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SPACECRAFT PROPULSION SYSTEM PERFORMANCE SIMULATIONS

by

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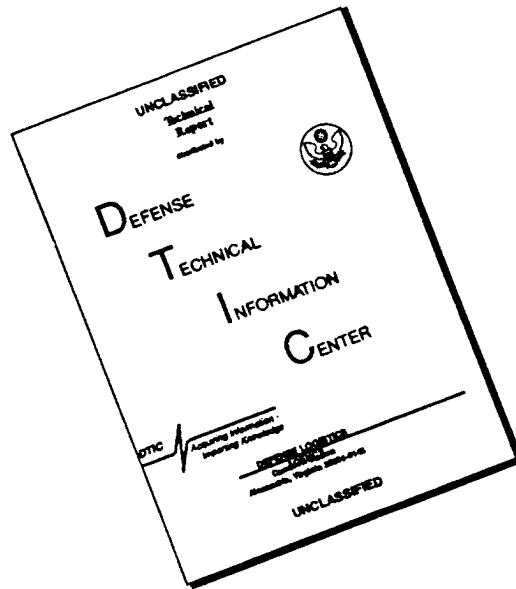
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ABSTRACT

This article takes the ducting system associated with the propulsion system of a certain spacecraft and sets up a distribution parameter form of mathematical model. Moreover, concentration parameter forms of mathematical model are then set up for such things as valves (illegible), injectors, as well as combustion chambers, and so on. Respective application is made of characteristic linear methods and fourth order Longge--Kuta (phonetic) methods to carry out mathematical simulations on 386 microcomputers. Going through large amounts of simulation calculations, a number of opinions are put forward associated with references that can be supplied.

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INTRODUCTION

The requirements presented by spacecraft with regard to propulsion systems are small mass and fast response. For this reason, orbital control engines and attitude control engines normally have a common supply system. In this way, when the operational configuration of a certain engine in the system gives rise to changes--for example, opening or closing--then the operation of several other engine units must experience "interference". This is particularly the case with attitude control engines. As far as the requirement for fast response is concerned, it is necessary to opt for the use of electromagnetic valves with high speed switches. Their operation will give rise to oscillations associated with fluid pressures and flow amounts in piping, that is, the so called "water hammer". With respect to the level of severity of water hammer, its influences on engine operation are, in all cases, problems that ought to be considered when designing propulsion systems.

I. Setting System Designs

Refering to relevent materials, there are two types of designs put forward for piping arrangements associated with spacecraft propulsion systems, that is, parallel tubing designs (see Fig.I) and series tubing designs (see Fig.II).
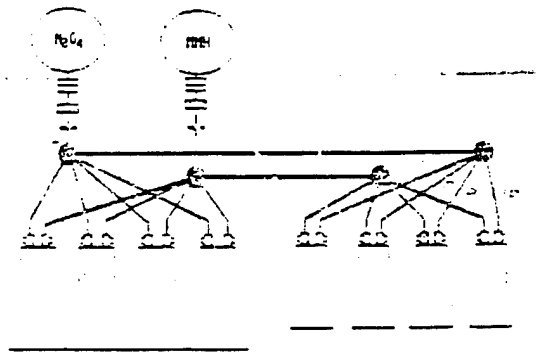

Fig.I Parallel Design Schematic

Compared to series, parallel possesses the following characteristics. Structures are simple. The number of components is few. Intake conditions are the same for various types of engines. Thrust magnitudes are in line with each other. During operation, the interference experienced is the same. They are advantageous to the installation and debugging of piping systems. They are advantageous to the operation of control systems. The
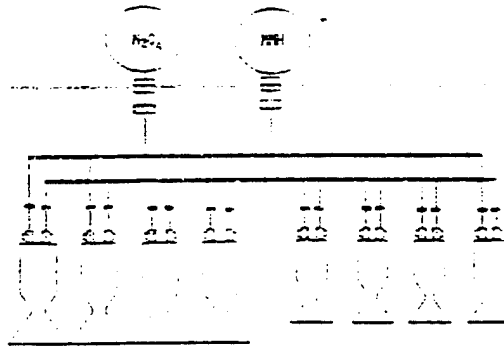
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Fig.II   Series Design Schematic

only drawback is the need for the working and special manufacture of multiple channel connector heads. However, series designs are just the reverse. Overall piping lengths will increase. Structural mass is large.

