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Modeling for Health Monitoring and Control with Applications to the Space Transportation Main Engine

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1 Introduction

The work reported herein represents a continuation of work begun at MSFC during the 1991 NASA/ASEE Summer Faculty Fellowship Program [5, 7]. During this period the author proposed and studied a paradigm for the analysis and synthesis of Integrated Health Monitoring and Control Systems (IHMCS) for rocket engines. This work was motivated by NASA's desire to develop advanced propulsion systems which could operate with increased reliability at decreased cost. The Space Transportation Main Engine (STME) whose function it is to provide primary thrust for the National Launch System (NLS) family of vehicles is a primary example of this trend [2, 9].

The need for an *integrated* approach to health monitoring and controls was established by the author who has identified significant interaction effects which exist between control and health monitoring functions [5, 7]. The nature of these interaction effects is such that unless they are taken into account during the design phase, significant performance degradation may occur in overall the system operation.

The specific approach proposed allows the designer to embed the IHMCS into a general system architecture wherein the wide array system analysis and design tools can be brought to bear. Within the this approach off-nominal conditions are modeled as indicated in Figure 1. Here p denotes some nominal component or subsystem within the rocket engine. In the first case (Figure 1(a)), off-nominal conditions are represented by exogenous signals f injected at either the component input or output. When off-nominal conditions of this sort are incorporated into the overall engine model, the IHMCS analysis and design tasks can be reduced to problems in tracking and disturbance rejection [5, 7]. In the second case (Figure 1(b)), off-nominal conditions are represented by exogenous component dynamics Δ which may augment the nominal component dynamics. When off-nominal conditions of this sort are incorporated into the overall engine model, the IHMCS analysis and design tasks can be reduced to problems in uncertainty accommodation and robustness [5, 7].

In either case, it is clear that the approach discussed above is model-based. Thus, in order to apply these results it necessary to have access dynamical models for both the nominal rocket engine system and all off-nominal conditions of interest. Alternatively, and perhaps more favorably, would be to have a method for obtaining such models in a systematic manner. It is the task of this report to present just such a method.

This methodology is based on the application and manipulation of the fundamental laws of conservation in order to derive dynamical models for thermo-fluid systems such as those contained in chemical propulsion systems. It has a number of significant features which make it well suited for use addressing the problems encountered in IHMCS design: First, it allows the assembly of dynamical nominal and off-nominal engine models of low order by indicating the significant dynamics. Second, it allows us to distinguish between those off-nominal conditions which are likely to be modeled as signal type (Figure 1(a)), and those likely to be modeled as uncertainty type (Figure 1(b)). Third, it allows for the easy incorporation of various sensor and actuator types. Finally, it provides models in a format suitable for direct computer simulation.

Due to space constraints, the development here is necessarily brief and the interested reader is referred to [6] for a more detailed treatment.

2 Development of Thermo-fluid Modeling Principles

Chemical propulsion systems such as the STME are basically thermo-fluid systems whose dynamics are governed by the laws of conservation of mass, momentum, and energy. Discussion of these basic laws of physics can readily be found in the literature (e.g., [3, 8]). Here we will apply these laws in order to develop a set of principles for model development by studying the dynamical behavior of the fluid in a generic engine component represented by the variable area control volume given in Figure 2. The results given here are motivated by treatments given in [8, 4].

The basic assumptions which are made for the purposes of the development below are given as follows: (i) Fluid is allowed to cross the boundary only at the inlet ($x = x_1$) and the outlet ($x = x_2$). (ii) We assume that the fluid flows in the component are quasi-one-dimensional, i.e., flow properties are axisymmetric and uniform in any plane normal to the direction of flow. (iii) Where the working fluid (i.e., the propellants, combustion products, etc.) are in gaseous state, they behave as ideal gases. Specifically, $p = \rho RT$, $e = c_v T$, and $h = c_p T$. (iv) Body forces are negligible. (v) The flow is inviscid.

Given these assumptions we can now develop dynamical expressions characterizing the behavior of the fluid in the generic engine component of Figure 2.[1] The behavior of this fluid can be completely characterized in terms of 4 state variables: $V(x,t)$ - flow velocity, $p(x,t)$ - pressure, $T(x,t)$ - temperature, and $\rho(x,t)$ - density. These 4 variables are constrained to obey the laws of conservation of mass, momentum, and energy which can be expressed for the control volume of Figure 2 as follows:

Conservation of Mass:

$$\frac{\partial}{\partial t}\iiint_{\mathcal{V}} \rho \, d\mathcal{V} = -\iint_S \rho \mathbf{V} \cdot d\mathbf{S} \tag{1}$$

Here the terms, from left-to-right, can be interpreted as follows: the rate of increase of mass in $\mathcal{V}$, and the mass flow out of S.

