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Briefing Notes on Propulsion Stability Codes ADMIT, NYQUIST, and SSFREQ

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Briefing Notes on
Propulsion Stability Codes
ADMIT, NYQUIST, and SSFREQ

W. C. Armstrong

March 1992

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1.0 Introduction

All the equations used by these codes, expect for an unequal pipe split, are developed in UAH-RI reports 5-32176 and 5-32441. These notes will not present all the equations used. There is a Users Manual available for each of these codes.

The piping in a liquid rocket can assume complex configurations due to multiple tanks, multiple engines, and structures that must be piped around. The capability to handle some of these complex configurations have been incorporated into the Low Frequency Code (ADMIT), the Nyquist Code (NYQUIST), and the Intermediate Frequency Code (SSFREQ). The capability to modify the input on line has been implemented.

The configurations allowed include multiple tanks, multiple engines, the splitting of a pipe into unequal segments going to different (or the same) engines. Straight pipes, bends, inline accumulators, tuned stubs, Helmholtz resonators, parallel resonators, and pumps are the types of piping that may be used.

The three codes require the computation of admittance looking toward the tank. Therefore, they all have a number of similar routines for reading in the tank, piping, and engine descriptions. They also have similar routines for computing the admittance looking toward the tank. ADMIT uses only one type of feedline, either a LOX or FUEL line. NYQUIST can use no feedlines, one feedline (either LOX or FUEL), or two feedlines (both LOX and FUEL). SSFREQ requires both feedlines to be present (LOX and FUEL).

The common features of the three codes are discussed first, with two sample runs described. Then each of the three codes are discussed along with the sample runs. Several on-line variations are suggested for the second sample run. Input descriptions and the input for the sample runs are given in the appendices.

Homework assignments for the codes are given in appendix III.

2.0 Common Features of the Codes

All three programs compute the admittance looking toward the tank and uses this admittance for other calculations. The tank, piping, and engine parameters are used in this calculation. The following types of piping may be used: straight sections, bends, inline accumulator or manifold, tuned stub, Helmholtz resonator, parallel resonator, pump. In addition, the pipe may be split into several pipes, either identical or different. If there is a split in the piping, an iteration is required to compute these impedances. Multiple tanks and engines may be used.

2.1 Sample Runs

The codes should be run from hard disk because the use temporary files which may exceed the free space on the floppy disk containing the codes. The codes are started by typing the name of the code (ADMIT, NYQUIST, or SSFREQ). After an introductory message, you are asked what units to use for frequency (rad/sec or Hertz). Then you are asked questions about the input files. If a split is present in the piping, a default value of 20 iterations is set. Then you are asked if you wish to change the number of iterations. If you are making some quick and dirty runs, lower the number; if making a final run, you may want to increase the number.

After the engine and piping files are read, questions about keyboard input or special files are asked. Where more than one value is requested, the input is in free format. That is, the values may be separated by spaces, commas, or carriage returns. For example, the following inputs give identical results:

```
Case #1.        1 40 40
Case #2.        1,40,40
Case #3.        1
                40
                40.
```

Note that real values may be given with or without a decimal point if it is an integral value. Be sure to include 0's in file input.

After the computations are complete, you are prompted for the graphical output desired. After a graph is made, the program waits for you to hit a carriage return <CR> before continuing. After the plots are finished, you are asked what you would like to do next, end, run a new case, or possibly run a new frequency range with the old data. At various points in the run you will be given a chance to modify data, rewind an input file, or bypass the current data. When a frequency range is asked for, if 0 0 0 is input the code will bypass that set of data.

Remember, graphics must have been run before running the application code to be able to dump the plots to the printer.

There are two sample runs included on the disks. The first is a complex configuration with two LOX and two FUEL tanks feeding three engines. One line splits into two unequal pipes going to two

different engines. The second tank feeds one engine. The second sample run is a straight pipe which will be used for the on-line variations.

The first sample run is to give the student a chance to run a complex problem. This problem will introduce the student to the code, keyboard input required, the graphs produced, and the time required to run a complex problem. The following table shows the run time (after keyboard input) on several computers for this problem. The 286 and 386 had co-processors.

Program	286/8 time / factor	386SX/16 time / factor	486/33 time / factor
ADMIT	133.03 / 26.14	32.41 / 6.37	5.09 / 1.00
NYQUIST	684.43 / 25.71	165.55 / 6.22	26.62 / 1.00
SSFREQ	1041.06 / 28.08	242.72 / 6.54	37.08 / 1.00

Where time is in seconds and factor is time divided by the 486/33 time. The runs made were for the following:

ADMIT
Hertz ENG.RLN & LOX.RLN
frequency range: 1,40,40
pipe sections: 5,9,10,4,5,7,7,7,4,3,3,4,3,3,4,3,4,3,4,
3,4,5,9,10,4,5,7,7,7,4,3,3,4,3,3,4,3,4

NYQUIST
Hertz ENG.RLN, LOX.RLN, & CONST.RLN (no fuel)
frequency range: 1,40,300

SSFREQ
Hertz ENG.RLN, LOX.RLN, FUEL.RLN, & IMODE.RLN
frequency range: 110,116,3
tau range: .0005,.0025,11

The second sample run is a simple configuration which is used to guide the student in on-line modification of data and the effects of certain variables on the output. Changes in geometry will be made in ADMIT and NYQUIST. The input unique to NYQUIST and SSFREQ will also be varied. When making variations, rewind those files not involved in the changes. This should help the student become familiar with the codes and also the effect of certain input on results.

3.0 Program ADMIT

Program ADMIT uses the impedance (reciprocal of admittance) looking toward the tank and also the impedance looking toward the engine in the calculation of the pressure transfer function. This is the only one of the programs which will plot the admittance looking toward the tank. The piping layout is plotted on the same graph as the admittance. Two other plots are available: a 3-D surface plot of the

pressure transfer function and a contour plot of the pressure transfer function. The plots may be in black and white or in the color of the user's choice.

