Aerodynamic Side Force Induced by Nozzle Entrance Flow Asymmetry

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The Star 48 upper stage system appears to precess in a coning motion, which affects the flight path. This motion is attributed to side forces generated because of deviations of the rocket nozzle entrance flow from truly axisymmetric conditions. In this paper, an experimental investigation is described in which intentional nozzle entrance flow misalignment is produced and consequent side force measured on a 1/50th scale Star 48 rocket nozzle at a simulated altitude of 1.7×10^5 ft. Side forces generated are quite small when compared to the predictions and measurements of previous investigators, but differences are attributed to varying locations in which the flow inclination occurs. When the flow is inclined at the nozzle throat, the downstream effect of the inclination is large. When the flow is inclined in the plenum upstream of the nozzle entrance, the downstream effect is smaller by an order of magnitude. The observed side forces show a dependence on the nozzle length, as indicated by earlier investigators.

Nomenclature

A	= nozzle cross-section area
F_x	= axial force (thrust) at nozzle throat
F_y	= side force at nozzle throat
ℓ	= distance from model c.g. to nozzle throat
M	= exit Mach number
M_z	= moment about Z-axis at throat section
$\dot{m}$	= mass flow rate
p	= pressure
R	= gas constant for nitrogen
Re	= Reynolds number
V_e	= nozzle exit velocity
y_t	= throat radius
α	= nozzle cone half-angle
γ	= ratio of specific heats
ρ_T	= radius of curvature at throat

Subscripts

a	= ambient conditions
e	= nozzle exit value
o	= plenum stagnation conditions
t	= at throat

Introduction

WITH spin-stabilized space vehicles, turning moments are observed that can lead to a coning motion in which the center of mass precesses about an axis through the nose of the vehicle, leading to instability and control problems. Coning occurs in the Star 48 upper stage rocket motor. Among potential causes for the turning moments are deviations of the rocket nozzle entrance flow from truly axisymmetric conditions.

Meyer[1] attributed the rocket motor gas flow deflection to the effect of Coriolis forces on the spinning vehicle. Darwell and Trubridge,[2] Hoffman and Maykut,[3] and Walters[4] calculated side force and moment on rocket nozzles from assumptions of angular misalignment and showed that the side force and moments varied in a damped sinusoidal manner with nozzle length. Darwell and Trubridge and Walters also conducted experiments that verified their calculations. In these analyses, the flow was assumed to be misaligned at the throat. Hoffman and Maykut define an initial value surface that is a constant property plane at the throat pitched at an angle with respect to the axis of an axisymmetric nozzle exit contour. In the experiments of Walters, the nozzles studied either had the throat extended on one side, or the throat entrance section shortened and tilted on one side, producing an asymmetric throat or throat entrance section in each case. Thus, a canted flow was produced at the throat as assumed in the analysis.

In the present experiment, the nozzle and entrance section were axisymmetric components, which were properly designed and fabricated. Only the flow entering the nozzle was turned, simulating the effects of Coriolis forces. The asymmetries associated with an axisymmetric nozzle in which the nozzle plenum flow is inclined with respect to the nozzle axis could thus be evaluated.

A force model was built in which misalignment of flow at the nozzle entrance could be produced, incorporating as much as practical the Star 48 nozzle configuration. This allowed for determination of whether the turning moments observed in the Star 48 system were connected with flow misalignment at the nozzle entrance. Since the Star 48 flies at a high altitude, the experiments were performed in a large vacuum tank that had been pumped down to a pressure simulating 52,000 m (170,000 ft).

This paper describes the model, and the side force measurements are presented for several nozzles of different lengths, expansion angles, and throat design. The observed side forces for these nozzles did depend on nozzle length, although their magnitudes were much smaller than those described by previous investigators.[2-4]

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a) Front view showing pitch axis, tanks and nozzle **b) Side view showing inclined flow tube**

Fig. 1 Idealized one-degree-of-freedom experimental model.

