have no bearing upon the spin of the rocket, which as stated before, remains constant.

The authors begin their analysis by stating that "the governing equations for the model can be written in a slightly modified form from Thomson."[2] Here lie the origins of misunderstanding. Thomson's model includes a cluster of nozzles, and in writing $\Sigma_i \dot{m}_i r_i^2$ he performs a summation of all the jets issuing from separate nozzles—a very different proposition from summing all the streamlines over a single nozzle, as in Ref. 1. Thus, in the case of Thomson's model, the rate of angular momentum loss along the axis of symmetry is indeed proportional to the spin velocity of the rocket, at least to the first degree of approximation. Variations in spin velocity of the rocket shown in Thomson's example are amenable to logical interpretation by assuming that all radially located nozzles are fed from a common fuel tank (or fuel core, if one insists upon interpreting his results in terms of a solid-fuel rocket) coaxial with the spin axis of the rocket. In such a case radial routing of the fuel and/or gases along some channels would provide the mechanism for production of Coriolis forces necessary for spin changes of the rocket.

Although data from actual flights do not bear out the phenomena reported in Ref. 1, small variations in the spin velocity of thrusting space rockets are commonly observed.[3] These are usually attributed to small jet damping in spin, which may result from complex phenomena associated with more elaborate geometries of the fuel core. The effect of a small spin torque that may be present due to combined thrust eccentricity and misalignment is negligible. Another source of spin velocity variations, which appears to have escaped attention so far, and yet is likely to be relatively large, exists in the form of a body-fixed transverse moment due to thrust. When a uniformly spinning, perfectly symmetric rocket is subjected to a body-fixed transverse moment due to thrust, the spin axis of the rocket originally coincident with the axis of symmetry tilts through an angle $\beta = -M/(I_x - I_y)n^2$, where M is the moment, n is the spin velocity of the rocket, and I_x and I_y are the roll and pitch moments of inertia, respectively. Since β is small and M is a purely transverse moment, it follows that the spin momentum about the new axis will be equal to the original spin momentum about the axis of symmetry. It is rather evident, therefore, that this rotational shift in the spin axis will be accompanied by a decrease in the spin velocity. As burning continues, M will increase and $(I_x - I_y)$ will decrease the two effects, resulting in a large increase of β; for a typical rocket, this increase of β is of an order of ten. As a consequence, a noticeable gradual drop in the spin rate during the later stages of burning may be produced, to be followed by a sharp increase in the spin rate immediately after burnout when the spin axis returns to the axis of symmetry. One should also note that misalignments and offsets (between the nozzle and fuel core, nozzle and spin axis, etc.) associated with formation and presence of moment due to thrust create conditions favorable for production of small Coriolis forces in transverse planes and small jet damping in spin. Postflight data from spin-stabilized solid-fuel rockets, based upon signal strength fluctuations, which this writer has examined, appear to support the foregoing, somewhat intuitive, deductions. This writer hopes that these deductions are sufficiently interesting (or provoking) to prompt other workers to a critical formal investigation of the subject.

References

[1] Warner, G. G. and Snyder, V. M., "A Re-Evaluation of Jet Damping," *Journal of Spacecraft and Rockets*, Vol. 5, No. 3, March 1968, pp. 364–366.

[2] Thomson, W. T., *Introduction to Space Dynamics*, Wiley, New York, 1961, pp. 221–227.

[3] Thomson, W. T. and Reiter, G. S., "Jet Damping of a Solid Rocket: Theory and Flight Results," *AIAA Journal*, Vol. 3, No. 3, March 1965, pp. 413–417.

Reply by Authors to P. Katz and to T. Papis

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THE comments are concerned with the basic assumption that the gases in the exit plane are rotating with the same angular velocity as the body. In the real vehicle this assumption may not be correct, but an accurate time history of the gas particles is difficult to obtain. The analysis could be modified as indicated by Katz if the rotational velocity were known a priori. It was indicated in both comments that no jet damping would be present for a frictionless gas. The authors' analysis[1] would give an upper bound to the effect of jet damping.

The mechanism for the transfer of angular momentum between the burned fuel and the vehicle is very complex. For the analysis presented by Warner and Snyder, the needed mechanism could be furnished best by a liquid-propellant rocket. The injector plate of the rocket engine would impart to the fuel some of the angular velocity required for the momentum transfer. A solid-propellant rocket is much easier to model mathematically than the liquid rocket but would rely mainly on the viscous effect of the gas.

Papis discussed other effects which could change the spin of the vehicle, and these effects may be greater than the jet damping. The authors are pleased with these constructive comments, for it is through discussions of this nature that knowledge is disseminated.

References

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Comment on "Shock-Wave Shapes around Spherical- and Cylindrical-Nosed Bodies"

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A KNOWLEDGE of shock-wave shape and detachment distance around hypersonic blunt bodies is important for estimating shock-wave interference effects on winged- or finned-body missile configurations, for calculating re-entry body convective heating in the presence of large inviscid shock-layer entropy gradients, and for predicting radiative heat transfer from the high-temperature shock layers around manned superorbital re-entry vehicles (to mention just a few examples). Such knowledge can be obtained from detailed, numerical blunt-body flowfield analyses that give solutions

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