Recent Occurrences of Combustion Instability in Solid Rocket Motors—An Overview

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There has been, and undoubtedly will continue to be, frequent occurrences of unacceptable oscillatory combustion in the development of high-specific-impulse, high-volumetric-loading solid-rocket motors. Some of the observations of instability cannot be explained quantitatively using existing *T*-burner and stability-prediction procedures. The paper will present a review of the extent and types of oscillatory combustion encountered in recent solid rocket motor development efforts at Aerojet. The intent is to illustrate the prevalence of the occurrence of the phenomenon, to show examples of each of three forms of combustion instability which have plagued real motors, and to indicate what actions were taken to reduce or eliminate the instabilities.

Introduction

COMBUSTION stability in a solid propellant rocket motor depends on the balance between energy gains and losses of the system. If the system gains exceed the losses, an oscillation will be amplified in magnitude; if the losses exceed the gains, the opposite occurs. Thus, stabilization of an unstable motor reduces to either diminishing energy source factors (gains) or increasing the effectiveness of dissipation mechanisms (losses) in the system. When an instability occurs, then qualitatively, gains exceed losses.

Combustion instability is a phenomenon which has plagued solid rocket motor development for many years. Its occurrence has produced events ranging from unsatisfactory ballistic performance to tolerated pressure oscillations and missile vibration. Catastrophic failure of the motor or complete malfunction of the missile have also resulted. Since combustion instability results from an interaction of the burning process with the acoustic mode in the gas cavity, it is related to the propellant formulation, the changing acoustic cavity and motor operating conditions.

With the ever-changing design features and propellant formulations used in solid rocket motors, a variety of instabilities have occurred and various cures have been attempted to reduce to an acceptable level or completely eliminate pressure oscillations. Several motor programs conducted with Aerojet motors are reviewed where combustion instability occurred during development or production. The intent is to provide an overview of the various types of instabilities and what cures have been used in the past.

Types of Instabilities

The oscillatory stability state of a solid rocket motor is the net sum of those design features that influence the gain-loss balance. The principal contributing parameters are the motor geometry, grain configuration, propellant driving potential, and the inherent losses due to the nozzle, particles, or structure. Current and future missile systems are imposing more stringent requirements on performance and design constraints, i.e., volume or weight limitations. The designer is therefore limited in the options available to minimize or eliminate oscillatory combustion by the use of geometry or propellant changes.

Presented as Paper 73-1296 at the AIAA/SAE 9th Propulsion Conference, Las Vegas, Nev., November 5–7, 1973; submitted November 29, 1973; revision received July 24, 1974.

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Since one of the prime parameters of combustion instability is the acoustic mode of the gas cavity, it is natural to classify the various types of instability by the type of mode which became unstable and by the mechanism of interaction of the combustion process with the acoustic mode. Over the past decade, the leading offender has been an instability in the longitudinal or organ pipe mode in the chamber. More recently, with a return to smokeless propellants, the tangential modes of the chamber have exhibited instability as well. Two major classes of instability in the longitudinal modes have been identified as being related to the mechanism of the interaction of the combustion process and the acoustic mode (i.e., pressure-coupled and velocity–coupled instability). The acoustic behavior of a solid motor will be reviewed briefly with the associated forms of instability for reference. Illustrations of these various forms of instability in a variety of motors will then be reviewed to provide a general overview of what has occurred in solid rocket motor development programs.

A. Longitudinal Mode Instability

First a little acoustics: The interior gas flow passage of a solid rocket motor is a confined acoustic cavity. At operating conditions, the sonic nozzle throat forms essentially a closed end tube (acoustically speaking) and the longitudinal direction of the motor behaves as a closed-closed tube. For a simple motor geometry like a cylindrical bore the acoustic modes are identical to the organ pipe (closed-closed tube) modes. Figure 1 displays for a cylindrical bore, the conventional pressure modal distribution at two extremes of a standing acoustic wave in a closed-closed tube with the gas density illustrated by the dot density.

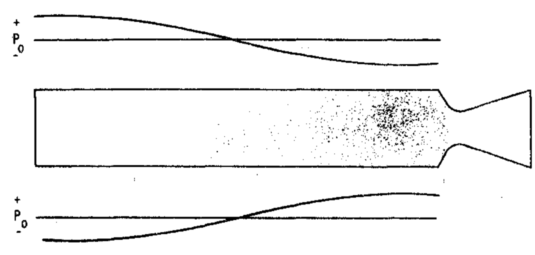

Fig. 1 Longitudinal modes.