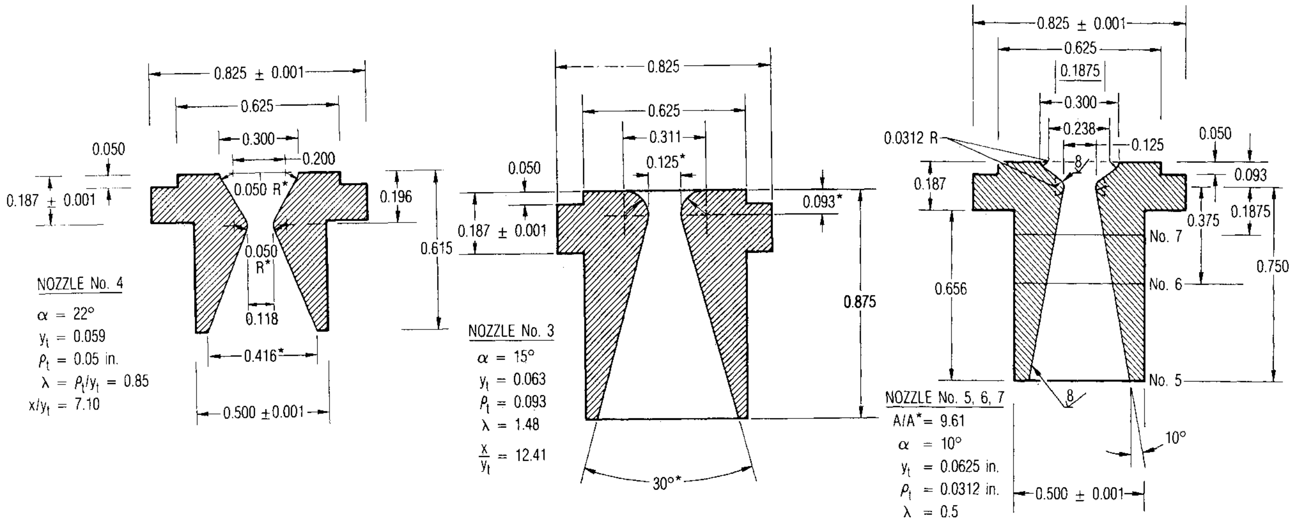

Fig. 2 Nozzle configurations used in the side force measurements.

Experimental Apparatus and Tests

The apparatus developed is shown schematically in Fig. 1. It consists of a nozzle, tanks to contain the gas for the flow, and a framework for supporting these components and for providing an axis normal to the thrust direction about which the model is constrained to rotate.

The flow misalignment or asymmetry is provided by tilting the supply tube for the nozzle plenum. The deflection angle is about 7.5 deg, and the tube can be rotated 180 deg so that differences of 15 deg in flow deflection can be obtained. A straight tube was built for supplying aligned flow that was used for initial alignment of the nozzle-block assembly.

The forces on the rig are the pressure and momentum forces on the nozzle throat entrance and the pressure forces on the nozzle wall. These forces are resolved into F_x and F_y acting at the nozzle throat. The total moment about a point at the c.g. of the rig at ℓ is then

$$M_{cg} = M_z + F_y \ell$$

Since F_x is constrained to act along the nozzle axis that is aligned with the rig c.g., there is no axial component about the c.g. The moment $F_y \ell$ is very large compared to M_z, because the moment arm of M_z is very small compared to ℓ. M_z is thus neglected. In our experiment ℓ is 45.7 cm (18 in.).

The side force is determined from a measurement of the displacement of one end of the model as it rotates during the test. The displacement is sensed by a Schaevitz Engineering Linear Variable Differential Transformer (LVDT). Calibration was provided in terms of force by hanging weights on the model through a pulley so that the calibrating force is applied in the direction of the side force at the throat.