The simulation calculations in question were carried out with a view to parallel designs. Oxidizer and fuel tubing parameters are seen in Table I. Flow resistance distributions associated with various parts of systems are seen in Table II. (Numerical values are selected from reference data [1].)   /2

Table I

Key: (1)   Tube No.   (2)   Diameter   (3)   Length   (4)   Wave Speed
       (5)   Resistance Coefficient

① 管道号	1	2—5	6	7—10
② 直径(M)	0.008	0.004	0.002	0.002
③ 长度(M)	0.39	0.49	0.49	0.45
④ 波速(M/S)	1300	1400	1500	1500
⑤ 阻力系数	0.22	0.008	0.0384	0.008

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Table II

Part Nomenclature	Pressure or Pressure Drop MPa (illegible)
Combustion Chamber	0.7
Injector Pressure Drop	0.5
Electromagnetic Valve Pressure Drop	0.15
Filter Device Pressure Drop	0.15
Electrical Detonation Valve Pressure Drop	0.05
Aperture Plate Pressure Drop	0.05
System Piping Pressure Drop	0.05
Storage Tank Pressure	1.65

II. Mathematical Models and Their Solution

(I) Tubing

Considering tubing as well as propellant elasticity, flow movements of propellant in tubing can be seen as a one dimensional nonsteady flow. Drag direction and velocity direction are opposite to each other. The squares of resistance magnitudes and velocities form a direct proportion.

Motion equations and continuity equations are as follows:

$$gH_x - VV_x - V_t - \frac{fV|V|}{2D} = .$$
(1)

$$VH_x - H_t - V\sin\alpha - a^2/gV_x = 0$$
(2)

In these, a---pressure wave propogation speed (wave speed);
D---piping diameter;
f---resistance coefficient;
Ht--partial derivative of pressure head vs. time
V---propellant flow velocity
Vx--partial derivative of propellant flow velocity vs. pipe length X;
Hx--partial derivative of pressure head vs. pipe length X;
Vt--partial derivative of flow velocity vs. time;
α---included angle between pipe axis line and hoizontal line.

The two equations discussed above are a pair of quasi linear hyperbolic type partial differential equations. Dependent variables are V and H. Independent variables are t and x. A relatively mature solution method for this type of equation is the so called "characteristic linear method". This is the use of characteristic lines, taking them and turning them into two pairs of ordinary differential equations, C+ and C-.   /3

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$$\frac{g}{a}\frac{dH}{dt} + \frac{dv}{dt} - \frac{fv|v|}{2D} = 0$$

(3)

$$\frac{dx}{dt} = +a$$

$$\left. \right\} C^+$$

(4)

$$\frac{-g}{a}\frac{dH}{dt} + \frac{dv}{dt} + \frac{fv|v|}{2D} = 0$$

$$\frac{dx}{dt} = -a$$

$$\left. \right\} C^-$$

(5)

(6)

Equations (4) and (6) are, respectively, limits of (3) and (5). As far as the two pairs of ordinary differential equations discussed above are concerned, it is possible to carry out finite differences. When specific gravities accounted for by friction terms are not large--with regard to the relationships of flow velocities V and X--it is possible to opt for the use of first order approximations, thus obtaining two algebraic equations describing propellant pressure head and flow transient propogation inside tubes.

$$C^+ H_P = H_A - B(Q_P - Q_A) - RQ_A|Q_A|$$

(7)

$$C^- H_P = H_B - B(Q_P - Q_B) - RQ_B|Q_B|$$

(8)

In the equations: B=a/gA;
                     R=fΔx/2gDA2;
                     A----circulation surface area;
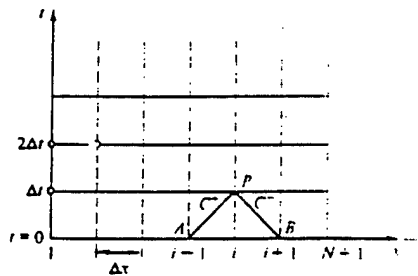   g----acceleration of gravity.

Fig.III   Single Tube x-t Network Diagram

As far as pressure heads and flow amounts at the center point of the tube are concerned, it is possible to make use of equations (7) and (8) to solve for them. With respect to the two ends of the tube, there is, respectively, only one equation, that is , (7) and (8). In order to make solutions, it is necessary to supplement the two boundary equations. For example, the top end of the first tube is a storage tank with a constant pressure head. With respect to the boundary equation: HP=HT=const, HP is the storage tank pressure head. The bottom boundary is a six tube connector head.