3.1 Sample Runs

ADMIT displays the maximum number of frequencies and maximum number of (integration) points along the pipe. These values are a function of the amount of memory available for programs. If these values are too small for your problem, try getting rid of most of the TSR's loaded. This will probably require changing the AUTOEXEC.BAT and possibly the CONFIG.SYS files and restarting the computer.

The maximum number of points along a pipe is measured from a tank to an engine. For sample run # 1, there are three pipes: tank #1 to engine #1, tank #1 to engine #2, and tank #2 to engine #3. Each of these pipes may contain the maximum number of points. The number of points is the cumulative total of points en each section from the tank to engine. Thus, a split pipe has the same number of points from the tank to the split, but, may have a different number of points from the split to the engine.

The admittance calculation is not affected by the number of points along a pipe, only the pressure transfer function. Therefore, if you are only interested in the admittance, set the number of points for each pipe section to one. If you are interested in the pressure transfer function, use near the maximum. You may try to set the number of points of a section to the length of the section. If this gives too many points, try half that value. Keep reducing the number of points until the total is less than the maximum. Try to keep at least two points per pipe section.

Sample run #1 using files ENG.RLN and LOX.RLN

Run a frequency range of 1 40 40. Make admittance plots of the three lines. Change colors of the plot. Then make surface plots trying the various options. Likewise, do contour plots of the lines. End the session.

Sample run #2 using files CLASS.ENG and CLASS.LOX

Start program by typing ADMIT and specifying Hertz. Remember to make the input files CLASS.ENG and CLASS.LOX. Again make the frequency range 1 40 40. This time, simply make the number of pipe segments equal to the length of the pipe (e.g. the first pipe is 20 feet long, therefore break it into 20 segments). Now look at the results.

3.2 On-line Variations

After looking at the results, change the piping for variation 1 as follows:

section 1	leave as is
section 2	leave as is

section 3	leave as is
section 4	leave as is
section 5	change to st. section 50 ft. long & 1 ft. diameter
section 6	leave as is
section 7	leave as is
section 8	leave as is
section 9	leave as is

After looking at the results, change the piping for variation 2 as follows:

section 1	leave as is
section 2	leave as is
section 3	leave as is
section 4	leave as is
section 5	change to st. section 30 ft. long & 2 ft. diameter
section 6	leave as is
section 7	leave as is
section 8	leave as is
section 9	leave as is

After looking at the results, change the piping for variation 3 as follows:

section 1	leave as is
section 2	change to a -90 deg. bend with 1.16245 ft. radius, 1 ft. diameter, and 0 ft. length beyond bend
section 3	leave as is
section 4	change to a 90 deg. bend with 1.16245 ft. radius, 1 ft. diameter, and 0 ft. length beyond bend
section 5	change to st. section 30 ft. long & 1 ft. diameter
section 6	change to a 90 deg. bend with 1.16245 ft. radius, 1 ft. diameter, and 0 ft. length beyond bend
section 7	leave as is
section 8	change to a -90 deg. bend with 1.16245 ft. radius, 1 ft. diameter, and 0 ft. length beyond bend
section 9	leave as is

Now look at the results. Note that the admittance curve changed with the first two variations, but changed very little with the addition of the bends (that kept the length and diameter of the piping the same as the straight pipe). The pressure transfer function changed considerably for all the three variations. If the admittance is relatively unchanged, the Nyquist and n-τ plots are unchanged.

4.0 Program NYQUIST

The Nyquist program can use the admittances Gox and Gf. The code was written to plot the Nyquist curves for the four cases: neither admittance used, Gox only, Gf only, and both admittances used. Three types of plots are available: the piping layout if either or both of the lines are present, Nyquist curve in the complex plane, and the phase-gain plots of the Nyquist equation.

In addition to the Nyquist plots of these four equations, Phase-Gain plots are also available.

4.1 Sample Runs

Sample run #1 using files ENG.RLN, LOX.RLN, and CONST.RLN

Run with only the LOX data with a frequency range of 1 40 300. Plot the three LOX lines. After computations are complete, try the plots available. When through looking at the curves, exit the program.

Sample run #2 using files CLASS.ENG, CLASS.LOX, and CLASS.CON

Again run only the LOX data with a frequency range of 1 40 300. When finished, make the following variations.

4.2 On-line Variations

For variations, make the same changes as for ADMIT (change length, diameter, and add bends. Then, change the transport lag (TAUT) by a factor of two.

5.0 Program SSFREQ

Program SSFREQ works in the intermediate frequency range where the piping, engine, and nozzle all interact. The program computes n (pressure interaction index) for a range of frequencies and a range of τ's (sensitive time lag). After the range of τ's for a given frequency have been run and the n's displayed on the screen, the user may request a plot of n vs τ for that frequency. After the range of frequencies have been run, n vs τ is plotted for all frequencies on one graph.

5.1 Sample Runs

Sample run #1 using files ENG.RLN, FUEL.RLN, LOX.RLN, and IMODE.RLN

For this run, you may enter the frequency range (110 116 3) and the tau range (.0005 .0025 11) or read them in with files IMODE.FRQ and IMODE.TAU. After each set of taus for a frequency is computed, you may wish to see the n-τ curve for that frequency. Simply enter y to see the curve or no to bypass the plot. After the complete frequency range is computed, a composite plot with all frequencies is presented for each engine.

Sample run #2 using files CLASS.ENG, CLASS.FUL, CLASS.LOX, and CLASS.IMO

Start as for sample run #1 except change all the input files to those starting with CLASS. After looking at the results, begin the changes.