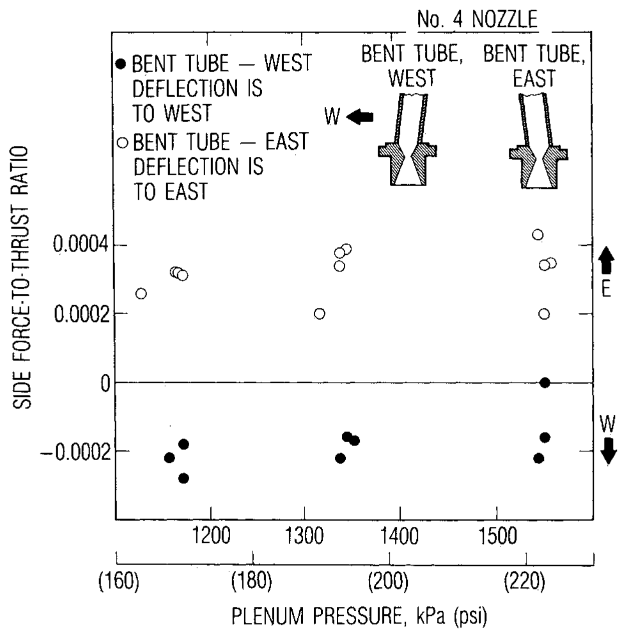

Fig. 3 Effect of plenum asymmetry on nozzle side force.

Three nozzles (Fig. 2) were built for use in this experiment. The shortest of the three is an adaption of the nozzle for the

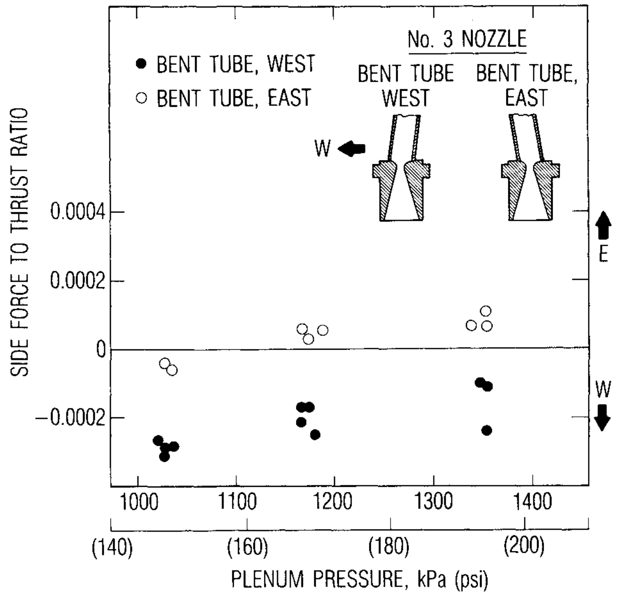

Fig. 4 Effect of plenum asymmetry on nozzle side force.

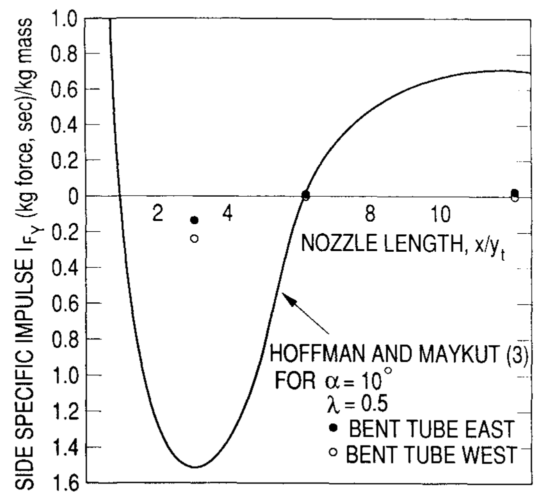

Fig. 5 Effect of nozzle length on side force; comparison with Ref. 3.

Star 48 upper stage rocket motor. The next nozzle was longer with a larger throat radius of curvature, and the last nozzle (actually three, since it was cut progressively to three different lengths) was built according to the analysis of Ref. 3 to correspond with the curve of Fig. 3 of Ref. 3 for cone half-angle, $\alpha = 10$ deg.

From plenum pressure, measured by an Endevco strain gage transducer installed just upstream of the nozzle throat, the thrust is calculated according to

$$\text{thrust} = (1/2)(1 + \cos\alpha)\dot{m}V_e + (p_e - p_a)A_e$$

or in terms of measured values

$$\text{thrust} = (1 + \cos\alpha)\, 0.290\, p_o\, \gamma A_t M \times [(1 + M^2/5)^{-1}]^{1/2} + (p_e - p_a)A_e$$

Where γ is assumed to be 1.4 for nitrogen, which is the gas used in the tests. Mach number and static pressure are calculated from the exit-throat area ratio. Ambient pressure p_a in these tests is so low relative to p_e that the pressure thrust term $(p_e - p_a)A_e$ is reduced to p_eA_e. The plenum pressure is relatively large in these experiments (1000 to 4000 kPa), so that *Re* at the nozzle exit is of the order of 10^5. As a result, viscous effects are expected to be negligible.