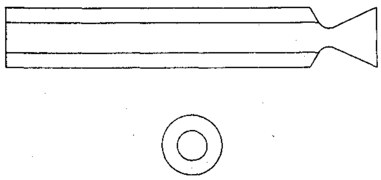

Fig. 2 Small tactical rocket motor.

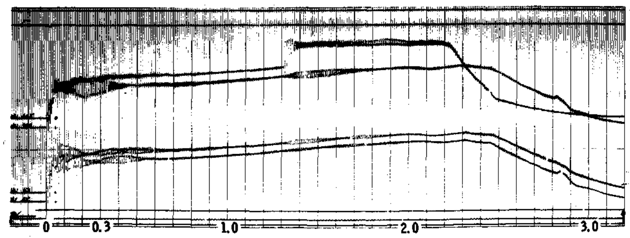

Fig. 3 Illustration of d.c. shift effects on motor thrust on small tactical motor quad tests.

During the time period between the first half cycle of oscillation (Fig. 1a to 1b), the gas particles are accelerated from one end of the chamber to the other, with a resultant particle velocity which varies in a sine function distribution. Both the acoustic pressure and the particle velocity variations are superimposed upon the mean chamber pressure and mean gas flow in the cavity.

Analytical treatments of combustion instability by McClure et al.,[1] and more recently by Culick,[2] have identified the interaction of the acoustic modes, the mean flow, and the combustion process. Their analyses have shown that in the presence of the burning surface the oscillating pressure can add energy to the acoustic mode. As previously indicated, when energy addition exceeds acoustic losses in the cavity the amplitude of the acoustic mode grows, or becomes unstable. In a similar sense the acoustic particle velocity, in conjunction with mean flow and pressure oscillations, can result in energy added to the acoustic mode which may also result in an increase in the oscillations. In this later interaction there can be an augmentation in the propellant burning rate resulting in a general increase in mean chamber pressure, usually called a d.c. shift. Within these very simple definitions of pressure-coupled and velocity-coupled instabilities those phenomena may be reviewed as observed in actual solid rocket motors and some of the design changes made to reduce or eliminate their occurrence.

Significance of instability: Before becoming completely lost in the instability, it is worth noting the significance of combustion instability, its range of severity and just what does it mean to a missile system. It must be emphasized that although we speak of an unstable condition or instability implying a self perpetrating increase in pressure oscillations, in actuality every oscillation will increase only to a limiting amplitude. In essence then the process is nonlinear. The limiting oscillatory amplitude may be a few psi or in the order of several hundred psi.

The results of pressure-coupled longitudinal mode instability are mechanical vibrations induced into the rocket motor that may produce component or structural failure. Low amplitude instabilities may be tolerated, depending on the frequency and the structural characteristics of the motor. The pressure oscillation will also produce an oscillatory force in the longitudinal direction which could be transmitted forward through the structure with resultant mechanical vibration and possible destruction of missile guidance components. The significance of the motor instability to the missile depends upon frequency of oscillation, mechanical stiffness of the interstage structure, and the sensitivity of upstage components to the induced mechanical vibration.

Generally speaking, a velocity-coupled instability will result in similar mechanical vibration of the motor and missile. In addition, however, the augmented burning rate usually associated with velocity-coupling produces an increase in mean chamber pressure and a decrease in motor firing duration. The significance of the ballistic change depends upon the particular missile system. The increase in chamber pressure may result in over pressurization and rupture of the case; the increased thrust could exceed the missile acceleration limits and/or the change in the motor duration can result in unacceptable performance of the system.

The severity of the instability, on the other hand, and/or the sensitivity of the missile system may be such that the presence of instability does not affect or compromise missile performance in any way. Hence, it is tolerated. Several rocket motor development programs have tolerated the presence of instabilities in the past.

Instance of Instability in Actual Motor Operation

A. Small Tactical Motors

The rocket motor shown in Fig. 2 is a small tactical motor less than 3-in. in diam with an empty fineness ratio (L/D) of approximately ten. The grain geometry is a simple cylindrical perforation and uses a single aluminized propellant. During the development of this motor, combustion instability did not appear to be a problem. Ballistic anomalies occurred on two occasions that were suspected to be an instability caused by the loss of a nozzle insert. In actuality, pressure-coupled instability had occurred early in the motor firing, but the presence of the instability had been obscured by inadequate instrumentation. A multitude of flight tests were conducted of the missile system with no detectable adverse conditions resulting from the pressure-coupled instability.