The boundary equation is:

$$H_{I'} = H_{m.85} = \bar{H}_{i'2.i} = \bar{H}_{i'3.i} = \bar{H}_{i'4.i} = \bar{H}_{i'5.i} = \bar{H}_{i'c.i}$$

$$Q_{i'1.85} - Q_{i'2.i} - Q_{i'3.i} - Q_{i'4.i} - Q_{i'5.i} - Q_{i'c.i} = 0$$

The terminals of the No.2 to No.5 tubes and the No.7 to No.10 tubes are all electromagnetic valves. Boundary equations are valve equations. Valve outlets are injector cavities. The pressures are Pinjo or Pinjf.
(II) The injector cavity pressure equation is

$$\frac{dPinj}{dt} = \frac{\beta}{V_{I)}} (\dot{m}_{1} - \dot{m}_{c})$$ (9)

/4

In the equation: Pinj----injector cavity propellant pressure;
              β----propellant volume modulus of elasticity;
              V----injector cavity volume;
              mj----input injector cavity mass flow amount;
              mc----output injector cavity mass flow amount;
              ρ----propellant density.

(III) Combustion Chamber Models
    a) The equation associated with combustion chamber pressure

    Pc is

$$\frac{V_{c}}{RT}\frac{dP_{c}}{dt} = \dot{m}_{ox}(t-\tau_{c}) + \dot{m}_{fc}(t-\tau_{c}) - [\frac{\Lambda_{n}\Lambda_{T}}{\sqrt{RT}} - \frac{V_{c}}{RT^{2}}\frac{\partial RT}{\partial K_{c}}\frac{dK_{c}}{d\tau}]P_{c}$$ (10)

    b) The equation for the mixture ration Kc of combustion
        gases inside combustion chambers is

                                                        (11)

$$\frac{dK_{c}}{dt} = \frac{(1+K_{c})RT}{P_{c}V_{c}}[\dot{m}_{oc}(t-\tau_{c}) - K_{c}\dot{m}_{fc}(t-\tau_{c})]$$

In equations:RT=f(Kc)
    In calculations, it is set as $RT = e^{A_{1}K_{c}^{2}+A_{2}K_{c}+A_{3}}$

Coefficients A1, A2, and A3 are theoretical values calculated from a set of heating powers, (that is, a set of RT for different Kc values). Use is made of least square methods to obtain

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$$A_n = \sqrt{n\left(\frac{2}{n-1}\right)^{\frac{1}{n-1}}}$$

At----throat area;
 n----gas isoentropic index.

Equations (9), (10), and (11) discussed above are a set of nonlinear variable coefficient ordinary differential equations. Numerical value solution methods are very numerous. Here, option is made for the use of fourth order Longge--Kuta (phonetic) methods. The order number of equations is not high. However, "rigidity" is relatively great--particularly, during start up and shut down processes. As a result, calculation increment lengths are generally required to be very small. Speaking in terms of tubing, calculation increment lengths can be somewhat larger. Calculation time can be shortened. Moreover, in programs, number set volumes can be very, very greatly reduced. Because of this, they are contradictory. During the calculations in question, option is made for the use of methods with different increment lengths. The integration increment lengths associated with ordinary differential equations are only one tenth of tube parameter calculation increment lengths. In this way, not only is the stability of ordinary differential equation calculations guaranteed, computer time is also reduced.

III. Brief Introduction to Programs

(I) Main Control Programs. Their function is to control input, output, transmission of data between subprograms, program operation, and so on.
(II) Steady State Value Calculation Subprograms. Their function is to calculate steady state values for pressure heads and flow amounts associated with various system points under various types of conditions. What is meant by various types of conditions is eight engine units full on as design condition, one turned off, two turned off, ... , seven--design conditions without all seven.
(III) Transient Value Calculation Subprograms. These include tubing center point pressure head and flow amount calculation subprograms, valve flow amount and pre valve pressure head calculation subprograms, valve open or closed subprograms, and so on. Their function is to calculate transient values associated with flow amounts and head pressures for various points in systems.

(IV) Ordinary Differential Equation Integration Subprograms. These are used in order to calculate pressures in front of jets, combustion chamber pressures, as well as combustion gas mixture ratios.

