JOURNAL OF PROPULSION AND POWER
Vol. 21, No. 1, January–February 2005

Technical Comments

Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the Journal of Propulsion and Power *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Comment On Dotson et al. "Structural Dynamic Analysis of Solid Motor Resonant Burning"

R. O. Hessler* and R. L. Glick†

THIS Article stresses the importance of motor pressure oscillation amplitudes in defining structural design load criteria for small, economical launchers. It also associates the pressure oscillations with combustion instability and vortex shedding. The purpose of this Comment is to present additional perspectives and research bearing on the problem.

Classical combustion instability theory[1] considers inviscid, irrotational flow in a stationary, rigid chamber containing homogeneous propellant and solely acoustic perturbations to obtain the transient solution for the motor acoustic modes. The transient solution contains no information about the amplitudes of oscillations in a motor, only whether such oscillations as might exist would grow or decay.

In reality, the flow is rotational, containing flow noise in the form of turbulence and vortices. A motor in flight is accelerating, and the case and propellant are nonrigid and vibrating. The propellant is commonly heterogeneous and often metallized, both causing combustion noise. When classical theory is extended to include these additional perturbations, the classical transient solution is augmented by a forced solution exactly analogous to that for structural vibrations.[2] Each of the nonacoustic perturbations acts as a forcing function to cause finite steady oscillations, even if the acoustic modes are rock-solid stable. Given empirical or analytical models for the forcing functions, the forced solution can be used to predict the time-varying spectra of motor pressure oscillations and, therefore, the force input to the airframe.

The extended theory indicates that motor acoustics are responsive to vibration of the motor's internal acoustic boundary and will consequently interact with the structural modes of the case and the flight vehicle or static firing stand. Because the compliance of the supporting structure is markedly different between flight and static firings, and because flight operation includes additional nonacoustic forcing functions due to vehicle buffeting and maneuvering, motor pressure oscillations should be expected to differ between flight and static firings. Furthermore, acceleration and vibration of the propellant burning surfaces can significantly affect the propellant burning rate and the surface retention, agglomeration, and combustion of metal additives,[3,4] which will affect the acoustics. Although the difference between static and flight environments (or between heavyweight and flight-weight motor cases) is generally considered small, very significant differences between static and flight acoustic behavior have been observed in several motors.[5] Consequently, reliance on static firing data alone to set structural design loads involves potentially significant risks, particularly as spin or transverse maneuvering accelerations are increased.

The extended theory indicates that the convected pressure perturbations associated with the passage of vortex or turbulence centers act as forcing functions to cause pressure oscillations, even in stable motors. The low-pressure distribution about a center of rotation tends to be hyperbolic, nonsinusoidal, and, therefore, rich in harmonics. Consequently, the presence in pressure spectra of harmonics unrelated to acoustic or structural mode frequencies should be considered probable evidence of vortex causation.

Analyses of log-magnitude spectra of motors during successive episodes of vortex-induced oscillations often indicate the simultaneous presence of multiple harmonics with fundamentals usually much lower than the axial mode frequencies, which suggests that the vortex generation frequencies are often quite low. This, in turn, suggests that the decreasing-frequency tracks observed in the Peacekeeper motor (Ref. 6, Fig. 3) represent the passage of fourth and fifth harmonics of the vortex frequency through the locale of the acoustic mode frequency.

There is also considerable evidence of more than one system of vortexes being generated concurrently (indicated by the presence of multiple sets of harmonics near the modes at the same time during larger episodes).[7] This suggests seeding of broaderband vortices at downstream discontinuity locations by narrowband vortex systems generated at upstream discontinuities.

Analysis of observed harmonic relations in monolithic motors with lengths to 4 m indicates a correlation of vortex generation frequencies with port velocity U and diameter D at the discontinuity causing a particular vortex system:

$$f_v = S_r(U/D) \tag{1}$$

This relation differs markedly from Eq. (2) of Ref. 6, which is based on the length from a causative discontinuity to the nozzle. However, several types of vortex phenomena have been reported,[8–10] so that the two relations may represent different types.

Two forms of variations in motor fast Fourier transform magnitudes are observed the square-root normal distribution characteristic of normally distributed time-domain variables and variations in the time when a vortex harmonic crosses a mode. Propellant temperature effects will cause harmonics of a vortex system correlated with Eq. (1) to cross the modes systematically at variable times.

