 \]

\[ \text{COMPUTE}_4 \]
CHART TITLE: SUBROUTINE SOLN/4HORE

ORIGINAL PAGE IS OF POOR QUALITY
COMPLEX OMEGA, P, AND, V, MR, T, OMEGA, VCD, VCD.

EXTERNAL XMOF
DATA PV1, V0, V1, V2

EXTERNAL XMOF
COMPLEX ASLCK, MEQ, DELAY, OSPF, ESPR, CHIPS, EPUS,

EXTERNAL XMOF
COMPLEX ASLCK, MEQ, DELAY, OSPF, ESPR, CHIPS, EPUS,

FORMAL, CTEST, PASS, KNT, FSTR, VISION, SUBSP.

EXTERNAL XMOF
FORMAL

8600 FORMAT/215, 1PM13.5/3, 1PM13.5; 1PM13.5/1PM13.5
8601 FORMATT/ **** UNABLE TO FIND ROOT FOR IMG PART OF F ****
8602 FORMATT/ WARNING! POSSIBLE LOSS IN FREQUENCY RANGE.

8965 FORMAT/215, 1PM13.5/3, 1PM13.5/1PM13.5
8970 FORMATT/ 8601 FORMATT/ WARNING! POSSIBLE LOSS IN FREQUENCY RANGE.

R-9803/8-82
IMPLICIT REAL*4,H,O-Z)
COMMON X,I,DA,F,AN,ANL,ACT,ACC,XY,I=1:RT,SR,IR,IR,AC,IP
COMMON X,AN,ANL
DIMENSION D(XH),DP,H,N,PRECISI,Y(S),G(S),DPA(S)
10 FORMAT(6X,PRINTING FROM CARD 2060: ,15X,15.6,15.6)
20 NI= ,15.6,15.6,15.6
61 FORMAT(6X,PRINTING FROM CARD 2060: ,15X,15.6,15.6,15.6)
1000 FORMAT(*X,).2,F10.6,0.5,10.5)
182
77.33

01

R

77.33

02

H

77.33

03

K

180
180
180
180

IF OUTSIDE THE RANGE

78.08

192

190

79.05

191

190

56

LAB Y

78.08

193
DIMENSION CON(51), CPR1(31:15,41), PREU(51), YS1, CPS1
16 FORMAT(32X, PRINTING FROM CARD 3180, /, 34, 'X', 'E', 16.8)
34, RH= 'E15.8', RH= 'E15.8', RH= 'E15.8', RH= 'E15.8'
81 FORMAT(32X, PRINTING FROM CARD 3700, /, 34, 'X', 'E', 16.8),
34, RH= 'E15.8', RH= 'E15.8', RH= 'E15.8', RH= 'E15.8'
1000 FORMAT(32X, 'E15.8', 'E15.8', 'E15.8', 'E15.8')
# APPENDIX C

## COMPUTER CODE LISTINGS

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<td>ZERØ</td>
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</table>
F S C S M MAIN PROGRAM

MAIN CONTROL PROGRAM FOR THE FEED SYSTEM COUPLED STABILITY MODEL
PROGRAM DEVELOPED BY ROCKETDYNE, A DIVISION OF ROCKWELL
INTERNATIONAL, CANOGA PARK, CALIF 91304
PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975

DIMENSION TITLE(18,2)

COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VX0,
1 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
2 COX10, COX11, COX12, COX13, COX14, COX15, COX16,
3 CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
4 CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
5 CNOA, GINJUX, GINJFU,
6 NOZA7, GINJOT, GINJFT,
7 FN, NOZAMR, GN,
8 COXT(16), CFUT(16),
9 COXT(16,2), CFUTT(16,2)

REAL MBOXI, MBFUI, MRB, MGRI, MGI, NUBOX, NUBFU, KF, KO, L, MWG

COMMON /COMGM/, XOX, HHFU, MBOXI, MBFUI, TAUHU, TAUHFU, VBOX,
1 VBU, GAMU, KG, DLHUX, DHLFU, PC, CO,
2 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
3 COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
4 CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
5 CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPOX,
6 CS, DCSMR, DHM, JRGDMR, ADVUX, ADDOX, TDRAGD, DELVUX,
7 NUBOX, DTUXDM, ADVFU, ADDFU, TDRAGF, DELVFX, NUBFU, DTFUDM

EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)
## FSCSM MAIN PROGRAM

```plaintext
COMMON /CUNSTS/ MR8(10G), TB(100), RHOB(100), VB(10G), QQ00C34C
1 UHRB(100), DRHOB(100), DVB(100), VAPBQX(100), VAPBFU(100), QQ00C35G
2 SSV1(10G), SSV2(100), SSV3(100), SSV4(100), QQ00C36G
3 SSV5(100), SSV6(10G), SSV7(100), SSV8(100), SSV9DX(100), QQ00C37G
4 SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100), QQ00C38G
5 SSV14(100), SSV15(100), SSV16(100), QQ00C39G
6 RHGCI, VGI, MRGI, MGI, QQ00C40G

COMMON /COMCHM/ P(100), RHOB(100), V(10G), MR(100), T(10G), QQ00C41G
1 VXU, OMEGA, CNOZA, DELP, QQ00C42G
2 COMMON /COMARE/ NXP, X(10G), XM(100), A(100), DA(100), DELX, QQ00C43G
1 XO, XNOZ, AINJ, QQ00C44G

COMMON /COMNOZ/ RLCX, RCTX, ANGLE, CRR, RINJ, INPNOZ, FREQM, QQ00C45G
1 FREUMI, IPRNOZ, QQ00C46G

COMMON /FZERU/ NOZ, NOZAMR, GN, FN, FNR, FNI, HN, ISCNT, ISLP, QQ00C47G

COMMON /DUMP/ IWT, QQ00C48G

DATA JK/1/, JKK/1/, PI/3.141593/ QQ00C49G

COMMON /SOLVE/ FREQ, DEFKQ, DELMX, EPSF, EPSX, EPSFS, EPSXS, QQ00C50G
1 FRQMXX, CTEST, IPASS, KNTR, ISTRT, KSCNT4, IWSKP, QQ00C51G
1 KNTRX, KNTSMX, KNTTRX, QQ00C52G

COMMON /COMTAP/ NFREQT, FREQT(100), NOZAT(100), GINJ01(100), QQ00C53G
1 GINJFT(100), ITAPN, ITACP, ITAPH, QQ00C54G

COMMON /HY/ ICSRT, IRFLAG, ITERM, ITYPE, IPHYD, IX, AA(30), CW(30), KF, KQ, QQ00C55G
1 L(30), R(30), RHOL(30), VV(30), VF, VO, WOLF, WOI0, ZF, ZO, OSAVE(188), QQ00C56G
1
```
FSCSM MAIN PROGRAM

2 FSAVE(16b)

1 CONTINUE

CALL HEAD

READ AND WRITE INPUT DATA

READ(5,490,END=9000) ((TITLE(I,J),I=1,18),J=1,2)

490 FORMAT(14A4)

WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)

900 FORMAT(1H1,///,26X,'FEED SYSTEM COUPLED STABILITY MODEL',/, 1 9X,18A4,/,9X,18A4)

READ(5,500,END=9000) INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN,

1 IPKHYD, IPKCOM, IPKNOZ, IPKCHM, IPRSTE, NXP

500 FORMAT(12I6)

WRITE(6,600) INPHYD, INPCOM, INPNOZ, ITAPH, ITAPC, ITAPN,

1 IPKHYD, IPKCOM, IPKNOZ, IPKCHM, IPRSTE, NXP

600 FORMAT(/,5X,'INPHYD =',I2,5X,'INPCOM =',I2,5X,'INPNOZ =',I2,

1 5X,'ITAPH =',I3,5X,'ITAPC =',I3,5X,'ITAPN =',I3,5X,

2 'IPKHYD =',I2,5X,'IPKCOM =',I2,5X,'IPKNOZ =',I2,5X,

3 'IPKCHM =',I2,5X,'IPRSTE =',I2,5X,'NXP =',I4)

READ(5,510) XU, XNOZ, RINJ, GAMO, CO, DELP

510 FORMAT(612I8)

WRITE(6,610) XU, XNOZ, RINJ, GAMO, CO, DELP

610 FORMAT(/,5X,'XU =',1PE11.4,7X,'XNOZ =',1PE11.4,5X,'RINJ =',

1 'GAMO =',1PE11.4,7X,'CO =',1PE11.4,7X,

2 'DELP =',

XU = XU*0.0254
XNOZ = XNOZ*0.0254
RINJ = RINJ*0.0254
CO = CO*0.304

00000670
00000680
00000690
00000700
00000710
00000720
00000730
00000740
00000750
00000760
00000770
00000780
00000790
00000800
00000810
00000820
00000830
00000840
00000850
00000860
00000870
00000880
00000890
00000900
00000910
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00000970
00000980
00000990
00010000
00010100
00010200
00010300
00010400
00010500
00010600
00010700
00010800
FS ChM MAIN PROGRAM

C  READ(5,500) NROOT, IWRIT, IWSKP, KNTRMX, KNTRMX, KNTSMX
    WRITE(6,620) NROOT, IWRIT, IWSKP, KNTRMX, KNTRMX, KNTSMX
620 FORMAT(/,5X,'NROOT =',I3,'5X,'IWRIT =',I2,'7X,'IWSKP =',I2,'6X,'1
     'KNTRMX =',I4,'4X,'KNTRMX =',I4,'3X,'KNTSMX =',I4)

C  READ(5,510) OMEGA, FRQMAX, DELFRQ, DELMX, CTEST,
    EPSF, EPSX, EPSFS, EPSXS
    WRITE(6,630) OMEGA, FRQMAX, DELFRQ, DELMX, CTEST, EPSF, EPSX,
    EPSFS, EPSXS
630 FORMAT(/,5X,'OMEGA(0) =',1PE11.4,2X,'OMEGA(I) =',E11.4,2X,
     'FRQMAX =',E11.4,3X,'DELFRQ =',E11.4,7X,'DELMX =',I1
     'TEST =',E11.4,5X,'EPSF =',E11.4,5X,
     'EPSX =',E11.4,5X,'EPSFS =',E11.4,5X,'EPSXS =',E11.4)

C  READ(5,510) PC, MBOXI, MBFUI
    WRITE(6,650) PC, MBOXI, MBFUI
650 FORMAT(/,5X,'PC =',1PE11.4,7X,'MBOXI =',E11.4,4X,'MBFUI =',1
     'E11.4')
    PCIN = PC
    WWIN = MBOXI
    WFIN = MBFUI
    PC = PC*6894.76
    MBOXI = MBOXI*0.453592
    MBFUI = MBFUI*0.453592

C  IF(NROOT.LT.0) OMEGA = 2.*PI*REAL(OMEGA) + (0.,-1.)*
     REAL(OMEGA)*AIMAG(OMEGA)

    NROOT = IABS(NROOT)
    VG = 0.0
    MG = 0.0

C
FS C S M MAIN PROGRAM

COMPUTE AREA AND DISTANCE PROFILES.

AINJ = PI*RI*NJ*RNJ
CALL AREA

READ IN AND COMPUTE FREQUENCY TABLE IF INPNOZ .LE. 3

IF(INPNOZ.GT.3) GO TO 1060
READ(5,520) NFREQT, FREQM1, FREQM2

520 FORMAT(112,5E12.8)
WRITE(6,640) NFREQT, FREQM1, FREQM2

640 FORMAT(1X,5X,5HNFREQT =,E14.10X,6HFREQM1 =E11.4,3X, 
       1 FREQM2 =,E11.4)
DEL = (FREQM2-FREQM1)/(NFREQT-1)
DO 1050 I=1,NFREQT
   FREQT(I) = FREQM1*(I-1)*DEL
1050 CONTINUE

SET FLAG (IR=1) TO INDICATE FIRST PASS.

1060 IR = 1

ISCNT = 1 : FREQUENCY BEING INCREMENTED TO ZERO IMAG F
2 : FREQUENCY STEP TO START TO START LOOP WITHIN LOOP
3 : LOOP WITHIN LOOP
4 : STARTING SECANT METHOD
5 : USING SECANT METHOD

OMEGA = OMEGA - 31.4

BEGIN DO LOOP TO SEARCH FOR OMegas THAT SATISFY BOUNDARY
CONDITION: UPSTREAM NOZZLE ADMITTANCE = DOWNSTREAM NOZZLE
ADMITTANCE.
FSCSM MAIN PROGRAM

C DO 5000 NRT = 1,NROOT
C
C CHANGE OMEGA BY 5 HERTZ TO START SEARCH FOR NEXT ROOT.
C OMEGA = OMEGA + 31.4
C
C INITIALIZE FLAGS AND COUNTERS.
C ISCNT = 1
C IPASS = 1
C KNTK = 0
C 1STRT = 0
C KSCNT4 = 0
C FKLQ = REAL(OMEGA)/(2.*PI)
C
C THIS IS RETURN POINT FOR ITERATION TO FIND FREQUENCIES THAT
C BRACKET A ROOT.
C OMEGA = 2.*PI*FREQ + (0.,1.)*AIMAG(OMEGA)
C IF(FREQ.GT.FRQMAX) GO TO 1
C ISLP = 1 SETS FLAG TO COMPUTE DERIVATIVES IF ISCNT = 1 OR 4
C ISLP = 1
C
C IF((INPHY.GE.3.OR.INPCOM.GE.3.OR.INPNOZ.GE.4)
C .AND.(IR.LE.0.OR.INPNOZ.LE.3))
C 1 CALL LOCFAC(JKK,FREQ,FREQT,NFREQT,I1,F1)
C COMPUTE DOWNSTREAM NOZZLE ADMITTANCE PARAMETER, NOZAMR.
C (THROUGH STATEMENT 40).
C
FSCSM MAIN PROGRAM

IF(INPNOZ.GT.3) GO TO 20
CALL NOZAMIR(K,IR,IRAM,IRMR,IRAMR)
IF(INPNOZ.LE.1) GO TO 40
IF(IPRNOZ.GT.0) WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)
GO TO 25
20 IF(IR.LE.0) GO TO 30
REWRAND ITAPN
READ(ITAPN) NFREQT
DO 22 I=1,NFREQT
READ(ITAPN) FREQT(I), NOZAT(I)
22 CONTINUE
25 CALL LQCFAC(JK,FREQ,FREQT,NFREQT,I1,F1)
30 NOZAMR = NOZAT(I1)*F1*(NOZAT(I1+1)-NOZAT(I1))
40 CONTINUE

COMPUTE FEED SYSTEM RESPONSE PARAMETERS, GINJOX AND GINJFU.
(THROUGH STATEMENT 70)

IF(INPHYD.GT.2) GO TO 50
CALL HYDRO(IR,INPHYD,FREQ,GINJOX,GINJFU,PCIN,WGIN,WF1N)
IF(INPHYD.GT.1) GO TO 45
45 IF(IPRHYD.GT.0) WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)
50 IF(IR.LE.0) GO TO 60
REWRAND ITAPH
READ(ITAPH) (GINJOT(I),GINJFT(I),I=1,NFREQT)
DO 55 I=1,NFREQT
GINJOT(I) = REAL(GINJOT(I))*CEXP((0.0,-1.0)*
1 AIMAG(GINJOT(I))*PI/180.*
GINJFT(I) = REAL(GINJFT(I))*CEXP((0.0,-1.0)*
1 AIMAG(GINJFT(I))*PI/180.*)
FS CSM MAIN PROGRAM

55 CONTINUE
60 GINJOX = GINJFT(I1)+F1*(GINJFT(I1+1)-GINJFT(I1))
GINJFU = GINJFT(I1)+F1*(GINJFT(I1+1)-GINJFT(I1))
70 CONTINUE

COMPUTE COMBUSTION COEFFICIENTS. (THROUGH STATEMENT 110)

IF(INPCCM.GT.2) GO TO 80
CALL COMBOY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCCM)
IF(INPCCM.LE.1) GO TO 110
80 IF(IR.LE.0) GO TO 82
REWARD ITAPC
READ(ITAPC) XKOX, TAUBOX, VBOX, DELHOX, TURAGO, ADVOX,
1 ADDOX, VELVOX, NUBOX, DTUOX, XIMPOX, XKFU, TAUFBX,
2 VBFU, DELHFU, TDRAPF, ADFU, ADFUU, DELVFU, NUBFU,
3 DTFUOM, XIMPFU, MWG, CS, DRGDMR, DCSDMR, DHDMR, RGO
110 = -1
82 NI = 1
84 NI = 110-11+1
86 DO 88 I=1,NI
88 BACKSPACE ITAPC
READ(ITAPC) (COXTT(J,1),CFUTT(J,1),J=1,16)
90 REAL(ITAPC) (COXTT(J,2),CFUTT(J,2),J=1,16)
GO TO 96
92 IF(I1.NE.110+1) GO TO 86
94 READ(ITAPC) (COXTT(J,1),CFUTT(J,1),J=1,16)
GO TO 90
96 I10 = I1
DO 100 J=1,16
COXTT(J) = COXTT(J,1)+F1*(COXTT(J,2)-COXTT(J,1))
100 CONTINUE
FSCSM MAIN PROGRAM

100 CFUT(J) = CFUTT(J,1) + F1*(CFUTT(J,2) - CFUTT(J,1))

110 CONTINUE

C

COMPUTE STEADY STATE PROFILES IF THIS IS FIRST PASS.

IF(IR.GT.0) CALL STEADY(IPRSTE)
IR = 0
VX0 = 0.0

CALL SOLWH TO FINISH COMPUTATIONS FOR THIS OMEGA/FREQUENCY.
UPDATE OMEGA TO NEW GUESS IF ISCNT = 4 OR 5 AND CONVERGENCE HAS
NOT BEEN REACHED. WHEN ISCNT=1 OR 4, TWO PASSES WILL BE MADE PAST
THIS POINT ONE WITH ISLP=1 AND ONE WITH ISLP=0) IN ORDER TO
COMPUTE JACOBIAN.

CALL SOLWH(KWHERE)
GO TO (10,15,225,225,5000), KWHERE

C

CONVERGENCE HAS BEEN REACHED. PRINT RESULTS
(THROUGH STATEMENT 300).

225 CONTINUE
C

IF(NRT.LE.1 OR IPRCHM.GT.0 OR IPRCOM.GT.0)
1      WRITE(6,900) ((TITLE(I,J),I=1,18),J=1,2)
1      IF(IPRCOM.LE.0) GO TO 1090
WRITE(6,1680)
1080 FORMAT(/",2X,'COMBUSTION DYNAMIC COEFFICIENTS',/)
DO 1085 I=1,16
WRITE(6,1061) I, COXT(I), I, CFUT(I)
1081 FORMAT(5X,'COXT(',I2,,') =',1PE1.4,';',',E11.4,5X,'CFUT(',I2,
1      ') =',E11.4,';',E11.4)
1085 CONTINUE
1090 CONTINUE
DEC = -AIMAG(OMEGA)/REAL(OMEGA)
WRITE(6,2000) FREQ, DEC, NOZA, GINJUX, GINJFU
2000 FORMAT(1X,'FREQUENCY=',F8.2,' Hz',1X,'10X,
1 'DECREMENT=',F8.5,'10X,
2 '10X,'NOZZLE ADMITTANCE=',F9.5,'10X,
3 'FEED SYSTEM RESPONSE=',/,'20X,'OXIDIZER=',F9.5,'10X,
4 '24X,'FUEL=',F9.5,'10X,
C
IF(IPRCHM.LE.0) GO TO 5000
IF(IPRCHM.GT.0) WRITE(6,90C)((TITLE(I,J),I=1,18),J=1,2)
WRITE(6,2010)
2010 FORMAT(1X,'10X,*OSCILLATORY*',/,'5X,*DISTANCE*',/,'6X,
1 'PRESSURE RATIO*',/,'7X,*VELOCITY RATIO*',/,'6X,
2 'TEMPERATURE RATIO*',/,'7X,*MIXTURE RATIO*',/,'5X,*INCHES',
3 '5X,*PHASE'),/)
DO 300 I=1,NXP
AP = CABS(P(I))
IF(AP.LE.0.0.AND.I.LT.NXP) P(I)=P(I+1)*1.E-10
IF(AP.LE.0.0.AND.I.GE.NXP) P(I)=P(I-1)*1.E-10
PV = ATAND(AIMAG(P(I)),REAL(P(I)))
AV = CABS(V(I))
IF(AV.LE.0.0.AND.I.LT.NXP) V(I)=V(I+1)*1.E-10
IF(AV.LE.0.0.AND.I.GE.NXP) V(I)=V(I-1)*1.E-10
PV = ATAND(AIMAG(V(I)),REAL(V(I)))
AT = CABS(T(I))
IF(AT.LE.0.0.AND.I.LT.NXP) T(I)=T(I+1)*1.E-10
IF(AT.LE.0.0.AND.I.GE.NXP) T(I)=T(I-1)*1.E-10
PT = ATAND(AIMAG(T(I)),REAL(T(I)))
AMR = CABS(MR(I))
IF(AMR.LE.0.0.AND.I.LT.NXP) MR(I)=MR(I+1)*1.E-10

FS CS M MAIN PROGRAM

IF(AMR.LE.0.0.AND.I.GE.NXP) MR(I)=MR(I-1)*1.E-10
PMR = ATAND(IMAG(MR(I)),REAL(MR(I)))
XP = X(I)/0.0254
WRITE(6,2020) XP, AP, PP, AV, PV, AT, PT, AMR, PMR
2020 FORMAT(5X,F8.4,4(5X,F8.5,2X,F7.2))
360 CONTINUE
C
C END OF DO LOOP TO FIND OMEGAS SATISFYING BOUNDARY CONDITIONS.
C
5000 CONTINUE
GO TO 1
C
9000 CALL EXIT
STOP
END
COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX, 
1 X0, XNOZ, AINJ

NXPM1 = NXP-1
DELX = (XNOZ-XG)/(NXPM1)
X(1) = XG
A(1) = AINJ
DA(1) = 0.0

DO 10 I=2,NXP
X(I) = XG+DELX*(I-1)
A(I) = AINJ
DA(I) = 0.0
10 CONTINUE

DO 20 I=1,NXPM1
XM(I) = (X(I)+X(I+1))/2.0
20 CONTINUE
XM(NXP) = XM(NXPM1)+DELX
A(NXP) = AINJ
DA(NXP) = 0.0

RETURN
END
SUBROUTINE CHAMBDY

SUBPROGRAM CALCULATES THE OSCILLATORY PRESSURE, TEMPERATURE, VELOCITY, MIXTURE RATIO, AND DENSITY PROFILES PLUS THE UPSTREAM NOZZLE ADMITTANCE FROM THE CHAMBER DYNAMIC EQUATIONS

