Solid Rocket Motor Combustion Chamber Aeroacoustics

Warren C. Strahle* and John C. Handley†
Georgia Institute of Technology, Atlanta, Ga.

Abstract

A SOURCE of solid rocket motor vibration is investigated by treating the problem of pressure fluctuations inside the motor cavity. Theoretical aeroacoustics is applied to the cavity gases and imbedded burning metal agglomerates. Several critical experiments are performed to provide numerical input to the theory. Consideration of turbulence, combustion, and entropy noise yields the conclusion that only one cause is dominant for the fluctuations in chamber pressure—that of interaction of turbulence with the exhaust nozzle. Typically, an 0.4% rms pressure fluctuation can be accounted for by this mechanism. Spectral distributions of the noise are presented and a comparison is made of the theory and an actual motor firing.

Contents

Rocket motor vibration is caused by a variety of sources, including pressure fluctuations inside the motor cavity. Such pressure fluctuations are the dominant vibration source in exospheric operation. Traditionally, the propulsion community has resigned itself to acceptance of a background chamber pressure noise level of the order of 1% of the mean pressure. There has been little concern over the cause of such fluctuations, or their reduction, except in cases where 1) they have substantially exceeded the 1% level, or 2) they have become phase coherent instabilities in a motor. There are, of course, reasons why it would be desirable to reduce the fluctuation level or at least understand the design parameters which influence the level. This program was conducted to understand the origin and scaling rules of the chamber pressure fluctuations in solid rocket motors.

In the backup report[1] a general theory of aeroacoustics of the gases in the motor cavity is developed. It is based upon a modified Lighthill[2] formalism for aeroacoustics. Included are the effects of propellant heterogeneity, turbulence of the chamber gases, burning of metal agglomerates, condensed phase drag, and feedback response of the propellant to incident pressure waves. The theory is restricted to frequencies below that of the first transverse acoustic mode of the chamber gases, although there is no restriction on frequency with respect to longitudinal resonances. The theory is restricted quantitatively to chambers with a nearly constant cross-section flow area vs axial distance. Excluded in the theory are erosive burning effects, although these are given some consideration in the experiments cited below. A stationary random fluctuation of pressure in the chamber gases is considered, and this requires that the motor be stable.

The sources of motor pressure fluctuations which emerge from the theory or are explicitly introduced into the theory are 1) combustion noise due to the propellant heterogeneity, in the case of a composite propellant, 2) combustion noise due to the burning of metal agglomerates in a turbulent field, in the case of metallized propellants, 3) turbulence encountering the flow restriction of the exhaust nozzle, 4) volume-distributed turbulence of the chamber gases, and 5) hot spots encountering the pressure gradient of the nozzle. The basic analytical result is an expression for the Fourier transform of the pressure fluctuation p_ω which is a sum of terms due to the individual noise sources. For example, the term for noise caused by turbulence encountering the nozzle (this is called vorticity-nozzle interaction noise) is

$$p_{\omega_{VN}}(x) = \int_{S_e} g_\omega(x,y) \frac{\partial}{\partial y_i} (T_{il})_\omega \, dS(y) \tag{1}$$

Here g_ω is the cavity Green's function for one-dimensional oscillations, which is calculated from the theory, x and y are axial distance, S_e is the nozzle entrance plane area, ω subscripts indicate a Fourier transform, and T_{il} is the il component of the Reynolds stress $\rho_e u_i u_l$. The 1 direction is axial.

In order to estimate the order of magnitude of the various terms in the theory, detailed spectral and spatial correlation data for fluctuating quantities are needed which are simply not available. Accordingly, several simple experiments were performed to provide numerical input to the theory, and the turbulence structure was assumed that of pipe flow[3] as modified by the results of Ref. 4. Experiments were conducted to determine 1) the magnitude and spectral content of combustion noise generated near the surface of a propellant, 2) the effect on part 1 of a crossflow to determine erosive burning effects, and 3) the magnitude and spectral content of temperature fluctuations in the flow downstream of the main combustion zone. The experiments were run at several elevated pressures and with several propellant types, metallized and nonmetallized, composite and CMDB.

Other inputs to the theory required are the nozzle acoustic behavior and the feedback response law of the propellant. For computational purposes, short nozzle theory was used and the "A-B" model[5] of the propellant response was adopted.

Subject to qualifications mentioned later, the conclusion of the experiments and theory was that there is a single dominant pressure fluctuation source, and it is due to the mechanism of Eq. (1). After several approximations, the spectral density of the pressure fluctuations may be constructed from Eq. (1) and the result is

$$G_p = \rho_e^2 \omega^2 g_\omega g_\omega^* S_e \frac{l_e^2}{[1 + (l_e S_t / D)]^2} G_u \tag{2}$$

Here ρ_e is the mean gas density entering the nozzle, ω is circular frequency, l_e is the integral transverse scale for axial velocity fluctuations, D is the port diameter, and G_u is the

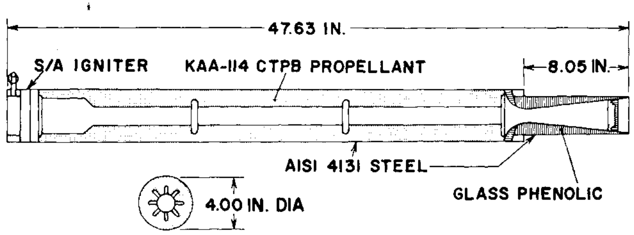

Fig. 1 Cutaway view of solid propellant motor.