Lower motor temperature reduces propellant burning rate and extends motor burning time, causing vortex-mode crossings to occur at later absolute times. Therefore, comparisons between motors should be made on normalized pressure–time scales.[11,12]

Lower temperatures also dilate the motor port area because of propellant shrinkage, which tends to reduce vortex frequencies more than axial mode frequencies, causing vortex-mode crossings to occur at earlier normalized time. The port area dilation distorts propellant surfaces, dependent on propellant modulus, which varies widely among propellants, between propellant mixes, and with propellant

Received 18 November 2002; revision received 8 April 2003; accepted for publication 8 April 2003.

*Consultant, 93 Cryer Cove Road, Somerville, AL 35670; rohesslerl@aol.com.
†Consultant. Associate Fellow AIAA.

age. Because the distortions are most variable near grain discontinuities, appreciable variation of vortex-mode crossing times should be expected.

The vorticity available for vortex formation arises primarily from the mean flow mass addition loss, the rotation of the inflow from burning propellant surfaces toward the nozzle. Although the mass addition loss is usually small relative to the mean flow, the potential rotational energy is usually large relative to the acoustic energy and is often the larges: nonacoustic perturbation. Consequently, motor temperature effects on vortex-mode crossing times also cause variations of the potential vortex strength and, ultimately, variations of pressure oscillation amplitudes. Although the vorticity can not be eliminated because the mass addition loss is always present, the propensity of the vorticity to form into vortices can be greatly inhibited by deliberate design to avoid internal flow discontinuities and maintain accelerating flow.[13,14]

The acoustic–structural analogy enables application of structural analysis tools (such as the use of Burg's method in modal analysis) to the motor acoustics problem to extract estimates of both acoustic mode properties and forcing function properties.[11,15] Systematic correlation of acoustic behavior with propellant temperature and static and flight accelerations that use this cross-disciplinary approach appears to offer a productive path to better understanding of the variations of pressure oscillation amplitudes, vortex formation, and flight effects.

References

[1]Culick, F. E. C., and Yang, V., "Prediction of the Stability of Unsteady Motions in Solid-Propellant Rocket Motors," *Nonsteady Burning and Combustion Stability of Solid Propellants*, edited by L. T. DeLuca, E. W. Price, and M. Summerfield, Vol. 143, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1992, pp. 719–779.

[2]Deur, J. M., and Hessler, R. O., "Forced Oscillation Theory," AIAA Paper 84-1356, July 1984.

[3]Anderson, J. B., and Reichenbach, R. E., "An Investigation of the Effect of Acceleration on the Burning Rate of Composite Propellant," *AIAA Journal*, Vol. 6, No. 2, 1968, pp. 271–277.

[4]Brundige, W. N., and Caveny, L. H., "Low Burning Rate Aluminized Propellants in Acceleration Fields," *AIAA Journal*, Vol. 22, No. 5, 1984, pp. 638–646.

[5]Blomshield, F. S., "Historical Perspective of Combustion Instability in Motors: Case Studies," AIAA Paper 2001-3875, July 2001.

[6]Dotson, K. W., Womack, J. M., and Grosserode, P. J., "Structural Dynamic Analysis of Solid Motor Resonant Burning," *Journal of Propulsion and Power*, Vol. 17, No. 2, 2001, pp. 347–354.

[7]Traineau, J.-C., Prevost, M., Vuillot, F., LeBreton, P., Cuny, J., Preioni, N., and Bec, R., "A Subscale Test Program to Assess the Vortex Shedding Driven Instabilities in Segmented Solid Rocket Motors," AIAA Paper 97-3247, July 1997.

[8]Flandro, G. A., "Vortex Driving Mechanisms in Oscillatory Rocket Flows," *Journal of Propulsion and Power*, Vol. 2, No. 3, 1986, pp. 206–214.

[9]Sukhinin, S. V., and Achmadeev, V. F., "Hydrodynamic Sources of Oscillations in Combustion Chambers," *Combustion, Explosion, and Shock Waves*, Vol. 29, No. 6, 1993.