5.2 On-line Variations

SSFREQ does not allow changes to the piping. However, the data unique to SSFREQ may be changed. Try the following variations:
1. increase diameter (CDIAM) by 20%
2. increase length (XLCD) by 10%
3. increase liquid velocity (ULOD) by 20%

6.0 Equations

6.1 Piping Equations

In the following equations, n = s/a.

1. Bend - The effective straight pipe length and diameter are computed using the equations on page II-4 of report UAH 5-32176 (curves on page II-II have been curve fit). The straight pipe equations are then applied to the effective length and diameter.

2. Straight Pipe

$$Z_t(I) = Z_0(I)\cdot\left[\frac{Z_t(I-1) + Z_0(I)\cdot\tanh(n\cdot l)}{Z_0(I) + Z_t(I-1)\cdot\tanh(n\cdot l)}\right]$$

$$Z_g(I) = \{e^{n\cdot l_1}\cdot[Z_0(I+1) + Z_g(I+1)]\cdot(1 - N\cdot M\cdot e^{-2\cdot n\cdot l}) - Z_0(I+1)\cdot(1 - N\cdot e^{-2\cdot n\cdot l}\cdot e^{2\cdot n\cdot l_1})\}/(1 + N\cdot e^{-2\cdot n\cdot l}\cdot e^{2\cdot n\cdot l_1})$$

where $N = [Z_0(I+1) - Z_t(I-1)]/[Z_0(I+1) + Z_t(I-1)]$

$M = [Z_0(I+1) - Z_g(I+1)]/[Z_0(I+1) + Z_g(I+1)]$

$l = L(I) + L(I+1)$

$l_1 = L(I+1)$

3. Inline Accumulator

$Z_e = 1/(C\cdot s)$

$Z_t(I) = Z_e\cdot Z_t(I-1)/[Z_t(I-1) + Z_e]$

$Z_g(I) = Z_e\cdot Z_g(I+1)/[Z_g(I+1) + Z_e]$

4. Tuned Stub

$Z_e = Z_0/\tanh(n\cdot l)$

$Z_t(I) = Z_e\cdot Z_t(I-1)/[Z_t(I-1) + Z_e]$

$Z_g(I) = Z_e\cdot Z_g(I+1)/[Z_g(I+1) + Z_e]$

5. Helmholtz Resonator

$$Z_e = (1 + L \cdot C \cdot s^2)/(C \cdot s)$$

$$Z_t(I) = Z_e \cdot Z_t(I-1)/[Z_t(I-1)+Z_e]$$

$$Z_g(I) = Z_e \cdot Z_g(I+1)/[Z_g(I+1)+Z_e]$$

6. Parallel Resonator

$$Z_e = L \cdot s/(1 + L \cdot C \cdot s^2)$$

$$Z_t(I) = Z_t(I-1) + Z_e$$

$$Z_g(I) = Z_g(I+1) + Z_e$$

7. Pump

$$Z_p = \frac{\partial p}{\partial \mathring{m}}$$

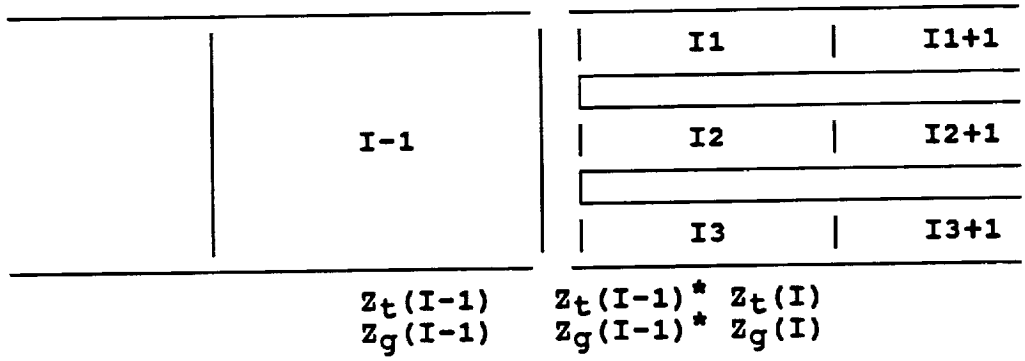
$$Z_t(I) = \{Z_t(I-1) + (Z_p + L \cdot s) \cdot [1 + Z_t(I-1) \cdot C \cdot s]\}/[1 + Z_t(I-1) \cdot C \cdot s]$$

$$Z_g(I) = [L \cdot s - Z_p + Z_g(I+1)]/\{1 + C \cdot s \cdot [L \cdot s - Z_p + Z_g(I+1)]\}$$

8. Split Pipe

The equations will be shown for a split into 3 unequal pipe segments.

Case I. Finding the impedance looking toward the tank (Z_t).

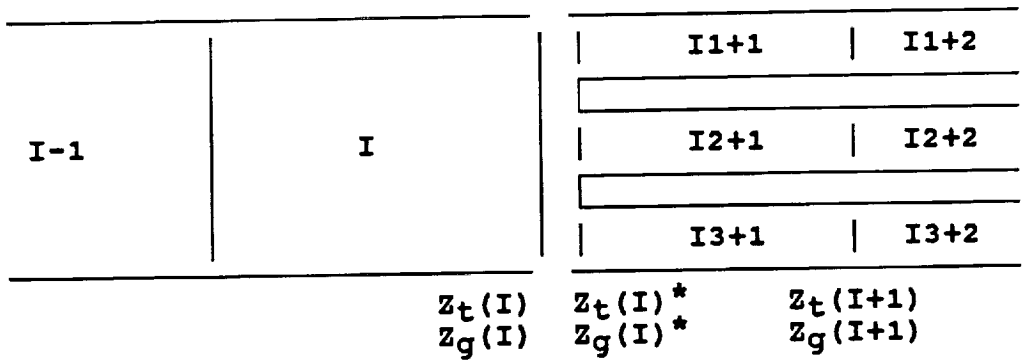


Section I1, looking toward the tank sees $Z_t(I-1)$ and (m-1) $Z_g(I-1)^*$'s in parallel. Therefore the effective $Z_e(I1)$ is

$$\frac{1}{Z_e(I1)} = \frac{1}{Z_g(I2-1)^*} + \frac{1}{Z_g(I3-1)^*} + \frac{1}{Z_t(I-1)}$$

This $Z_e(I1)$ is used in the equations developed for $Z_t(I1)$ instead of $Z_t(I-1)$.