Conservation of Momentum:

$$\frac{\partial}{\partial t}\iiint_{\mathcal{V}} \rho \mathbf{V} \, d\mathcal{V} + \iint_S (\rho \mathbf{V} \cdot d\mathbf{S})\mathbf{V} = -\iint_S p \, d\mathbf{S} \tag{2}$$

Here the terms, from left-to-right, can be interpreted as follows: the rate of increase of momentum in $\mathcal{V}$, the momentum flow across S, the total body force in $\mathcal{V}$, and the total pressure force on S.

Conservation of Energy:

$$\dot{Q} + \dot{W}_{\text{shaft}} - \iint_S p\mathbf{V} \cdot d\mathbf{S} = \frac{\partial}{\partial t}\iiint_{\mathcal{V}} \rho\left(e + \frac{V^2}{2}\right) d\mathcal{V} + \iint_S \rho\left(e + \frac{V^2}{2}\right)\mathbf{V} \cdot d\mathbf{S} \tag{3}$$

Here the terms, from left-to-right, can be interpreted as follows: the rate of heat added across S, the rate of shaft work done in $\mathcal{V}$, the rate of work done on S by pressure forces, the rate of change of energy in $\mathcal{V}$, and the rate of flow of energy across S.

Compressible Flow: We begin with the case where the fluid flow is considered compressible. The assumption of compressibility is necessary in the rear stages of a rocket engine system where the propellants/combustion products are in gas phase. Under these conditions equation 1 can be simplified to yield:

$$\frac{\partial \rho}{\partial t} = \frac{A}{\mathcal{V}}\left(\rho_1 V_1 \frac{A_1}{A} - \rho_2 V_2 \frac{A_2}{A}\right)$$

where A denotes the mean area between inlet, x_1, and outlet, x_2.

It is clear from this expression that if the ratio $A/\mathcal{V}$ is large, then the dynamics corresponding to the mass equation for the component tend to equilibrium quickly. In such cases, the dynamic mass equation can be replaced by the algebraic equation $\rho_1 V_1 A_1 = \rho_2 V_2 A_2$ for that component, and the mass equation does not contribute to the system's dynamic order.

In a similar manner, equation 2 can be simplified yielding the expression

$$\frac{\partial(\rho V)}{\partial t} = \frac{1}{x_2 - x_1}\left(\rho_1 {V_1}^2 \frac{A_1}{A} - \rho_2 {V_2}^2 \frac{A_2}{A} + p_1 \frac{A_1}{A} - p_2 \frac{A_2}{A}\right).$$

From this expression it is clear that if $1/(x_2 - x_1)$ is large, then the dynamics corresponding to the momentum equation for the component tend to equilibrium quickly. In such cases, the dynamic momentum equation can be replaced by the algebraic equation $\rho_1 {V_1}^2 A_1 + p_1 A_1 = \rho_2 {V_2}^2 A_2 + p_2 A_2$ for that component, and the momentum equation does not contribute to the system's dynamic order.

Finally, equation 3 can be simplified yielding the expression

$$\frac{\partial}{\partial t}\left[\rho\left(e + \frac{V^2}{2}\right)\right] = \frac{1}{\mathcal{V}}(\rho_1 A_1 V_1 c_p T_1 - \rho_2 A_2 V_2 c_p T_2 + \dot{W}_{\text{shaft}} + \dot{Q}).$$

From this expression it is clear that if $\mathcal{V}$ is small, then the dynamics corresponding to the energy equation for the component tend to equilibrium quickly. In such cases, the dynamic energy equation can be replaced by the algebraic equation $\rho_1 A_1 V_1 c_p T_1 + \dot{W}_{\text{shaft}} + \dot{Q} = \rho_2 A_2 V_2 c_p T_2$ for that component, and the energy equation does not contribute to the system's dynamic order.

[1] Table 1 provides a catalog of the symbols used here.

Incompressible Flow Dynamics: Next, we consider the case where the fluid flow is incompressible. The assumption of incompressibility is especially reasonable in the front stages of a rocket engine system where the propellants are still in liquid phase. In this case $\rho(x,t)$ is constant and so not a dynamic state variable, and the energy equation is not needed. The equations for conservation of mass and momentum given above can be simplified to yield

$$V_1 = V_2 \quad , \quad \frac{dV}{dt} = \frac{A}{\rho(x_2 - x_1)}(p_2 - p_1) \ .$$

Summary: Based on the analysis given here, the relative sizes for

$$\frac{A}{V} , \frac{1}{x_2 - x_1} , \frac{1}{V} , \frac{A}{\rho(x_2 - x_1)}$$

for a given engine component can be used to decide which dynamics are required to model that component, and which dynamics can be replaced by algebraic relationships.

3 Application to the STME

The results outlined above were applied to develop preliminary models of the STME for the purposes of studying the health monitoring and control functions.

Figure 4 provides a schematic diagram of the engine [2]. As it indicates the STME will employ a gas generator cycle with liquid hydrogen and oxygen propellants. Figure 3 provides a preliminary indication of the physical layout of the STME roughly to scale thereby providing of the relative dimensions of the various components [2].

