Engineering Notes

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Moment Characteristics of Liquid Injection Thrust Vector Control

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Nomenclature

d_* = nozzle throat diameter
F_s = side force
g = acceleration of gravity
I_{sps} = $F_s/(g\cdot \dot{m}_i)$, effective specific impulse of injectant
L = distance from virtual apex of nozzle cone to virtual point of action of side force on nozzle axis (Fig. 4)
L_{cg} = distance from virtual apex of nozzle cone to the center of gravity of a rocket (Fig. 4)
M_a = moment about virtual apex of nozzle cone
$\dot{m}_i$ = mass flow rate of injectant
$\dot{m}_m$ = mass flow rate of propellant
α = half-angle of nozzle cone
ϵ_e = nozzle expansion ratio at exit
ϵ_i = nozzle expansion ratio at point of injection
ϵ_{imm} = nozzle expansion ratio at point of injection where the moment about the center of gravity of a rocket is maximum

Introduction

WHEN liquid injection is used for thrust vector control of a rocket motor, one of the most important quantities that must be known is the magnitude of induced moment about the center of gravity of a rocket. Information about the side force and the locations of a virtual point of action of the side force and the center of gravity of a rocket is necessary to estimate the moment. Many experimental results[1,2] on the side force have been reported and some theoretical models[3,4] to predict it have been proposed. But there have been only a few reports in which the virtual point of action of the side force is mentioned. Satisfactory reports regarding the moment characteristics of liquid injection thrust vector control (LITVC) have not been published yet as far as we know.

The experiments presented in this paper were conducted to investigate the characteristics of LITVC used on an upper stage motor. The results on the side force, the point of action of the side force, and deduced moment characteristics will be presented.

Experimental Apparatus and Procedures

Solid propellant motors having a nominal thrust of 3 kN were used in this experimental program. As these experiments were conducted in the High Altitude Test Facility of the National Aerospace Laboratory,[5] ambient pressure was held at less than 1.5 kPa during the combustion. The test nozzles were conical with 15 deg half-angles and had 23.2 mm diam. throats. The secondary injection port had a 1.0 mm diam. and was normal to the axis of the nozzle.

This experimental program was intended mainly to investigate the effects of injectants and nozzle expansion ratios at the injection point ϵ_i and at the exit ϵ_e on the characteristics of LITVC. Injectants were Freon-114B2, strontium perchlorate/water solutions, and hydrogen peroxide. More than thirteen different combinations of ϵ_i and ϵ_e were tested with each injectant.

The measurement of thrust and moment was made with a four-component thrust stand, which is schematically illustrated in Fig. 1. It has two features: 1) all the measuring load cells are installed to the keystone block where the motor is also attached; and 2) both main thrust and yaw moment are measured with four load cells (4–7) which are symmetrically installed near the motor. Since the second feature makes the force placed on each load cell due to the moment relatively large and equally divided, an accurate measurement of the moment is possible. The ranges and accuracies of the thrust stand are as follows: main thrust 7 kN, 0.15% F.S.; side force 600 N, 0.3% F.S.; yaw moment 180 N·m, 0.8% F.S. The other details of this experimental program can be obtained from Ref. 6.

Results and Discussions

When we vary only ϵ_e and fix the other injection parameters, we can obtain a simple relation between F_s and L. If the side force increment due to the increase of nozzle exit expansion ratio from ϵ_e to $\epsilon_e+\Delta\epsilon_e$ is denoted by ΔF_s, the moment increment ΔM_a is a product of resultant force normal to the nozzle wall ΔF_s secα, and arm length $\frac{1}{2}d_*\sqrt{\epsilon_e}$ cot$\alpha\cdot$secα. Therefore F_s and L are related as follows:

$$\frac{\partial(L/d_*)}{\partial\epsilon_e}=\frac{\sqrt{\epsilon_e}\csc(2\alpha)-(L/d_*)}{F_s}\frac{\partial F_s}{\partial\epsilon_e} \tag{1}$$

where $L=M_a/F_s$. As the coefficient of the right-hand side of Eq. (1) is always positive, F_s and L have maximum values at the same ϵ_e. Therefore, regardless of the location of the center of gravity of a rocket, the moment also has a maximum at this ϵ_e. The $L/d_*-\epsilon_e$ curve can be obtained by the numerical integration of the experimentally determined $I_{sps}-\epsilon_e$ curve (I_{sps} is directly proportional to F_s when the flow rate of the injectant is fixed). This $L/d_*-\epsilon_e$ curve agreed fairly well with experimental results.[6]

On the other hand, when the injection point is varied and the other parameters are fixed, which is more important for its practical application, such a simple relation between F_s and L/d_* as Eq. (1) does not hold. Figure 2 shows the results of I_{sps}. Results only for 70% Sr $(ClO_4)_2$ injection will be indicated, while the other injectants show similar tendencies. As we move the injection point from the exit toward the throat, I_{sps} increases at first, because the high pressure regions due to the evaporation, decomposition, and chemical reaction of the injectant and also due to the detached shock wave exist only on the injection port side of the nozzle wall. But, further movement of the injection point to the throat causes the shock wave to propagate to the opposite side of the wall, and it produces negative side force. Therefore I_{sps} has a maximum at a certain ϵ_i, and then decreases.

