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NEW CONCEPTS OF SRM IGNITION SYSTEM

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Abstract

Restricting partially and temporally the initial propellant burning surfaces with thin HTPB inhibitors realized a new method of controlling the chamber pressure rise rate at ignition. The merits of the method are to be manufactured easily, to hardly affect the whole motor thrust pattern, and low in cost. The ground firing tests with sub-scale motors have verified the method to be reliable and flexible.

The principal concept of a "staged ignition system" is to replace the igniter main charge by an "ignition cavity" perforated at the fwd-end of the motor propellant grain. This 'ignition cavity' generates the combustion gas required for igniting the remaining portion of the grain. It has been employed in the designs of two ISAS' solid motors now under development and has contributed to simplification of the ignition systems.

1. Introduction

In development of the motors for M-3SII and M-V launch vehicles, design criteria for the motor type igniters had been established. Currently some space missions are planned and the development of the improved version of the M-V launch vehicle is performed in ISAS. In those activities, two new ignition systems have been developed.

As the improved version of the M-V 2nd stage motor, the M-25 motor is now under development to be replaced with the existing M-24. The M-25 will employ a filament wound (FW) casing instead of the existing metallic one. On the way of designing analyses, an anxiety was shown that the rapid extension of the FW case caused by the motor ignition spike might impose an excessive shock on the upper stage structures. The authors invented a simple and reliable method to inhibit partially and temporally the initial propellant burning surfaces by thin HTPB layers, which are to be cured simultaneously with the propellant grain. Changing the surface areas of the HTPB inhibitor can easily control the pressure rise rate at ignition.

Recently a new system called "staged ignition system" has been proposed. The principal concept is that the igniter main charge is to be replaced by a cavity followed by a confined nozzle portion perforated at the fwd-end of the motor propellant grain. This "ignition cavity" once ignited will generate and supply a sufficient amount of combustion gases to ignite the remaining portion of the grain. The "staged ignition system" design has been employed in both the designs of the small spherical DASH-DOM (Demonstrator of Atmospheric Reentry System with Hyperbolic Velocity-Deorbit Motor) weighing 20 kg and of the improved booster of S-310 sounding rocket having a large L/D now under development. This new ignition system will well contribute to simplification and cost reduction of the SRM ignition system.

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2. Initial Chamber Pressure Rise Rate (P_c-dot) Control System

2.1 Background

An important index to evaluate the shock induced by the rapid chamber pressure rise is a maximum chamber pressure rise rate $(dP_c/dt)_{max}$="P_c-dot-max". Since it is so difficult to deal with the unsteadiness and the non-uniformity of the phenomena in an ignition transient period, we make a simple analysis to justify the experimental findings by using the following quasi-steady-state mass balance equation for the overall motor chamber at any given time:

$$\frac{d}{dt}\left(\rho V_0\right) = \rho_p r_b A_b + K_{ig}\dot{m}_{ig} - \frac{P_c A_t}{C^*} \tag{1}$$

where

ρ = combustion gas density
V_0 = chamber free volume
ρ_p = solid propellant density
r_b = propellant linear burning rate
A_b = propellant burning surface area
K_{ig} = correction factor
m_{ig} = igniter gas flow rate
P_c = chamber pressure
A_t = nozzle throat area
C^* = characteristic exhaust velocity.

For simplicity, we introduced following assumptions:

1. The entire burning surface is ignited at a time.
2. The burning rate characteristic in a chamber-filling process is the same as in the steady state.
3. The changes of V_0 and A_b in the ignition transient period are negligible.

Then the expression for P_c-dot in the chamber-filling period is obtained by substituting the equation of state into the Eq. (1) . The expression of the linear burning rate is given by

$$r_b = aP_c^n$$

where a is the constant and n is the pressure exponent. Hence the "P_c-dot-max" is derived from the above equation.

$$\dot{P}_{c\max} = \left(\frac{dP_c}{dt}\right)_{\max}$$

$$= \frac{RT}{L^*_i}\left[(1-n)(nC^*)^{\frac{n}{1-n}}(\rho_p a K_{ni})^{\frac{1}{1-n}} + \frac{K_{ig}m_{ig}}{A_t}\right] \tag{2}$$

where

R = gas constant of combustion product
T = adiabatic flame temperature in chamber
K_{ni} = A_{bi}/A_t
L^*_i = chamber characteristic length V_{0i}/A_t
V_{0i} = initial chamber free volume
A_{bi} = initial burning surface area.