PROGRAMMED BY K. W. FERTIG AND M. D. SCHUMAN, HUCKETODYNE, MAY 1975

COMPLEX*16 AMA(4,5), CMA(4)

COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
1 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
2 COX10, COX11, COX12, COX13, COX14, COX15, CCX16,
3 CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
4 CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16

COMPLEX DM1, DM3, DM4, DM5, DM6, DM70X, DM7FU, DM80X,
1 DM8FU, G1UX, G1FU, G2UX, G2FU, G3UX, G3FU, G4UX, G4FU,
2 RBSOX, RBSFU, PINTOX, PINTFU, RHNTOX, RHNTFU, MRNTOX,
3 MRNTFU, VINTOX, VINTFU, II
4 DM9OX, DM9FU

REAL MECXI, MBEFU1, MRB, MRS, MGI, MGI, NUBOX, NUBFU, MFG

COMMON /COMCM/ XKUX, XKUFU, XBOXI, XBFUI, TAUBOX, TAU1FU, VBOX,
1 VBPU, VAM0, VKO, DELUX, DELFU, PC, CU,
2 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
3 COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
4 CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
5 CFU12, CFU13, CFU14, CFU15, CFU16, MFG, XIMPUFU, XIMPOX,
6 CS, OCSMR, OUMDR, OCRGMR, ADV0, ADQ0, AD00X, TDRAGD, DEL00X,
7 NUBOX, UTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, OTFUDM

COMMON /CONST/ MRB(100), TB(100), RHOB(100), VB(100)
FSCSM SUBROUTINES

1  DMRB(100), DMBHOB(100), DVB(100), VAPBDX(100), VAPBFU(100),
   CCCCC6340
2  SSV1(100), SSV2(100), SSV3(100), SSV4(100),
   CCCCC6350
3  SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9X(100),
   CCCCC6360
4  SSV9FU(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
   CCCCC6370
5  SSV14(100), SSV15(100), SSV16(100),
   CCCCC6380
6  RHOGI, VGI, MRGI, MGI
   CCCCC6390
C
   COMMON /COMCHM/ P(100), RH0(100), V(100), MK(100), T(100),
   CCCCC6410
1   VXG, OMEGA, CNOZA, DLP
   CCCCC6420
C
   COMMON /CMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
   CCCCC6430
1   XC, XNOZ, AINJ
   CCCCC6440
C
   COMMON /ADARND/ G10X, G20X, G30X, G40X, G1FU, G2FU, G3FU, G4FU, PINTOX,
   CCCCC6450
1   RHNTOX, MRNTOX, VINTOX, PINTFU, RHNTFU, MRNTFU, VINTFU, RB5OX,
   CCCCC6460
2   RB5FU, DM1, DM3, DM4, DM5, DM6, DM7OX, DM8OX, DM9OX, DM7FU,
   CCCCC6470
3   DM8FU, DM9FU, II, DM2, DM22, RHOINJ
   CCCCC6480
C
   COMMON /DUMP/ IWRT
   CCCCC6490
C
   EQUIVALENCE (AMA(1,5), CMA(1))
   CCCCC6500
C
   NXPML = NXP-1
   CCCCC6510
C
   COMPUTE BOUNDARY CONDITIONS AT X=X0.
   CCCCC6520
C
   RHOINJ = DLP/GAMO
   CCCCC6530
   DM2 = C1**2*RHOGI/(GAMO*PC)
   CCCCC6540
   DM22 = SQRT(DM2)
   CCCCC6550
   DM1 = CEXP((G2, -1,)*OMEGA/CO*DM2*VGI/CO*XG)
   CCCCC6560
   DM3 = DM22*OMEGA*XG/CO
   CCCCC6570
   P(1) = DM1*(DLP**CCUS(DM3)*(0, 1,)*GAMO*DM22*VXO*CSIN(DM3))
   CCCCC6580
   RHO(1) = P(1)/GAMO
   CCCCC6590
FSCSM SUBROUTINES

V(1) = DM1*(D*,1.)*DELPL/(GAMO*DM22)*CSIN(DM3)+VXM*COEUS(DM3))
DM1 = CEXP(D*,1.)*OMEGAXO/VOBOX
DM3 = CEXP(D*,1.)*OMEGAXO/VBFU
1
DM4 = DELPL/(COX1+DM1-CFU1*DM3)+P(1)/(COX2-CFU2)
2
+ VXM/(COX7*DM1-CFU7*DM3)+RHO(1)/(COX4-CFU4)
1
+ VXM/(COX7*DM1-CFU7*DM3)+V(1)/(COX8-CFU8)
1
1
DM2 = (MRG1+1.)*MRG1*MBFUI/(A(1)*RHOGICD)
DM4 = DM2*DM4 - V(1)*MRG1*(MRG1+1.)*(1-RHO1*MBFUI/MBOXI)
1
(MRG1+2.)
1
DM5 = DM2*(COX5*DM1-CFU5*DM3 + COX6-CFU6)
DM5 = MBFUI*(MRG1+1.)/(A(1)*RHOGICD) - (C*,1.)*OMEGA*TAFBU
1
1
*VBFU/CO - DM5
1
MR(1) = DM4/DM5
1
T(1) = P(1) - RHO(1) - MR(1)*DRGD/((RHO1+1.1)
1
1
+ DRGDMR*(MRG1-MBOXI/MBFUI/RGO))

INITIALIZE INTEGRALS USED IN VAPORIZATION EXPRESSION.

PINAX = (0.0,0)
PINAX = (0.0,0)
MRNULL = (0.0,0)
PINAX = (0.0,0)
PINAX = (0.0,0)
PINAX = (0.0,0)
PINAX = (0.0,0)
RNFU = (0.0,0)
MRNULL = (0.0,0)
MRNULL = (0.0,0)
MRNULL = (0.0,0)
MRNULL = (0.0,0)
MRNULL = (0.0,0)

IF (IWRI.GT.0) WRITE(6,9000) OMEGA,I,P(1),RHO(1),MR(1),V(1),T(1)
9000 FORMAT(///, OMEGA = *,1P2E13.5//3X,*I*,11X,*P*,19X,*RHO*,
1   21X,*MR*,32X,*V*,21X,*T*/1X,13,1P1/E11.4)
FSC5M SUBROUTINES

C
10 CONTINUE
C
CALL CHMCON(I)
C
DM1 = -Omega*DeltaX/CO
C
ENERGY EQUATION
C
AMA(1, 1) = DM1 + 2.*SSV1(I) + SSV7(I) - SSV2(I)*(SSV5(I)*G10X
1 + SSV6(I)*G1FU)
AMA(1, 2) = -SSV2(I)*(SSV5(I)*G20X + SSV6(I)*G2FU)
AMA(1, 3) = 2.*GAMO + SSV8(I) - SSV2(I)*(SSV5(I)*G40X
1 + SSV6(I)*G4FU)
AMA(1, 4) = -SSV2(I)*(SSV5(I)*G30X + SSV6(I)*G3FU - SSV90X(I)
1 + SSV9FU(I))
CMA(1) = SSV2(I)*(SSV5(I)*RBSUX + SSV6(I)*RBSFU - SSV90X(I)*
1 MK(I) + SSV9FU(I)*MR(I))
2 - P(I)*DM1 - 2.*SSV1(I) + SSV7(I))
3 - V(I)*(-2.*GAMO + SSVR(I))
C
CONTINUITY EQUATION
C
AMA(2, 1) = -SSV10(I)*(G10X + G1FU)
AMA(2, 2) = DM1 + 2.*SSV1(I) + SSV4(I) - SSV10(I)*(G20X + G2FU)
AMA(2, 3) = 2.*SSV1(I) - SSV10(I)*(G40X + G4FU)
AMA(2, 4) = -SSV10(I)*(G30X + G3FU)
CMA(2) = SSV10(I)*(RBSUX + RBSFU) - DM1*RHO(I) + 2.*V(I)
1 - V(I)*SSV1(I) + 2.*SSV1(I)*RHO(I) - RHO(I)*SSV4(I)
C
MOMENTUM EQUATION
C
FS CSM SUBROUTINES

C

\[ \text{AMA}(3,1) = \text{SSV12}(I) \]
\[ \text{AMA}(3,2) = (0.,0.) \]
\[ \text{AMA}(3,3) = \text{DM1} + 2.*\text{SSV1}(I) + \text{SSV3}(I) \]
\[ \text{AMA}(3,4) = (0.,0.) \]
\[ \text{CMA}(3) = \text{V}(I)*(-\text{DM1} - \text{SSV3}(I) + 2.*\text{SSV1}(I)) + \text{SSV12}(I)*P(I) \]

\[ \text{AMA}(4,1) = -\text{SSV13}(I)*(G10X-MRB(I)*G1FU) \]
\[ \text{AMA}(4,2) = \text{SSV14}(I) - \text{SSV13}(I)*(G20X-MRB(I)*G2FU) \]
\[ \text{AMA}(4,3) = \text{DELX*UMR8(I)} - \text{SSV13}(I)*(G40X-MRB(I)*G4FU) \]
\[ \text{AMA}(4,4) = \text{DM1} + 2.*\text{SSV1}(I) - \text{SSV13}(I)*(G30X-MRB(I)*G3FU) \]
\[ \text{CMA}(4) = \text{SSV15}(I)*(RBSOX-MRB(I)*RBSFU) + \text{MR}(I)*((\text{SSV15}(I) \times \text{V}(I)) \times \text{RHO}(I) \times \text{V}(I) + \text{DM1} + 2.*\text{SSV1}(I)) - \text{DELX*UMR8(I)}*((\text{SSV1}(I)*\text{RHO}(I) \times \text{V}(I)) \times \text{V}(I)) \]

\[ \text{SOLVE 4 BY 4 SYSTEM OF COMPLEX EQUATIONS} \]

\[ \text{CALL CMMAT(AMA,4,4)} \]

\[ \text{IP1} = I+1 \]

\[ \text{P FROM ENERGY EQUATION} \]

\[ \text{P(IP1)} = \text{CMA}(1) \]

\[ \text{RHO FROM CONTINUITY EQUATION} \]

\[ \text{RHO(IP1)} = \text{CMA}(2) \]

\[ \text{V FROM MOMENTUM EQUATION} \]

\[ \text{V(IP1)} = \text{CMA}(3) \]
FS C S M SUBROUTINES

V(IP1) = CMA(3)

MR FROM MIXTURE RATIO EQUATION.
MR(IP1) = CMA(4)

T FROM EQUATION OF STATE.
T(IP1) = P(IP1)-RHO(IP1)-SSV16(I)*MR(IP1)
IF(IWRT.GT.0) WRITE(6,9100) IP1,P(IP1),RHO(IP1),MR(IP1),
V(IP1),T(IP1)

9100 FORMAT(I13,1P10E11.4)

UPDATE INTEGRLS FOR NEXT STEP.
D7O = 2.*D7O*CEXP(-II*OMEGA*X(I)/VBOX)
PINTUX = PINTUX + D7O*(P(IP1)*D8O+P(IP1)*D9O)
RHINTUX = RHINTUX + D7O*(RHO(I)*D8O+RHO(IP1)*D9O)
MRINTUX = MRINTUX + D7O*(MR(I)*D8O+MR(IP1)*D9O)
VINTUX = VINTUX + D7O*(V(I)*D8O+V(IP1)*D9O)

D7FU = 2.*D7FU*CEXP(-II*OMEGA*X(I)/V5FU)
PINTFU = PINTFU + D7FU*(P(IP1)*D8FU+P(IP1)*D9FU)
RHINTFU = RHINTFU + D7FU*(RHO(I)*D8FU+RHO(IP1)*D9FU)
MRINTFU = MRINTFU + D7FU*(MR(I)*D8FU+MR(IP1)*D9FU)
VINTFU = VINTFU + D7FU*(V(I)*D8FU+V(IP1)*D9FU)

I = I+1
IF(I.LE.NXP+1) GO TO 10

COMPUTE UPSTREAM NOZZLE ADMITTANCE.
CNO = GAMO*V(NXP)/P(NXP)
FSCEM SUBROUTINES

C
1 RETURN
END
SUBROUTINE   CHMCON(I)

ROUTINE TO CALCULATE PARAMETERS FOR SUBPROGRAM CHAMDY
PROGRAMMED BY K. W. FERTIG, ROCKE T D Y NE, MAY 1975

COMPLEX OMEGA, P, RHO, V, MR, T, CNOZA, VXO,
1   COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
2   COX10, COX11, COX12, COX13, COX14, COX15, COX16,
3   CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
4   CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16

COMPLEX DM1, DM3, DM4, DM5, DM6, DM7OX, DM7FU, DM8OX,
1   DMFU1, DMFU2, DMFU3, DMFU4, DMFU5, DMFU6, DMFU7, DMFU8,
2   RHFU1, RHFU2, RHFU3, RHFU4, RHFU5, RHFU6, RHFU7, RHFU8,
3   MRNTFU1, MRNTFU2, MRNTFU3, MRNTFU4, MRNTFU5, MRNTFU6,
4   MRNTFU7, MRNTFU8, MRNTFU9, MRNTFU10, MRNTFU11, MRNTFU12, MRNTFU13

REAL    MBOXI, MBFU1, MRB, MRGI, MGI, NUBOXI, NUBFU1, NUBFU2, NUBFU3, NUBFU4, NUBFU5, NUBFU6, NUBFU7, NUBFU8, NUBFU9, NUBFU10, NUBFU11, NUBFU12, NUBFU13, NUBFU14, NUBFU15, NUBFU16

COMMON  /COMCBM/ XKOX, XKFU, MBOXI, MBFU1, MBOX1, MBOX2, MBOXI, TAUBOX, TAUBFU, TAUBX, VBOX,
1   VFU, GMDO, RGO, DELHDX, DELHFU, PC, CO,
2   COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
3   COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
4   CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
5   CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XMIPFU1, XMIPFU2, XMIPFU3, XMIPFU4, XMIPFU5, XMIPFU6, XMIPFU7, XMIPFU8, XMIPFU9, XMIPFU10, XMIPFU11, XMIPFU12, XMIPFU13, XMIPFU14, XMIPFU15, XMIPFU16
6   CS, DCSMGR, DCMGR, DCMGRM, ADVEX, ADDOX, TDRAGE, DELVEX, DELVEX,
7   NUBOX, DTOXDM, ADVFU, ADDFU, TURAGF, DELVFX, NUBFU1, NUBFU2, NUBFU3, NUBFU4, NUBFU5, NUBFU6, NUBFU7, NUBFU8, NUBFU9, NUBFU10, NUBFU11, NUBFU12, NUBFU13, NUBFU14, NUBFU15, NUBFU16

COMMON  /CONSTS/ MRB1(100), TB(100), RHOB1(100), VBD(100),
1   DMRF(100), DRHOF(100), DVF(100), VAPROX(100), VAPBFU(100),
2   SSV1(100), SSV2(100), SSV3(100), SSV4(100),
3   SSV5(100), SSV6(100), SSV7(100), SSV8(100), SSV9FX(100),
4   SSV9FX(100), SSV10(100), SSV11(100), SSV12(100), SSV13(100),
5   SSV14(100), SSV15(100), SSV16(100),
COMMON /COMCHM/ P(100), PHO(100), V(100), MR(100), T(100),
1 VXC, OMEGA, CNOZA, DEXP

COMMON /COMAREF/ NXP, X(100), XM(100), A(100), DA(100), DELX,
1 X0, XNOZ, AINJ

COMMON /ADARN/ G10X, G20X, G30X, G40X, G1FU, G2FU, G3FU, G4FU, PINTOX,
1 RHINTOX, MRINTOX, VINTOX, PINTFU, RHINTFU, MRINTFU, VINTFU, RBSOX,
2 RBSFU, DM1, DM3, DM4, DM5, DM6, DM7OX, DM8OX, DM9OX, DM7FU,
3 DM8FU, DM9FU, II, DM2, DM22, RHOINJ

DM1 = CEXP(II*OMEGA*(XM(I)))/VBOX
DM2 = (XM(I)-X0)/(TAUBOX*VBOX)
DM6 = CEXP(II*OMEGA*DELX/VBOX)
DM3 = CEXP(II*OMEGA*X(I)/VBOX) * (1 + DM6)/2

CALCULATE OXIDIZER VAPORIZATION PARAMETERS.

DM7OX = VBOX/(2 * OMEGA**2 * DELX * TAUBOX)
DM8OX = 1 - II*OMEGA*DELX/VBOX - 1/DM6
DM9OX = 1 - II*OMEGA*DELX/VBOX - DM6
DM4 = DM7OX*DM8OX*DM6
DM5 = DM7OX*DM9OX
DM9UX = DM9UX/DM6
RESOX = DEXP*DM1*(COX1+COX9*DM2)
1 +RHUINJ*DM1*(COX3+COX11*DM2)+MR(1)*DM1*(COX5+COX13*DM2)
2 +VX0*DM1*(COX7+COX15*DM2)
RBSOX = RBSOX*DM3*(COX10*PINTOX+COX12*RHINTOX+COX14*MRINTOX
1 +COX16*VINTOX)
RBSUX = RBSOX*P(1)*COX2/2*COX10*DM4 + PHO(1)*(COX4/2*
1 +COX12*DM4) + MR(1)*(COX6/2*COX14*DM4)
FS S M SUBROUTINES

2 + V(I)*(COX/2.*COX16*DM4)
RBSOX = VAPHOX(I)*RBSOX
G10X = VAPBOX(I)*(COX2/2.*COX10*DM5)
G20X = VAPBOX(I)*(COX4/2.*COX12*DM5)
G30X = VAPBOX(I)*(COX6/2.*COX14*DM5)
G40X = VAPBOX(I)*(COX8/2.*COX16*DM5)

C

DM1 = CEXP(I*OMEGA*(XM(I))/VBFU)
DM2 = (XM(I)-XO)/TaubFU*VGFU
DM6 = CEXP(I*OMEGA*DELX/VBFU)
DM3 = CEXP(I*OMEGA*X(I)/VBFU)*(1.+DM6)/2.*

C

CALCULATE FUEL VAPORIZATION PARAMETERS.

DM7FU = VBFU/(2.*OMEGA**2.*DELX*TAUBFU)
DM8FU = 1. - II*OMEGA*DELX/VBFU - 1./DM6
DM9FU = 1. + II*OMEGA*DELX/VBFU - DM6
DM4 = DM7FU*DM8FU*DM6
DM5 = DM7FU*DM9FU
DM9FU = DM9FU/DM6
RBSFU = DELP*DM1*(CFU1+CFU9*DM2)
1 +RHOINJ*DM1*(CFU3+CFU11*DM2)*MR(I)*DM1*(CFU5+CFU13*DM2)
2 +VX0*DM1*(CFU7+CFU15*DM2)
RBSFU = RBSFU+DM3*(CFU10*PINTFU+CFU12*RHTFU*CFU14*MRNTFU
1 +CFU16*VINTFU)

RBSFU = RBSFU+P(I)*(CFU2/2.+CFU10*DM4) + RHO(I)*(CFU4/2.
1 +CFU12*DM4) + MR(I)*(CFU6/2.+CFU14*DM4)
2 + V(I)*(CFU8/2.+CFU16*DM4)

RBSFU = VAPBFU(I)*RBSFU
G1FU = VAPBFU(I)*(CFU2/2.+CFU10*DM5)
G2FU = VAPBFU(I)*(CFU4/2.+CFU12*DM5)
G3FU = VAPBFU(I)*(CFU6/2.+CFU14*DM5)
G4FU = VAPBFU(I)*(CFU8/2.+CFU16*DM5)
SUBROUTINE COGAEEL(A,N)
DIMENSION A(62,126)

C
C GAUSSIAN ELIMINATION OF COMPLEX MATRIX.
C PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975
C
NM1 = N - 1
NP1 = N + 1
Z2 = 10.0E-30

DO 27 J = 1,N
   C J IS THE COLUMN BEING ELIMINATED BELOW THE DIAGONAL.
   C
   JMAX = J
   JJ = J + NP1
   CMAX = A(J,J)**2 + A(J,JJ)**2
   JP1 = J + 1
   IF (J - N) 25,5,6
   25 DO 2 K = JP1,N
      CCC = A(K,J)**2 + A(K,JJ)**2
      IF (CCC - CMAX) 2,2,3
   3 JMAX = K
      CMAX = CCC
   2 CONTINUE
   C INTERCHANGE ROWS IF REQUIRED TO OBTAIN MAXIMUM PIVOTAL ELEMENT.
   C
   IF (J - JMAX) 4,5,6
   4 WRITE (6,12) J,JMAX
   5 CONTINUE
   6 WRITE (6,12) J,JMAX
   12 FORMAT (61H1ERROR IN COGAEEL SUBROUTINE, J AND JMAX EQUAL, RESPECTIC1012310
   C
   END
IVESY (2112)
CALL EXIT

4 DE 7 K = J, NP1
K'J = K + NP1
HOLD = A(J, K)
A(J, K) = A(JMAX, K)
A(JMAX, K) = HOLD
HOLD = A(J, KN)
A(J, KN) = A(JMAX, KN)
A(JMAX, KN) = HOLD
7 CONTINUE

C
DIVIDE PIVOT ROW BY PIVOT ELEMENT. PIVOT ELEMENT BECOMES 1.0.