IV. Calculation Result Analysis

(I) Steady State Value Calculation Results (See Table III)
From Table III, it can be seen that attitude control engine

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chamber pressures increase as a function of increases in the number of units shut down. The reason is that attitude control engine intake pressures increase following along with increases in the number of shut down units. Maximum relative deviations reach 14.1984%. A method for improvement is to take attitude control engine intakes and shift them in the direction of storage tanks, taking tubing components such as filters, aperture plates, and so on, and installing them below attitude control engine intakes. Among attitude control engine intake tubes (6), there is also a need to install such parts as filters. This then increases system structural mass.   /5

(II)   The Influences of "Water Hammer" Phenomena

This article makes two types of configurational simulations, that is, configurations corresponding to "cold tests" and "hot tests". The difference between them is that during cold tests, chamber pressure is the atmospheric pressure outside from

Table III

Shut Off Unit Number	Orbital Control Engine Chamber Pressure (Relative Value)	Attitude Control Engine Chamber (Relative Value)
0	1.00	1.00
1	1.049247	1.049238
2	1.090170	1.090153
3	1.118029	1.118007
4	0	1.128888
5	0	1.134937
6	0	1.139325
7	0	1.141984

beginning to end. However, as far as hot test configuration is concerned, chamber pressures are, by contrast determined by flow amounts. Under these two different types of configurations, "water hammer" phenomena in pipes are very greatly different. See Fig.IV.

Fig.IV is the status of changes of pressures in front of jets in attitude control engines when two orbital control engines are shut down from an on state and another two units are turned on from an off state (carried out at the same time). Nondotted lines are "cold test" configurations. Dotted lines are hot test configurations. From the Fig.'s, it can be seen that--during "cold tests"--maximum water hammer pressure values are 3.6 times design values. Oscillation frequencies are relatively high. Attenuation is relatively fast. However, with respect to "hot test" configurations, maximum water hammer pressure values are only 1.85 times design values. There are low frequency residual oscillations, and attenuation is relatively slow. The reason for the analysis is that "hot test" configurations have an inhibiting effect on water hammer in tubing inside chambers. From the angle

of control, it can be seen as a "negative feedback". From the point of view of energy, it can be seen as a pressure accumulator. Besides that, there is coupling with chamber pressure oscillations.

Therefore, there is the appearance of low frequency residual oscillation.

(III) During combustion, calculation results associated with lag τ c=0 and τ c=0.003s are seen in Fig.V and Fig.VI. Fig.V is pressures in front of jets. Fig.VI is oxydizer flow amounts. From the Fig.'s, it can be seen that, during combustion time lag periods, oscillations are very violent. Maximum pressure peaks reach over 6 times design values. Low pressures reach saturated steam pressures for the temperatures at the places in question. However, once chamber pressures are set up, pressure oscillations are then immediately inhibited. Flow amount changes and pressure changes are basically the same. However, with the appearance of negative values--that is, reverse flow--once chamber pressures are set up, then oscillations disappear, verifying further the inhibiting effects of chamber pressures on oscillation.

(IV) Simulation Calculations Associated with Various Mutual Engine Interferences

A) The calculations in question were made with regard to the influences on attitude control engines when two orbital control engines open up, and, at the same time, two orbital control engines close down. The results are seen in Fig.VII. What the Fig. shows is change curves associated with chamber pressures during processes where orbital control engines open up and close down. At the same time, chamber pressure changes after attitude control engines experience interference are given. From the Fig.'s, it can be seen that attitude control engine chamber pressures produce very large fluctuations. Maximum deviations reach 40%. The lowest values also drop close to 40%. Moreover, continuation times are relatively long. Only after close to 20ms do things then stabilize. This is nothing else than the harms that come with a commonly used system. The reason is that orbital control engines are much bigger than attitude control engines. Methods of avoidance and methods of eliminating steady state deviations are the same--take attitude control engine intakes and move them up the flow.

B) As far as the calculations in question are concerned, computations were also done of the influences of attitude control engines on orbital control engines. That is, when two attitude control engines open up and, at the same time, two other attitude control engines close down, orbital control engine chamber pressures then fluctuate--see Fig.VIII. From the Fig.'s, it can be seen that orbital control engine chamber pressure changes are not great. The reason is clear and easily seen.