From this expression, the important parameters governing the P_c-dot-max are clear.

Fig.2-1 shows the relationship between the P_c-dot-max values obtained from the experimental data existing and the parameter $K_{ni}^{1/(1-n)}L^{*}{}_i^{-1}$ on a motor configuration. A broken line shows the calculated result without the influence of an igniter gas flow by Eq. (2). From the results presented in this figure, it is apparent that P_c-dot-max is nearly proportional to the parameter.

$$\dot{P}_{c\max} \propto \frac{K_{ni}^{1/(1-n)}}{L^*_i} \tag{3}$$

We can control, therefore, the P_c-dot-max by reducing the initial burning area A_{bi} or by increasing the initial chamber free volume V_{0i}.

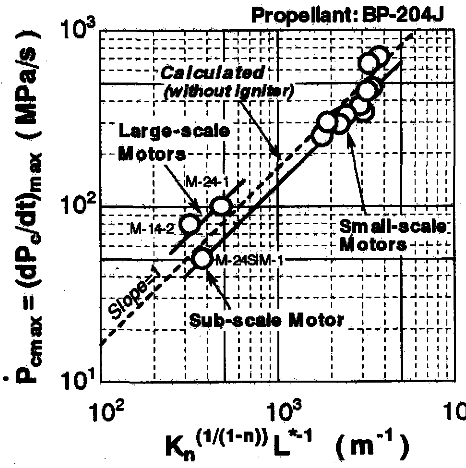

Fig. 2-1 Relationship between P_c-dot-max and $K_{ni}^{1/(1-n)}L^{*}{}_i^{-1}$

2.2 Approach

So far, so as to meet the requirement, the method of designing the propellant grain with a configuration of small initial burning surface has been employed. However, this design approach is necessary for peculiar and complicated considerations and gives an unfavorable thrust pattern with poor performance.

The authors have, therefore, proposed another simple method to inhibit partially and temporally the initial propellant burning surfaces by thin inhibitor layers. The inhibitor is to be bonded to the initial burning surfaces or to be cured simultaneously with the propellant grain. The expectable merits are to be manufactured easily, to hardly affect a thrust pattern and a performance, and to be applicable to every existing motor.

From the preliminary test results by firing lab-scale motors, we determined to employ an HTPB rubber for the inhibitor. Since the HTBP is widely used for the fuel-binder of the solid propellant, it is easy to be bonded to the propellant surfaces, is easy to be obtained, and is low in cost.

The authors recognize that this method is a new adaptation of a Strand's "Low-Acceleration Ignition System"[1].

2.3 Experimental Verification

A. Purposes

To verify the feasibility of the new method, the authors conducted firing tests with small-scale motors. Main purposes of the experiments are to demonstrate the feasibility of the concept, to determine the important parameter governing the system, and to obtain the design guidelines for practical use.

B. Motor hardware

The main characteristics of test motors are listed in Table 2-1. Table 2-2 shows the composition and combustion properties of the loading propellant designated BP-204J.

The existing TM110 motor with a circular cross section was used for the tests to determine the inhibitor configuration and to investigate the effect of A_{bi} on P_c-dot-max. The TM160S and TM160T motors with a thick web, and a circular cross sectional propellant grains were employed to verify the effect of a presence of the inhibitor on an entire motor pressure profile.

The TM160G motor was specially designed to demonstrate the feasibility of the concept and to verify the manufacture of the inhibitor with a star grain. Fig.2-2 is the schematic of the TM160G motor having a 5-pointed gear grain and the inhibitor configuration.

The inhibitors bonded to the propellant surfaces are thin belt-like configurations parallel to the motor axis and are 0.5mm in thickness. The configuration for the other motors was similar to that of the TM160G's.