Received May 10, 1978; revision received Aug. 15, 1978. Full paper available from National Technical Information Service, Springfield, Va., 22151 as N78-28170 at the standard price (available upon request).

Index categories: Noise; Combustion and Combustor Designs; Structural Dynamics.

*Regents' Professor of Aerospace Engineering. Associate Fellow AIAA.

†Senior Research Engineer. Member AIAA.

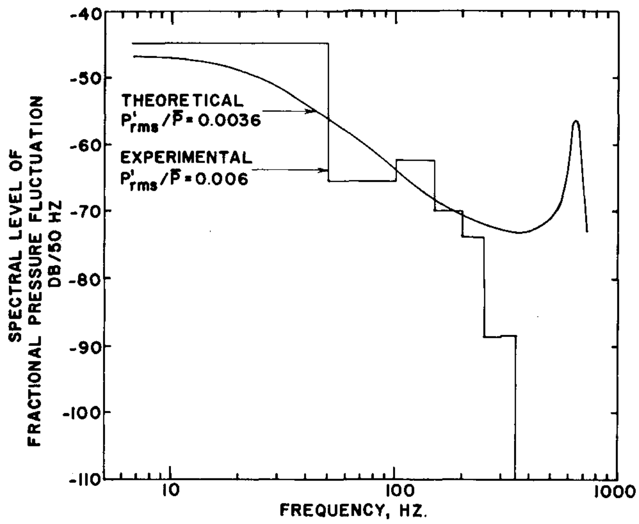

Fig. 2 Comparison of theoretical and experimental spectra for motor of Fig. 1.

spectral density of axial turbulent velocity fluctuations. S_t is the Strouhal number defined by $S_t = \omega D/u_e$, where u_e is the gas velocity at the nozzle entrance plane.

For approximation purposes an analytical form for the Green's function, valid at low frequencies, was developed. It is

$$g_\omega g_\omega^* = l \Big/ \left[M_e^2 S_e k^2 \left(\frac{5-\gamma}{2} - \gamma\bar{\mu}\right)\left(\frac{5-\gamma}{2} - \gamma\bar{\mu}\right)^* \right] \qquad (3)$$

Here M_e is the Mach number at the nozzle entrance plane, k is the wave number, γ is the specific heat ratio, and $\bar{\mu}$ is the propellant response function. The asterisk denotes a complex conjugate. In actual computations, the exact Green's function was used, and for estimation purposes Eq. (3) was used.

Comparison of Eq. (2) with experiment for the Hercules/ABL motor of Fig. 1 is presented in Fig. 2. The calculation is carried out to frequencies just beyond that of the first longitudinal mode; higher frequencies do not add anything further to the mean square pressure. The experimental spectrum from a Kistler transducer mounted in the head end is also seen in Fig. 2. While the overall rms level is predicted with remarkable accuracy, considering the approximations introduced, the experimental spectrum is shifted to lower frequencies as compared with theory.

The following conclusions were derived from the work:

1) There is a single noise source which is dominant in producing pressure fluctuations within a solid rocket motor cavity. This noise is caused by turbulence encountering the exhaust nozzle and is dominant whether or not the propellant is metallized or is composite. The only caveats are that a) there is a possibility that at low-port-to-throat the turbulence distributed through the chamber volume may become important as a noise source, and b) there is still an unknown effect of turbulence interaction with the flame zone near the propellant surface, which may be an additional noise source.

2) The noise floor due to the mechanism just mentioned is at a level of roughly 0.4% fluctuation of chamber pressure, is low frequency in nature, and can be larger than the stated level if the motor grain design induces a high turbulence level in the chamber gases.

3) The nosie level is predictable but the spectral distribution needs some further experimental work, because the theory predicts a slower high frequency roll-off than is indicated experimentally.

4) For simple motor geometry the noise considered is relatively invariant with motor design variables, when quoted as the magnitude of the fractional pressure fluctuation.

5) A simple theory of aeroacoustics, based upon the Lighthill approach, has recovered all of the expected physics of the noise problem. It allows a framework to calculate noise magnitudes excluded here if future experimental work shows the neglected sources should be included.

6) As opposed to results of instability analysis, the effects of metal and metal oxide damping and of the propellant feedback response functions are weak in noise analysis, as long as one is reasonably well removed from a stability limit.

7) If the source frequencies are primarily below that of the first transverse acoustic mode of the chamber gases, the pressure oscillations and, hence, the motor vibration is purely axial, except for manufacturing misalignments and small local, rather than global, pressure fluctuations.

Acknowledgments

This work was supported by the U.S. Army Ballistics Missile Defense Agency Advanced Technology Center under Contract No. DASG60-77-C-0054.

References

[1] Strahle, W. C. and Handley, J. C., "Prediction of Combustion Induced Vibration in Rocket Motors," U.S. Army Ballistic Missile Defense Agency, Advanced Technology Center, Final Rept. Contract No. DASG60-77-C-0054, April 1978.

[2] Lighthill, M. J., "On Sound Generated Aerodynamically; I. General Theory," *Proceedings of the Royal Society, London*, Ser. A211, 1952, pp. 564-578.

[3] Laufer, J., "The Structure of Turbulence in Fully Developed Pipe Flow," NACA TR 1174, 1954.

[4] Yamata, K., Soto, M., and Ishikawa, N., "Simulative Study on the Erosive Burning of Solid Rocket Motors," *AIAA Journal*, Vol. 14, Sept. 1976, pp. 1170-1176.

[5] Culick, F. E. C., "A Review of Calculations for Unsteady Burning of a Solid Propellant," *AIAA Journal*, Vol. 6, Dec. 1968, pp. 2241-2254.