[10]Lupoglazoff, N., and Vuillot, F., "Parietal Vortex Shedding as a Cause of Instability for Long Solid Propellant Motors—Numerical Simulations and Comparisons with Firing Data," AIAA Paper 96-0761, Jan. 1996.

[11]Hessler, R. O., Glick, R. L., Bertelé, R., Cedro, D., Fiorentino, G., and DeLuca, L. T., "Frequency Response of a Model Subscale Rocket Motor," *Combustion of Energetic Materials*, edited by K. K. Kuo and L. T. DeLuca, Begell House, New York, 2002, pp. 889–902.

[12]DeLuca, L. T., Morandi, C., Ratti, A., Annovazzi, A., Tosti, E., Hessler, R. O., and Glick, R. L., "Burning Rate Data Reduction of Ariane Boosters Small-Scale Test Motors," *Proceedings of the 2nd European Conference on Launcher Technology*, Centre National d'Etudes Spatiales, Toulouse, France, Aug. 2001.

[13]Hessler, R. O., "Design Strategies to Avoid 'Spontaneous Combustion Instability' Almost Entirely," *Workshop on Measurement of Thermophysical and Ballistic Properties of Energetic Materials*, Politecnico di Milano, Milan, June 1998.

[14]Hessler, R. O., Glick, R. L., Bertelé, R., Cedro, D., Fiorentino, G., DeLuca, L. T., Pastrone, D. G., Saretto, S. R., and Vassallo, E., "Acoustic Response of a Model Rocket Chamber," *Proceedings of the 2nd European Conference on Launcher Technology*, Centre National d'Etudes Spatiales, Toulouse, France, Aug. 2001.

[15]Hessler, R. O., Glick, R. L., DeLuca, L. T., Tion, C., Stramezzi, F., Bertele, R., and Cedro, D., "Passive Stability Measurements in a Model Rocket Motor," Associazione Italiana di Aeronautica e Astronautica AIDAA, Sept. 2001.

JOURNAL OF PROPULSION AND POWER
Vol. 21, No. 1, January–February 2005

Technical Comments

Brief discussion of previous investigations in the aerospace sciences and technical comments on papers published in the Journal of Propulsion and Power *are presented in this special department. Entries must be restricted to a maximum of 1000 words, or the equivalent of one* Journal *page including formulas and figures. A discussion will be published as quickly as possible after receipt of the manuscript. Neither the AIAA nor its editors are responsible for the opinions expressed by the correspondents. Authors will be invited to reply promptly.*

Reply to Technical Comment from R. O. Hessler and R. L. Glick

K. W. Dotson*
The Aerospace Corporation,
Los Angeles, California 90009-2957

THE interest in Ref. 1 shown by these two readers is appreciated. As mentioned in Ref. 1, although solid rocket motor pressure oscillations have been studied for decades, the impact of these oscillations on structural integrity has received little attention. Three major points in the Comment are addressed in this reply.

First, Hessler and Glick[2] note that the frequency of vortex generation in motors up to 4 m in length has been observed to be inversely proportional to the motor internal diameter, not to an axial motor distance, as indicated by Eq. (2) of Ref. 1. The model in Ref. 1 postulates that the initiation of vortices at a propellant grain discontinuity and their subsequent "impingement" on a protruding inhibitor, or on the motor nozzle, constitutes a feedback loop.[3] Therefore, the time required for a vortex to travel this axial distance and for the sound thus generated to reach the initiation point defines the period of the vortex shedding. Harmonics of the corresponding frequency are sometimes also evident in pressure oscillation spectra.

Theoretical models and numerical simulations subsequently published by Anthoine et al.[4,5] generally support this form of aeroacoustic coupling for motors with large length-to-diameter ratios and recessed nozzles. However, in Refs. 4 and 5 it is shown that sound is generated not by impingement or destruction of the vortex at the nozzle entrance but rather by deviation of the vortex path caused by the nozzle recess. The data presented in Ref. 1 for the Peacekeeper solid rocket motor demonstrate that this feedback model, with a dependence on axial motor distance, may also explain pressure oscillations in single-segment motors that have a cavity forward of the nozzle throat.