C
5 CONTINUE
DO 8 K = JP1, NP1
KN = K + NP1
IF (ABS(A(J, J)) - ZZ) 14, 14, 13
14 IF (ABS(A(J, J)) - ZZ) 15, 15, 13
15 DUM1 = A(J, J)
DUM2 = A(J, JJ)
WRITE (6, 16) DUM1, DUM2
8 CONTINUE

16 FORMAT (61H1MATRIX IS SINGULAR. EXIT FROM COGAEL. THE PIVOT ELEMENT) 12540
ITS ARE, 2E14, 6)
CALL EXIT

13 REALA = (A(J, K) + A(J, J)) + A(J, KN)*A(J, JJ))/CMA
VIMAG = (A(J, K) + A(J, J) - A(J, K)*A(J, JJ))/CMA
A(J, K) = REALA
A(J, KN) = VIMAG
8 CONTINUE

C
ELIMINATE ELEMENTS BELOW DIAGONAL. THE ELEMENTS ELIMINATED ARE NOT CALCl LATED.
C

00012320
00012330
00012340
00012350
00012360
00012370
00012380
00012390
00012400
00012410
00012420
00012430
00012440
00012450
00012460
00012470
00012480
00012490
00012500
00012510
00012520
00012530
00012540
00012550
00012560
00012570
00012580
00012590
00012600
00012610
00012620
00012630
00012640
FSCSM SUBROUTINES

C
IF (J - N) 26, 27, 6
26 JPI = J + 1
  DO 9 I = JPI, N
    DO 9 K = JPI, NPI
    KN = K + NPI
    REALA = A(I, K) - A(J, K) * A(I, J) + A(J, KN) * A(I, JJ)
    VIMAG = A(I, KN) - A(J, KN) * A(I, J) - A(I, JJ) * A(J, K)
    A(I, K) = REALA
    A(I, KN) = VIMAG
  9 CONTINUE
27 CONTINUE
RETURN
END
SUBROUTINE COMBDY(IR,FREQ,GINJOX,GINJFU,IPRCOM,INPCOM)

SUBPROGRAM TO CALCULATE THE COMBUSTION COEFFICIENTS.
PROGRAMMED BY M. D. SCHUMAN, HOCHETDUYNE, MAY 1975

COMPLEX GINJOX, GINJFU, DUM, NOZAT, GINJOT, GINJFT,
1  COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
2  COX10, COX11, COX12, COX13, COX14, COX15, COX16,
3  CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
4  CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16,
5  COXT(16), CFUT(16), RM, RU, RD, RFU

REAL MBOXI, MBFUI, MWH, NUBOX, NUBFU

COMMON /COMTAP/ NFRQFT, FREQT(100), NOZAT(100), GINJOT(100),
1  GINJFT(100), ITAPN, ITAPC, ITAPH

COMMON /COMCBM/ XKDX, XKFU, MBOXI, MBFUI, TAUBOX, TAUBFU, VBOX,
1  VBUFU, GAM0, RGO, DELHOU, DELFUI, DGB, CO,
2  COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
3  COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
4  CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
5  CFU12, CFU13, CFU14, CFU15, CFU16, MWG, XIMPFU, XIMPXO,
6  CS, DCS4MR, DHDLMR, DRGDMR, ADVUX, ADDOX, TCRADG, DELDVOX,
7  NUBOX, UTXDM, ADVFU, ADDFU, TCRAGF, DELVFU, NUBFU, DTFU DM

EQUIVALENCE (COXT(1),COX1), (CFUT(1),CFU1)

DATA PI/3.14159/

IF(IR.LT.0) GO TO 100
FS CST M SUBROUTINES

THIS IS FIRST PASS FOR THIS CASE. READ INPUT DATA.

READ(5,1) XKOX, TAUFOX, VBOX, DELFOX, TDRAGU, ADVFOX,
1    ADVFOX, DELFOX, NUBOX, DTOXM, XIMPOX
1 FORMAT(6E12.4)
WRITE(6,2) XKOX, TAUFOX, VBOX, DELFOX, TDRAGU,
1    ADVFOX, ADDFOX, DELFOX, NUBOX, DTOXM, XIMPOX
2 FORMAT(5X,'XKOX = ',1PE11.4,5X,'TAUFOX = ',
1    E11.4,3X,'VBOX = ',E11.4,5X,'DELFOX = ',E11.4,'/',27X,
2    TUKAGF = ',E11.4,3X,'ADVFOX = ',E11.4,'/',5X,'ADDOX = ',E11.4,
3    4X,'DELFOX = ',E11.4,3X,'NUBOX = ',E11.4,4X,'DTOXM = ',
4    E11.4,'/',27X,'XIMPOX = ',E11.4)
XKOX = XKUX*0.0254
VBOX = VBOX*6.3048
DELFOX = DELFOX*1054.35/0.453592
XIMPOX = XIMPOX*0.0254

READ(5,1) XKFU, TAUFOX, VBFU, DELF, TDRAGF, ADVFU,
1    ADDFU, DELFU, NUBFU, DTDFUM, XIMFU
WRITE(6,3) XKFU, TAUFOX, VBFU, DELF, TDRAGF,
1    ADVFU, ADDFU, DELFU, NUBFU, DTDFUM, XIMFU
3 FORMAT(5X,'XKFU = ',1PE11.4,5X,'TAUFOX = ',
1    E11.4,3X,'VBFU = ',E11.4,5X,'DELHU = ',E11.4,'/',27X,
2    TUKAGF = ',E11.4,3X,'ADVFU = ',E11.4,'/',5X,'ADDOX = ',E11.4,
3    4X,'DELFU = ',E11.4,3X,'NUBFU = ',E11.4,4X,'DTDFUM = ',
4    E11.4,'/',27X,'XIMFU = ',E11.4)
XKFU = XKFU*0.0254
VBFU = VBFU*6.3048
DELH = DELHU*1054.35/0.453592
XIMFU = XIMFU*0.0254
READ(5,1) MWG, CS, URGDM, DGSDM, DHDMR
FS CS M SUBROUTINES

WRITE(6,4) MWG, CS, DREGMR, DCSDMR, DHDMR
4 FORMAT(9E5X,*MWG =,1PE11.4,6X,*CS =,E11.4,
1 9E11.4,*DREGMR =,E11.4,3X,*DCSDMR =,E11.4,7,27X,*DHDMR =
2 E11.4)
CS = CS*C.3048
DREGMR = DREGMR*1.8135582/0.453592
DCSDMR = DCSDMR*0.3048
DHDMR = DHDMR*1054.35/0.453592
RGO = 8314.34/MWG
REWIND ITAPC

C

100 CONTINUE
C
IF INPCOM LE 1, COMPUTE COMBUSTION COEFFICIENTS FOR INPUT
C FREQUENCY(FREQ). IF INPCOM GT 1, COMPUTE COMBUSTION
C COEFFICIENTS FOR ENTIRE FREQUENCY TABLE AND SAVE ON ITAPC.

FRE = FREQ
I = 0
IF(INPCOM.LE.1) GO TO 200
FRE = FREQ(I)
WRITE(ITAPC) XKOX, TAUBOX, VBOX, DELBOX, TURAG, AVBOX,
1 ADDUX, DELVX, NUBOX, DTOXDM, XIMPOX, XKFU, TAUBFU,
2 VBFU, DELFU, TURAGF, ADVFU, ADDFU, DELVU, NUBFU,
3 DTDFU, XIMPP, MWG, CS, DREGMR, DCSDMR, DHDMR, RGO

200 I = I+1
DUM = (0.0,1.0)*2.*PI*FRE*XKOX/VBOX
RM = (1.0-DUM)*GINJOX
PJ = GINJUX
DUM = DUM*XIMPOX/XKOX
RD = (AVBOX-0.5*ADDUX*DUM)*GINJOX
RFR = 0.5
DL = 2.*PI*FRE*TURAG
FSGSM SUBROUTINES

RFU = 0.5/DELVOX*(D1*D1-(0.0,1.0)*D1)/(1.+D1*D1)

COX1 = RM-RU-2.*RD+(NUBOX-2.)*0.5*RD/NUBOX

COX2 = 0.0

COX3 = 0.0

COX4 = RFR*(NUBOX-2.)/NUBOX

COX5 = 0.0

COX6 = -DTDFUM/TAUBOX

COX7 = 0.0

COX8 = RFU*(NUBOX-2.)/NUBOX

COX9 = 2.*RD-(NUBOX-2.)*0.5*RD/NUBOX+RU

COX10 = 0.0

COX11 = 0.0

COX12 = -COX4

COX13 = 0.0

COX14 = -COX6

COX15 = 0.0

COX16 = -COX8

DUM = (0.0,1.0)*2.*PI*FRF*VKFU/VBFU

RM = (1.-DUM)*GINJFU

RU = GINJFU

DUM = DUM*IMPFU*VKFU

RD = (ADVFU-0.5*ADDFU*ADU)*GINJFU

RFR = 0.5

D1 = 2.*PI*FRF*TDRAGF

RFU = 0.5/DELVFUM*(D1*D1-(0.0,1.0)*D1)/(1.+D1*D1)

CFU1 = KM-RU-2.*RD+(NUBFU-2.)*0.5*RD/NUBFU

CFU2 = 0.0

CFU3 = 0.0

CFU4 = RFR*(NUBFU-2.)/NUBFU

CFU5 = 0.0

CFU6 = -DTDFUM/TAUBFU

CFU7 = 0.0

CFU8 = RFU*(NUBFU-2.)/NUBFU
FSCMS SUBROUTINES

CFU9 = 2*R0*(NUBFU-2)*G.5*RD/NUBFU+KU
CFU10 = 0.0
CFU11 = 0.0
CFU12 = -CFU4
CFU13 = 0.0
CFU14 = -CFU6
CFU15 = 0.0
CFU16 = -CFU8

C IF(INP.COM.LE.1) RETURN

C WRITE(ITAPC) (CoXT(J),CFUT(J),J=1,16)
C IF(I.GT.NFREQ) GO TO 900
C FRE = FREQ(I+1)
C GO TO 240

900 END FILE ITAPC

C RETURN
C END
FSCSM SUBROUTINES

SUBROUTINE COMMAT(A, NRA, N)

C ROUTINE SOLVES: AX = B, WHERE A, X, AND B ARE COMPLEX.
C A(I,J) IS N BY N COMPLEX MATRIX
C B(I) IS N BY 1 COMPLEX VECTOR. IT IS STORED IN A(I, N+1) FOR
C I = 1,N
C ANSWER IS RETURNED IN A(I, N+1) I=1,N
C NRA IS THE NUMBER OF ROWS IN THE DIMENSION STATEMENT FOR
C MATRIX A IN THE CALLING PROGRAM.
C
C A, X, AND B ARE ALL COMPLEX*16
C
C PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975
C
C COMPLEX*16 A(NRA,1), W
C
NM1 = N-1
NP1 = N+1
C
C MATRIX TRIANGULARIZATION IS PERFORMED THROUGH STATEMENT 20
C
DO 20 IR = 1, NM1
I1R = IR+1
IF(CDABS(A(IR, IR)) .LE. 0.0) GO TO 100
C
DO 10 I = IR1, N
W = -A(I, IR)/A(IR, IR)
DO 10 J = IR1, NP1
10 A(I, J) = A(I, J) + W*A(IR, J)
C
20 CONTINUE
C
FSGSM SUBROUTINES

C BACKWARDS SUBSTITUTION IS PERFORMED THROUGH STATEMENT 50
  C A(N,NP1) = A(N,NP1)/A(N,N)
  C DO 50 IR = 1,NM1
  C I = N-IR
  C I1 = I+1
  C DO 40 J = I1,N
  C 40 A(I,NP1) = A(I,NP1) - A(I,J)*A(J,NP1)
  C 50 A(I,NP1) = A(I,NP1)/A(I,I)

C RETURN

C ALGORITHM HAS FAILED DUE TO ZERO DIAGONAL ELEMENT

C 100 WRITE(6,9600) IR,((I,J,A(I,J),I=1,N),J=1,NP1)
  C 9600 FORMAT(// ' **** DIVIDE CHECK IN COMMAT *****/
  C 1 'IR = ',10I10/* MATRIX A(I,J) = */
  C 2 (5X,2(1PE15.6,'*') ,1PE15.6))
  C CALL EXIT
  C RETURN
  C END
FS CS M SUBROUTINES

SUBROUTINE FRESPI(ACRT, IWRITE, IX)

FREQUENCY RESPONSE ROUTINE WITH TIME DELAY

PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975

DIMENSION OM(101), OMSCPS(101), W(101), OMS(101), IDT(126), CP(62, 126)
DIMENSION LX1(3), LL(3), J1(3), C7(3), C(62, 126), TD(62, 63), D1(D126)
DIMENSION XMA(62), NO(62), XRLA(62), XMA(62), GAIN(101), FAZE(101)
DIMENSION VARR(62), VARI(62), PHAN(5, 101), DECB(5, 101)
DIMENSION ATD(126), IDF(18)
COMMON/F/NW, NCRTD, NR, KEQ, TRIG, IRPS, OMI, OMFL, W, ID, C, TD, ATD,
   FREQ, GINJX, GINJFU, PC, NO, WF
COMPLEX NOZAT(100), GINJOT(100), GINJFT(100), GINJX, GINJFU
COMMON/CUMTAP/NFREQ, FREQT(100), NOZAT, GINJOT, GINJFT, ITAPN, ITAPC,
   DELTA(Q001FL) = 1.0 - ABS(Q001FL) / AMAX1(ABS(Q001FL), 146936794E-38)
   UNIT(Q002FL) = 0.5 + SIGN(0.5, DELTA(Q002FL) + Q002FL * (1.0 - DELTA(Q0066136))
   102FL))
   THETA(Q003FL, Q004FL) = (180.0 * (1.0 * UNIT(Q003FL) * (1.0 - 2.0 * UNIT(Q004FL))
   11)) + SIGN(1.0, Q003FL * Q004FL) / ATAN((ABS(Q004FL) / (1.0 - DELTA(Q0066162))
   2FL)) / (ABS(Q003FL) + DELTA(Q003FL)) / (ABS(Q003FL) + DELTA(Q003FL))
   * (1.0 - DELTAC0066170)
   31(Q003FL) * 180.0 * DELTA(Q003FL) * (1.0 - DELTA(Q004FL)) * (1.0 - UNIT(Q0040000618)
   4FL))
IS NECESSARY TO ZERO MATRIX STORAGE SPACE

10 DO 2001 KK = 1, 62
   DO 2001 LL = 1, 126
   2001 CP(KK, LL) = C
   IF(TRIG .NE. 1.) GO TO 2006
   DO 2002 KK = 1, 62
      DO 2002 LL = 1, 126
         2002 C(KK, LL) = 0.0
   DO 2003 KK = 1, 62
      DO 2003 LL = 1, 63
         2003 C(KK, LL) = 0.0
   DO 2004 KK = 1, 62
      DO 2004 LL = 1, 63
         2004 C(KK, LL) = 0.0
   DO 2005 KK = 1, 62
      DO 2005 LL = 1, 63
         2005 C(KK, LL) = 0.0
   DO 2006 KK = 1, 62
      DO 2006 LL = 1, 63
         2006 C(KK, LL) = 0.0
   END
FS CSM SUBROUTINES

2003 TD(KK,LL)=0.0
2004 DO 2004 KK=1,5
     DO 2004 LL=1,101
     PHAK(KK,LL)=0.0
2004 DECB(KK,LL)=0.0
     IF(TRIG .NE. 1.) GO TO 444
     IF(TRIG .EQ. 1.) READ(5,120)NW,NCTD,NR,ICRT,KEQ,TRIG,IRPS,OMI,OMFL
120 FORMAT(I12,I3,I9,I3,I9,F2.3,I10,2F12.5)
     IF(NW)1216,1215,1216
1216 IF(NW+100)1217,1217,1218
1218 WRITE (6,122)
122 FORMAT(46H-NUMBER OF SHUFFLED IN FREQUENCIES EXCEEDS 100)
     GO TO 9
1217 IF(TRIG .EQ. 1.) READ (5,121)(W(I),I=1,NW)
1219 IF(TRIG .EQ. 1.) READ (5,121)(ID(I),I=1,NK)
     IF(KEQ-62)1221,1221,1222
822 WRITE (6,124)
124 FORMAT(31H-NUMBER OF EQUATIONS EXCEEDS 62)
     GO TO 9
1221 IF(OMI)1671,3,1667
     WRITE (6,115)
     GO TO 9
1667 OM(I)=OMI
     J=2
     RATIO=(OMFL/OMI)**(1./AMAX1(1.,FLOAT(NFREQT-2)))
1668 OM(J)=OM(J-1)*RATIO
     IF(OM(J) .GE. 9999*OMFL .OR. J.EQ. 100) GO TO 1670
     0006300
     0006310
     0006320
     0006330
     0006340
     0006350
     0006360
     0006370
     0006380
     0006390
     0006400
     0006410
     0006420
     0006430
     0006440
     0006450
     0006460
     0006470
     0006480
     0006490
     0006500
     0006510
     0006520
     0006530
     0006540
     0006550
     0006560
     0006570
     0006580
     0006590
     0006600
     0006610
     0006620
FS6SM SUBROUTINES

1669 J=J+1
1670 IF(J>1)GOTO 1670
1671 OMI=ABS(OMI)
1672 J=1
1673 N=0
1674 M=-1
1675 T=-1.0
1676 R=0.1
1677 IF(OMI<0)15,8,8
1680 IF(OMI-R)>10.0GOTO 4
1685 K=1
1690 NEW CARD—INITIALIZATION OF L
1695 L=0
1700 OMI(J)=UNIT(T)*(((2.0**L)*3.0*1.0-0.0*M)/2.0)+UNIT(-T)*(2.0**L)*16.0*OMI(J)
1710 IF(L>3)26,27,25
1715 L=L+1
1720 T=-T
1725 IF(L>3)26,27,25
1730 IF(T<0)24,23
1735 L=L+1
1740 T=-T
1745 IF(L>3)26,27,25
1750 M=M+1
1755 GOTO(11,16),K
1760 IF(OMI(1)-OMI(1))12,15,13
1765 OMI(2)=OMI(1)
1770 OMI(1)=OMI(1)
FS CSM SUBROUTINES

J=3
K=2
GO TO 12
15 OM(1)=OM1
   K=2
16 J=J+1
   IF(OM(J-1)-OMFL)12,18,13
18 OM(J-1)=OMFL
   NUM=J-1
17 J=1
   IF(NW)28,28,49
28 OMS(J)=OM(J)
   IF(OMS(J)-OMFL)30,32,32
30 J=J+1
   IF(J-J0G)28,28,45
29 N=0
   I=1
35 K=J+N
   IF(OM(J)-W(I))20,34,34
20 IF(U-NOM)33,33,34
33 OMS(K)=OM(J)
   J=J+1
   GO TO 35
34 OMS(K)=W(I)
   N=N+1
   IF(I-NW)36,37,37
37 IF(J-NUM)31,31,386
31 W(I)=OMFL
   GO TO 3b
36 I=I+1
   IF(J-NUM)38,38,35
38 IF(OMS(K)-OMFL)35,32,32
380 OMFL=OMS(K)
FSOM Subroutines

444 IF(NFREQ.T.GT.100) GO TO 45
   OMS(1)=.001
   NPI=NFREQ+1
   DO 445 I=2,NPI
   445 OMS(I)=FREQ(I-1)
   IF(NW.EQ.1) OMS(I)=FREQ
   GO TO 32
45 WRITE (6,117)
117 FORMAT(38H1THE NUMBER OF FREQUENCIES EXCEEDS 100)
   GO TO 9
32 J=1
431 IF(IRPS)343,432,43
432 OMFLC=OMFL
   OMFL=2.0*3.1415927*OMFL
43 IF(IRPS)39,39,40
39 OMSCPS(J)=OMS(J)
   OMS(J)=2.0*3.1415927*OMSCPS(J)
   GO TO 41
40 OMSCPS(J)=OMS(J)/(2.0*3.1415927)
41 IF(OMS(J)-OMFL)42,44,44
42 J=J+1
   GO TO 43
44 IF(TRIG.EQ.1.)READ (5,50)(LXI(I),II(I),J1(I),C7(I),I=1,3)
50 FORMAT(5I5)
   IF(TRIG.NE.1.) GO TO 60
   DU47 I=1,3
   IF(LXI(I))300,301,301
301 IF(II(I))47,47,60
47 L9=II(I)
   J9=J1(I)
   C(I9,J9)=C7(I)
   IF(LXI(I))47,47,60
60 GO TO 50
FS CS M SUBROUTINES

300 IF (II(I)) 47, 47, 302
302 ITD = II(I)
       JT = J1(I)
       TD(ITD, JT) = C7(I)
       IF (LXI(I) + 1) 47, 60, 60
47 CONTINUE
49 GO TO 44
60 I = 1
       KEQ = KEQ + 1
       IF (TRIG EQ 1) READ (5, 113)
113 FORMAT (72H1)
       )
       IF (IWRITE GT 1) WRITE (6, 113)
       IF (IWRITE GT 1) WRITE (6, 59) (ID(I), I = 1, NR)
59 FORMAT (16H I-D. VECTOR /(1MO, 24I4))
       DO 111 J = 1, KEQ
111 IF (IWRITE GT 1) WRITE (6, 112) I, (C(J), J = 1, NR)
112 FORMAT (13H0 EQUATION , I3 /(4H0 , 1P7E14.6))
       IF (IWRITE GT 1) WRITE (6, 310)
310 FORMAT (27H1 MATRIX OF TIME DELAY TERMS)
       DO 311 I = 1, KEQ
311 IF (IWRITE GT 1) WRITE (6, 112) I, (TD(I, J), J = 1, KEQ )
       IF (NCTD) 75, 75, 309
309 IF (TRIG EQ 1) READ (5, 121) (ATD(K), K = 1, NCTD)
75 DO 662 J = 1, KEQ
       IJ = J + KEQ
       LS = 0
       LK = 0
       L = 0
       I = 0
76 I = I + 1
       IF (LK) 7, 62, 610
       IF (KEQ = L) 64, 64, 65
62
FS CSM SUBROUTINES

65 LF=LF+1
   IM=IEQ+LF
67 IR=I+LS
   IF(1D(IR)) 69, 68, 69
68 LS=LS+1
   GO TO 67
69 II=IR-1
   LK=LS
   CREAL=0.0
   CIMAG=0.0
   R=1.0
   S=0.0
   LS=LS+1
55 CREAL=CREAL + R*C(J,IR)*DMS(IW)**S
   LS=LS-1
   IF(1S) 7, 57, 56
56 CIMAG=CIMAG+R*C(J,II)*DMS(IW)**(S+1.0))
   S=S+2.0
   R=(-1.0)*R
   IK=IR-2
   II=II-2
   LS=LS-1
   IF(1S) 7, 57, 55
57 CP(J,LF)=CREAL
   CP(J,IM)=CIMAG
   GO TO 61
64 IR=I+LS
   IF(1D(IR)) 70, 71, 70
71 LS=LS+1
   GO TO 64
70 II=IR-1
   LK=LS
   DREAL=0.0
FSM SUBROUTINES

312 ANGLE = ABS(TD(I,J)*OMS(IW))-6.283165*IFIX(ABS(TD(I,J)*OMS(IW))/6.283185)
1185)
I  CP(I,J) = CP(I,J)+TD*COS(ANGLE)
CP(I,J) = CP(I,J)-TD*SIN(ANGLE)
313 CONTINUE
K = KEQ+1
DO 73 I = 1, KEQ
L = KEQ+1
IF(TD(I,K)) 72, 73, 72
72 ANGLE = ABS(TD(I,K)*OMS(IW))-6.283165*IFIX(ABS(TD(I,K)*OMS(IW))/6.283185)
185)
D(I) = D(I)+COS(ANGLE)
U(I) = U(I)+SIN(ANGLE)*SIGN(1.0, TD(I,K))
73 CONTINUE
NPH = 2*KEQ
IF(IW = 1) 303, 305, 305
303 IF(IWRITE.GT.1) WRITE (6,323)
DO 304 I = 1, KEQ
IJ = I*KEQ
304 IF(IWRITE.GT.1) WRITE (6,321), D(I), D(IJ), (CP(I,J), J = 1, NPH)
305 CONTINUE
C ADD D-VECTUK TO CP-MATRIX. SHIFT COLUMNS OF IMAG CP BY 1 TO RIGHT.
C REAL D INTO COL. KEQ+1. IMAG D INTO COL. 2KEQ+2.