Case II. Finding the impedance looking toward the engine (Z_g).



Section I, looking toward the engine sees m sections I+1 in parallel. Therefore the effective $Z_g(I)$ is a function of three pipes, Thus, compute Z_g^* for each pipe and then

$$\frac{1}{Z_g(I)} = \frac{1}{Z_g(I1)^*} + \frac{1}{Z_g(I2)^*} + \frac{1}{Z_g(I3)^*}$$

6.2 Pressure Transfer Function

The equation for the pressure at any point in a pipe is derived on page 25 of NASA Contractor Report 5-32176.

$$\frac{p(x,s)}{p_g(s)} = \left(\frac{Z_0}{Z_0 + Z_g}\right)\cdot\left[\frac{e^{-n\cdot x} - N\cdot e^{-n\cdot(2\cdot l - x)}}{1 - N\cdot M\cdot e^{-2\cdot n\cdot l}}\right]$$

where $n = s/a$

where $N = \dfrac{Z_0 - Z_t}{Z_0 + Z_t}$

$M = \dfrac{Z_0 - Z_g}{Z_0 + Z_g}$

6.3 Nyquist Equations

On page 47 of the report the following equation is derived

$$\frac{e^{-\tau\cdot s}}{(1+\Theta_c\cdot s)}\cdot\left\{\left[1 + \frac{(1+\bar{r})}{C^*}\cdot\left(\frac{\partial C^*}{\partial r}\right)\right]\cdot G_{ox} + \left[1 - \frac{\bar{r}\cdot(1+\bar{r})}{C^*}\cdot\left(\frac{\partial C^*}{\partial r}\right)\right]\cdot G_f\right\} = -1.$$

In order to simplify the notation, the following definitions are used:

$$K_1 = \frac{e^{-\tau \cdot s}}{(1+\Theta_c \cdot s)}$$

$$A_1 = [1 + \frac{(1 + \bar{r})}{c^*} \cdot (\frac{\partial c^*}{\partial r})]$$

$$A_2 = [1 - \frac{\bar{r} \cdot (1 + \bar{r})}{c^*} \cdot (\frac{\partial c^*}{\partial r})]$$

Thus, the equation may be expressed as $K_1 \cdot (A_1 \cdot G_{ox} + A_2 \cdot G_f) = -1$.

The equations used are

$K(j\omega) = 2 \cdot K_1$	neither admittance used,
$K(j\omega, G_{ox}) = K_1 \cdot A_1$	G_{ox} used,
$K(j\omega, G_f) = K_1 \cdot A_2$	G_f used,
$K(j\omega, G_{ox}, G_f) = K_1 \cdot (A_1 + A_2)$	both admittances used.

In addition to the Nyquist plots of these four equations, Phase-Gain plots are also available.

6.4 Intermediate Frequency Equations (n - τ)

The equations to analyze intermediate mode instabilities were developed in UAH report 5-32176. In some cases with long and laborious mathematics. The pertinent equations are presented as used by the code SSFREQ.

$$X_1 = (\gamma - 1)\bar{u}u_0 + (1 + \bar{r})(\overline{dh_L/dr})(\bar{M}/s)e^{-s\tau}T(G_{ox} - \bar{r}G_f)P_{00}$$

$$Y_1 = -\bar{u}p_0$$

$$Z_1 = (1/\gamma)\bar{u}p_0 + \bar{\rho}_L \circ u_L \circ$$

$$W_1 = 2\bar{u}u_0$$

$$M_1 = \bar{M}\{e^{-s\tau}T[K(s) + H(s)]P_{00} - P(s)p_0\}$$

$$p_0 = P_{00} \cosh(sx)$$

$$u_0 = -(1/\gamma)P_{00} \sinh(sx)$$

$$u_1 = Y_1 + \int_0^x \{[s(W_1 - X_1) + M_1]\cosh[s(x - x')]$$

$$+ s(Y_1 + Z_1)\sinh[s(x - x')]\}dx'$$

$$p_1/\gamma = -W_1 - \int_0^x \{[s(W_1 - X_1) + M_1]\sinh[s(x - x')]$$

$$+ s(Y_1 + Z_1)\cosh[s(x - x')]\}dx'$$

$$u'(L_c) + A\,p'(L_c) + C\,\sigma'(L_c) = 0$$

$$\sigma' = \sigma_0 + \sigma_1 = -(1/\bar{u})\int_0^x \{((\gamma - 1)/\gamma)p_0 + (1 + \bar{r})(\overline{dh_L/dr})(G_{ox}$$

$$- \bar{r}G_f)P_{00}e^{-s\tau_T}\}\bar{M}\,\exp[-s\int_{x'}^x (1/\bar{u})dx'']dx'$$

where $u' = u_0 + u_1$ and $p' = p_0 + p_1$.

$$H(s) = (1 + \bar{r})[(\bar{r}/\bar{c}^*)(\partial c^*/\partial r) - n_r s\bar{\tau}](G_{ox} - \bar{r}G_f)/\bar{r}$$

$$K(s) = (1 + s\tau_T)(G_{ox} + G_f)$$

$$P(s) = n(1 - e^{s\tau})$$

For small perturbations, A and C may be approximated by

$A \approx M(\gamma - 1)/(2\gamma)$ where M is Mach number at intersection of the chamber and nozzle