Table 2-1 Main Characteristics of Test Motors

Motor Designation	D_t (mmφ)	P_c (MPa)	t_b (s)	L* (m)
TM110	21	9	2	4.8
TM160S	22	10	4	6.2
TM160T	31	10	4	5.8
TM160G	39	11	5	3.7

Table 2-2 Propellant Properties of BP-204J

Composition (mass%)		
Oxidizer	AP(NH_4ClO_4)	68%
Binder	HTPB	12%
Fuel	Al	20%
Additive	Fe_2O_3	0.3-0.5%
Linear Burning Rate		
r_b (@5MPa, 20℃)		9.2±0.3mm/s
Pressure Exponent, n		0.4
Combustion Gas Properties		
(@5MPa, Frozen equilibrium)		
Adiabatic Flame Temperature		3529K
Mean Molecular Weight		29.66g/mol
Mean Specific Heat Ratio		1.165

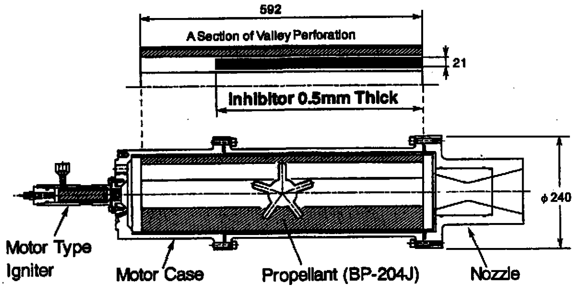

Fig. 2-2 TM160G motor with a 5-pointed gear grain and inhibitor configuration

C. Test Results

Fig.2-3 shows a typical test results of motor chamber pressure-time histories and evaluated P_c-dot profiles in the period from the igniter started burning until the chamber pressure reached equilibrium, which obtained with the TM160S motor loading the same grain configuration except the inhibitor. A broken line shows a result using the propellant grain without the inhibitor and a solid line shows that with the inhibitor covering a 35% of the initial burning surface area. These test data indicate the following:

1. Restricting partially the initial burning surface with the thin HTPB inhibitor can reduce P_c-dot-max.

2. Motor ignition delay time is hardly affected by the presence of the inhibitor.

3. The HTPB inhibitor 0.5mm thick seems to be gradually recessed and to be burnt away from the propellant surfaces within 1s after ignition.

Entire motor pressure-time histories of the TM160S motor indicates that the pressure profile is hardly affected by this method in case of using a thin inhibitor.

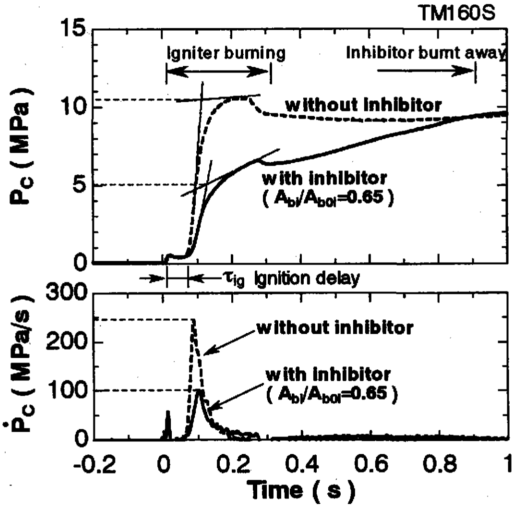

Fig. 2-3 Chamber pressure and evaluated Pc-dot histories of TM160S

The results obtained with all the other motors are similar to those described above, therefore, are explained and discussed in the same way.

From the results presented Fig. 2-4, it is obvious that the Pc-dot-max is almost proportional to the parameter $K_{ni}^{1/(1-n)}L^{*}{}_{i}^{-1}$.

2.4 Design Guidelines

As the results of the experimental verification, we obtained the following design guidelines of the system:

1. The ignition delay time is hardly affected by the presence of the inhibitor.

2. The inhibitor having a thin belt-like configuration is burnt away from the propellant surfaces within 1s after ignition.