Results and Conclusions

The results of these tests are summarized in Figs. 3 and 4 for the short nozzle (no. 4) and the longer nozzle (no. 3). In these figures, the measured side force normalized with respect to the thrust calculated from the measured plenum pressure is plotted as a function of plenum pressure. During a test, the plenum pressure decreases with time as the gas storage tanks are depleted. To reduce the data, three measurements were made of the side force and plenum pressure; at the beginning of the trace, the middle, and at the end. Hence, each test is represented by three points on Figs. 3 and 4 for three plenum pressures.

For the short nozzle, the results seem unequivocal. For the nozzel entrance flow inclined in one direction, e.g., bent tube east, a side force appears in that direction. When the entrance flow is rotated 180 deg, i.e., bent tube west, the force is also. For the long nozzle, the forces are smaller than for the short nozzle as expected from the analyses in Refs. 2 and 3, which predict that side force varies in a damped sinusoidal manner with nozzle length.

For both nozzles the side forces measured are not symmetrical about zero, and for the longer nozzle in which the side forces are smaller there is also a variation with plenum pressure. The asymmetry is probably caused by the nozzle asymmetry itself. After each nozzle is installed in the rig, tests are made using a straight tube to provide uninclined flow at the nozzle entrance. In these tests, a sensitivity to azimuthal position of the nozzle and block appeared. The nozzle and block assembly were rotated to the position of minimum side force. The nozzle and block could only be rotated in 90-deg increments so a zero side force baseline position could not be attained. As a result, there is some test bias in the data. The variation of side force with plenum pressure is probably caused by the same bias, but is more pronounced because these forces are less than half those of nozzle no. 4.

Cone angle and throat radius of curvature for nozzles 3 and 4 are much different from those upon which the analyses were based. Therefore, new nozzles were built (Fig. 2) in which the cone half-angle α and the throat radius of curvature-to-throat-radius-ratio $\rho_t/y_t = \lambda$ were the same as those values of one of the nozzles studied by Hoffman and Maykut. Their predictions for this nozzle for $\alpha = 10$ deg and $\lambda = 0.5$ and plenum conditions of 6895 kPa (1000 psi), 3333°K, $\gamma = 1.2$ are reproduced in Fig. 5. Measurements were taken of the side force for this nozzle for three nozzle lengths, $x/y_t = 12$, 6, and 3. The side force values obtained are plotted in Fig. 5. For these tests, plenum temperature and pressure are 296°K and 3100 kPa (450 psi), respectively. The mass flow rate is determined from plenum conditions according to

$$\dot{m} = 0.579\left(\frac{\gamma}{RT_0}\right)^{1/2} P_0 A_t$$

These results demonstrate the predicted effect of nozzle length on the measured side force. For $x/y_t = 12$ and for plenum flow angled to the west, the largest positive side force occurs (deflection to the east is positive in the laboratory system). For $x/y_t = 3$, the side force swings to the west, and at $x/y_t = 6$, it is close to zero.

The initial direction of flow at the throat entrance section for nozzles 5, 6, and 7 appears to have little effect on the direction and magnitude of the side force compared to the effect of the nozzle length. For nozzle nos. 3 and 4, when the tube leading to the nozzle entrance section was inclined to the west, the observed side force was inclined to the west (Fig. 3) or at least inclined west of the direction resulting when the tube was inclined to the east (Fig. 4). For nozzle nos. 5, 6, and 7, however, the westward inclining nozzle produced eastward directed side force until the side force went to zero ($x/y_t = 6$). then it appeared that the force and entrance flow direction again agreed.