C DO 202 I = 1, KEQ
IN = 2*KEQ + 1 - I
INP1 = IN + 1
DO 202 J = 1, KEQ
CP(J, INP1) = CP(J, IN)
202 CONTINUE
IN = KEQ + 1
INN = 2*KEQ + 2
DO 203 J = 1,KEQ
CP(J,IN) = D(J)
JN = J + KEQ
CP(J,IN) = D(JN)
203 CONTINUE

CALL COGAEL TO TRIANGULARIZE THE COMPLEX MATRIX BY GAUSSIAN ELIMINATION.

CALL COGAEL(CP,KEQ)

BACK SUBSTITUTE TO DETERMINE REAL AND IMAGINARY PART OF VARIABLES.
THEN DETERMINE MAGNITUDE AND PHASE.

NP1 = KEQ + 1
NNP1 = 2*NP1
XREAL(KLU) = CP(KEQ,NP1)
XIMAG(KLU) = CP(KEQ,NNP1)
XMAG(KEQ) = SQRT(XREAL(KEQ)**2 + XIMAG(KEQ)**2)
FAZE(KEQ) = TAN(XREAL(KEQ),XIMAG(KEQ))

DO 205 J = 2,KEQ
JJ = KEQ - J + 1
JJP1 = JJ + 1
SUMR = 0.0
SUMI = 0.0
DO 206 K = JJP1,KEQ
KN = K + KEQ + 1
SUMR = SUMR + CP(JJ,K)*XREAL(K) - CP(JJ,KN)*XIMAG(K)
SUMI = SUMI + CP(JJ,K)*XREAL(K) + CP(JJ,KN)*XIMAG(K)
206 CONTINUE

XREAL(JJ) = CP(JJ,NP1) - SUMR
XIMAG(JJ) = CP(JJ,NNP1) - SUMI
XMAG(JJ) = SQRT(XREAL(JJ)**2 + XIMAG(JJ)**2)
FAZE(JJ) = TAN(XREAL(JJ),XIMAG(JJ))
FS CMS SUBROUTINES

IF (IW - 1) 82,82,83
82 CONTINUE
IF (WRITE,GT,1) WRITE (6,52) DM5(I), (I,XMAG(I),FAZE(I)), I=1,KEQ
52 FORMAT (6H1 VARIABLE MAGNITUDES USING A FREQUENCY OF 1PE14.6,5H RPS, 1HO, 84H 2LE NUMBER MAGNITUDE PHASE / (1HO, 84H 3127,1PE30,6))
770 IF (WRITE,GT,1) WRITE (6,1001)
1001 FORMAT (70 H1 THESE ARE INTERMEDIATE RESULTS PRODUCED AFTER EACH MAGNESIUM)
TRIX INVERSION./53H0 INPUT FREQUENCY IN RADIANS/SECOND AND CYCLES/SEC 3TC. )
323 FORMAT (37H INITIAL VALUES OF COEFFICIENT MATRIX)
321 FORMAT (13,5X,1PE20.6/(4HO, 1PE14.6))
771 IV=1
J=3
NO(1)=17
NO(2)=55
DO 78 I=1,NR
IF (ID(I)) 79,80,81
79 IV=IV+1
80 GO TO 78
81 IF (IV .NE. 17 .AND. IV .GE. 55) NO(J)=IV
IF (IV .NE. 17 .AND. IV .GE. 55) J=J+1
IV=IV+1
78 CONTINUE
NGPRT=MING(5,J-1)
83 DO 84 K=1,NGPRT
JX=NO(K)
VARR(K) = XREAL(JX)
VAR1(K) = XIMAG(JX)
84 CONTINUE
86 DO 87 I=1,NGPRT
FS S M SUBROUTINES

90 PHAN(I, IW) = THETA(VARR(I), VARI(I))

96 DECIB(I, IW) = 20.0 * ALOG10(AMAX1(1.0E-30, SQRT(VARR(I)**2 + VARI(I)**2)))

87 CONTINUE

IF(TRIG(960, 960, 961)

960 IF(IWRITE.GT.1) WRITE (6, 1000) OMS(IW), OMSCPS(IW), (NO(NOW), DECIB(NOW)

1, IW), PHAN(NOW, IW), NOW=1, NOPRT)


18.2, F7.1, I4, F8.2, F7.1))

961 IF(OMS(IW).GE.OMFL.OR.IW.EQ.101) GO TO 95

85 IW = IW + 1

GO TO 75

95 CONTINUE

53 FORMAT(21H1 FREQUENCY, 5(13H VARIABLE, I2, 3H 1/21H0)

1 RPS CPS, 5(18H DECIBELS PHASE /))

54 FORMAT(1P2E10.2, 5(2H /, 0P2F8.2))

NZ = 5

NY = 1

NX = NOPRT

97 IF(NX(100, 100, 98)

98 IF(IWRITE.GT.1) WRITE (6, 53)(NO(I), I = NY, NZ)

DO 99 J = 1, IW

99 CONTINUE

NY = NY + 5

NZ = NZ + 5

NX = NX - 5

GO TO 97

100 CONTINUE

DO +30 J = 1, NOPRT

DO 102 K = 1, IW

C AIN(K) = DECIB(J, K)

FAZE(K) = PHAN(J, K)
FS CSM SUBROUTINES

IF(K.GT.101.OR.IW.LE.2.OR.K.EQ.1) GO TO 102
IW.J.EQ.1.AND.IX.LE.1)GINJOT(K-1)=COMPLX(PC/WD*(10**2*(GAIN(K)/20.)) )
&,(FAZE(K))
IF(J.EQ.2.AND.IX.NE.1)GINJFT(K-1)=COMPLX(PC/WF*(10**2*(GAIN(K)/20.)) )
&,(FAZE(K))
102 CONTINUE
IF(J.EQ.1.AND.IX.LE.1)GINJOX=COMPLX(PC/WD*(10**2*(GAIN(1)/20.)) )
&,(FAZE(1))
IF(J.EQ.2.AND.IX.NE.1)GINJFU=COMPLX(PC/WF*(10**2*(GAIN(1)/20.)) )
&,(FAZE(1))
IF(IW.LE.2.OR.ICRT.LT.1) GO TO 400
IF(IRPS)104,104,103
103 L=1
CALL TDPLTOMS,GAIN,IW,OMI,OMFL,L )
CALL PRINTV(-21,21H GAIN IN DECIBELS ,400,470)
CALL PRINTV(-21,21H FREQUENCY IN RADIANS,400,005)
L=2
CALL TDPLTOMS,FAZE,IW,OMI,OMFL,L )
CALL PRINTV(-21,21H PHASE IN DEGREES ,400,995)
GO TO 105
104 L=1
CALL TDPLTOMS,GAIN,IW,OMI,OMFLC,L )
CALL PRINTV(-21,21H GAIN IN DECIBELS ,400,470)
CALL PRINTV(-21,21H FREQUENCY IN CPS ,400,005)
L=2
CALL TDPLTOMS,FAZE,IW,OMI,OMFLC,L )
CALL PRINTV(-21,21H PHASE IN DEGREES ,400,995)
105 CALL PRINTV(-21,20H VARIABLE NUMBER 
&,(PNO=ND(J)
CALL LABLV (PNO,560,1016,4,2,3)
400 CONTINUE
999 RETURN
9 CALL EXIT
FSCSM SUBROUTINES

SUBROUTINE HEAD

ROUTINE TO PRINT HEADING
PROGRAMMED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975

WRITE(6,10)
10 FORMAT(1HI,,/,,43X,'ANALYTICAL DESCRIPTION',,,/,,
        1 44X,'FEED SYSTEM COUPLED',,,/,,47X,'STABILITY MODEL',,,/,,
        2 47X,'COMPUTER MODEL',,,/,,25X,'PROGRAM NAME: FSFCSM, FIV VER',,,/,,
        3 'SION, MAY 1975',,,/,,25X,'DEVELOPED BY: M. D. SCHUMAN',,,/,,
        4 'J. K. HUNTING, AND K. W. FERTIG',,,/,,42X,'ADVANCED PROGRAMS',,,/,,
        5 'ROCKETDYNE',,,/,,42X,'DIVISION OF ROCKWELL INTERNATIONAL',,,/,,
        6 'CANOGA PARK, CALIF 91304',,,/,,
        7 'SPONSORED BY: NASA/LYNDON B. JOHNSON SPACE CENTER',,,/,,
        8 'HOUSTON, TEXAS 77058',,,/,,42X,'UNDER CONTRACT NAS9-14315')

RETURN
END
FS CSM SUBROUTINES

BLOCK DATA
COMMON/HY/ICRT,IRFLAG,ITEM,ITYPE,IWRITE,IXA,CW,KF,KO,L,R,RHOL,V,00013010
&VF,VO,VOLF,VOLU,ZF,ZO,OSAVE(188),FSAVE(188)
REAL A(30),CW(30),KF,KO,L(30),R(30),RHOL(3G),V(30)
DATA ICRT/0/,IRFLAG/0/,ITEM/0/,ITYPE/1/,IWRITE/0/
END
SUBROUTINE HYDROD(IR, INPHYD, FREQ, GINO, GINF, PCIN, WOIN, WFIN)

SUBROUTINE HYDROV(IR, INPHYD, FREQ, GINJOX, GINJFU, PC, WO, WF)

SUBPROGRAM TO CALCULATE FEED SYSTEM RESPONSE
PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975

ARGUMENT LIST VARIABLES:
IR - DATA FLAG: =0-NO DATA READ; =1-READ NEW DATA CASE;
    =2-MODIFY EXISTING DATA CASE
INPHYD - MODE FLAG: =1-CALCULATE INJ. FLOW GAIN & PHASE AT 1 FREQ.
        =2-CALC. & SAVE INJ. FLOW GAIN & PHASE FOR FREQ. RANGE
FREQ - INPUT FREQUENCY FOR CASE WITH INPHYD=1
GINJOX - OUTPUT COMPLEX NUMBER WITH AMPLITUDE AND PHASE ANGLE OF
        OXID. INJECTOR FLOW OSCILLATIONS AT FREQUENCY, FREQ
GINJFU - OUTPUT COMPLEX NUMBER WITH AMPLITUDE AND PHASE ANGLE OF
        FUEL INJECTOR FLOW OSCILLATIONS AT FREQUENCY, FREQ
PC - STEADY STATE OPERATING CHAMBER PRESSURE (LB/IN**2)
WG - STEADY STATE OXIDIZER INJECTOR FLOW (LB/SEC)
WF - STEADY STATE FUEL INJECTOR FLOW (LB/SEC)

LABELED COMMON BLOCK /COMTAP/ VARIABLES:
FREQT - ARRAY OF FREQUENCIES (100 MAX.) FOR INPHYD=2 CASE
NFREQT - NUMBER OF FREQUENCIES IN ARRAY, FREQT
GINJOT - TABLE OF COMPLEX NUMBERS WITH GAINS AND PHASE ANGLES OF
        OXID. INJECTOR FLOW OSCILLATIONS AT FREQT FREQUENCIES
GINJFT - TABLE OF COMPLEX NUMBERS WITH GAINS AND PHASE ANGLES OF
        FUEL INJECTOR FLOW OSCILLATIONS AT FREQT FREQUENCIES

NAMELIST /HYD/ VARIABLES:
ICRT - PLOT FLAG: =0-NO PLOTS; =1- PLOT GAIN&PHASE VS FREQUENCY
IWHITE - PRINT FLAG: =-2-NO PRINT; =-1-PRINT OUTPUT ONLY;
           =0-PRINT INPUT ONLY; =1-PRINT INPUT & OUTPUT;
           =2-PRINT INPUT, OUTPUT & INTERMEDIATE CALCULATIONS
IRFLAG - READ FLAG: =0-CARD INPUT; =1-TERMINAL INPUT FROM TERM

00000005 00000010 00000020 00000021 00000022 00000020
00000030 00000040 00000050 00000060 00000070 00000080
00000090 00000100 00000110 00000120 00000130 00000140
00000150 00000160 00000170 00000180 00000190 00000200
00000210 00000220 00000230 00000240 00000250 00000260
00000270 00000280 00000290 00000300
**SCS M SUBROUTINES**

**ITEM** - TERMINAL INPUT FLAG: 0-NO TERMINAL; >0-TERMINAL UNIT NO. 00000310

**NOTE:** ITERM>0 CHANGES IFLAG TO 1 00000320

**ITYPE** - SYSTEM TYPE FLAG: 1-BOTH OXID. & FUEL SYSTEMS DESCRIBED 00000330

WITH 1 DATA READ; 2- OXID. SYSTEM DATA READ AND CALCULATED FIRST, THEN FUEL SYSTEM DATA READ & CALCULATED 00000340

**ID** - DUMMY NAME TO ALLOW USE OF SEQUENCE NUMBERS ON NAMELIST 00000350

**INPUT CARDS** 00000370

**A** - ARRAY WITH FEED SYSTEM SEGMENT FLOW AREAS (IN**2) 00000390

**CW** - ARRAY WITH SEGMENT WALL COMPLIANCE VALUES (IN**2/LB) 00000390

**FREQ** - (SEE ARGUMENT LIST VARIABLES) 00000400

**FREQT** - (SEE COMMON BLOCK VARIABLES) 00000410

**KF** - FUEL INJECTOR FACE FLEXIBILITY CONSTANT (IN**2) 00000420

**KO** - OXID. INJECTOR FACE FLEXIBILITY CONSTANT (IN**2) 00000430

**L** - ARRAY WITH FEED SYSTEM SEGMENT LENGTHS (IN) 00000440

**NFREOT** - (SEE COMMON BLOCK VARIABLES) 00000450

**R** - ARRAY WITH SEGMENT LINEARIZED RESISTANCES (SEC/IN**2) 00000460

**RF** - FUEL INJECTOR LINEARIZED RESISTANCE (SEC/IN**2) 00000470

**RO** - OXID. INJECTOR LINEARIZED RESISTANCE (SEC/IN**2) 00000480

**RHUL** - ARRAY WITH SEGMENT FLUID DENSITY VALUES (LB/IN**3) 00000490

**V** - ARRAY WITH SEGMENT FLUID ACOUSTIC VELOCITY VALUES (IN/SEC) 00000500

**VF** - FUEL INJECTOR FLUID ACOUSTIC VELOCITY (IN/SEC) 00000510

**VO** - OXID. INJECTOR FLUID ACOUSTIC VELOCITY (IN/SEC) 00000520

**VOLF** - VOLUME OF FUEL INJECTOR (IN**3) 00000530

**VOLO** - VOLUME OF OXIDIZER INJECTOR (IN**3) 00000540

**ZF** - FUEL INJECTOR INERTANCE (SEC**2/IN**2) 00000550

**ZO** - OXID. INJECTOR INERTANCE (SEC**2/IN**2) 00000560

**DEFAULT VALUES FOR VARIABLES:**

**ICKT=0, IWRITE=0, IFLAG=0, ITERM=0, ITYPE=1**

**A=1., CW=0., KF=0., KO=0., L=.001, R=1000000., RF=1., RO=.1,**

**RHUL=.64, V=40000., VF=40000., VO=40000., VOLF=.01, VOLO=.01,**

**ZF=.0004, ZO=.0004**
FS S M SUBRoutines

NOTE: MAXIMUM OF 100 VALUES IN FREQT ARRAY
MAXIMUM OF 30 VALUES IN A, CW, L, R, RHOL & V ARRAYS

COMMON/HY/ICRT, IRFLAG, ITERM, IWRITE, IX, A, CW, KF, KO, L, R, RHOL, V, OCC00640
&VF, VO, VOLF, VOLD, ZF, ZO, OSAVE(188), FSAVE(188), OCC00650
REAL X(188), OCC00660
EQUIVALENCE (X(1), A(1)), OCC00670
COMMON/F/NW, NCTD, NR, KEQ, TRIG, IRPS, OMI, OMFL, W, IH, C, TD, ATD, OCC00680
1FREQ, GINJOX, GINJFU, PC, WF, OCC00690
COMPLEX NOZAT(100), GINJOT(100), GINJFT(100), GINJOX, GINJFU, OCC006A0
&GINO, GINF
COMMON/COMTAP/NFREQT, FREQT(100), NOZAT, GINJOT, GINJFT, ITAPN, ITAPC, OCC006B0
1ITAPH
REAL L(30), R(30), A(30), V(30), C(62, 126), TD(62, 63), ATD(126), W(101), OCC006C0
6, CW(30), RHOL(30), KO, KF
INTEGER*4 IH(126), OCC006D0
NAMELIST/HYD/L, R, A, V, OMI, OMFL, FREQ, NFREQT, IWRITE, ICRT, ZF, RF, VOLF, OCC006E0
&VF, ZO, RO, VOLF, VO, FREQT, IH, ITERM, IRFLAG, KO, KF, CW, RHOL, ID, ITYPE, IX
1X = 0
IF(INPHYD.EQ.2) REWIND ITAPH, OCC006F0
G = 386.4
FREQ = FRE
PC = PCIN
WO = WFIN
WF = WFIN
5 DO 10 I = 1, 62
   DO 10 J = 1, 126
10 C(I, J) = 0
   DO 20 I = 1, 62
      DO 20 J = 1, 63
20 T(I, J) = 0
FSCSM SUBROUTINES

DO 30 I=1,126
  30 IH(I)=-1
      IH(16)=0
      IH(18)=0
      IH(19)=1
      IH(55)=0
      IH(58)=0
      IH(59)=1
      IH(62)=0
      NW=0
      NCTD=113
      NR=63
      KEQ=57
      TRIG=0.
      IRPS=0
      OMI=FREQT(1)
      OMFL=FREQT(NFREQT)

      IF(IR.EQ.0) GO TO 100
      IF(IR.EQ.2) GO TO 45

      DO 40 I=1,30
      R(I)=1000000.
      V(I)=4000000.
      A(I)=1.
      CH(I)=0.
      RMOL(I)=.04

      40 L(I)=.001
      ZF=.000004
      ZO=.000004
      RF=.1
      RU=.1
      VF=40000.
      VO=40000.
      KF=0.

0001230
0001240
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0001520
0001530
0001540
0001550
0001560
F S C S M SUBROUTINES

KO=0.
VOLF=.01
VLO=0.1
45 IF (IRFLAG.EQ.0) READ(5,HYD,END=60)
   IF (ITEMT.GT.0) IRFLAG=1
   IF (ITEMT.GT.0) WRITE(ITEMT,50)
50 FORMAT(' INPUT NAMELIST & HYD DATA / VARIABLES ARE: L,R,A,V,CW,RHOL,CC163C
   &L,VFREQT,FREQT,WRITE,ITEMT / ICNT,ZF,RF,VD,KDF,V,F,20,RO,VOL',CC164C
   &VOL,FAIL,ITYPE,IRFLAG)
60 IF (ITEMT.GT.0) READ(ITEMT,HYD,END=499)
   IF (ITEMT.GT.0) WRITE(ITEMT,66)
66 FORMAT('END OF HYD INPUT')
   IF (WRITE.GE.0) WRITE(6,HYD)
100 IF (ITYPE.EQ.2) IX=MINO(IX+1,2)
C GENERATE COEFFICIENT MATRIX FOR FREQUENCY RESPONSE ROUTINE
   DU 161 I=1,30
101 V(1)=SQRT(1./((1./V(1)/V(1)+RHOL(1)*CW(1)/G))
   C(1,1)=1.
   C(1,2)=R(1)+V(1)/G/A(1)
   C(2,1)=1.
   C(2,4)=-V(3)/G/A(3)
   C(3,3)=1.
   C(3,5)=R(3)+V(3)/G/A(3)
   C(4,1)=1.
   C(4,2)=-(R(2)+V(2)/G/A(2))
   C(4,4)=R(2)+V(2)/G/A(2)
   C(5,3)=1.
   C(5,6)=-V(5)/G/A(5)
   C(6,3)=1.
   C(6,5)=-V(4)/G/A(4)
   C(6,6)=V(4)/G/A(4)
   C(7,21)=1.
   C(7,20)=R(4)+V(4)/G/A(4)
FS G S M SUBROUTINES

\[ C(8,7) = 1. \]
\[ C(8,8) = R(5) + V(5)/G/A(5) \]
\[ C(9,7) = 1. \]
\[ C(9,8) = V(6)/G/A(6) \]
\[ C(10,9) = 1. \]
\[ C(10,10) = -(R(7) + V(7)/G/A(7)) \]
\[ C(10,11) = R(7) + V(7)/G/A(7) \]
\[ C(11,9) = 1. \]
\[ C(11,11) = V(8)/G/A(8) \]
\[ C(12,12) = 1. \]
\[ C(12,13) = R(8) + V(8)/G/A(8) \]
\[ C(13,12) = 1. \]
\[ C(13,13) = -V(9)/G/A(9) \]
\[ C(14,14) = 1. \]
\[ C(14,27) = R(9) + V(9)/G/A(9) \]
\[ C(15,14) = 1. \]
\[ C(15,27) = V(10)/G/A(10) \]
\[ C(16,16) = 1. \]
\[ C(16,17) = R(10) + V(10)/G/A(10) \]
\[ C(17,16) = 1. \]
\[ C(17,18) = -20 \]
\[ C(17,19) = -RC \]
\[ C(18,15) = 1. \]
\[ C(18,17) = (V0 + V0*KO)/G/VOLO \]
\[ C(18,19) = V0*V0/G/VOLO \]
\[ C(18,62) = V0*V0*KO/G/VOLO \]
\[ C(19,21) = 1. \]
\[ C(19,22) = V(14)/G/A(14) \]
\[ C(20,29) = 1. \]
\[ C(20,28) = -(R(14) + V(14)/G/A(14)) \]
\[ C(21,21) = 1. \]
\[ C(21,20) = -V(11)/G/A(11) \]
\[ C(21,22) = -V(11)/G/A(11) \]
F S C S M SUBROUTINES