Figure 3 shows the corresponding results of L/d_*. When the injection point is at the exit, the high pressure region which contributes to produce the side force is limited to the

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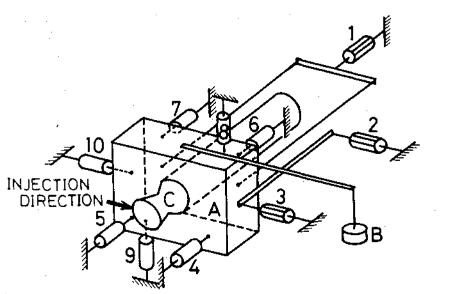

Fig. 1 Schematic sketch of thrust stand. A: keystone block. B: weight for roll moment calibration. C: rocket motor. 1–3: load cell for calibration. 4–10: load cell for measurement.

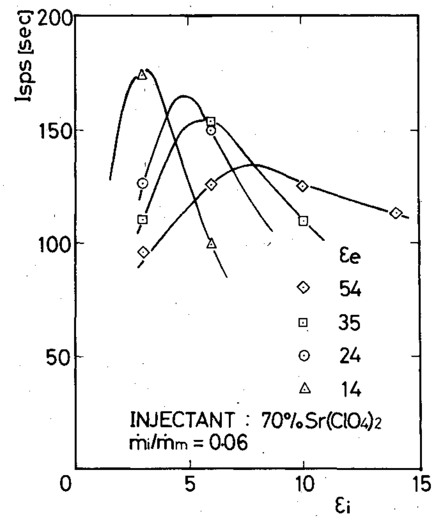

Fig. 2 Effective specific impulse of injectant vs injection location.

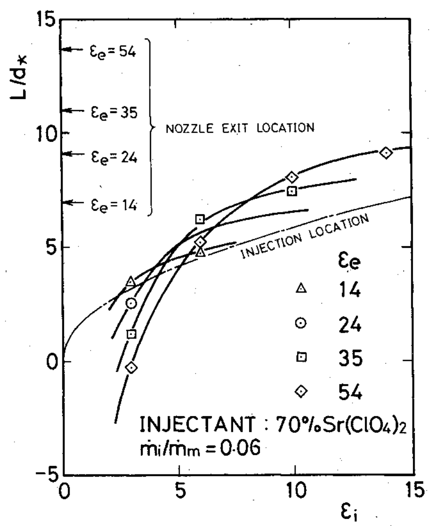

Fig. 3 Location of point of action of side force vs injection location.

separated region in front of the injection port. Therefore, the location of the point of action of the side force must be near the injection point. When we move the injection point toward the throat, only the positive side force is produced in the downstream region of the injection point in the first stage, and the point of action of the side force goes downstream of the injection point. But in the next stage, as mentioned previously, further decrease of ϵ_i creates negative side force near the exit. This negative side force has a greater influence on moment than on side force, and results in a rapid decrease of L. Because of this, the point of action of the side force goes

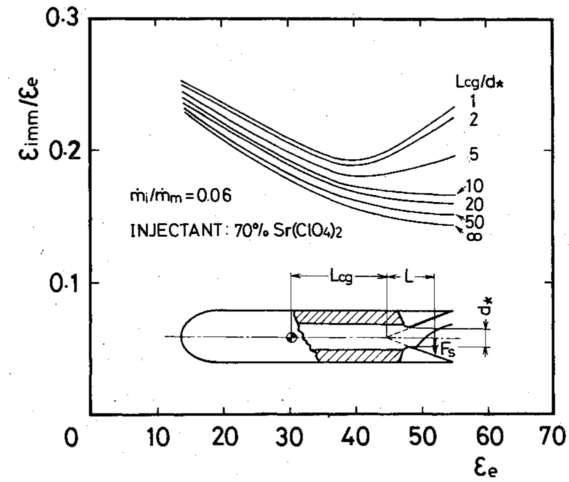

Fig. 4 Injection location where the moment about the center of gravity of a rocket is maximum; effect of the location of the center of gravity of the rocket.

upstream of the injection point and, in some cases, goes even into the combustion chamber of the motor beyond the throat.

As we can see in Figs. 2 and 3, L does not have a maximum at ϵ_i where I_{sps} has a maximum. This indicates that the location of the center of gravity of a rocket should also be considered to determine the injection location where the moment about the center of gravity of the rocket is maximum. Figure 4 shows the injection location of the maximum moment deduced from Figs. 2 and 3 and the location of the center of gravity of the rocket L_{cg} as a parameter. The curve indicated by $L_{cg}/d_* = \infty$ coincides with the injection location where the side force is maximum. The smaller the L_{cg} is, the larger the $\epsilon_{imm}/\epsilon_e$ is. In this case, the larger the ϵ_e is, the larger the variation of $\epsilon_{imm}/\epsilon_e$ due to the variation of L_{cg}/d_* is. But the value of the moment varies little near the maximum. For instance, in the case of $\epsilon_e = 54$ and $L_{cg}/d_* = 10$, moment is more than 98% of the maximum value in the region of $0.148 < \epsilon_i/\epsilon_e < 0.218$. Opposite tendencies of F_s and L in the region result in a flatness of the moment-ϵ_i curve near the maximum. But it is important to note that the moment decreases suddenly if the injection point goes to the upstream of the location where the side force is maximum, because both F_s and L decrease.

For larger values of $\dot{m}_i/\dot{m}_m$ than the present data, the family of curves in Fig. 4 would be displaced upward. Therefore, the increase of $\dot{m}_i$ would qualitatively correspond to the decrease of ϵ_i. In designing LITVC, the optimum injection location must be determined for the maximum value of $\dot{m}_i$ expected in the mission.

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