C) Interference Between Attitude Control Engines

a. When two attitude control engines close down at the same time as two other attitude control engines open up, one discovers--after engine start up--chamber pressures giving rise to relatively long periods of oscillation--see Fig.IX. The reason is

possibly that--after the rapid shut down of two engines--water
hammer pressures in tubing create flow amount pulsations and
coupling associated with chamber pressure oscillations.   /6
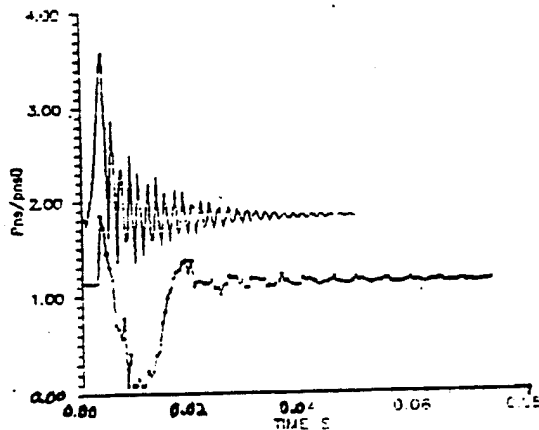Attenuations are also relatively slow.

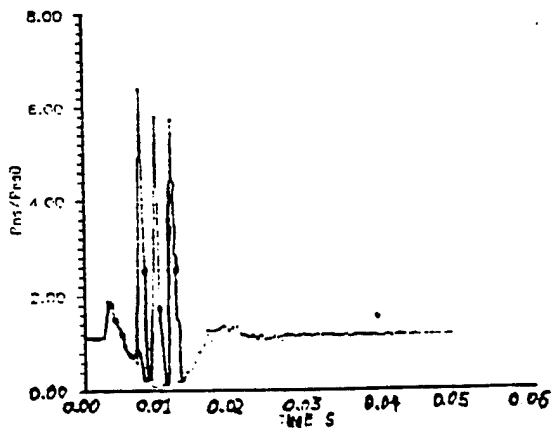Fig.IV Pressure Change Curves in Front of Jets

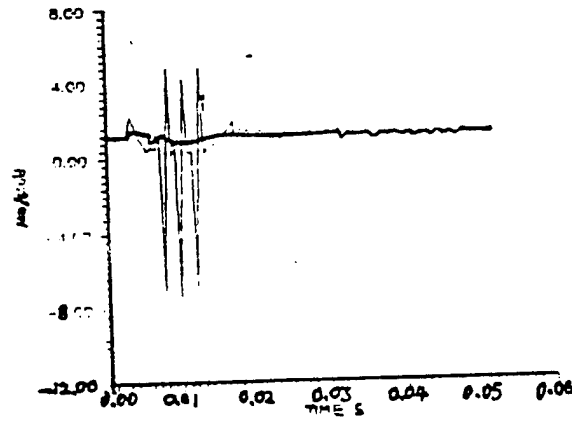Fig.V Pressure Change Curves in Front of Jets
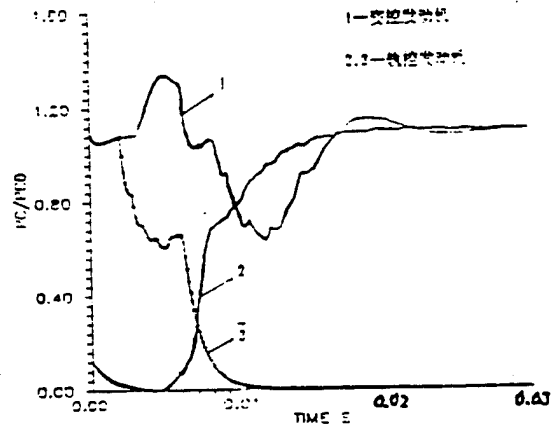
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Fig.VI Flow Amount Change Curves

Fig.VII Chamber Pressure Change Curves   1--Attitude Control Engine
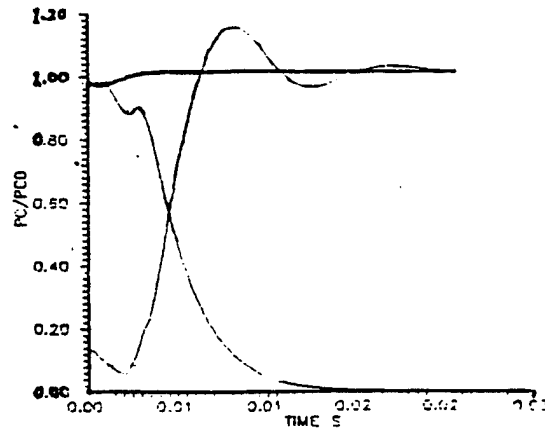
2,3--Orbital Control Engine