C(22,24)=1.
C(22,23)=R(11)+V(11)/C/A(11)
C(23,24)=1.
C(23,23)=-(R(13)+V(13)/G/A(13))
C(23,25)=R(13)+V(13)/G/A(13)
C(24,24)=1.
C(24,25)=-V(12)/G/A(12)
C(25,21)=1.
C(25,30)=R(15)+V(15)/G/A(15)
C(26,31)=1.
C(26,30)=V(16)/G/A(16)
C(27,29)=1.
C(27,28)=R(16)+V(16)/G/A(16)
C(27,32)=R(16)+V(16)/G/A(16)
C(28,43)=1.
C(28,44)=R(22)+V(22)/G/A(22)
C(29,43)=1.
C(29,45)=-V(24)/G/A(24)
C(30,43)=1.
C(30,44)=-(R(23)+V(23)/G/A(23))
C(30,45)=R(23)+V(23)/G/A(23)
C(31,29)=1.
C(31,32)=-(R(17)+V(17)/G/A(17))
C(32,33)=1.
C(32,34)=V(17)/G/A(17)
C(33,41)=1.
C(33,42)=V(21)/G/A(21)
C(33,46)=V(21)/G/A(21)
C(34,33)=1.
C(34,35)=R(21)+V(21)/G/A(21)
C(35,33)=1.
C(35,34)=-V(18)/G/A(18)
C(35,35)=-V(18)/G/A(18)

APPENDIX C - 56
FSM SUBROUTINES

C(36,36)=1.
C(36,37)=R(18)+V(18)/G/A(19)
C(37,36)=1.
C(37,37)=-(R(19)+V(19)/G/A(19))
C(37,38)=R(19)+V(19)/G/A(19)
C(38,36)=1.
C(38,38)=-V(20)/G/A(20)
C(39,40)=-(R(20)+V(20)/G/A(20))
C(40,41)=1.
C(40,46)=-V(25)/G/A(25)
C(41,47)=1.
C(41,48)=R(25)+V(25)/G/A(25)
C(42,47)=1.
C(42,48)=-V(26)/G/A(26)
C(43,49)=1.
C(43,50)=R(26)+V(26)/G/A(26)
C(44,49)=1.
C(44,50)=-(R(27)+V(27)/G/A(27))
C(44,51)=R(27)+V(27)/G/A(27)
C(45,49)=1.
C(45,51)=-V(28)/G/A(28)
C(46,52)=1.
C(46,53)=R(28)+V(28)/G/A(28)
C(47,52)=1.
C(47,53)=-V(29)/G/A(29)
C(48,54)=1.
C(48,59)=R(29)+V(29)/G/A(29)
C(49,54)=1.
C(49,59)=-V(30)/G/A(30)
C(50,56)=1.
C(50,57)=R(30)+V(30)/G/A(30)
C(51,56)=1.
C(51,58)=-ZF
FS CSM SUBROUTINES

C(51,59)=-RF
C(52,55)=+VF*VF*KF/G/VOLF
C(52,57)=-(VF*VF/G/VOLF)
C(52,59)=VF*VF/G/VOLF
C(52,62)=VF*VF*KF/G/VOLF
C(53,9)=1.
C(53,10)=R(6)+V(6)/G/A(6)
C(54,26)=-(R(12)+V(12)/G/A(12))
C(55,41)=1.
C(55,42)=R(24)+V(24)/G/A(24)
C(56,60)=1.
C(57,61)=1.
C(17,63)=1.
C(51,63)=1.

C GENERATE TIME DELAY MATRIX FOR FREQUENCY RESPONSE ROUTINE

TD(1,1)=L(1)/V(1)
TD(1,2)=2.*L(1)/V(1)
TD(2,3)=L(3)/V(3)
TD(2,5)=L(3)/V(3)
TD(3,1)=L(3)/V(3)
TD(3,4)=L(3)/V(3)
TD(4,1)=2.*L(2)/V(2)
TD(4,2)=2.*L(2)/V(2)
TD(4,4)=2.*L(2)/V(2)
TD(5,7)=L(5)/V(5)
TD(5,8)=L(5)/V(5)
TD(6,18)=L(4)/V(4)
TD(6,19)=L(4)/V(4)
TD(7,3)=L(4)/V(4)
TD(7,5)=L(4)/V(4)
TD(7,6)=L(4)/V(4)
TD(8,3)=L(5)/V(5)
TD(8,6)=L(5)/V(5)
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<tr>
<th>Subroutine</th>
<th>Formula</th>
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<td>TD(9,9)</td>
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<tr>
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<tr>
<td>TD(10,9)</td>
<td>2*L(7)/V(7)</td>
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<tr>
<td>TD(10,10)</td>
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</tr>
<tr>
<td>TD(10,11)</td>
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</tr>
<tr>
<td>TD(11,12)</td>
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</tr>
<tr>
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<td>L(8)/V(8)</td>
</tr>
<tr>
<td>TD(12,9)</td>
<td>L(8)/V(8)</td>
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<tr>
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<td>L(8)/V(8)</td>
</tr>
<tr>
<td>TD(13,14)</td>
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<tr>
<td>TD(13,25)</td>
<td>L(9)/V(9)</td>
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<tr>
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</tr>
<tr>
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</tr>
<tr>
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<tr>
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<tr>
<td>TD(23,22)</td>
<td>2*L(13)/V(13)</td>
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<tr>
<td>TD(23,23)</td>
<td>2*L(13)/V(13)</td>
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<tr>
<td>TD(24,24)</td>
<td>L(12)/V(12)</td>
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<tr>
<td>TD(24,25)</td>
<td>L(12)/V(12)</td>
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<td>TD(25,28)</td>
<td>2*L(15)/V(15)</td>
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<tr>
<td>TD(25,29)</td>
<td>2*L(15)/V(15)</td>
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</tbody>
</table>
### FSCSM SUBROUTINES

| TD(26, 26) = L(16)/V(16) | 5000353C |
| TD(26, 27) = L(16)/V(16) | 50003540 |
| TD(26, 30) = L(16)/V(16) | 50003550 |
| TD(27, 28) = L(16)/V(16) | 50003560 |
| TD(27, 29) = L(16)/V(16) | 50003570 |
| TD(28, 41) = 2 * L(22)/V(22) | 50003580 |
| TD(28, 42) = 2 * L(22)/V(22) | 50003590 |
| TD(29, 39) = L(24)/V(24) | 50003600 |
| TD(29, 40) = L(24)/V(24) | 50003610 |
| TD(30, 41) = 2 * L(23)/V(23) | 50003620 |
| TD(30, 42) = 2 * L(23)/V(23) | 50003630 |
| TD(30, 43) = 2 * L(23)/V(23) | 50003640 |
| Tu(31, 31) = L(17)/V(17) | 50003650 |
| TD(31, 32) = L(17)/V(17) | 50003660 |
| TD(32, 27) = L(17)/V(17) | 50003670 |
| TD(32, 30) = L(17)/V(17) | 50003680 |
| TD(33, 31) = L(21)/V(21) | 50003690 |
| TD(33, 33) = L(21)/V(21) | 50003700 |
| TD(34, 39) = L(21)/V(21) | 50003710 |
| TD(34, 40) = L(21)/V(21) | 50003720 |
| TD(34, 44) = L(21)/V(21) | 50003730 |
| TD(35, 34) = L(18)/V(18) | 50003740 |
| TD(35, 35) = L(18)/V(18) | 50003750 |
| TD(36, 31) = L(18)/V(18) | 50003760 |
| TD(36, 32) = L(18)/V(18) | 50003770 |
| TD(36, 33) = L(18)/V(18) | 50003780 |
| TD(37, 34) = 2 * L(19)/V(19) | 50003790 |
| TD(37, 35) = 2 * L(19)/V(19) | 50003800 |
| TD(37, 36) = 2 * L(19)/V(19) | 50003810 |
| TD(38, 38) = L(20)/V(20) | 50003820 |
| TD(38, 57) = L(20)/V(20) | 50003830 |
| Tu(39, 34) = L(20)/V(20) | 50003840 |
| Tu(39, 36) = L(20)/V(20) | 50003850 |

**APPENDIX C - 60**
FSCSM SUBROUTINES

\[
\begin{align*}
TD(40,45) &= L(25)/V(25) \\
TD(40,46) &= L(25)/V(25) \\
TD(41,39) &= L(24)/V(25) \\
TD(41,44) &= L(25)/V(25) \\
TD(42,47) &= L(26)/V(26) \\
TD(42,48) &= L(26)/V(26) \\
TD(43,45) &= L(26)/V(26) \\
TD(43,46) &= L(26)/V(26) \\
TD(44,47) &= 2*L(27)/V(27) \\
TD(44,48) &= 2*L(27)/V(27) \\
TD(44,49) &= 2*L(27)/V(27) \\
TD(45,50) &= L(28)/V(28) \\
TD(45,51) &= L(28)/V(28) \\
TD(46,47) &= L(28)/V(28) \\
TD(46,49) &= L(28)/V(28) \\
TD(47,37) &= L(29)/V(29) \\
TD(47,52) &= L(29)/V(29) \\
TD(48,50) &= L(29)/V(29) \\
TD(48,51) &= L(29)/V(29) \\
TD(49,53) &= L(30)/V(30) \\
TD(49,54) &= L(30)/V(30) \\
TD(50,37) &= L(30)/V(30) \\
TD(50,52) &= L(30)/V(30) \\
TD(53,7) &= L(6)/V(6) \\
TD(53,8) &= L(6)/V(6) \\
TD(54,22) &= L(12)/V(12) \\
TD(54,23) &= L(12)/V(12) \\
TD(55,41) &= L(24)/V(24) \\
TD(55,43) &= L(24)/V(24)
\end{align*}
\]

C GENERATE TIME DELAY COEFFICIENT ARRAY FOR FREQUENCY RESPONSE ROUTINE

\[
\begin{align*}
ATD(1) &= 1.0 \\
ATD(2) &= R(1) - V(1) / G / A(1) \\
ATD(3) &= -1.0
\end{align*}
\]
FS BSM SUBROUTINES

\begin{align*}
\text{ATD}(4) = & -(R(3) - V(3)/G/A(3)) \\
\text{ATD}(5) = & -1. \\
\text{ATD}(6) = & -V(3)/G/A(3) \\
\text{ATD}(7) = & -1. \\
\text{ATD}(8) = & R(2) - V(2)/G/A(2) \\
\text{ATD}(9) = & -(R(2) - V(2)/G/A(2)) \\
\text{ATD}(10) = & -1. \\
\text{ATD}(11) = & -(R(5) - V(5)/G/A(5)) \\
\text{ATD}(12) = & -(R(4) - V(4)/G/A(4)) \\
\text{ATD}(13) = & -1. \\
\text{ATD}(14) = & -1. \\
\text{ATD}(15) = & -V(4)/G/A(4) \\
\text{ATD}(16) = & V(4)/G/A(4) \\
\text{ATD}(17) = & -1. \\
\text{ATD}(18) = & -V(5)/G/A(5) \\
\text{ATD}(19) = & -1. \\
\text{ATD}(20) = & -(R(6) - V(6)/G/A(6)) \\
\text{ATD}(21) = & -1. \\
\text{ATD}(22) = & R(7) - V(7)/G/A(7) \\
\text{ATD}(23) = & -(R(7) - V(7)/G/A(7)) \\
\text{ATD}(24) = & -1. \\
\text{ATD}(25) = & -(R(8) - V(8)/G/A(8)) \\
\text{ATD}(26) = & -1. \\
\text{ATD}(27) = & V(8)/G/A(8) \\
\text{ATD}(28) = & -1. \\
\text{ATD}(29) = & -(R(9) - V(9)/G/A(9)) \\
\text{ATD}(30) = & -1. \\
\text{ATD}(31) = & -V(9)/G/A(9) \\
\text{ATD}(32) = & -1. \\
\text{ATD}(33) = & -(R(10) - V(10)/G/A(10)) \\
\text{ATD}(34) = & -1. \\
\text{ATD}(35) = & -V(10)/G/A(10) \\
\text{ATD}(36) = & R(14) - V(14)/G/A(14) \\
\end{align*}
## F S C S M SUBROUTINES

<table>
<thead>
<tr>
<th>Equation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ATD(37) = -1.$</td>
<td></td>
</tr>
<tr>
<td>$ATD(38) = -1.$</td>
<td></td>
</tr>
<tr>
<td>$ATD(39) = V(14)/G/A(14)$</td>
<td></td>
</tr>
<tr>
<td>$ATD(40) = -(R(11) - V(11))/G/A(11))</td>
<td></td>
</tr>
<tr>
<td>$ATD(41) = -1.$</td>
<td></td>
</tr>
<tr>
<td>$ATD(42) = V(11)/G/A(11)$</td>
<td></td>
</tr>
<tr>
<td>$ATD(43) = -1.$</td>
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</tr>
<tr>
<td>$ATD(44) = V(11)/G/A(11)$</td>
<td></td>
</tr>
<tr>
<td>$ATD(45) = R(13) - V(13)/G/A(13)$</td>
<td></td>
</tr>
<tr>
<td>$ATD(46) = -1.$</td>
<td></td>
</tr>
<tr>
<td>$ATD(47) = -(R(13) - V(13))/G/A(13))</td>
<td></td>
</tr>
<tr>
<td>$ATD(48) = -(R(12) - V(12))/G/A(12))</td>
<td></td>
</tr>
<tr>
<td>$ATD(49) = -1.$</td>
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</tr>
<tr>
<td>$ATD(50) = R(15) - V(15)/G/A(15)$</td>
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</tr>
<tr>
<td>$ATD(51) = 1.$</td>
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</tr>
<tr>
<td>$ATD(52) = -(R(16) - V(16))/G/A(16))</td>
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</tr>
<tr>
<td>$ATD(53) = -1.$</td>
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</tr>
<tr>
<td>$ATD(54) = -(R(16) - V(16))/G/A(16))</td>
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</tr>
<tr>
<td>$ATD(55) = V(16)/G/A(16)$</td>
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</tr>
<tr>
<td>$ATD(56) = -1.$</td>
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</tr>
<tr>
<td>$ATD(57) = 1.$</td>
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</tr>
<tr>
<td>$ATD(58) = R(22) - V(22)/G/A(22)$</td>
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</tr>
<tr>
<td>$ATD(59) = -1.$</td>
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</tr>
<tr>
<td>$ATD(60) = -(R(24) - V(24))/G/A(24))</td>
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</tr>
<tr>
<td>$ATD(61) = -1.$</td>
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</tr>
<tr>
<td>$ATD(62) = R(23) - V(23)/G/A(23)$</td>
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</tr>
<tr>
<td>$ATD(63) = -(R(23) - V(23))/G/A(23))</td>
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</tr>
<tr>
<td>$ATD(64) = -1.$</td>
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</tr>
<tr>
<td>$ATD(65) = V(17)/G/A(17)$</td>
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</tr>
<tr>
<td>$ATD(66) = -1.$</td>
<td></td>
</tr>
<tr>
<td>$ATD(67) = R(17) - V(17)/G/A(17)$</td>
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</tr>
<tr>
<td>$ATD(68) = -1.$</td>
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</tr>
<tr>
<td>$ATD(69) = -(R(21) - V(21))/G/A(21))</td>
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</tr>
</tbody>
</table>

R-9808/C-64
FS CSM SUBROUTINES

ATD(70) =-1.
ATD(71) =-V(21)/G/A(21)
ATD(72) =V(21)/G/A(21)
ATD(73) =-1.
ATD(74) =-(R(18)-V(18)/G/A(18))
ATD(75) =-1.
ATD(76) =-V(18)/G/A(18)
ATD(77) =-V(18)/G/A(18)
ATD(78) =-1.
ATD(79) =R(19)-V(19)/G/A(19)
ATD(80) =-(R(19)-V(19)/G/A(19))
ATU(81) =-(R(20)-V(20)/G/A(20))
ATU(82) =-1.
ATD(83) =1.
ATD(84) =V(20)/G/A(20)
ATD(85) =-1.
ATU(86) =-(R(25)-V(25)/G/A(25))
ATU(87) =-1.
ATD(88) =-V(25)/G/A(25)
ATD(89) =-1.
ATD(90) =-(R(26)-V(26)/G/A(26))
ATD(91) =-1.
ATD(92) =V(26)/G/A(26)
ATU(93) =-1.
ATU(94) =R(27)-V(27)/G/A(27)
ATD(95) =-(R(27)-V(27)/G/A(27))
ATD(96) =-1.
ATD(97) =-(R(28)-V(28)/G/A(28))
ATU(98) =-1.
ATD(99) =-V(28)/G/A(28)
ATD(100) =-(R(29)-V(29)/G/A(29))
ATD(101) =-1.
ATD(102) =-1.
FS C S M SUBROUTINES

A(163) = -V(29)/G/A(29)
A(104) = -1.
A(105) = -(R(30) - V(30)/G/A(30))
A(106) = -V(26)/G/A(30)
A(107) = -1.
A(108) = -1.
A(109) = -V(6)/G/A(6)
A(110) = 1.
A(111) = V(12)/G/A(12)
A(112) = -1.
A(113) = -V(24)/G/A(24)

400 IF (INPHYD .GT. 1) GO TO 500
   NW = 1
   500 CALL FRESM (ICPT, IWRITE, IX)
   IF (IX .LT. 2) GO TO 502
   DU 501 I = 1, 188
   FSAVE(I) = X(I)
   501 X(I) = USAVE(I)
   GO TO 510
   502 IF (IX .EQ. 4) GO TO 510
   DU 503 I = 1, 188
   503 USAVE(I) = X(I)
   GO TO 5
   510 IF (INPHYD .LE. 1) GO TO 700
   511 WRITE(6, 550) (FREQ(J), GINJOT(J), GINJFT(J), J = 1, NFEQ)
   550 FORMAT(1H1, ' //, 18X, 'FEED SYSTEM RESPONSE PARAMETERS', //,
      1 ' 5X, 'FREQUENCY', 4X, 'OXIDIZER INJECTION RATE', 4X,
      2 'FUEL INJECTION RATE', 18X, 'AMPLITUDE', 5X, 'PHASE',
      3 '6X, 'AMPLITUDE', 5X, 'PHASE', '9X, (5X, GPFY.3, 5X, 1PE11.4,
      4 GPFY.2, 5X, 1PE11.4, GPF.2))

INPHYD = 3
SUBROUTINE LUOFC/(JK, X, NX, JX, FX)

ROUTINE FOR LINEAR INTERPOLATION
  IF JK EQ. 1, CHECKS ORDER OF X ARRAY (NX ITEMS) FOR
  CONSISTANTLY INCREASING OR DECRASING VALUES.
  FINDS LOCATION OF FIRST (OR ONLY) ARRAY ITEM FOR SCALING
  LOCATION OF X FROM TX(JX)
  CALCULATES SCALING FACTOR FX = (X-TX(JX)) / (TX(JX+1)-TX(JX))

PROGED BY M. D. SCHUMAN, ROCKETDYNE, MAY 1975

DIMENSION TX(1)

JX = 1
FX = 0.
IF(NX.LE.1) GO TO 200
S = 1.
IF(TX(1).GE.TX(NX)) S = -1.
XR2 = ABS(TX(NX)-TX(1))*0.5
IF(JK.NE.1) GO TO 90

JK = 0
IF(JG.GT.0) GO TO 30
DO 20 I=2,NX
   IF(TX(I).GT.TX(I-1)) GO TO 50
20 CONTINUE
   GO TO 90
30 DO 40 I=2,NX
   IF(TX(I).LT.TX(I-1)) GO TO 50
40 CONTINUE
   GO TO 90

50 WRITE(6,60)
60 FORMAT(1H1,1X,27HE RR U R I N T A B L E )
SUBROUTINES

C

90 NX1 = 2
IF (NX.LE.20) GO TO 110
DO 100 J=1,NX,10
NX1 = 1 + 1
100 IF ((TX(I)-X)*S) 120,200,130
110 CONTINUE C

130 IF (JX.GT.1) JX = JX-1
FX = (X-TX(JX))/ (TX(JX+1)-TX(JX))
IF (X.LT.AMIN1(TX(I),TX(NX))-XR2) GO TO 150
IF (X.GT.AMAX1(TX(I),TX(NX))+XR2) GO TO 150
GO TO 200

C

150 WRITE(6,160)
160 FORMAT (1H1 22X 64HE R R O R - EXTRAPOLATION OF TABLE IS BEYOND REASONABLE LIMITS )
GO TO 70

C

200 RETURN
END

SUBROUTINE NUZADM(IR, GAMX, CO, FREQ, NOZA)