$C \approx 0$

6.5 Nomenclature

a - speed of sound	ft/sec
A - nozzle pressure admittance coefficient	
C - capacitance	sec
C* - characteristic velocity	ft/sec
C - nozzle entropy admittance coefficient	
G - admittance	
h - enthalpy	(ft/sec)^2
H - combustion response function for mixture ratio oscillations	
K - combustion response function for mass flow oscillations	
l - length	ft
L - length	ft
L - inductance	sec
$\mathring{m}$ - mass flow	lbm/sec
M - combustion response	
M - Mach number	
n - pressure interaction index	
n_r - mixture ratio interaction index	
p - pressure	lbf/ft^2
P_{00} - maximum overpressure	lbf/ft^2
P - combustion response function for pressure	
r - mixture ratio	
s - complex frequency	1/sec
u - velocity	ft/sec
x - distance along pipe	ft
Z - impedance	
γ - ratio of specific heats	
Θ - characteristic time constant	sec
ρ - density	lbm/ft^3
σ - entropy	
τ - time lag	sec

Subscripts

c - chamber
e - effective
f - fuel
g - looking toward engine
g - generator
L - liquid
ox - oxidizer
p - pump
t - looking toward tank
T - total
0 - lossless line
0 - first element of expansion
1 - second term of expansion

Superscripts

* - seen by split
' - perturbation value
° - value at ejector face

7.0 Summary

Three codes for the PC have been written using the admittance looking from the engine toward the tank. Because of the complexity of the codes, they should be run on a 386 with co-processor or more powerful PC. They will all work on most any graphics monitor (monochrome, CGA, EGA, or VGA). The colors of most of the graphs may be set by the user. If the DOS graphics TSR has been run (i.e. typing GRAPHICS at the DOS prompt), the graphs may be sent to a printer by hitting the PrtSc key.

ADMIT computes the pressure transfer function. The admittance curve, pressure transfer function surface plot (3-D), and contour plot may made. Colors may be specified for each of the plots separately. The surface plot allows the user to change view angle, type of plot (wire frame or solid), and color. Input data may be modified at the keyboard.

NYQUIST solves the Nyquist equation for no lines, FUEL line only, LOX line only, and/or FUEL and LOX lines. Nyquist plots or phase-gain plots may be made for any condition run. Also, a plot of the lines available may be made on request.

SSFREQ solves the intermediate frequency equations to generate a n-τ curve. This code couples the lines, chamber, and nozzle to obtain the effect in the intermediate frequency range.

All of the codes were written in Microsoft FORTRAN 5.0. ADMIT and SSFREQ used GRAFMATIC plot routines by Microcompatibles, Inc. The plot routines in FORTRAN 5.0 was used in NYQUIST.

Appendix I

I.1 Common Input

Description of file ENG.RLN

```
Card # 1
   MENG        - number of engines
 Card # 2
    TFLOW(I)    - total flow in engine                    lbm/sec
    PCHAMB(I)   - chamber pressure                        lbf/ft^2
    DPROR(I)    - pressure drop across orifice            lbf/ft^2
 Read card # 2 "number of engines" times
```

Description of files LOX.RLN or FUEL.RLN

```
Card # 1
   TITL        - LOX or FUEL title
Card # 2
   MTANK       - number of tanks
 Card # 3
    VOL(I)      - volume                                  ft^3
    LFLOW(I)    - mass flow                               lbm/sec
    KTANK(I)    - bulk modulus                            lbf/ft^2
    DENS(I)     - density                                 lbm/ft^3
 Read card # 3 "number of tanks" times
Card # 4
   MLINE       - number of lines leaving tank
 Card # 5
    ITANK(I)    - tank number
    IENG(I)     - engine number (0 if split follows)
 Card # 6
    SEGMN(I)    - number of segments
    SPLIT(I)    - number of unique splits
  Card # 7
     SECTN(I,M) - section type
     PIPE1(I,M) - radius                                  ft
                  length                                  ft
                or volume                                 ft^3
     PIPE2(I,M) - angle                                   deg
                  diameter                                ft
                or bulk modulus                           lbf/ft^2
     PIPE3(I,M) - diameter                                ft
                  volume                                  ft^3
                  dp/dm
                or 0.0
     PIPE4(I,M) - end length                              ft
                  L                                       sec
                or 0.0
     PIPE5(I,M) - C                                       sec
                or 0.0
   Read card # 7 "number of segments" times
```

```
if split > 0
  Card # 8
     SEGMN(I)    - number of segments
     NOLINE(I)   - number of identical lines
     IENG(I)     - engine number
   Card # 9
      SECTN(I,M) - section type
      PIPE1(I,M) - radius                                    ft
                   length                                    ft
                or volume                                    ft^3
      PIPE2(I,M) - angle                                     deg
                   diameter                                  ft
                or bulk modulus                              lbf/ft^2
      PIPE3(I,M) - diameter                                  ft
                   volume                                    ft^3
                   dp/dm
                or 0.0
      PIPE4(I,M) - end length                                ft
                   L                                         sec
                or 0.0
      PIPE5(I,M) - C                                         sec
                or 0.0
   Read card # 9 "number of segments" times
  Read card # 8-9 "number of splits" times
 Read card # 5-9 "number of lines" times
```

type	name	PIPE1	PIPE2	PIPE3	PIPE4	PIPE5
0	bend	radius	angle	diameter	end len.	0.0
1	straight	length	diameter	0.0	0.0	0.0
2	inline	length	diameter	0.0	0.0	0.0
3	tuned	length	diameter	0.0	0.0	0.0
4	Helmholtz	length	diameter	volume	0.0	0.0
5	parallel	length	diameter	volume	0.0	0.0
6	pump	length	diameter	$\dot{dp/dm}$	L	C
7	manifold	volume	bulk mod.	0.0	0.0	0.0