The fact that frequency correlations with motor diameter have also been observed[2] suggests that a general relationship linking vortex shedding with both axial motor distance and motor diameter probably exists. The correlation with axial motor distance [Eq. (2) of Ref. 1] appears to model approximately the phenomenon for segmented motors with large length-to-diameter ratios (such as those used for the Titan IV, space shuttle, and Ariane 5 launch vehicles) but may not be applicable for motors that are not in this class.

Second, Hessler and Glick[2] correctly stress the importance of propellant temperature in the structural dynamic analysis of solid rocket motor pressure oscillations. The times when the vortex shedding and acoustic mode frequencies coincide do indeed systematically vary with propellant temperature, and this is evident in both Peacekeeper and Titan IV solid rocket motor upgrade (SRMU) spectra.[1,3] This point was not discussed in Ref. 1 because structural design loads were only sought for a nominal propellant temperature.

In Ref. 3, the timescales of the Titan IV SRMU pressure oscillation measurements were dilated for tests conducted at hot-propellant temperatures and were contracted for tests conducted at cold-propellant temperatures, to yield a family of four static firings with a nominal web action time. In Ref. 1, all 17 of the Peacekeeper test motors used for the loads predictions were conditioned to the same propellant temperature. Peacekeeper static firings conducted under extreme temperatures were not included in the forcing function set because of the effects of temperature on the pressure oscillation amplitude and frequency variations. Because 17 cases comprise a reasonable population for statistical loads analysis, it was deemed unnecessary to include hotter and colder static firings through the use of timescaling, such as that employed for the Titan IV SRMU. Spectral analyses were also conducted to confirm that the changes in vortex stage number for the 17 Peacekeeper static firings were consistent. The time intervals used for the statistical analysis of the pressure oscillation amplitudes (Table 1 and Fig. 6 of Ref. 1) were selected based on inspection of the frequency trends for the 17 static firings. In summary, the results presented in Ref. 1 are not compromised by propellant temperature effects.

Third, Hessler and Glick[2] point out that the propulsion system and the launch vehicle structure may interact. Consequently, they caution against reliance solely on static firing pressure oscillations in the development of forcing functions for flight loads predictions. Some published test data show that propulsion–structure interactions may exist and may have adverse effects. Carr et al.[6] concluded that an instability in retrograde rocket motors observed during a drop test of the Mars Pathfinder was caused by coupling of the motor pressure oscillations with structural vibration of the backshell structure. Harris and Wong[7] also found that structural vibration can affect pressure waveforms measured during pulse testing. However, the motors tested in both studies are very short, 0.83 and 0.51 m (Refs. 6 and 7), with respect to launch vehicle motors.

The theory presented by Deur and Hessler[8] accounts for the effects of structural motion on motor pressure oscillations. In Ref. 8, it is shown that, when the equations of motion are linearized, motor chamber vibration acts as a force that excites the motor's acoustic modes. However, this force is coupled with the perturbational acoustic pressure and, hence, generally alters the effective frequency and damping values of the acoustic modes. The solid rocket motor, therefore, may experience an interaction between oscillatory pressure and structural acceleration that can lead in some cases to self-excitation of the propulsion–structure system. An independent causative force such as combustion noise is required to initiate the acoustic and structural responses, which, under stationary conditions, eventually converge to a limit-cycle state.

The term forced oscillation is generally applied only if the external forces are independent of the resulting motion. The use of *forced oscillation* rather than *self-excitation* appears to have caused confusion in this field and has led some investigators[9] to conclude that all of the forcing functions developed by Deur and Hessler[8] are uncoupled from oscillatory pressure.

Received 7 March 2004; accepted for publication 9 March 2004.

*Senior Engineering Specialist, Structural Dynamics Department, P.O. Box 92957-M4/911. Associate Fellow AIAA.

Propulsion–structure interaction in launch vehicles with liquid rockets is called pogo and can have disastrous consequences in flight.[10] Stability analyses are conducted to establish the feed system design such that pogo in liquid rockets is avoided under a wide range of dispersed conditions.[11] For reasons that can currently only be speculated, it does not appear that any medium or large launch vehicle has experienced a catastrophic event induced by feedback between structure and the solid rocket motor thrust.[12] Nevertheless, the writer agrees with Hessler and Glick[2] that the potential for propulsion–structure interaction in launch vehicle motors should be assessed and that the existence of an interaction may call into question the sufficiency of static firing pressure oscillations for the development of loads analysis forcing functions.