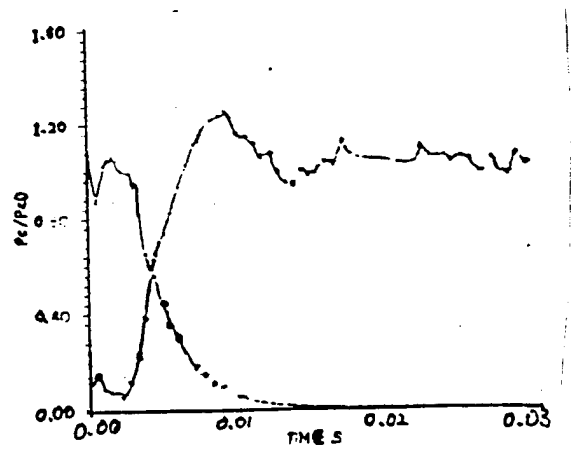Fig.VIII   Chamber Pressure Change Curves
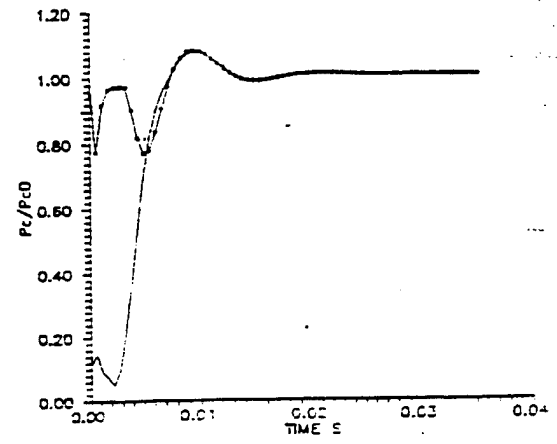
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Fig.IX Chamber Pressure Change Curves

Fig.X Chamber Pressure Change Curves

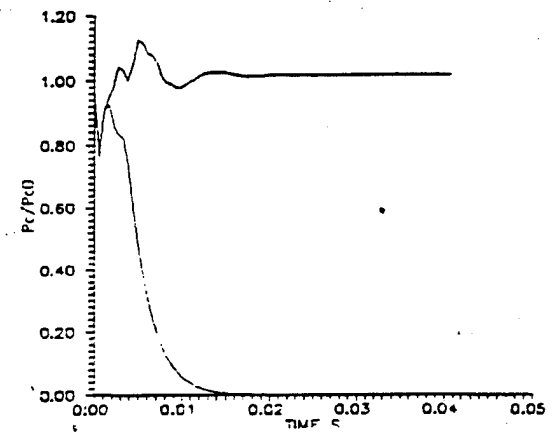Fig.XI Chamber Pressure Change Curves

b. As far as the interference associated with the starting up of two engines on another two engines is concerned, see Fig.X. For the influences of shuting down two engines on another two engines,

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see Fig.XI. From the Fig.'s, it can be seen that interference will be experienced in all cases. Chamber pressures will give rise to oscillations in every case. Right up until the end of start up or shut down processes, this interference will always exist. It will be approximately 20ms. Peak fluctuation values are not very large--under ±20%.

(V) Attitude Control Engine Response Characteristics

During start up, T90 is approximately 6ms. Overshoot δ reaches 8%. The course of transitional processes is 15ms. Rises in engine chamber pressures associated with start up give rise to drops in engine chamber pressures associated with stable operation.

Drops in engine chamber pressures associated with start up, by contrast, lead to rises in engine chamber pressures associated with stable operations. Mutual interferences begin to be comparatively obvious.

During shut down, T10 is approximately 9ms. The course of transitional periods is relatively long--approximately 15ms. Influences with respect to steady state operation of engines and start up processes are similar. The reason that dynamic courses are relatively long may be that combustion chamber volume Vc is made comparatively large.

V. A Few Opinions

(I) As far as relatively severe "water hammer" phenomena in tubing is concerned, considerations should be made of it when tubing is designed and installed. One is strength. Another is the mechanical vibration in tubing and even in the entire system. In tubing, although "water hammer" phenomena are very intense, combustion chambers, however, are capable of giving rise to inhibiting effects. It is only before chamber pressures are set up--that is, within ignition delay periods--that tubing undergoes influences. Moreover, chamber pressure changes which are not great do not have large influences with regard to normal engine operation.

(II) Attitude control engine operational configurations are severly interfered with by orbital control engines. During system design, appropriate measures should be adopted, when necessary, sacrificing a bit structural mass characteristics in order to guarantee attitude control engine operational reliability.

(III) Small pulses can also be produced. The key technique is to improve response characteristics.

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