3. The important parameters in controlling the P_c-dot-max are the K_{ni} and the L^{*}_{i}.

$$\dot{P}_{c\,\max} \propto \frac{K_{ni}{}^{1/1-n}}{L^{*}_{i}}$$

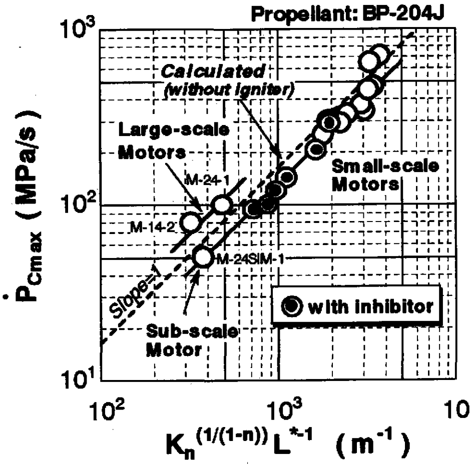

Fig. 2-4 Relationship between P_c-dot-max and $K_{ni}^{1/(1-n)}L^{*}{}_{i}^{-1}$

2.5 Future Works

The firing test to be considered the variable thickness of the inhibitor has not been attempted yet. In order to apply this new method to a thrust pattern control, further study is required to understand the recession characteristics of the inhibitor.

3. Staged Ignition System

3.1 Concept

As a new technique to reduce the mass and the cost of SRM ignition system, the "staged ignition system" has been proposed by Nakano [2]. The principal concept of the system is to replace the igniter main charge by the combustion surface surrounding an "ignition cavity" perforated at the fwd-end of the motor propellant grain.

A conventional, small pyrotechnic IG-booster is used to ignite the internal surface of the ignition cavity. The ignition cavity once ignited generates and supplies the sufficient amount of combustion gases required for igniting the remaining portion of the grain.

3.2 Experimental Verification

A. Purposes

The authors carried out firing tests with small-scale motors. Main purposes of the experiments are to demonstrate the feasibility of the concept, to confirm the technical issues to be solved, and to obtain the design guidelines for practical use.

B. Motor hardware

Fig. 3-2 is the schematic of a test motor designated TM80. The composition and the combustion properties of the propellant are listed in Table 3-1.

The tests were performed under low-ambient pressure conditions in a low-pressure cell without ejector. The parameters in the tests were the mass of the booster charge m_{IB}, the initial volume and the initial throat diameter of the ignition cavity V_{fcavi}, D_{tcavi}. An ambient pressure changed from 0.54kPa at ignition to the maximum of about 4kPa during the motor burning.

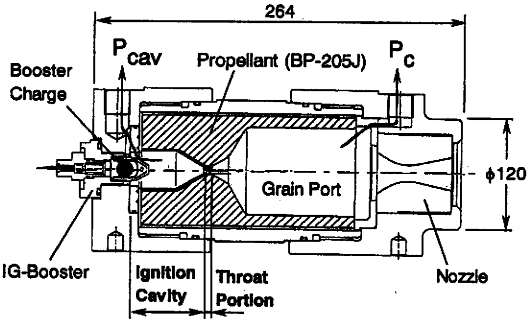

Fig.3-2 TM80 Motor

Table3-1 Propellant Properties of BP-205J

Composition (mass%)		
Oxidizer	AP(NH_4ClO_4)	68%
Binder	HTPB	12%
Fuel	Al	20%
Linear Burning Rate		
r_b (@5MPa, 20℃)		7.3±0.3mm/s
Pressure Exponent, n		0.3
Combustion Gas Properties		
(@5MPa, Frozen equilibrium)		
Adiabatic Flame Temperature		3531K
Mean Molecular Weight		29.51g/mol
Mean Specific Heat Ratio		1.166

C. Results and Design Guidelines

The results obtained by the firing tests with the TM80 motor are summarized as follows:

1. The ignition characteristics of the ignition cavity can be estimated by the following expression based on the conventional igniter design criteria:

$$\tau_{igcav}^{1/2} m_{IB}^{4/5} = K V_{cav}^{2/3}$$

where

τ_{igcav} = ignition delay time of the ignition cavity
m_{IB} = mass of the booster charge
K = constant (= 3.6)
V_{cav} = initial volume of the ignition cavity.

2. The mass flow rate of the ignition cavity required for igniting the remaining portion of the grain can be estimated by the conventional design criterion for the motor type igniter.

3. In the design of the ignition cavity configuration, we must pay attention to the following:
   - The propellant grain around the throat portion should have sufficient strength so that it will not fail under dynamic loading due to pressure difference between the ignition cavity and the grain port at ignition.
   - Motor ignition must be completed while the ignition cavity is burning above its L* combustion limit.