Dimensions:

radius, length, diameter, end length	ft
angle	deg
volume	ft^3
$\dot{dp/dm}$ (non-dimensionalized by $\dot{m}/p_c$)	
L	sec
C	sec
bulk modulus	lbf/ft^2

I.2 Input Unique to NYQUIST

Description of file CONST.RLN

```
Card # 1
   TAUT(I)     - transport lag                                          sec
   CSTAR(I)    - characteristic velocity (Pc·At/m̊)                      ft/sec
   RBAR(I)     - mixture ratio
   THETAC(I)   - characteristic time constant (ρc·Vc/m̊)                 sec
   DCDR(I)     - dc*/dr                                                 ft/sec
Read card # 1 "number of engines" times
```

I.3 Input Unique to SSFREQ

Description of file IMODE.RLN

```
Card # 1
   TITLF       - title of IMODE file
Card # 2
   NVAL        - number of x stations
 Card # 3
    XBARD(I)    - x location                                            ft
    PBAR(I)     - pressure                                              lbf/ft^2
    TBAR(I)     - temperature                                           °R
 Read card # 3 "number of x stations" times
Card # 4
   DTAUD       - invariant time lag                                     sec
   NRD         - mixture ratio interaction index
   LAMDAD      - damping part of frequency
Card # 5
   CDIAM       - chamber diameter                                       ft
   TDIAM       - throat diameter                                        ft
   XLCD        - length of combustion chamber                           ft
Card # 6
   GAMMAD      - ratio of specific heats
   RGAS        - gas constant                                           (ft/sec)^2/°R
   P00D        - maximum overpressure                                   lbf/ft^2
   RBADR       - mixture ratio
Card # 7
   DCSDRD      - dc*/dr                                                 ft/sec
   DHLDRD      - dh/dr                                                  (ft/sec)^2
   RHOLOD      - mass of liquid per unit chamber volume                 lbm/ft^3
   ULOD        - axial component of liquid velocity                     ft/sec
Read card # 2-7 "number of engines" times
```

Appendix II

II.1 Files for First Sample Run

Common Input for First Sample Run

ENG.RLN file for First Sample Run:

```
3
853.5       4.502040E+05      1.610532E+06
1707.0      4.502040E+05      1.610532E+06
3414.0      4.502040E+05      1.610532E+06
```

LOX.RLN file for First Sample Run:

```
Sample Run
2
1.956300E+04    2928.0    1.185883E+07    71.4
1.956300E+04    2928.0    1.185883E+07    71.4
2
1 0
13 2
1    15.0       1.416     0.0       0.0     0.0
0    35.0       45.0      1.416     0.0     0.0
1    30.0       1.416     0.0       0.0     0.0
0    3.5        135.0     1.416     0.0     0.0
1    15.0       1.416     0.0       0.0     0.0
1    20.641     1.416     0.0       0.0     0.0
1    20.558     1.416     0.0       0.0     0.0
1    20.558     1.416     0.0       0.0     0.0
1    8.541      1.416     0.0       0.0     0.0
1    6.383      1.416     0.0       0.0     0.0
0    4.25       90.0      1.416     0.0     0.0
1    9.33       1.416     0.0       0.0     0.0
0    3.33       80.0      1.416     0.0     0.0
5    1  1
1    3.53       0.708     0.0       0.0     0.0
1    12.2       0.708     0.0       0.0     0.0
0    1.28       35.0      0.708     0.0     0.0
1    12.2       0.708     0.0       0.0     0.0
7    13.5   1.183346E+07  0.0       0.0     0.0
5    1 2
1    3.53       1.00126   0.0       0.0     0.0
1    12.2       1.00126   0.0       0.0     0.0
0    1.28       35.0      1.00126   0.0     0.0
1    12.2       1.00126   0.0       0.0     0.0
7    13.5   1.183346E+07  0.0       0.0     0.0
2 3
18 0
1    15.0       1.416     0.0       0.0     0.0
0    35.0       45.0      1.416     0.0     0.0
1    30.0       1.416     0.0       0.0     0.0
```

```
0    3.5          135.0      1.416      0.0      0.0
1    15.0         1.416      0.0        0.0      0.0
1    20.641       1.416      0.0        0.0      0.0
1    20.558       1.416      0.0        0.0      0.0
1    20.558       1.416      0.0        0.0      0.0
1    8.541        1.416      0.0        0.0      0.0
1    6.383        1.416      0.0        0.0      0.0
0    4.25         90.0       1.416      0.0      0.0
1    9.33         1.416      0.0        0.0      0.0
0    3.33         80.0       1.416      0.0      0.0
1    3.53         1.416      0.0        0.0      0.0
1    12.2         1.416      0.0        0.0      0.0
0    1.28         35.0       1.416      0.0      0.0
1    12.2         1.416      0.0        0.0      0.0
7    13.5    1.183346E+07    0.0        0.0      0.0
```

FUEL.RLN file for First Sample Run:

```
FUEL Split: 3-1,1-0
2
4.055000E+03    486.0    1.185883E+07    72.13
4.055000E+03    486.0    1.185883E+07    72.13
2
1 0
8 2
1    17.97       1.04154  0.0        0.0      0.0
0    1.2785      75.0     1.04154    0.0      0.0
1    8.138       1.04154  0.0        0.0      0.0
0    1.2785     -75.0     1.04154    0.0      0.0
1    32.51       1.04154  0.0        0.0      0.0
0    1.2785      75.0     1.04154    0.0      0.0
1    8.65        1.04154  0.0        0.0      0.0
0    1.2785     -75.0     1.04154    0.0      0.0
2 1 1
1    6.2         0.52077  0.0        0.0      0.0
7    4.5    1.183346E+07  0.0        0.0      0.0
2 1 2
1    6.2         0.73648  0.0        0.0      0.0
7    4.5    1.183346E+07  0.0        0.0      0.0
2 3
10 0
1    17.97       1.04154  0.0        0.0      0.0
0    1.2785      75.0     1.04154    0.0      0.0
1    8.138       1.04154  0.0        0.0      0.0
0    1.2785     -75.0     1.04154    0.0      0.0
1    32.51       1.04154  0.0        0.0      0.0
0    1.2785      75.0     1.04154    0.0      0.0
1    8.65        1.04154  0.0        0.0      0.0
0    1.2785     -75.0     1.04154    0.0      0.0
1    6.2         1.04154  0.0        0.0      0.0
7    4.5    1.183346E+07  0.0        0.0      0.0
```