C

SUBPROGRAM TO CALCULATE THE DOWNSTREAM NOZZLE ADMITTANCE

C

PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
FSCSM SUBROUTINES

C REF. NASA CR-141129
C MODIFIED FOR THE FEED SYSTEM COUPLED STABILITY MODEL
C BY M. O. SCHUMAN, ROCKEYDYNE, MAY 1975
C
C IMPLICIT REAL*(A-H,0-Z)
C COMPLEX NOZA, NOZAT, GINJOT, GINJFT
C REAL FREQ, GAMX, RCCX, RCTX, ANGLEX, CRR, RINJ, CO, FREQMX,
1 FREQMI, FREQT, FREQ1, FREQ2
C
C DIMENSION D(5,4), G(5), GP(5), Y(5)
C
C COMMON /X1/GAM,SVN,ANGLE,RICT,RCC /X2/T,RT,Q,R1,R2,WC,IP
1 /X3/Z1H,Z1L /X4/CM
C
C COMMON /CIMTAP/,NFRXT, FREXT(100), NOZAT(100), GINJOT(100),
1 GINJFT(100), ITAPN, ITAPC, ITAPH
C
C COMMON /CIMNO/, RCCX, RCTX, ANGLEX, CRR, RINJ, INPNOZ, FREQMX,
1 FREQMI, IPNOZ
C
C IF(INPNOZ.EQ.3) REWIND ITAPN
C IF(IR.EQ.0) GO TO 2
C
C INPUT DATA REQUIRED BY THE SUBPROGRAM
C
C 9000 READ(5,900) RCCX, RCTX, ANGLEX, CRR
C 9000 FORMAT(6E12.8)
C WRITE(6,9010) RCCX, RCTX, ANGLEX, CRR
C 9010 FORMAT(5X,'RCCX =',1PE11.4,5X,'RCTX =',1PE11.4,5X,'ANGLEX =',1E11.4,5X,'CRR =',1E11.4)
2 GAM = GAMX
   RCC = RCCX
   RCT = RCTX
   ANGLE = ANGLEX
C
   IF(INPNOZ.EQ.3) WRITE(ITAPN) NFREQT
   IP = 0
   SVN = 0.0
   IF(INPNOZ.LE.1) GO TO 2000
   DWC = 6.283185*RINJ/CO*(FREQMX-FREQMI)/(NFREQT-1)
   WC = 6.283185*RINJ/CO*FREQMI-DWC
   NWC = NFREQT
   GO TO 2016
2000 DWC = 0.0
   WC = 6.283185*RINJ/CO*FREQ
   NWC = 1
   2010 CONTINUE
   DP = -0.001
   T = 3.1415927*ANGLE/180.0
   IF(CRK.LE.0.0) GO TO 7
   CM=0.0
   5 CM=1./CR**(2.*)((GAM-1.)*((GAM-1.)*0.5*CM**CM))
   **{(GAM+1.)/(2.*((GAM-1.))}
   ER=DABS((CM-1)/CM)
   CM=CM
   IF(ER.GT.1.E-06) GO TO 5
   7 CONTINUE
   IF(INPNOZ.GT.0.AND.INPNOZ.GT.1)
   1 WRITE(6,1000) CM, SVN, GAM, ANGLE, RCT, RCC
   DO 10 N=1,NWC
   20 WC = WC + DWC
   25 RT = (CM**0.5)*((1+((GAM-1.)*CM**CM/2)**((-GAM-1.)/(4*(GAM-1.))))
      *(((2/(GAM+1.))**((-GAM-1.)/(4*(GAM-1.))))
      )
      +1.0)
      -1.0)
      *(1+((GAM-1.)*CM**CM/2)**((-GAM-1.)/(4*(GAM-1.))))
      10 CONTINUE
\[ Q = (Q \cdot 25 \cdot R T \cdot (2/(G A M + 1)))^{\ast ((G A M + 1)/(4 \cdot (G A M - 1)))} \]

\[
\begin{align*}
PHIR & = 1 \\
PHII & = 0 \\
R1 & = R T \cdot R C T \cdot (1 - D C O S (T)) \\
R2 & = 1.0 - R C C \cdot (1 - D C O S (T)) \\
P & = 0 \\
U & = 2/(G A M + 1) \\
SRTr & = (R T \cdot R C T) \cdot C \cdot 5 \\
AIR & = -4/(G A M + 1) \cdot S R T R \\
BOI & = -A I R \\
BO1 & = 4 \cdot W C/(G A M + 1) \\
SVNR & = S V N / R T \\
C0R & = W C \cdot W C - ((S V N R \cdot S V N R) \cdot 2/(G A M + 1)) \\
C0I & = -2 \cdot W C/(G A M - 1)/(G A M + 1) \cdot S R T R \\
B1R & = (24 + 4 \cdot G A M)/(3 \cdot R C T \cdot R T/(G A M + 1)) \\
B1I & = E \cdot W C/((S R T R \cdot (G A M + 1)) \\
C1R & = 2/(G A M - 1) \cdot S V N R \cdot S V N R/((S R T R \cdot (G A M + 1)) \\
C1I & = -1 \cdot R W C/(G A M - 1) \cdot 0.5 \\
ZOR & = (B O R \cdot C O R + B O I \cdot C O I)/(B O R \cdot B O R + B O I \cdot B C I) \\
ZOI & = (B O R \cdot C O I - B O I \cdot C O R)/(B C I \cdot B O R + B O I \cdot B O I) \\
F1 & = B1R \cdot ZO1 - H11 \cdot ZO1 - ZOR \cdot ZOR \cdot A I R \cdot A I R \cdot ZO1 \cdot ZO1 - C1R \\
F2 & = B1I \cdot ZOR + E1R \cdot ZO1 - 2 \cdot A I R \cdot ZO1 \cdot ZOR - C1I \\
F1 & = (F1 \cdot (A I R - B O R) - F2 \cdot B O I)/(A I R - B C R)/(A I R - B O R) + B O I \cdot ZO1 \\
F2 & = (F2 \cdot (A I R - B O R) + F1 \cdot B O I)/(A I R - B C R)/(A I R - B O R) + B O I \cdot B O I \\
C & = U \\
G(1) & = U \\
G(2) & = Z O R \\
G(3) & = Z O I \\
G(4) & = PHIR \cdot Z O R - PHII \cdot Z O I \\
G(5) & = PHII \cdot Z O R + Z O I \cdot PHIR \\
DY(1,1) & = -A I R \\
DY(2,1) & = Z1R \\
DY(3,1) & = Z1I \\
\end{align*}
\]
FS CSM SUBROUTINES

DY(4,1) = PHIR
DY(5,1) = PHII
IQZ = 2
DO 30 I = 2,4
CALL RKTZ(5,DP,P,G,GP,IQZ)
P = P+DP
U = G(1)
ZR = G(2)
ZI = G(3)
PHIR = G(4)
PHII = G(5)
DY(1,I) = GP(1)
DY(2,I) = GP(2)
DY(3,I) = GP(3)
DY(4*,I) = GP(4)
DY(5,I) = GP(5)
30 Y(1) = U
Y(2) = ZR
Y(3) = ZI
Y(4) = PHIR
Y(5) = PHII
CALL ZADAMS(5,DP,P,Y,DY,IQZ)
IF(IP.EQ.1) GO TO 10
U = Y(1)
ZR = Y(2)
ZI = Y(3)
PHIR = Y(4)
PHII = Y(5)
QBAR = U**0.5
C = 1-U**0.5*(GAM-1)
RHO = C**1/(GAM-1)
F = QBAR/(GAM*RHO)
IF(IQZ.EQ.1) GO TO 35
FS CSM SUBROUTINES

ZDN = (U*U*ZR*ZR)+(WC+U*ZI)*(WC+U*ZI)
YR = -(U*(ZR+ZI*ZI)+WC*ZI)*F/ZDN
YI = F*WC/ZH/ZDN
GO TO 40
35 TR = Y(2)
TI = Y(3)
TDN = (U-WC*TI)*(U-WC*TI)+(WC*TR)*(WC*TR)
YR = -F*(U-WC*TI)/TDN
YI = F*WC*TR/TDN
40 SYR = GAM*(C*(GAM+1)/(2*(GAM-1)))*YR
SYI = GAM*(C*(GAM+1)/(2*(GAM-1)))*YI
W = WC*(C*(-0.5))
ZDN = 1/(W*W+SVN*SVN*CM*CM)
IF(W*W-SVN*SVN*(1-C*CM))<50, 50, 50, 45
45 F = ((W*W-SVN*SVN*(1-C*CM))*0.5)*ZDN
C = SVN*SVN*CM*ZDN
TR = (SYR+C)/F
TI = SYI/F
U = (((1+TR)*(1+TR)+TI*TI)/((1-TR)*(1-TR)+TI*TI))*0.5
ALP = 0.159155*LOG(U)
U = (1-TR+TR-TI*TI)+(((1+TR)*(1+TR)+TI*TI)*((1-TR)*(1-TR)+TI*TI))
1 **0.5
U = U/(2*T1)
BET = 0.31831*DATAN(U)
FREQ1 = WC*CO/(6.283185*RINJ)
FREQ2 = WC*CO/(6.283185*RINJ)
IF(IPRNOZ.GT.0.AND.INPNOZ.GT.1)
1 WRITE(6,1005) FREQ1,YR,YI,FREQ2,SYR,SYI,ALP,BET
GO TO 8
50 FREQ1 = WC*CO/(6.283185*RINJ)
FREQ2 = WC*CO/(6.283185*RINJ)
IF(IPRNOZ.GT.0.AND.INPNOZ.GT.1)
1 WRITE(6,105) FREQ1,YR,YI,FREQ2,SYR,SYI
FSCSM SUBROUTINES

8 NOZA = SYR*(0.0,1.0)*SYI
IF(INPNOZ.LT.1) GO TO 10
1 FREQT(N) = FREQ2
NOZAT(N) = NOZA
C
C SAVE ADMITTANCE DATA ON TAPE UNIT ITAPN
C
C IF(INPNOZ.EQ.3) WRITE(ITAPN) FREQ2,NOZA
10 CONTINUE

1000 FORMAT(1H1,//,1X,30X,30X'THEORETICAL NOZZLE ADMITTANCES',/,'23X,
1 14HMACH NUMBER = ,F3.2,7H SVN = ,F6.4,9H GAMMA = ,F5.3,//,
2 7X,15HNOZZLE ANGLE = ,F4.1,2X,21HRAD11 OF CURVATURE:
3 9HTHroat = ,F6.4,12H ENTRANCE = ,F6.4,//,9X,2HFC,
4 7X,2HYC,8X,2HYI,8X,1HF,6X,3HSYR,8X,3HSYI,
5 6X,5HALPHA,5X,4HBETA,/)
SUBROUTINE RK1DIF(P,G,GP)

ROUTINE FOR SUBPROGRAM NOZADM
PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
REF. NASA CR-121120

IMPLICIT REAL*8(A-H,O-Z)
COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP
DIMENSION G(5), GP(5)

U = G(1)
TR = G(2)
TI = G(3)
PHIR = G(4)
PHII = G(5)

C = 1-(GAM-1)*U*0.5
R = Q**(-1)*U*(1-GAM)*((1-U)**(-1))**0.5

FORMAT(3X,*PRINTING FROM CARD 4570,*3X,*R=*,E15.8,
1 3X,*R1=*,E15.8,3X,*RT=*,E15.8)

1 IF(R1) 22,22,50
22 IF(R1) 25,30,30
25 DR = -(2*RCT*(R-RT)-(R-RT)**C.5)/(RT+RCT-R)
GO TO 45
30 IF(R-RT) 35,40,40
35 DR = -DTAN(1)
GO TO 45
40 DR = ((2*RCC*(1-R1)-(R1)**C.5))/((1-R1-RCC)
45 DR = -(U**0.75)**(1-GAM-1)**(2*(GAM-1))**Q**(-1-GAM-1)**U**.5
GP(1) = DU*DR
GO TO 55
50 GP(1) = 0.6
55 A = U*(-U)
BR = U*GP(1)/C
BI = 2*WC*U
FS CSM SUBROUTINES

CR = WC*WC-(SVN*SVN*C)/(R*R)
CI = -(GAM-1)*WC*U*GP(1)*0.5/C
GP(2) = 1-((BR*TR-BI*TI)-(CR*(TR*TR-TI*TI)-2*CI*TR*TI))/A
GP(3) = (-BR*TI-BI*TR+CI*(TR*TR-TI*TI)+2*CR*TR*TI)/A
T2 = TR*TR+TI*TI
GP(4) = (TR*PHIR-TI*PHII)/T2
GP(5) = (TR*PHII+TI*PHIR)/T2
RETURN
END
FSCT SM SUBROUTINES

SUBROUTINE RKTZ(NU,H,T1,U,DUM,JOPT)

C ROUTINE FOR SUBPROGRAM NOZADM
C PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
C REF. NASA CR-121120

IMPLICIT REAL*8(A-H,O-Z)
COMMON /X2/T,K,T,Q,R1,R2,WC,IP
DIMENSION U(5),A(5),UZ(5),FZ(4,5),DUM(5)
A(1) = 0.6
A(2) = 0.9
A(3) = 0.8
A(4) = 0.5
A(5) = 1.0
TZ = T1
DO 10 J = 1,NU
   UZ(J) = U(J)
10 DUM(J) = FZ(1,J)
   IF(JOPT.EQ.2) GO TO 15
   CALL RK1DIF(TZ,UZ,DUM)
   GO TO 20
15 CALL RK2DIF(TZ,UZ,DUM)
20 DO 25 J = 1,NU
25 FZ(1,J) = DUM(J)
   DO 30 I = 2,4
      TZ = T1 + A(I-1)*H
   30 DO 35 J = 1,NU
      UZ(J) = U(J) + A(I-1)*H*FZ(I-1,J)
   35 DUM(J) = FZ(1,J)
      IF(JOPT.EQ.2) GO TO 40
   CALL RK2DIF(TZ,UZ,DUM)
   GO TO 45
40 CALL RK2DIF(TZ,UZ,DUM)

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**FSCSM SUBROUTINES**

```fortran
45 DO 50 J=1,NU
50 FZ(I,J) = DUM(J)
30 CONTINUE
   DO 55 J=1,NU
55 U(J) = U(J)+HEM(FZ(1,J)+2*(FZ(2,J)+FZ(3,J))+FZ(4,J))/6.0
   GO TO (60,65),JOPT
60 CALL RKTDIF(TZ,U,DUM)
   GO TO 70
65 CALL RKZDIF(TZ,U,DUM)
70 IF(IP.EQ.0) GG TO 75
   PR = WC*U(5)-U(1)*DUM(4)
   PI = -WL*U(4)-U(1)*DUM(5)
   PMAG = DSQRT(PR*PR+PI*PI)
   PARG = DATAN(PI/PR)
   WRITE(6,1000) TZ,PMAG,PARG
1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
75 RETURN
END
```
SUBROUTINE RKZDIF(P,G,GP)

ROUTINE FOR SUBPROGRAM NOZADM
PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY
REF. NASA CR-121129

IMPLICIT REAL*8(A-H,O-Z)
COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,W,C,IP
1 /X3/Z1R,Z1I
DIMENSION G(5), GP(5)
U = G(1)
ZR = G(2)
Z1 = G(3)
PHIR = G(4)
PHII = G(5)
IF(P) 15,10,15
10 GP(1) = 4/(((GAM+1)*((RCT*RT)**0.5))
GP(2) = Z1R
GP(3) = Z1I
GP(4) = Z1R
GP(5) = Z1I
GO TO 20
15 C = 1-(GAM-1)*U*0.5
R = Q*(U/(2.*((GAM-1.)**(U**(-0.25)))*4.*0
16 FORMAT(3X,"PRINTING FROM CARD 5000",/3X,"ETC",/3X,"R=",F15.8)
1 IF(R.LT.RT) RT=4
2 IF(R.LT.RT) R1=RT
3 IF(R-1) 24,22,50
22 IF(R-11) 10,30,30
25 DR = -(((2*RCT*(R-RT)-(R-RT)*(R-RT)**0.5)/(RT+RCT-R)
30 IF(R-2) 35,40,40
FS CS M SUBROUTINES

35 DR = -DTAN(T)
GO TO 45

40 DR = ((C*RCC*(1-R)-(R-1)*(1-R)**0.5)/(1-R-RCC)

45 DU = -(U**U**75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U**5))

GO TO 55

GP(1) = DU*DR

GO TO 55

50 GP(1) = 0.0

55 A = U*(C-U)

BR = U*GP(1)/C

BI = 2*WC*U

CR = WC*WC-SVN*SVN*/(R*R)

CI = -(GAM-1)*WC*U*GP(1)*0.5*(1/C)

GP(2) = ((BR*ZR-BI*ZI-CR)/A)-ZR*ZR+ZI*ZI

GP(3) = ((BI*ZR+BR*ZI-CI)/A)-2*ZR*ZI

GP(4) = ZR*PHI*ZI*PHII

GP(5) = ZR*PHII+ZI*PHIR

20 RETURN
END
SUBROUTINE SOLWV(KWHERE)

SUBPROGRAM SOLVES FOR THE COMPLEX FREQUENCY BASED ON THE
UPSTREAM AND DOWNSTREAM NOZZLE ADMITTANCE
PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975

WHEN ISCNT = 1, 4, OR 5 THIS PROGRAM COMPUTES CNOZA-NOZA FOR A
GIVEN OMEGA. WHEN ISCNT = 1 OR 4, THIS ROUTINE ALSO FINDS
IMAG(OMEGA) THAT MINIMIZES CNOZA-NOZA KEEPING REAL(OMEGA) CONSTANT.

FURTHER, WHEN ISCNT = 1 OR 4, TESTING IS PERFORMED TO DETERMINE
IF A ROOT IS NEARBY.

COMPLEX OMEGA, P, KHO, V, MR, T, CNOZA, VXO,
1 NOZA, OMEGA,
2 DOM, Z1, Z2, Z3, FN, NOZAMR, GN,
3 CNOZU, NUZU, FN0, GNO, OMEGUS

COMMON /COMCHM/ P(100), KHO(100), V(100), MR(100), T(100),
1 VXO, OMEGA, CNOZA, DELP

COMMON /FZERO/ NOZA, NOZAMR, GN, FN, FNR, FNI, HN, ISCNT, ISLP

EXTERNAL XIMAGF

DATA PI/3.141593/

COMMON /SOLVE/ FREQ, DELFREQ, DELMX, EPSF, EPSX, EPSFS, EPSXS,
1 FROMAX, CTST, IPASS, KNTR, ISTR1, KSCNT4, IWSKP,
2 KNMX, KNTRMX, KNTRMX

APPENDIX C- 81
FS CSM SUBROUTINES

\[ X1 = \text{AIMAG}(\Omega) \]

\[ \text{XIMAGF COMPUTES FNR*(0,1)*FNI=CN0ZA-NOZA, HN=CNABS(CNOZA-NOZA).} \]

\[ \text{WHEN ISCNT = 1 OR 4 AND ISLP = 1, XIMAGF=D(HN**2)/D(\text{IMAG}(\Omega))} \]

\[ \text{F1 = XIMAGF(X1)} \]

\[ \text{H1 = HN} \]

\[ \text{IF(1PASS.EQ.0) GO TO 225} \]

\[ \text{WHEN ISCNT = 5, BYPASS MINIMIZATION OF CNABS(CNOZA-NOZA) W.R.T.} \]

\[ \text{IMAG(\Omega) AND COMPUTATION OF JACOBIAN OF FNR,FNI W.R.T. OMEGA.} \]

\[ \text{IF(ISCNT.EQ.5) GO TO 195} \]

\[ \text{IF ISLP=0, THEN (CNOZA-NOZA) AT OMEGA + DELTA REAL(\Omega) HAS} \]

\[ \text{JUST BEEN COMPUTED IN XIMAGF. GO TO 146 TO FINISH COMPUTATION} \]

\[ \text{OF JACOBIAN AND THEN COMPUTE FT=TEST2.} \]

\[ \text{IF(ISLP.EQ.0) GO TO 146} \]

\[ \text{ISLP EQUALS 1, PROCEED TO MINIMIZE CNABS(CNOZA-NOZA) W.R.T.} \]

\[ \text{IMAG(\Omega). THIS IS DONE UP TO STATEMENT 145.} \]

\[ \text{KNT = 0} \]

\[ \text{X2 = X1 - HN/(2*F1)} \]

\[ \text{X2 = AMIN1(X1+DELMX,AMAX1(X1-DELMX,X2))} \]

\[ \text{110 F2 = XIMAGF(X2)} \]

\[ \text{H2 = HN} \]

\[ \text{AF = AMAX1(.01,CNABS(NOZA))} \]

\[ \text{IF F1 AND F2 HAVE OPPOSITE SIGNS, THEN MIN POINT HAS BEEN CROSSED} \]

\[ \text{TRANSFER TO 125 FOR CONVERGENCE TESTS.} \]
115 IF(F1*F2.LE.0.) GO TO 125
C USE TIGHTENED CRITERIA TO CHECK TO SEE IF CONVERGENCE HAS BEEN
C REACHED WITHOUT CHANGING SIGN.
C IF(ABS(F2/AF).LE.EPSFS.AND.ABS((X1-X2)/AMAX1(X1,X2)).LE.EPSXS
 1 ANU.H2.LE.H1) GO TO 145
  IER = 0
IF(IABS(IWSKP).GE.2) WRITE(6,8490) KNT,IER,X1,X2,F1,F2,OMEGA,
 1 FN,GN,HN
8490 FORMAT(215,1PE13.5/2X,3(1PE13.5,':','1PE12.5),1PE15.5)
IF(H2.LT.H1) GO TO 117
C LAST STEP TOO LARGE. CUT GUESS IN HALF.
C X2 = (X1+X2)/2.
GO TO 116
117 IF(X1.LT.X2.AND.F1.LT.F2) GO TO 120
IF(X1.GT.X2.AND.F2.LT.F1) GO TO 120
C ESTIMATE NEXT GUESS BY TRYING TO HALVE THE ERROR.
C X3 = X2 - HN**2/(2.*F2)
  IERK = -16
118 KNT = KNT+1
I IF(KNT.GT.KNTMX) GO TO 140
X3 = AMIN1(X2+DELMX,AMAX1(X2-DELMX,X3))
X1 = X2
F1 = F2
X2 = X3
GO TO 116
C ESTIMATE NEXT GUESS USING FALSE POSITION.
FSM Subroutines

C
120 X3 = (F2*X1-F1*X2)/(F2-F1)
GO TO 118
125 FANS = F2
AN = AIMAG(OMEGA)
135 IF(ABS(FANS)/AF.LE.EPSF.AND.ABS((X1-X2)/Amax1(1.,AN))).LE.
1 1, EPSX) GO TO 145
IF(X1.LT.X2) GO TO 137
X3 = X2
F3 = F2
X2 = X1
F2 = F1
X1 = X3
F1 = F3
137 X = 0
C
CALL ZER0(XIMAGF,X1,X2,F1,F2,ANS,FANS,EPSF,EPSX,AF,KNT,KNTMX,IER,IKC)
140 IF(IER.EQ.0) GO TO 145
140 WRITE(6,8601) X1,F1,X2,F2,X3,F3,ANS,FANS,KNT,IER,OMEGA
8601 FORMAT(\"*** UNABLE TO FIND ROOT FOR IMAG PART OF F \"
1 \" X1,F1,X2,F2,X3,F3,ANS,FANS,KNT,IER,OMEGA = \"
2 \" 3X,1PE13.5/3X,2I10/3X,1PE13.5,\" : \",1PE13.5)"
GO TO 5000
C
(CNOZA-NOZA) HAS BEEN MINIMIZED W.R.T. IMAG(OMEGA). SAVE VALUES
FOR COMPUTATION OF DERIVATIVES W.R.T. REAL(OMEGA).
C
145 CNOZA = CNOZA
NOZA = NOZA
FS CST M SUBROUTINES

FR3 = FNR
F13 = FNI
XR3 = REAL(OMEGA)
X13 = AIMAG(OMEGA)
FNO = FN
HNO = HN
GNU = GN
OMEGA = OMEGA
DFRDY = REAL(GN)
DFIDY = AIMAG(GN)
DM = AMAX1(0.01, .001*REAL(OMEGA))
ISLP = C
OMEGA = OMEGA+DM
FREQ = REAL(OMEGA)/(2.*PI)
GO TO 15

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C

COMPUTE DERIVATIVES, FTEST2 (TEST FUNCTION), DET2 (DETERMINANT OF JACOBIAN), AND COND2 (CONDITION NUMBER OF JACOBIAN).