It does not appear that flight data have been used to investigate rigorously if propulsion–structure interactions exist for launch vehicles with solid rocket stages. Provided that adequate instrumentation is available, the frequency, amplitude, and phase of flight motor pressure and structural accelerations can be computed to establish if feedback between motor vibration and thrust occurs. Such data analyses are very useful for establishing the existence of liquid rocket pogo.[13] As a result of the Comment, an investigation of propulsion–structure interaction in the Titan IV SRMU has been initiated. The findings from this data analysis will be presented at an upcoming AIAA conference.[14]

References

[1] Dotson, K. W., Womack, J. M., and Grosserode, P. J., "Structural Dynamic Analysis of Solid Rocket Motor Resonant Burning," *Journal of Propulsion and Power*, Vol. 17, No. 2, 2001, pp. 347–354.

[2] Hessler, R. O., and Glick, R. L., "Comment on Dotson et al. 'Structural Dynamic Analysis of Solid Motor Resonant Burning,'" *Journal of Propulsion and Power*, Vol. 21, No. 1, 2005, pp. 190, 191.

[3] Dotson, K. W., Koshigoe, S., and Pace, K. K., "Vortex Shedding in a Large Solid Rocket Motor Without Inhibitors at the Segment Interfaces," *Journal of Propulsion and Power*, Vol. 13, No. 2, 1997, pp. 197–206.

[4] Anthoine, J., Buchlin, J.-M., and Hirschberg, A., "Effect of Nozzle Cavity on Resonance in Large SRM: Theoretical Modeling," *Journal of Propulsion and Power*, Vol. 18, No. 2, 2002, pp. 304–311.

[5] Anthoine, J., Buchlin, J.-M., and Guéry, J.-F., "Effect of Nozzle Cavity on Resonance in Large SRM: Numerical Simulations," *Journal of Propulsion and Power*, Vol. 19, No. 3, 2003, pp. 374–384.

[6] Carr, C. E., Jr., McGrath, D. K., and Compton, L. E., "System-Induced Combustion Instability in the Retrograde Rocket Motor During Mars Pathfinder Development Drop Testing," *Joint Army–Navy–NASA–Air Force (JANNAF) Propulsion Meeting*, CPIA Publ. 680, Vol. 2, Chemical Propulsion Information Agency, Columbia, MD, 1998, pp. 511–526.

[7] Harris, P. G., and Wong, F. C., "The Influence of Structural Vibrations on Pulse-Triggered Nonlinear Instability in Solid Rocket Motors—An Experimental Study," AIAA Paper 96-3250, July 1996.

[8] Deur, J. M., and Hessler, R. O., "Forced Oscillation Theory," AIAA Paper 84-1356, June 1984.

[9] Culick, F. E. C., and Seywert, C., "Some Influences of Noise on Combustion Instabilities and Combustion Dynamics," *Joint Army–Navy–NASA–Air Force (JANNAF) Propulsion Meeting*, CPIA Publ. 691, Vol. 1, Chemical Propulsion Information Agency, Columbia, MD, 1999, pp. 461–487.

[10] Rubin, S., "Longitudinal Instability of Liquid Rockets Due to Propulsion Feedback (POGO)," *Journal of Spacecraft and Rockets*, Vol. 3, No. 8, 1966, pp. 1188–1195.

[11] Oppenheim, B. W., and Rubin, S., "Advanced Pogo Stability Analysis for Liquid Rockets," *Journal of Spacecraft and Rockets*, Vol. 30, No. 3, 1993, pp. 360–373.

[12] Chang, I.-S., "Investigation of Space Launch Vehicle Catastrophic Failures," *Journal of Spacecraft and Rockets*, Vol. 33, No. 2, 1996, pp. 198–205.

[13] Dotson, K. W., Rubin, S., and Sako, B. H., "Effects of Unsteady Pump Cavitation on Propulsion–Structure Interaction (Pogo) in Liquid Rockets," AIAA Paper 2004-2027, April 2004.

[14] Dotson, K. W., Sako, B. H., and Murdock, J. W., "An Investigation of Propulsion–Structure Interaction in Solid Rocket Motors," AIAA Paper 2004-4183, July 2004.