Input Unique to NYQUIST for First Sample Run

CONST.RLN file for First Sample Run:

```
  0.1   6219.0   2.67   2.330000E-03 -315.0
  0.1   6219.0   2.67   2.330000E-03 -315.0
  0.1   6219.0   2.67   2.330000E-03 -315.0
```

Input Unique to SSFREQ for First Sample Run

IMODE.RLN file for First Sample Run:

```
  Sample Run
  2
  0.000000        450204.00         4000.000
  4.00000         450204.00         4000.000
  0.000697        0.01              0.000000
  3.214000        2.232000         4.000000
  1.200000        1716.000         142500.0        2.670000
 -315.0000        0.010000         0.440000        1965.000
  2
  0.000000        450204.00         4000.000
  4.00000         450204.00         4000.000
  0.000697        0.01              0.000000
  3.214000        2.232000         4.000000
  1.200000        1716.000         142500.0        2.670000
 -315.0000        0.010000         0.440000        1965.000
  2
  0.000000        450204.00         4000.000
  4.00000         450204.00         4000.000
  0.000697        0.01              0.000000
  3.214000        2.232000         4.000000
  1.200000        1716.000         142500.0        2.670000
 -315.0000        0.010000         0.440000        1965.000
```

IMODE.FRQ file for First Sample Run:

```
  3
  110
  113
  116
```

IMODE.TAU file for First Sample Run:

```
  11
  0.0005 0.0007 0.0009 0.0011 0.0013 0.0015 0.0017 0.0019 0.0021
  0.0023 0.0025
```

II.2 Files for Second Sample Run

Common Input for Second Sample Run

CLASS.ENG file for Second Sample Run:

```
1
   3.112000E+03    9.504000E+04    4.464000E+04
```

CLASS.LOX file for Second Sample Run:

```
Basic Configuration
1
   4.055000E+03    2.264000E+03    1.185883E+07    7.213000E+01
1
1 1
   10 0
    1   2.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   4.000000E+00   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   3.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   4.000000E+00   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   2.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    7   4.500000E+00   1.183346E+07   0.0             0.0         0.0
```

CLASS.FUL file for Second Sample Run:

```
Basic Configuration
1
   4.055000E+03    8.48000E+02     1.185883E+07    7.213000E+01
1
1 1
   10 0
    1   2.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   4.000000E+00   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   3.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   4.000000E+00   1.000000E+00    .000000E+00    .000000E+00 0.0
    1   2.000000E+00   1.000000E+00    .000000E+00   0.000000E-00 0.0
    1   2.000000E+01   1.000000E+00    .000000E+00    .000000E+00 0.0
    7   4.500000E+00   1.183346E+07   0.0             0.0         0.0
```

Input Unique to NYQUIST for Second Sample Run

CLASS.CON file for Second Sample Run:

```
    1.000000E-03  6219.000000  2.670000  2.330000E-03 -315.000000
```

Input Unique to SSFREQ for Second Sample Run

CLASS.IMO file for Second Sample Run:

```
Basic Configuration
    2
  0.000000        95040.00        4000.000
  4.00000         95040.00        4000.000
  0.000697        0.01             0.000000
  3.214000        2.232000        4.000000
  1.200000        1716.000        142500.0        2.670000
 -315.0000        0.010000        0.440000        1965.000
```

CLASS.FRQ file for Second Sample Run:

```
  3
  110 113 116
```

CLASS.TAU file for Second Sample Run:

```
  11
  0.0005 0.0007 0.0009 0.0011 0.0013 0.0015
  0.0017 0.0019 0.0021 0.0023 0.0025
```

Appendix III

Homework Problem:

One configuration is given for all three codes, therefore the engine file and piping files need be developed only once. This is enough for ADMIT, but NYQUIST and SSFREQ will require their unique files to be developed. The configuration consists of two LOX tanks, one FUEL tank and two engines. The two LOX tanks and the two engines are identical, one LOX line going to one engine. The fuel line has a split and feeds both engines.

Assignment # 1

Develop the files for the engine (HW.ENG), the LOX line (HW.LOX), and the FUEL line (HW.FUL). Run both the LOX line and the FUEL line using ADMIT. Use a frequency range of 1 40 40.

Assignment # 2

Develop the file unique to NYQUIST and run the code using both FUEL and LOX lines. Use a frequency range of 1 40 300.

Assignment # 3

Develop the file unique to SSFREQ and run the code using files IMODE.FRQ and IMODE.TAU for the frequency and tau ranges.