146 DFRDX = (FNR-FR3)/DM
DFDIX = (FNI-F13)/DM
OMEGA = OMEGA
FREQ = REAL(OMEGA)/(2.*PI)
CNOZA = CNOZO
NOZA = NOZO
FN = FNO
GN = GNU
HN = HNU
DET2 = UFRDX*DFIDY - DFAIX*DFRDY
FNR = FR3
FNI = F13
FTEST2 = 2.*(FNR*DFRDX + FNI*DFDIX)/DET2
FS CSM SUBROUTINES

AA1 = DFDRX**2+DFDRY**2
AA2 = DFIDX**2+DFIDY**2
AA3 = (DFDRX*DFIDX+DFDRY*DFIDY)**2
COND2 = (AA1+AA2+SQRT((AA1-AA2)**2+4*AA3))/2
1
COND2 = SQRT(COND2)
KNTR = KNTR + 1
1IF(AABS(IWSKP).GE.1) WRITE(6,8500) ISCNT,KNTR,KSCT4,OMEGA,CNOZA,
8500 FORMAT(315,3(1PE14.5,' ',1PE12.5)/X,1PE13.5)
1IF(AABS(IWSKP).GE.2) WRITE(6,8510) FN,DFDRX,DFIDX,DFDRY,DFIDY
8510 FORMAT(2X,1PE14.5,' ',1PE12.5,2X,1PE13.5)
IER = 0
IF(ISCNT.EQ.4) GO TO 183
IF(ISCTR.EQ.0) GO TO 150
IF(ISCNT.EQ.3) GO TO 17C
IER = -15
IScnt=1 AND ISTRF=1(NOT FIRST TIME THROUGH OR FIRST TIME THROUGH
AFTER A SINGULARITY IN THE JACOBIAN HAS BEEN CROSSED). TEST FOR
EXISTANCE OF ROOT IN CURRENT FREQUENCY RANGE (FREQ-DFLRQ,FREQ).
1IF(FTST2*FTST1.LE.0..AND.DET2*DET1.GT.0..AND.
1AMAX1(COND1,COND2).LE.CTEST) GO TO 160
IF(KNTR.GT.KNTRMX) GO TO 205
TRANSFER VALUES FROM 2 TO 1 AND 3 TO 2.
147 CONTINUE
F11 = F12
X11 = X12
FR1 = FR2
XR1 = XR2
FS CSM SUBROUTINES

150 FR2 = FR3
1 XR2 = XR3
F12 = F13
XL2 = X13
FTST1 = FTST2
COND1 = COND2
DET1 = DET2

C C IF ISCNT = 1, UPDATE FREQ BY DELFRO. IF ISCNT = 4, FREQ HAS
C ALREADY BEEN CHANGED BY METHOD OF FALSE POSITION.
C
C IF(ISCNT.EQ.4) GO TO 1G
ISTK1 = 1
FREQ = FREQ + DELFRO
GO TO 1C
160 IF(ISCNT.EQ.1) GO TO 18C
ISCNT = 3
170 IF(ABS(FR2/FR3)*ABS(XR3)/ABS(XR1) .LE. EPSFS .AND. ABS((XR3-XR1)/XR3) .LE. EPSXS) GO TO 220
1 IF(FR1*FR3.LE.0.) GO TO 175
FR1 = FR2
XR1 = XR3
GO TO 177
175 XR2 = XR3
FR2 = FR3
GO TO 177
177 XR3 = (FR2*XR1-FR1*XR2)/(FR2-FR1)
FREQ = XR3/(2.*PI)
GO TO 1G

C C TENTATIVE ROOT HAS BEEN BRACKETED. CONTINUE WITH ISCNT = 4 (I.E.
C FREQ WILL BE CHANGED BY FALSE POSITION) UNTIL EITHER IT IS
C DETERMINED THAT THE JACOBIAN IS SINGULAR OR THAT A ROOT IS
C ACTUALLY THERE. THE LATTER IS ASSUMED BY DEFAULT IF THREE

00001996
00002000
00002010
00002020
00002030
00002040
00002050
00002060
00002070
00002080
00002090
00002100
00002110
00002120
00002130
00002140
00002150
00002160
00002170
00002180
00002190
00002200
00002210
00002220
00002230
00002240
00002250
00002260
00002270
00002280
00002290
00002300
00002310
FSCEM SUBROUTINES

.iterations have been performed without the jacobian changing sign and the condition number remains less than CTEST and the error (CABS(OMEGA-X12)/CABS(OMEGA)) is less than 2.5*EPSF.

180 ISCNT = 4
IP = 0
OMEGSV = OMEGA
DET2S = DET2
FTSTZ2S = FTST2
CONDOZS = COND2
FR3S = FR3
XR3S = XR3
FI3S = FI3
XI3S = XI3
KSCNT4 = 0

181 FTST0 = FTST1
DETO = DET1
COND0 = COND1
IP = MAXO(IP,0) + 1

182 KSCNT4 = KSCNT4 + 1
XR4 = (FTST2*XR2-FTST1*XR3)/(FTST2-FTST1)
IF(IAABS(IP).LT.2) GO TO 1825
IP = .0
XR4 = (XR3+XR2)/2.

1825 CONTINUE
OMEGA = XR4 + (0.1.)*AIMAG(OMEGA)
FREQ = XR4/(2.*PI)
GO TO 147

183 KNTR = KNTR - 1
IF(COND2.GT.CTEST.OR.DET2*DET1.LE.0.) GO TO 184
IF(HN/CABS(NOA)).LE.EPSFS.AND.AMIN1(CABS(OMEGA-XR2-(0.,1.)*X12)
CABS(OMEGA-X11-(0.,1.)*X12)/CABS(OMEGA)).LE.EPSFS) GO TO 220
IF(HN/CABS(NOA)).LE.2.5*EPSF.AND.KSCNT4.GE.3) GO TO 185

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F S C S M SUBROUTINES

IF(KSCNT4.GT.10) GO TO 184
IF(FTST1*FTST2.LE.0.) GO TO 181
XR2 = XR1
XI2 = XI1
FR2 = FI1
DET1 = LET0
COND1 = COND0
FTST1 = FTST0
IP = MIN0(IP,C) - 1
GO TO 182

C
C  JACOBIAN IS SINGULAR NEAR THIS FREQUENCY. RETURN TO ISCNT=1
C  SEARCH METHOD WITH UPDATED FREQUENCY.

184 OMEGA = OMEGSV
DET2 = DET2S
F1S12 = FTS12S
FR3 = FR3S
XR3 = XR3S
COND2 = COND2S
F13 = F13S
XI3 = XI3S
FREQ = REAL(OMEGA)/(2.*PI)
FRQ = FREQ-DELFREQ
IF(KSCNT4.GT.10) WRITE(6,8450) FRQ,FREQ

8450 FORMAT(//"**** WARNING, POSSIBLE ROOT IN FREQUENCY RANGE: ",
       1 1PE15.6///"**** *************///)
KSCNT4 = 0
ISCNT = 1
GO TO 15C

C
C  ACTUAL ROOT HAS BEEN BRACKETED. USE 2-DIMENSIONAL SECANT METHOD
TO CONVERGE ON THIS ROOT (UP TO STATEMENT 205).

185 ISCNT = 5
KNTS = 0
190 DET = FR2*FI1- FR1*FI2- FR3*FI1+ FR1*FI3+ FR3*FI2- FI3*FR2
PIO = (FR2*FI1- FR1*FI2)/DE
PI1 = -(FR3*FI1- FR1*FI3)/DE
PI2 = (FR3*FI2- FR2*FI3)/DE
XI4 = PIO*XI3 + PI1*XI2 + PI2*XI1
XR4 = PIO*XRI3 + PI1*XR2 + PI2*XR1
OMEGA = OMEGA
OMEGA = XR4 + (C,1.)*XI4
DOM = OMEGA - OMEGA
SF = AMIN1(1.,50.)/ABS(DOM))
OMEGA = OMEGA + SF*DOM
XR4 = REAL(OMEGA)
XI4 = AIMAG(OMEGA)
FREQ = REAL(OMEGA)/(2.*PI)
GO TO 15
195 FR4 = FNIK
FI4 = FNI
KNTS = KNTS + 1
IF(IABS(IWSPK).GE.1) WRITE(6,8515) ISCNT,KNTS,OMEGA,CNOZA,NOZA,HN
8515 FORMAT(2I5,3(1PE14.5,99,1PE12.5),1PE14.5)
IF(IABS(IWSPK).GE.2) WRITE(6,8520) XR1,XI1,FR1,FI1,XR2,XI2,FR2,FI2,DOM
8520 FORMAT(2X,4(1PE14.5,99,1PE12.5)/2X,4(1PE14.5,99,1PE12.5)
Z1 = XR1 + (C,1.)*XI1
Z2 = XR2 + (C,1.)*XI2
Z3 = XR3 + (C,1.)*XI3
ADM = CABS(OMEGA)
C

TEST FOR CONVERGENCE ON ROOT.

IF(CABS(FN)/CABS(NOZA).LE.EPSFS.AND.AMIN1(CABS(OMEGA-Z1)/ADOM,
1   CABS(OMEGA-Z2)/ADOM,CABS(OMEGA-Z3)/ADOM).LE.EPSXS) GO TO 220
IER = -60
IF(KNTS.GT.KNTSMX) GO TO 205
IF(MOD(KNTS-1,6).LE.2) GO TO 200

TRANSFER VALUES 3 TO 2, 2 TO 1, AND REPLACE 3 WITH NEW GUESS.

XI1 = XI2
XR1 = XR2
FI1 = FI2
FR1 = FR2
XR2 = XR3
FR2 = FR3
FI2 = FI3
XI2 = XI3
XR3 = XR4
FR3 = FR4
FI3 = FI4
GO TO 190

REPLACE POINT WITH LARGEST ERROR WITH THE NEW GUESS.

200  AF1 = FR1**2 + FI1**2
     AF2 = FR2**2 + FI2**2
     AF3 = FR3**2 + FI3**2
     IF(AF1.LE.AF2) GO TO 202
     IF(AF3.GT.AF1) GO TO 203

201  XI1 = XI4

XR1 = XR4
F S C S M SUBROUTINES

F11 = F14
FR1 = FR4
GO TO 190
202 IF(AF3, GT, AF2) GO TO 203
X12 = X14
XR2 = XR4
F12 = F14
FR2 = FR4
GO TO 190
203 X13 = X14
XR3 = XR4
F13 = F14
FR3 = FR4
GO TO 190
205 WRITE(6, 8602) IER, KNTS, KNTR, ISCNT, XR1, XI1, FR1, FI1, XR2, X12, FR2, FI2
XR3, X13, FR3, F13, XR4, X14, FR4, F14
8602 FORMAT( XIV " **** EXCEED CONVERGENCE LIMIT ****/ "
1 XIV " IER, KNTS, KNTR, ISCNT = '4110' */ X,F FROM 1-4 = */ "
2 XIV " 3X,1PE15.5, ' : * ,1PE15.5,1PE18.5, * : * ,1PE15.5) "
GO TO 5000

C WHERE DETERMINES TRANSFER LOCATION IN CALLING PROGRAM
UPON RETURN.

10 WHERE = 1
GO TO 6000
15 WHERE = 2
GO TO 6000
220 WHERE = 3
GO TO 6000
225 WHERE = 4
GO TO 6000
5000 WHERE = 5
GO TO 6000
FSM SUBROUTINES

PRINT TITLES FOR STEADY STATE VARIABLES

IF(IPRST.GT.0) WRITE(6,10)
10 FORMAT(1H1,//,31X,"STEADY STATE SOLUTION",//,
       1 7X,"DISTANCE",
       3 6X,"DENSITY",7X,"PERCENT VAPORIZED",/,
       4 "(KANKINE)",4X,"(FT/5)",5X,"RATIO",5X,
       5 "(LBM/FT**3)",6X,"FUEL",3X,"OXIDIZER",/)

INJECTOR END GAS MIXTURE RATIO AND GAS DENSITY

MRBINJ = MuOX1/NBFU
IF(MGI.GT.0.0) GO TO 15
MRGI = MRBINJ*TAUBFU*VBFU/(TAUBOX*VBOX)
RHOGI = GAMC*PC*(MRGI+1.)/(GAMD-1.)/(MRGI*DELHOX+DELHFU)
       -MRGI*(1.+MRGI)*UDMR)
GO TO 16
15 RHOGI = MGI/(AINJ*VGI)
16 CONTINUE

MAIN DISTANCE DU LOOP

DO 30 I=1,NXP

VAPOORIZATION RATE PARAMETERS

PHICX = EXP(-(XM(1)-XO)/(TAUBOX*VBOX))
PHIFU = EXP(-(XM(1)-XO)/(TAUBFU*VBFU))

GAS MIXTURE RATIO, VELOCITY, DENSITY, TEMPERATURE, OXIDIZER
AND FUEL VAPORIZATION RATES
FS CSM SUBROUTINES

\[ \text{MRB}(I) = (\text{MRGI}/(1.0+\text{MRGI}))*\text{MGI}+\text{MBOXI}/(1.0+\text{MBOXI}) \]
\[ + \text{MFIN}/(1.0+\text{MFIN}) \]
\[ \text{AMDOT} = \text{MGI}+\text{MBOXI}/(1.0+\text{MBOXI})+\text{MFIN}/(1.0+\text{MFIN}) \]
\[ \text{VB}(I) = 1.0/(\text{GAMO}+\text{PC}*(\text{AI}))*(\text{GAMO}+\text{PC})*\text{MGI}/(\text{GAMO}+1.0) \]
\[ \text{RB}(I) = \text{AMDOT}/(\text{AI})*\text{VB}(I) \]
\[ \text{TB}(I) = \text{PC}/(\text{RHOB}(I))*\text{RGQ}*(1.0+\text{DRGMR})*\text{RGQ}*(\text{MRB}(I)-\text{MRB}(INJ)) \]
\[ \text{VAPBOX}(I) = \text{MBOXI}+\text{PHIOX}/(\text{TAUBOX}+\text{VBOX})/\text{AI} \]
\[ \text{VAPBFU}(I) = \text{MBFUI}+\text{PHIFU}/(\text{TAUBFU}+\text{VBFU})/\text{AI} \]

**DERIVATIVES WITH RESPECT TO DISTANCE**

\[ \text{DMRB}(I) = (\text{MRB}(I)+1.0)/(\text{RHOB}(I)^{0.5})*\text{VAPBFU}(I) \]
\[ \text{DV}(I) = -\text{VB}(I)/\text{AI}+\text{DA}(I)+(\text{GAMO}+1.0)/(\text{GAMO}+\text{PC})*\text{VAPBOX}(I) \]
\[ \text{DRHOB}(I) = -\text{RHOB}(I)^{-0.5} \]

**STEADY STATE PARAMETERS REQUIRED BY THE CHAMBER DYNAMICS**

\[ \text{SSV1}(I) = \text{VB}(I)/\text{CO} \]
\[ \text{SSV2}(I) = 2.0*\text{DELX}*(\text{GAMO}+1.0)/(\text{PC}+\text{CO}) \]
\[ \text{SSV3}(I) = \text{DELX}+\text{DV}(I)/\text{CO} \]
\[ \text{SSV4}(I) = \text{DELX}+\text{SSV1}(I)*(\text{DA}(I)+\text{DRHOB}(I))/\text{RHOB}(I)+\text{SSV3}(I) \]
\[ \text{SSV5}(I) = \text{DELX}+\text{DHH}(I)+(2.0*\text{MRB}(I)+1.0) \]
\[ \text{SSV6}(I) = \text{DELX}+\text{DHH}(I)*\text{MRB}(I) \]
\[ \text{SSV7}(I) = \text{DELX}+\text{GAMO}*(\text{SSV1}(I)+\text{DA}(I)+\text{DV}(I))/\text{CO} \]
\[ \text{SSV6}(I) = \text{DELX}+\text{GAMO}*(\text{DA}(I)+\text{AI}) \]
\[ \text{SSV9}(I) = \text{VAPBFU}(I)*\text{DHH} \]
FSCSM SUBROUTINES

SSV9FU(I) = VAPBFU(I)*DHDMR*MRB(I)
SSV10(I) = 2*DELX/(RHOB(I)*CO)
SSV11(I) = DELX*(DA(I)/A(I)+DRHOB(I)/RHCB(I))
SSV12(I) = 2.*PC/(RHOB(I)*CO*CO)
SSV13(I) = 2.*DELX*(MRB(I)+1.)/(RHOB(I)*CO)
SSV14(I) = DELX*SSV1(I)*DMRB(I)
SSV15(I) = DELX*(VAPBOX(I)-(2.*MRB(I)+1.)*VAPBFU(I))/
1. (RHOB(I)*CO)
1F(I.GT.1) SSV16(I-1) = ORGDMR*(RHOB(I-1)*TB(I-1)/PC+RHOB(I)*
1. TB(I)/PC)/2.

PRINTOUT OF STEADY STATE VARIABLES

IF(IPRSTE.LE.0) GO TO 30
PBOX = 100.*(1.-PHIOX)
PBFU = 100.*(1.-PHIFU)
XP = XM(I)/C.0254
TP = TB(I)*1.6
VP = VB(I)/0.3948
RHOB = PPHOB(I)/16.01846
WRITE(6,20) XP, TP, VP, MRB(I), RHOB,
1 PBFU, PBOX

30 CONTINUE

RETURN
END
FSCSM SUBROUTINES

SUBROUTINE TADAMS(N,H,X,Y,DY,IOZ,IO) 00000010
C
C ROUTINE FOR SUBPROGRAM NOZADM 00000020
C PROGRAM DEVELOPED BY GEORGIA INSTITUTE OF TECHNOLOGY 00000030
C REF. NASA CR-121129 00000040
C
IMPLICIT REAL*8(A-H,O-Z) 00000050
COMMON /X1/GAM,SVN,ANGLE,RCT,RCC /X2/T,RT,Q,R1,R2,WC,IP 00000060
COMMON /X4/CM 00000070
DIMENSION COR(5), DP(5), DY(5,4), PRED(5), Y(5), G(5), GP(5) 00000080
10 CONTINUE 00000090
DU 15 I=1,N 00000100
PRED(I) = Y(I)+H*(55.*DY(I,4)-59.*DY(I,3)+37.*DY(I,2)-9.*DY(I,1)) 00000110
1 /24.*H 00000120
15 CONTINUE 00000130
X = X+H 00000140
U = PRED(1) 00000150
TR = PRED(2) 00000160
TI = PRED(3) 00000170
PHIR = PRED(4) 00000180
PHII = PRED(5) 00000190
C = 1.-(GAM-1.)*U*0.5 00000200
R = Q*((C)**(-1./2./GAM-1.))/*(U**(-0.25))*4.0 00000210
16 FORMAT(3X,*PRINTING FROM CARD 2180*,/3X,*R=*,E15.8, 00000220
1 3X,*R1=*,E15.8,3X,*RT=*,E15.8) 00000230
IF(R-1.) 17,17,100 00000240
17 IF(R-RT) 20,25,25 00000250
20 DR = -(2.*RCT*(R-RT)-(R-RT)**.5)/(RT+RCT-R) 00000260
GO TO 40 00000270
25 IF(R-R2) 30,35,35 00000280
30 DR = -DTAN(T) 00000290
GO TO 40 00000300
35 DR = ((2.*RCC*(1.-R)-(1.-R)*(1.-R)**.5)/(1.-R-RCC)) 00000310
GO TO 40 00000320
100 H = H/2 00000330
FS CSM SUBROUTINES

40 DU = (-U**.75)*(C**((2.*GAM-1.)/(2.*((GAM-1.)))))/(Q*(I-1.-(GAM+1.))
    *U*5))
    DP(1) = UR*DU
    A = U*(C-U)
    BR = U*DP(1)/C
    BI = 2.*WC*U
    CR = WC*WC-(SVN*SVN*C)/(R*R)
    CI = -(GAM-1.)*WC*U*DP(1)*.5/C
    DP(2) = 1.*(-BR*TR+BI*TI+CR*(TR*TR-TI*T1)-2.*CI*TR*T1)/A
    DP(3) = (-BR*TI-BI*TR+CI*(TR*TR-TI*T1)+2.*CR*TR*T1)/A
    T2 = TR+TR+TI*TI
    DP(4) = (TR*PHIR-TI*PHII)/T2
    DP(5) = (TR*PHII+TI*PHIR)/T2
    DU 45 1=1*N

45 Y(1) = (251.*G0K(I)+19.*PRED(I))/270.
    U = Y(1)
    T1 = Y(3)
    PHIR = Y(4)
    PHII = Y(5)
    C = 1.*(-((AM-1.)*U/.5

52 DU 55 1=1*N

55 DY(I,1) = DY(I,2)
    DY(I,2) = DY(I,3)

60 K = Q*(C**(-1./I2.*((GAM-1.))))*(U**(-0.25)*)4.0

61 FORMAT(3X,*PRINTING FROM CARD 2570*,/3X,*R=*E15.8,
   1 3X,*K1=*,E15.8,3X,*RT=*,E15.8)
   IF(R-1.) 62,62,100
F S C S M SUBROUTINES

