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Flowfield Computations in Rotating Propulsive Nozzles

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Abstract

An analysis is presented for calculating the flowfield and the forces and moments acting on the supersonic section of a propulsive nozzle during both nozzle and vehicle rotations. The governing equations are derived in a noninertial reference frame attached to the nozzle for the most general case where the nozzle has both angular velocity and acceleration with respect to the vehicle and the vehicle has both angular velocity and acceleration as well as linear acceleration with respect to Earth. The resulting equations are placed in characteristic form for steady, three-dimensional, nonequilibrium, chemically reacting, supersonic flow. A production computer program was developed to compute the flowfield using a second-order, three-dimensional, bicharacteristic method. Examples are presented to illustrate the type of results that can be expected.

Contents

A common method of thrust vector control for solid propellant rocket motors is based on rotating the nozzle, thus generating side forces and torques due to the change in direction of the gas flowfield. In most applications, the rate of rotation and nozzle flow rates are such that the forces due to the angular motion are relatively small and may be ignored. However, for fast response systems using very large nozzles and high chamber pressures, the gasdynamic forces due to angular motion of the nozzle and/or vehicle may be significant. The angular motion of the nozzle and/or vehicle causes the flowfield to become three-dimensional even if the nozzle geometry is axisymmetric. Thus, to determine the flowfield requires using a three-dimensional algorithm.

The objective of this study was to develop an analysis for calculating the flowfield and the forces and moments acting in a propulsive nozzle during nozzle and vehicle rotations. The approach consisted of expanding an existing computerized analysis for steady, three-dimensional, nonequilibrium, chemically reacting, supersonic flow to include momentum equation terms due to nozzle and vehicle rotations. The existing computer program was based on the work of Ransom et al.[1] and Cline and Hoffman.[2] The governing equations were derived for the most general case where the nozzle has both angular velocity and acceleration as well as linear acceleration with respect to Earth. A numerical integration procedure based on a three-dimensional method of characteristics was developed. The principal modifications consisted of incorporating into the analysis the appropriate body forces to account for the angular velocity and acceleration of the vehicle and/or nozzle. The calculation technique is restricted to the expansion section of the nozzle due to the assumption of supersonic flow. The assumption of steady flow restricts the program to the analysis of flows that are at least quasisteady.

Figure 1 illustrates the physical arrangement. Cartesian coordinate system XYZ is an intertial reference frame attached to Earth. The vehicle is located at the position $\bar{R}_V$ and may have the linear velocity $\bar{V}_V$, the linear acceleration $\bar{a}_V$, the angular velocity $\bar{\omega}_V$ and the angular acceleration $\bar{\alpha}_V$, all with respect to the inertial reference frame XYZ. Cartesian coordinate system $x'y'z'$ is a noninertial reference frame attached to the vehicle. The nozzle center of rotation is located at the position $\bar{r}'_N$ with respect to coordinate system $x'y'z'$, and it is fixed in that reference frame. The nozzle may, however, have the angular velocity $\bar{\omega}_N$ and the angular acceleration $\bar{\alpha}_N$ with respect to the vehicle coordinate system $x'y'z'$. Cartesian coordinate system xyz is a noninertial reference frame attached to the nozzle.

The forces and torques acting on the nozzle are obtained by solving for the flowfield in the nozzle relative to the nozzle reference frame. That is accomplished by expressing the governing equations in the noninertial reference frame xyz. The governing equations are the continuity equation, the component momentum equations, the energy equation, and the equations of state. A complete discussion of those equations is given by Hoffman et al.[3]

A three-dimensional bicharacteristic method was used to solve the system of governing equations. A planar initial-value surface is specified in the nozzle throat region, and the

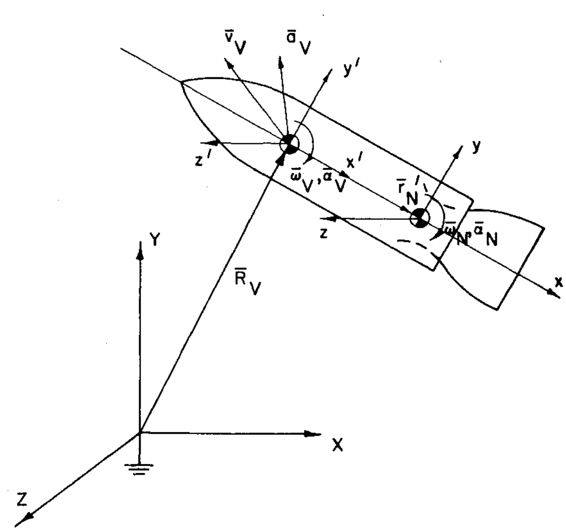

Fig. 1 Physical arrangement.

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Index categories: Solid and Hybrid Rocket Engines; Nozzle and Channel Flow; Supersonic and Hypersonic Flow.