Description of Configuration

LOX data (both tanks have the same values) -
32' diameter sphere
mass flow rate of 3,000 lbm/sec
density of 71.4 lbm/ft^3
bulk modulus of 11,800,000 lbf/ft^2
manifold volume of 15 ft^3
manifold bulk modulus of 11,800,000 lbf/ft^2
diameter of piping from tank to engine is 1 ft

FUEL data -

two 32' hemispheres separated by 25' cylindrical section
mass flow rate of 1,000 lbm/sec
density of 72.1 lbm/ft^3
bulk modulus of 11,800,000 lbf/ft^2
manifold volume of 5 ft^3
manifold bulk modulus of 11,800,000 lbf/ft^2
diameter of piping from tank to split is 1.4 ft
diameter of piping from split to engine is 1 ft

Engine data (both engines have the same values) -

total mass flow of 3,500 lbm/sec
chamber pressure of 660 lbf/in^2
pressure drop across orifice of 312.5 lbf/in^2

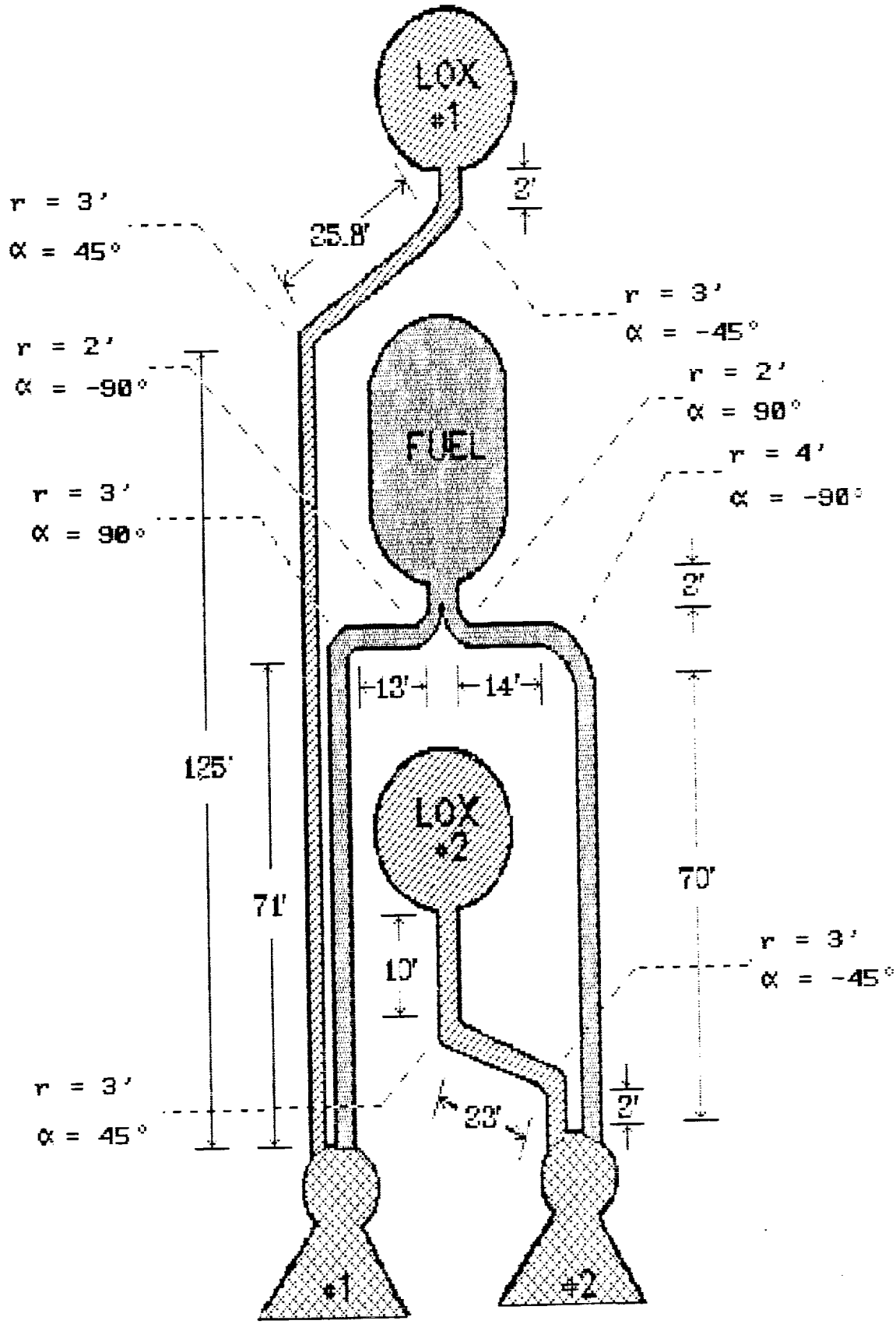
Combustion data -

transport lag of 0.01 sec
characteristic velocity of 6,200 ft/sec
mixture ratio of 3
characteristic time constant of .0023 sec
change in velocity with mixture ratio of -300 ft/sec

Chamber and Nozzle data (both engines have the same values) -

length of combustion zone is 5 ft
pressure is constant at 660 lbf/in^2
temperature varies linearily from ejector (4,000 °R) to the nozzle (5,000 °R). (Use 3 stations at x=0', 2.5', and 5.0'.)
ratio of specific heats is 1.22
chamber diameter of 3.2 ft
throat diameter of 2.2 ft
length of chamber of 5 ft
invariant time lag of 0.0005 sec
mixture ratio interaction index of 0.01
gas constant of 1,716 (ft/sec)^2/°R
maximum overpressure of 25,000 lbf/ft^2
dc*/dr of -300 ft/sec
dh/dr of 0.01 (ft/sec)^2
mass of liquid/unit chamber volume of 0.45 lbm/ft^3
axial component of liquid velocity of 2000 ft/sec
no damping

The physical layout is shown in the figure on the following page.


LOX
#1
2'
r = 3'
α = 45°
25.8'
r = 3'
α = -45°
r = 2'
α = -90°
r = 2'
α = 90°
FUEL
r = 4'
α = -90°
r = 3'
α = 90°
2'
13'
14'
125'
71'
LOX
#2
70'
10'
r = 3'
α = -45°
r = 3'
α = 45°
23'
2'
#1
#2