62 IF(R-R1) 65,70,70
65 DR = -(2*RCT*(R-RT)-(R-RT)*(R-RT)**.5)/(RT+RCT-R)
GO TO 85
70 IF(R-R2) 75,80,80
75 DR = -DTAN(T)
GO TO 85
80 DR = (2*RCC*(1.-R)-(1.-R)*(1.-R)**.5)/(1.-R-RCC)
85 DU = -(U**.75)*(C**((2.*CAM-1.)/(2.*GAM-1.)))/(Q*(1.-(GAM+1.))
1 *U*.5))
   DY(1,4) = DR*DU
   A = U*(C-U)
   BR = U*DY(1,4)/C
   BI = 2.*WC*U
   CR = WC*WC-{SVN*SVN*C}/(R*R)
   CI = -(GAM-1.)*WC*U*DY(1,4)*0.5/C
   DY(2,4) = 1.+(-BR*TR+BI*TI+CR*(TR*TR-TI*T1)-2.*CI*TR*TI)/A
   DY(3,4) = (-BR*TI-BI*TR+CI*(TR*TR-TI*T1)+2.*CR*TR*TI)/A
   DY(4,4) = (TR*PHIR-PHI1*TI)/T2
   DY(5,4) = (TR*PHII+PHIR*TI)/T2
   IF(IP.EQ.0) GO TO 87
   PR = WC*PHII-U*DY(4,4)
   PI = -WC*PHIR-U*DY(5,4)
   PMAG = (PR*PR+PI*PI)**.5
   PARG = DATAN(PI/PR)
   WRITE(6,1000) X,PMAG,PARG
87 GO TO 10
90 I02 = 2
   Y(2) = TR/T2
   Y(3) = -TI/T2
   TPR = DY(2,4)
   TPI = DY(3,4)
   DY(2,4) = -{(TPR*(TR*TR-TI*T1)+2.*TR*TI*TP1)/(T2*T2)}
   DY(3,4) = (2.*TPR*TR*TI-TPI*(TR*TR-TI*T1))/(T2*T2)
FS C S M SUBROUTINES

G(1) = U
G(2) = Y(2)
G(3) = Y(3)
G(4) = PHIR
G(5) = PHII
DY(1,1) = DY(1,4)
DY(2,1) = DY(2,4)
DY(3,1) = DY(3,4)
DY(4,1) = (PHIR*TR-PHI*TI)/T2
DY(5,1) = (PHII*TR-PHI*TI)/T2
DO 95 I=2,4
CALL RKTZ(5,H,X,G,GP,IQZ)
X = X+H
U = G(1)
ZR = G(2)
ZI = G(3)
PHIR = G(4)
PHII = G(5)
DY(1,1) = GP(1)
DY(2,1) = GP(2)
DY(3,1) = GP(3)
DY(4,1) = GP(4)
95 DY(5,1) = GP(5)
Y(1) = U
Y(2) = ZR
Y(3) = ZI
Y(4) = PHIR
Y(5) = PHII
IQ = 1
GO TO 105
100 IJ = 2
1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
105 RETURN
SUBROUTINE TDPLT(W,Y,NFP,TL,XR,LL)

ROUTINE TO GENERATE CRT PLOTS
PROGRAMMED BY J. K. HUNTING, ROCKETDYNE, MAY 1975

DIMENSION W(101),Y(101)
YMAX=Y(2)
YMIN=Y(2)
UMAX=3,NFP
YMAX=AMAX(YMAX,Y(J))
YMIN=AMINI(YMIN,Y(J))

100 CONTINUE
DY=AIN(T(2.0+(YMAX-YMIN)/10.0)
YT=DY*AINT(1.5+YMAX/DY)
YB=DY*AINT(YMIN/DY-1.5)
IF(W(2)/TL-1.01,01,01,5

5 XL=W(2)
I=1
GO TO 200

201 YMAX=AMAX(YMAX,Y(1))
YMIN=AMINI(YMIN,Y(1))
XL=TL
I=2

200 CONTINUE
K=0
L=0

10 L=L+1
IF(L.GT.9)GO TO 30
IF(10.0**K/TL.LE.1.0.AND.10.0**K/TL.GT.0.1)GO TO 20
IF(10.0**K/TL.GT.1.0)K=K-1
IF(10.0**K/TL.LE.0.1)K=K+1
GO TO 10

20 XL=10.0**K
FS CSM SUBROUTINES

30 K=0
   IF(LL-1) 31, 31, 60
31 CALL CAMRAV(9)
   IF(LL-1) 50, 50, 60
50 CALL SETMIV(40, 10, 24, 560)
   GO TO 61
60 CALL SETMIV(40, 10, 500, 70)
   CALL SMXYV(1, 0)
   CALL GRID1V(LL, XL, XR, Y8, YT, 1.0, DY, 1, 1, -1, -1, -2, -3)
180 GO TO (181, 182), I
181 CALL APLUTV(NFP-1, W(2), Y(2), 1, 1, 1, 44, IERR)
   GO TO 40
182 CALL APLUTV(NFP, W(1), Y(1), 1, 1, 1, 44, IERR)
   K=K+1
40 GO TO (180, 18C, 180, 190), K
190 IF(LL-1) 191, 191, 192
191 CALL LBLV(Y(1), 600, 470, 6, 2, 3)
   GO TO 193
192 CALL LBLV(Y(1), 600, 995, 6, 2, 3)
193 RETURN
   END
FUNCTION XIMAGF(XIMOMG)

ROUTINE TO COMPUTE NOZZLE ADM. DIFF AS FUNCTION OF
IMAGINARY PART OF OMEGA
PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975

COMPLEX OMEGA, NOZA, CNOZA, P, RHO, V, MR, T, VXO, FN, NOZAMR, GN,
1 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9,
2 COX10, COX11, COX12, COX13, COX14, COX15, COX16,
3 CFU1, CFU2, CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9,
4 CFU10, CFU11, CFU12, CFU13, CFU14, CFU15, CFU16
5 , DMLGO

REAL MBOXI, MBFU1, NUBOX, NUBFU, MGW

COMMON /COMGBM/ XBOX, XDIFF, MBFU1, MBOXI, MBFU1, TAUBOX, TAUBFU, VBOX,
1 VBFX, GAMO, RGO, DELHUX, DELHFX, PC, CO,
2 COX1, COX2, COX3, COX4, COX5, COX6, COX7, COX8, COX9, COX10,
3 COX11, COX12, COX13, COX14, COX15, COX16, CFU1, CFU2,
4 CFU3, CFU4, CFU5, CFU6, CFU7, CFU8, CFU9, CFU10, CFU11,
5 CFU12, CFU13, CFU14, CFU15, CFU16, MGW, XIMPFU, XIMPOX,
6 CS, DCSMR, DDMR, DRGDUR, ADVOX, ADDOX, TDRAGO, DELVOX,
7 NUBOX, DTOXDM, ADVFU, ADDFU, TDRAGF, DELVFU, NUBFU, DTFUDM

COMMON /FZERG/ NOZA, NOZAMR, GN, FN, FNR, FN1, HN, ISCNT, ISLP

COMMON /GUMCHM/ P(100), RHO(100), V(100), MR(100), T(100),
1 VXO, OMEGA, CNOZA, DELP

COMMON /COMARE/ NXP, X(100), XM(100), A(100), DA(100), DELX,
1 X0, XNOZ, AINJ

RECOMPUTE OMEGA USING NEW IMAGINARY PART.
FS CSM SUBROUTINES

C OMEGA = REAL(OMEGA) + (0.,1.)*XIMOMG
C IP = 0
C IF((ISCNT.NE.1.AND.ISCNT.NE.4).OR.ISLP.NE.1) GO TO 10
C SAVE OMEGA THEN ALTER IMAG PART BY 0.1 PERCENT TO COMPUTE DERIV.
C OMEGA = OMEGA
C DM = AMAX1(.01*AIMAG(OMEGA),1)
C OMEGA = OMEGA + (0.,1.)*DM
C CHAMDY COMPUTES UPSTREAM NOZZLE ADMITTANCE AND OSCILLATORY
C PROFILES.
C 10 CALL CHAMDY
C NOZA = NOZAMR*(1.-DCSOMR*MR(NXP)**2.*GAMO/(CS*P(NXP)*(GAMO-1.)))
C FN = (CNOZA - NOZA)
C IF(IP.EQ.0 .AND.((ISCNT.EQ.1.OR.ISCNT.EQ.4).AND.ISLP.EQ.1))
C 1 GO TO 20
C FNR = REAL(FN)
C FN1 = AIMAG(FN)
C HN = CABS(FN)
C XIMAGE = FN1
C IF IP EQUALS ZERO AT THIS POINT, THEN DERIVATIVES WERE NOT
C REQUIRED; HENCE, RETURN WITHOUT COMPUTING THEM.
C IF(IP.EQ.0) RETURN
C GO TO 30
C 20 IP = 1
C RESTORE OMEGA AND SAVE VALUES FOR COMPUTATION OF DERIVATIVES.
FS CSM SUBROUTINES

OMEGA = OMEGA
HND = CABS(FN)
GND = FN
GO TO 10

C
C
C

30 GND = (GND-FN)/DM
XIMAGF = (HND**2-HN**2)/DM
RETURN
END
FS CSM SUBROUTINES

SUBROUTINE ZADAMS(NH,X,Y,DY,IQZ)

COMMON /X1/GAM,SVN,ANGLE,RECT,RCC /X2/T,R7,Q,R1,R2,WC,IP
1 /X4/CM
10 CONTINUE
DO 15 I=1,N
PRED(I) = Y(I) + H*(55.*DY(I,4)-59.*DY(I,3)+37.*DY(I,2)-9.*DY(I,1))
1 /24.*C
15 CONTINUE
X = X+H
U = PRED(I)
ZI = PRED(3)
PHI = PRED(4)
PHII = PRED(5)
C = 1-(GAM-1)*U*0.5
C = 1-(GAM-1)*U*0.5
R = Q*((C)**(-1./(2.*(GAM-1.))))*(U**(-0.25))*4.*C
16 FORMAT(3X,*PRINTING FROM CARD 3430,*15.8)
1 3X,*R1=*,E15.8,3X,*RT=*,E15.8
IF(R-1) 17,17,160
17 IF(R>R1) 20,25,25
20 DR = -((2*RTC*(R-RT)-(R-RT)*(R-RT))**0.5)/(RT+RTC-R)
GO TO 40
25 IF(R>R2) 30,35,35
30 DK = -DTAN(T)
GO TO 40
35 DK = ((2*RCC*(1-R)-(1-R)*(1-R))**0.5)/(1-R-RCC)
FSKSM SUBROUTINES

40 DU = -(U**0.75)*(C**((2*GAM-1)/(2*(GAM-1))))/(Q*(1-(GAM+1)*U**0.5))
    DP(1) = DR*DU
    A = U*(C-U)
    BR = U*DP(1)/C
    BI = 2*WC*U
    CR = WC*WC-(SYN*SYN*C)/(R*R)
    CI = -(GAM-1)*WC*U*DP(1)/0.5/C
    DP(2) = ((BR*ZRIZIC)/A)-ZRIZI*ZI
    DP(3) = ((BI*ZRIZIC)/A)-2*ZRIZI
    DP(4) = ZRIZIC*ZI*PHII
    DP(5) = ZRIZIC*ZI*PHII
    DO 45 I=1,N
    COR(I) = Y(I)+H*(DY(I,2)-5.*DY(I,3)+19.*DY(I,4)+9.*DY(I,5))/24.0
    Y(I) = (251.*COR(I)+19.*PRED(I))/270.0
    U = Y(I)
    ZR = Y(5)
    ZI = Y(3)
    PHIR = Y(4)
    PHII = Y(5)
    C = 1-(GAM-1)*U**0.5
45  DO 55 I=1,N
    DY(I,1) = DY(I,2)
    DY(I,2) = DY(I,3)
55  DY(I,3) = DY(I,4)
    ZMAG = (ZRIZI*ZI)**0.5
    IF(ZMAG<10) 60,90,90
70  IF(ZMAG>10) 60,90,90
60  R = Q*(C)**(-1)/(2*(GAM-1)))*(U**(-0.25))*4.0
61  FORMAT(3X,*PRINTING FROM CARD 3790*,/13X,*RT=*,E15.8,
        1 3X,*R=*,E15.8)
    IF(R-1) 62,62,100
62  IF(R-1) 65,70,70
65  DR = -((-2*RCT*(R-RT)-(R-RT)*(R-RT))**0.5)/((R-RT)**)
    GO TO 65
FSCLS SUBROUTINES

70 IF(R-R2) 75,80
75 DR = -DTAN(T)
GO TO 85
80 DR = ((Z**2-RCC*(1-R)-(1-R)*(1-R)**0.5)/(1-R-RCC)
85 DU = -(U*(R.75)*C**(2*(GAM-1)/Z*(GAM-1)))/(Q*(1-(GAM+1)*U/2))
D Y1,4) = DR*DU
A = U*(C-U)
BR = U*DY1,4)/C
B1 = 2*WC*U
CR = WC*WC-(SVN*SVN*C)/{R*R}
CI = -(GAM-1)*WC/U*DY(1,4)*0.5/C
DY(2,4) = (BR*ZR-BI*ZI-CK)/A-ZR*ZR+ZI*ZI
DY(3,4) = (BI*ZR*BR*ZI-CI)/A-2.*ZR*ZI
DY(4,4) = ZR*PHIR-ZI*PHII
DY(5,4) = ZR*PHII+ZI*PHIR
IF(IP.EQ.0) GO TO 87
PR = WC*PHII-U*DY(4,4)
PI = -WC*PHIR-U*DY(5,4)
PMAG = (PR**PR+PI*PI)**0.5
PARG = DATAN(PI/PR)
WRITE(6,100C) X, PMAG, PARG
87 GO TO 10
90 IQZ = 1
Z2 = ZMAG*ZMAG
Y(2) = ZR/Z2
Y(3) = -ZI/Z2
ZPR = DY(2,4)
ZPI = DY(3,4)
DY(2,4) = -(ZPR*(ZR*ZI-ZI*ZI)**0.5)/Z2**Z2
DY(3,4) = (ZPR**ZPI*(ZR*ZI-ZI))/Z2**Z2
G(1) = U
G(2) = Y(2)
G(3) = Y(3)
FS CSM SUBROUTINES

G(4) = PHIR
G(5) = PHI II
DY(1,1) = DY(1,4)
DY(2,1) = DY(2,4)
DY(3,1) = DY(3,4)
DY(4,1) = PHIR*ZR-PHI I*ZI
DY(5,1) = PHI II*ZR+PHIR*ZI
DO 95 I=1,4
CALL 4K1Z(5,H,X,G,GP,IQZ)
X = X+H
U = G(1)
TR = G(2)
TI = G(3)
PHIR = G(4)
PHI II = G(5)
DY(1,1) = GP(1)
DY(2,1) = GP(2)
DY(3,1) = GP(3)
DY(4,1) = GP(4)
DY(5,1) = GP(5)
Y(1) = U
Y(2) = TR
Y(3) = TI
Y(4) = PHIR
Y(5) = PHI II
CALL TADAMS(N,H,X,Y,DY,IQZ,IQ)
GO TO (10,100),10
1000 FORMAT(46X,F6.4,1X,F10.5,3X,F10.5)
100 RETURN
END
SUBROUTINE ZERO(F1,T1I,T2I,F1I,F2I,ANS,FAN,S,EPF,EPX,AF,INCT,NCNT,IER,K)

ROUTINE TO FIND T S.T. F(T) = 0 WHERE F1(T1)*F(T2) <= 0
PROGRAMMED BY K. W. FERTIG, ROCKETDYNE, MAY 1975

F(X) = S4*F1(X)
INCT = 6
SN = 1.
T4 = 1.E+60
IER = 0
T1 = T1I
T2 = T2I
IF ( K.EQ. 0 ) GO TO 15
F1 = F(T1I)
F2 = F(T2I)
5 IF (F1*F2.LE.0.) GO TO 50

ROOT IS NOT BRACKETED.
10 IER = -1
RETURN
15 F1 = F1I
F2 = F2I
GO TO 5
50 SN = 1.
IF ( F2.LT.0. .OR. F1.GT. 0. ) SN=-1.
F1 = F1*SN
F2 = F2*SN

BEGIN ITERATION TO FIND ROOT. FIRST GUESS USES BISECTION.
220 T3 = (T1+T2)/2.
ICVT = ICNT + 1
IF ( ICNT .GT. NCNT) GO TO 500
F3 = F(T3)
T4OLD = T4

CONVERGENCE TEST FOR BISECTION GUESS.

IF(ABS((T1-T2)/T3).*LE.EPSX.AND.ABS(F3)/AF.LE.EPSF) GO TO 300
A = F1-2.*F3+F2
B = F2-F1
C = 2.*F3

TEST TO MAKE SURE MAXIMUM/MINIMUM OF PARABOLA FITTING T1,T2,T3
IS OUTSIDE THE INTERVAL (T1,T2). IF SO, UPDATE T USING PARABOLIC
INTERPOLATION.

IF ( ABS( 2.*A/B ) .GT. 0.9) GO TO 245
B4AC = B**2-4.*A*C
IF ( B4AC.LT. 0.) GO TO 600
B4AC = SQRT(B4AC)
IF ( ABS( A*C/B**2 ) .GT. EPS/100. ) GO TO 230
T4 = T3 + (T3-T1)*(-C/B -A*C**2/B**3)
GO TO 246

230 T4 =(1-B+B4AC)/(2.*A)*(T3-T1) + T3

MAKE SURE T4 IS COMPATIBLE WITH PREVIOUS VALUES; TEST FOR
CONVERGENCE AND THEN REPLACE T1,T2,F1, AND F2 APPROPRIATELY.

240 IF ( T4.LE.T3 .AND. T4.GE.T1 .AND. F3.GE. 0.) GO TO 250
IF ( T4.LE.T2 .AND. T4.GE.T3 .AND. F3.LE. 0.) GO TO 260

245 IF ( F3.LE. 0.) GO TO 270
T2 = T3
F2 = F3
FSM SUBROUTINES

250 F4 = F(T4)
IF((ABS((T4-T40LD)/T4)).LE.EPSX.AND.ABS(F4)/AF.LE.EPSF) GO TO 400
IF ( F4 .LT. 0.) GO TO 255
T2 = T4
F2 = F4
GO TO 220

255 T1 = T4
F1 = F4
T2 = T3
F2 = F3
GO TO 220

260 F4 = F(T4)
IF((ABS((T4-T40LD)/T4)).LE.EPSX.AND.ABS(F4)/AF.LE.EPSF) GO TO 400
IF ( F4 .GT. 0.) GO TO 265
T1 = T4
F1 = F4
GO TO 220

265 T1 = T3
F1 = F3
T2 = T4
F2 = F4
GO TO 220

270 T1 = T3
F1 = F3
GO TO 220

300 T4 = T3
F4 = F3

400 ANS = T4
FANS = F4
RETURN

500 IER = 1
RETURN
APPENDIX D

SAMPLE CASE INPUT
OME FEED SYSTEM COUPLED STABILITY IMPROVEMENT - 5L MARCH 31, 1972
2 1 4 3 1 3

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6K OMS ENGINE TECHNOLOGY DEVELOPMENT - T-1-5-0-9-8708/D-2
APPENDIX E

SAMPLE CASE OUTPUT
ANALYTICAL DESCRIPTION

FEED SYSTEM COUPLED

STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME: FSCSM, FIV VERSION, MAY 1975

DEVELOPED BY: M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKEFELLER DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF 91304

SPONSORED BY: NASA/LYNNON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77054
UNDER CONTRACT NASA-14315
FEED SYSTEM COUPLED STABILITY MODEL
ONE-STEP SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
6K OMS ENGINEERING TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1

INPHYD = 2  INPCOM = 1  INPNOZ = 3  ITAPH = 1  ITAPC = 2  ITAPN = 3
IPRHYD = 1  IPRCUM = 1  IPRNOZ = 1  IPRCHM = 1  IPRSTE = 1  NXP = 70

XO = 8.0000E+01  XNUZ = 7.7000E+00  RINJ = 4.1000E+00  GAMO = 1.2300E+00
CU = 3.9851E+03  DELP = 1.0000E-01

NRDCT = -1  IWRT = 0  IWSKP = 0  KNTMX = 50  KNTKMX = 100  KNTSMX = 20

OMEGAR = 1.9000E+02  OMEGAI = -1.0000E-01  FREQ = 4.0000E+02  DELFRO = 5.0000E+00
DELMX = 5.0000E+01  CTST = 7.5000E+01

EPSF = 1.0000E-02  EPSX = 1.0000E-02  EPSFS = 5.0000E-04  EPSXS = 5.0000E-04
PC = 7.1150E+01  MBUXI = 6.5730E+00  MBFU1 = 3.4030E+00

NFREQ = 20  FREQM = 1.5000E+02  FREQMX = 4.0000E+02

RCCX = 4.1100E+00  RCTX = 9.9300E-01  ANGLEX = 1.4550E+01  CRR = 1.9850E+04
THEORETICAL NOZZLE ADMITTANCES

MACH NUMBER = .31 SVN = 0.0  GAMMA = 1.730

NOZZLE ANGLE = 14.6  RADIUS OF CURVATURE: THROAT = 0.4930 ENTRANCE = 4.1100

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### FEED SYSTEM COUPLED STABILITY MODEL

**OME FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION**

**6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1**

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FEED SYSTEM COUPLED STABILITY MODEL
ONE FEED SYSTEM COUPLED STABILITY INVESTIGATION - MODEL VERIFICATION
6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #1

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ANALYTICAL DESCRIPTION

FEED SYSTEM COUPLED

STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME: FSCSM, FIV VERSION, MAY 1975

DEVELOPED BY: M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKETDYNE
DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF 91304

SPONSORED BY: NASA/LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058
UNDER CONTRACT NAS9-14314
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6K OMS ENGINE TECHNOLOGY PROGRAM - TEST NUMBER 12 - CASE #2

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DECREMENT = 0.09211

NOZZLE ADMITTANCE = 0.04465: 0.21491

FEED SYSTEM RESPONSE
OXIDIZER = -0.12902: 0.48896
FUEL = -0.01911: 0.20861
ANALYTICAL DESCRIPTION
FEED SYSTEM COUPLED
STABILITY MODEL

COMPUTER MODEL

PROGRAM NAME:  FSCSM, FIRST VERSION, MAY 1975

DEVELOPED BY:  M. D. SCHUMAN, J. K. HUNTING, AND K. W. FERTIG
ADVANCED PROGRAMS, ROCKETDYNE DIVISION OF ROCKWELL INTERNATIONAL
CANOGA PARK, CALIF  91304

SPONSORED BY:  NASA/LYNDON B. JOHNSON SPACE CENTER
HOUSTON, TEXAS 77058
UNDER CONTRACT NAS9-14315