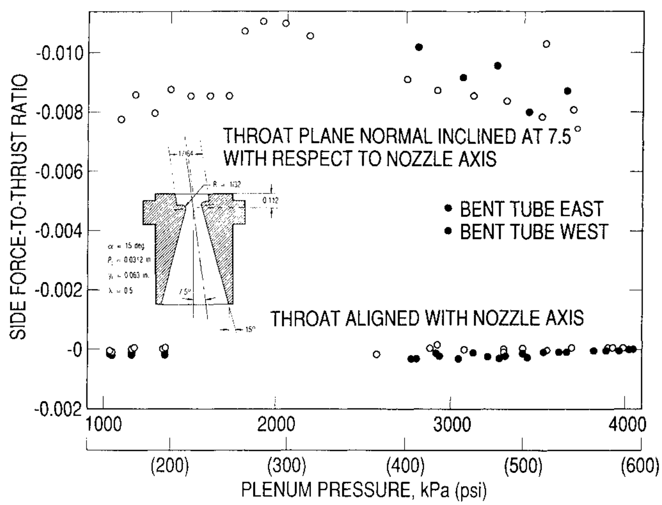

Fig. 6 Effect of nozzle throat alignment on side force, nozzle no. 3.

The magnitude of the measured side force for all the nozzles is of the order of 10^{-4} of the thrust. This value is very low compared to those values predicted and measured previously[2-4] and shown in Fig. 5 for nozzle nos. 5, 6, and 7. The conclusion could be made that when the flow is inclined in the plenum, some straightening can occur during subsonic expansion in the converging part of the nozzle. Thus, the asymmetry at the throat may be greatly reduced and the observed side forces much smaller compared with when the flow is canted at the nozzle throat. To confirm this viewpoint, nozzle no. 3 was modified by tilting the throat. The resulting nozzle is shown in Fig. 6 along with the measured side force plotted as a function of plenum pressure. The side force generated when the nozzle throat is tilted (that is, when the asymmetry in the flow is extended to the plane of the throat) is much greater than when the asymmetry is limited to the plenum. In fact, the effect of the plenum flow misalignment, as exhibited in Fig. 4 by the open and closed circles, is masked by the effect of the asymmetric throat as shown in Fig. 6.

It seems reasonable to conclude, therefore, that when the nozzle and throat entrance section are properly axisymmetric, the effect of misalignment of the flow entering the throat is small relative to the effects of misalignment of the throat itself. If the Star 48 rocket motor is so constructed, it is questionable whether or not the reduced side force generated is large enough to cause the observed coning motion.

The data of Fig. 6 also show that this nozzle was almost in perfectly "tuned" condition. The flowfield misalignment is reduced from 7.5 deg at the throat to approximately 0.5 deg (arctan 0.009, the side force-to-thrust ratio) at the nozzle exit. This is in qualitative agreement with Hoffman and Maykut.[3] Quantitative agreement is not possible because the γ of the tests is 1.4 for nitrogen, whereas the calculations were made for $\gamma = 1.2$, approximating that of actual combustion products. Also, the experiments were done with the largest possible misalignment angle in order to emphasize the effect, whereas the calculations were limited to a flowfield misalignment of 2 deg, beyond which nonlinear effects are expected.

Summary

In this series of experiments the side force produced on an axisymmetric nozzle was measured when the flow at the nozzle entrance section was inclined to the axis of symmetry of the nozzle. The side force in these measurements appeared to vary, according to predictions,[2-4] in a damped sinusoidal manner with nozzle length. However, the magnitudes of the forces observed were an order of magnitude less than those previously reported.

As noted in previously reported research, the flow at the nozzle throat was tilted with respect to the nozzle axis rather than at the nozzle entrance section. Tests conducted on a nozzle with a tilted throat obtained much larger side force, comparable to those previously reported. It can be concluded that the magnitude of the side force depends on where the flow inclination or misalignment occurs. When the flow is inclined at the nozzle throat, the downstream effect is large. When the flow is inclined in the plenum upstream of the nozzle, its downstream effect is smaller by an order of magnitude.

Acknowledgment

The authors wish to acknowledge the contributions of Richard Aurandt, who assembled and prepared the model for testing and who was instrumental in running the tests.

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