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Table 1 Geometric parameters and thermodynamic properties

Throat diameter, m	0.613	Chamber pressure, N/m^2	2.41×10^7
Exit plane diameter, m	1.353	Chamber temperature, K	3326.1
Length (throat to exit), m	1.193	Specific heat ratio	1.15
Initial expansion angle, deg	26.0	Molecular weight	26.71
Exit lip angle, deg	13.7	Ambient pressure, N/m^2	1.01×10^5

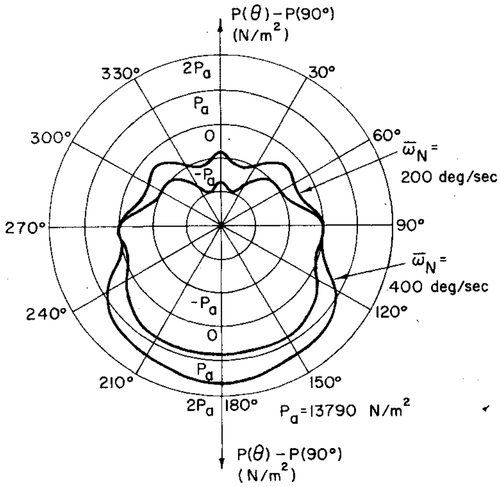

Fig. 2 Exit plane wall pressure profile.

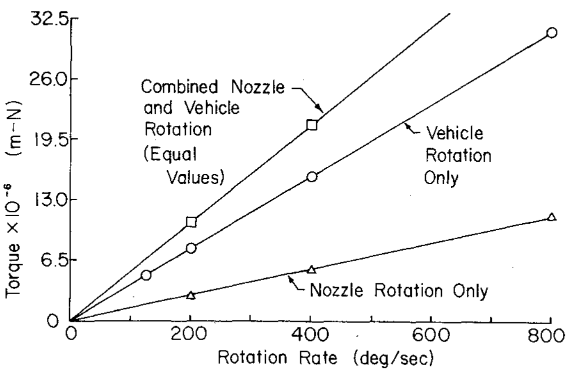

Fig. 3 Torque as a function of rotation rate.

integration scheme follows streamlines passing through the points on that surface. The solution is generated on a series of parallel planes that are located by the Courant-Friedrichs-Lewy stability criterion which requires that the difference network must always include the domain of dependence of the differential equations. The final solution plane corresponds to the nozzle exit plane. After each solution surface is computed, the three thrust components, the three torque components, and the mass flow rate are calculated.

The flow entering the nozzle orginates in the solid rocket motor. Consequently, the determination of the initial-value data in the throat region requires the solution for the subsonic flowfield in the solid propellant grain. When the vehicle is accelerating or rotating, the noninertial force terms must be accounted for in that flowfield also. Moreover, if the nozzle axis is not aligned with the motor axis, then the nozzle entrance flowfield is three-dimensional. Thus, the general initial-value flowfield is quite complicated. The computer program allows the tabular input of the initial-value data.

Numerical results are now presented for an axisymmetric nozzle undergoing rotation in the pitch plane. The geometric parameters defining the elliptically contoured nozzle are presented in Table 1. Also presented in this table are the thermodynamic properties of the flow. The thermodynamic model was assumed to be the isentropic flow of a thermally and calorically perfect gas.

The initial-value surface was generated from a modified version of the transonic flow analysis developed by Kliegel and Levine.[4] The two-dimensional method of characteristics was used in conjunction with this analysis to obtain the planar supersonic initial-value surface required by the three-dimensional algorithm. The effects of vehicle rotation were not accounted for in this calculation.

The nozzle exit plane circumferential wall pressure profile is presented in Fig. 2. The radial dimension is the difference between the local wall pressure and the wall pressure at nozzle circumferential positions of 90 deg or 270 deg. The nozzle is rotated in an upward direction which results in an increase in the pressure on the bottom, or 180 deg position, of the nozzle and a decrease in pressure on the top, or 0 deg positon, of the nozzle. Increasing the nozzle rotation rate from 200 deg/s to 400 deg/s increases the distortion of the pressure profile as expected. The wall pressure at the exit plane for zero nozzle rotation is 1.1549×10^6 N/m^2. The wall pressure at 180 deg for a toration rate of 400 deg/s is increased by 2.3442×10^4 N/m^2, and the wall pressure at zero degrees is reduced by 2.4131×10^4 N/m^2. The wall pressure at 90 deg and 270 deg is 1.1542×10^6 N/m^2 and is essentially unaffected by nozzle rotation.

The effect of nozzle and vehicle rotation rates on torque is shown in Fig. 3. Torque is seen to be linear with rotation rate for both nozzle and vehicle rotations. Figure 3 also indicates that for combined nozzle and vehicle rotations the torque is simply the sum of the torques due to nozzle rotation alone and vehicle rotation alone.

Acknowledgment

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References

[1] Ransom, V.H., Hoffman, J.D., and Thompson, H.D., "A Second-Order Bicharacteristics Method for Three-Dimensional, Steady, Supersonic Flow," *AIAA Journal,* Vol. 10, Dec. 1972, pp. 1573-1581.

[2] Cline, M.C. and Hoffman, J.D., "The Analysis of Nonequilibrium, Chemically Reacting, Supersonic Flow in Three Dimensions Using a Bicharacteristics Method," *Journal of Computational Physics,* Vol. 12, May 1973, pp. 1-23.

[3] Hoffman, J.D., Vadyak, J., and Whitesides, R.H., "Analysis of the Effects of Rotation on the Thrust and Torque Developed by Propulsive Nozzles, Vol. I, Theoretical Development," Rept. No. U-77-09, Thiokol/Huntsville Division, Huntsville, Ala., Oct. 1977.

[4] Kliegel, J.R. and Levine, J.N., "Transonic Flow in Small Throat Radius of Curvature Nozzles," *AIAA Journal,* Vol. 7, July 1968, pp. 1375-1378.