3.3 Development of DASH-DOM

A. Motor Description

After successful firing tests with TM80 motor, the authors determined to apply this new system to the design of the small spherical DASH-DOM.

DASH-DOM (Demonstrator of Atmospheric Reentry System with Hyperbolic Velocity-Deorbit Motor) is a small spherical motor weighing about 20kg designed to be used to deorbit an atmospheric reentry test vehicle designated DASH from the GEO transfer orbit. The requirements in the motor design were as follows:

1. The loading density should be as high as possible to achieve the minimum DASH system mass.
2. The ignition must be soft and the thrust level just after ignition should be as low as possible to keep the DASH attitude disturbance at a minimum.

The propellant grain was then designed to have a configuration of smaller initial burning surface and of small initial free volume.

B. Ground Firing Tests

Two static firing tests of the full-scale motors were performed with high altitude test system at ISAS' Akiruno Research Center in 1999. Fig. 3-3 shows a DASH-DOM-2 motor was fired in October 1999. The motors had thick motor case and pressure ports for measuring P_{cav} and P_c.

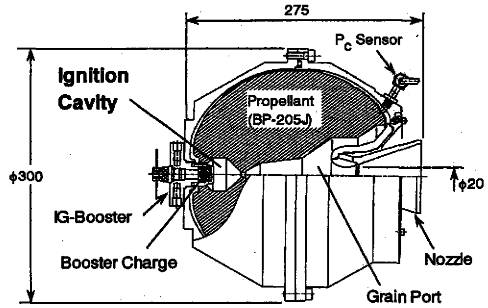

Fig. 3-3 DASH-DOM-2 Motor

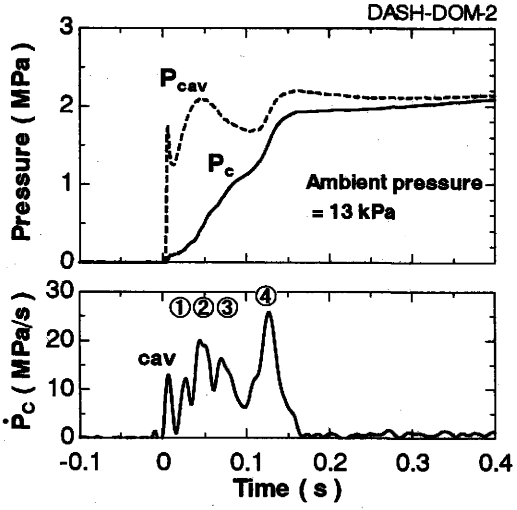

Fig. 3-4 Pressure-time histories of P_{cav} and P_c and an evaluated P_c-dot history

Fig. 3-4 shows the pressure-time histories of P_{cav} and P_c and an evaluated P_c-dot history in the period from the moment the IG-booster starts to burn until the pressure reaches equilibrium state. The pressure histories indicate a proper ignition transient followed by a stable combustion. Then the P_c-dot history in the ignition transient period shows that the flame spreads over the burning surface in four steps and that the P_c-dot must be controlled lower level.

The test results show that the staged ignition system is suited for the requirements in the DASH-DOM motor design.

3.4 Future Works

The "staged ignition system" design has also been employed in the design of the improved booster of S-310 sounding rocket having a large L/D as high as 12 now under development. To develop the design criteria further experimental studies are continued at present.

4. Conclusions

The feasibility of the initial chamber pressure rise rate (P_c-dot) control system was successfully demonstrated by the firing tests with small-scale motors. The design guidelines of the system with a thin belt-like HTPB inhibitor were obtained for practical use. To apply this new method to an active control of thrust pattern further studies are required for understanding the recession characteristics of the HTPB inhibitor in the motor.

The "Staged Ignition System" has been suitably applied to the design of DASH-DOM. The design guidelines of the system applied to certain small motors have been obtained. To develop the generalized design criteria of the system further experimental studies are continued at present.

References

[1] Strand, L. D., "Low Acceleration Solid Propellant Rocket Ignition Study," NASA-CR-124574, Jet Propulsion Laboratory, Dec. 1971.

[2] Nakano, N., Tanno, H., and Kohno, M., "Experimental Study on Staged Ignition System," (in Japanese), Proceedings of the Symposium on Space Transportation 1998, Institute of Space and Astronautical Science, Jan. 13-14, 1999.