Based on the information contained in Figure 4 the STME is modelled using the concepts from Section 2 by first breaking it up into four major assemblies: Main Combustion Chamber, Fuel Turbo-pump, Oxidizer Turbo-pump, and Gas Generator. Next, the relative dimension information given in Figure 3 is used to characterize the behavior of each subassembly using the appropriate combination of dynamic and algebraic equations. This resulted in a 17th order dynamical engine model. Finally, the overall model was encoded into MARSYAS [1] and used for simulation studies.

References

[1] *MARSYAS User's Manual: Marshall System for Aerospace Simulation*, July 1992.

[2] STME technical information document. Technical report, The Space Transportation Propulsion Team, June 1992.

[3] J. D. Anderson. *Modern Compressible Flow With Historical Perspective*. McGraw-Hill, 2nd edition, 1990.

[4] K. M. Eveker and C. N. Nett. Model development for active surge control/rotating stall avoidance in aircraft gas turbine engines. In *Proc. 1991 Amer. Cont. Conf.*, 1991.

[5] A. J. Helmicki. Rocket engine health monitoring: A system's perspective. Technical report, NASA Marshall Space Flight Center, August 1991. Detailed report for NASA/ASEE Summer Faculty Fellowship Program.

[6] A. J. Helmicki. Health monitoring and control for the STME: A case study. Technical report, NASA Marshall Space Flight Center, September 1992. Detailed report for NASA/ASEE Summer Faculty Fellowship Program.

[7] A. J. Helmicki, F. Kuo, and D. P. Vallely. Rocket engine health monitoring and control: Some connection and their implications. In *Proc. 3rd Annual Health Monitoring Conf. for Sp. Prop. Sys.*, Cincinnati, OH, November 1991.

[8] C. C. Lin and L. A. Segel. *Mathematics Applied to Deterministic Problems in the Natural Sciences*. Macmillan, 1974.

[9] J. W. Smelser and M. T. Constantine. STME: Streamlining the engine of change. *Aerospace America*, pages 22–25, July 1992.

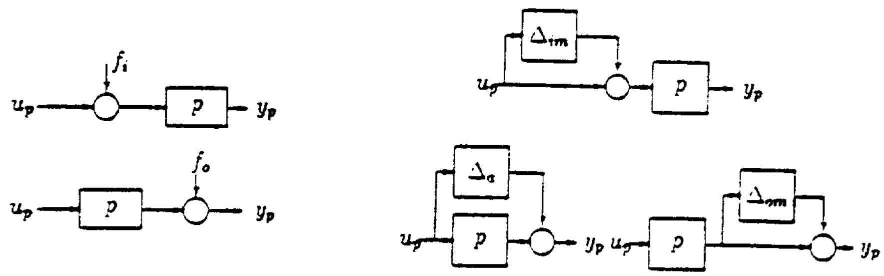

Figure 1: (a) Signal type and (b) Uncertainty type off-nominal conditions.

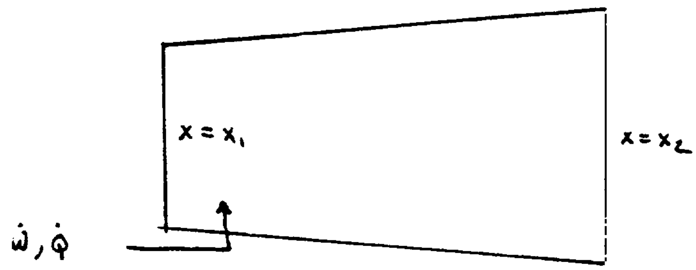

Figure 2: Generic engine component control volume.

Symbol	*Variable*
p	pressure
e	internal energy
h	enthalpy
ρ	density
T	temperature
V	flow velocity
A, S	area, surface area
$\mathcal{V}$	volume
Q	heat

Table 1: General variable definitions.

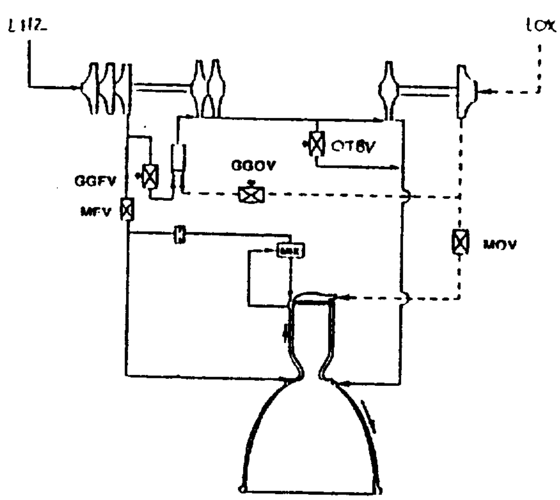

Figure 4: STME flow schematic.

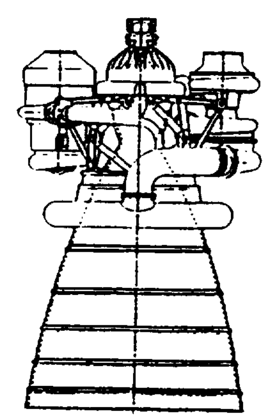

Figure 3: STME physical layout.