The motor program proceeded into mass production. During the course of routine production motor tests, pressure anomalies did occur in a few lot acceptance firings. The results of one of these firings are shown in Fig. 3. The figure is an actual oscillograph trace of the thrust time histories of four motors fired simultaneously. The oscillations observed are due to ringing of the thrust stand, not an instability. The upper firing trace which shows the large discontinuity is an occurrence of a d.c. shift due to a velocity-coupled instability. The actual thrust oscillations resulting from the instability are almost obscured by the frequency response of the test stand; however, they could be identified. Several things are notable from the firing curve: 1) the sudden increase in mean motor thrust, 2) the limiting of the thrust increase, and 3) the decrease in total motor duration. The instability observed in this motor was attributed to the ejection of a portion of the nozzle throat which initiated a pressure pulse in the motor.

A heavy wall version of this motor has been used as a test vehicle to evaluate suppression devices. The heavy wall con-

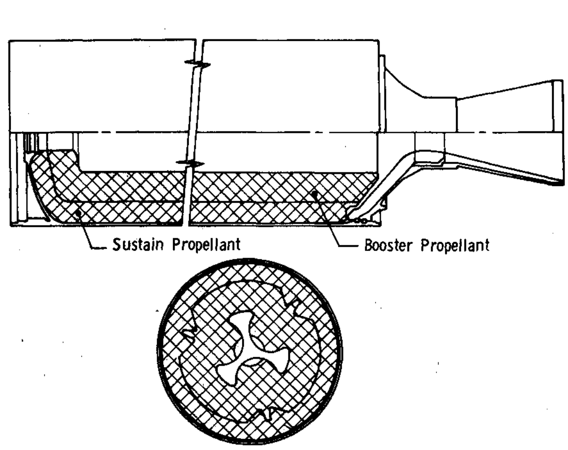

Fig. 4 Large dual thrust dual propellant tactical motor.

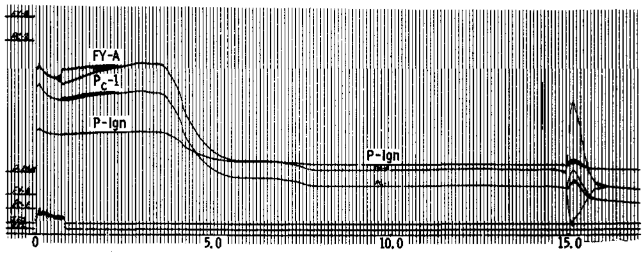

Fig. 5 Illustration of pressure and velocity coupled instability on large tactical motor.

figuration contained a pulsing device and provisions for high frequency pressure measurements. The motor was stable until pulsed. A pressure pulse of approximately 50 psi was induced into the motor at 1.0 sec. Following the pulse, pressure oscillations grew to approximately 240 psi and an increase in mean pressure of 900 psi occurred. It had been concluded that this motor configuration was stable until pulsed, instability occurred either from the direct pressure pulse or the ejection of material through the throat.

B. Large Tactical Motor

Both pressure-coupled and velocity-coupled instabilities were encountered during the development and qualification program of a dual thrust, dual grain tactical motor having a diameter of over fourteen inches, shown in cross section in Fig. 4. This motor used an aluminized propellant in the boost phase and a very slow burning nonaluminized propellant in sustain. During the development period, both pressure and velocity-coupled instabilities were encountered as illustrated on Fig. 5. Pressure-coupled instabilities during the boost phase were quite numerous and occurred almost routinely. Various changes in the propellant oxidizer particle size and aluminum particle size were tried. Eventually the motor was stabilized by changes in the boost propellant formulation. Velocity coupled instabilities during sustain especially near tailoff were more random in occurrence. These continued to occur even through the production program and sporadically in missile flight tests.

Recently, during a test of a production motor, an instability was observed to accompany the ejection of a piece of material through the nozzle throat which led to various speculations. To verify (or refute) that an instability could be initiated by the ejection of a piece of material (i.e., igniter case insulation), and to determine the approximate size of ejecta required to trigger an instability, a special pulse test was conducted. In this test, it was planned to eject silica-filled polyurethane plug cylinders of three different sizes at three different times during the sustain phase. It was found, however, that a velocity coupled longitudinal mode instability was initiated by the ejection of the second cylindrical plug having a length and diameter of 0.75 in. A copy of the actual pressure and thrust trace as replayed from the tape recorder is shown on Fig. 6. In addition to the pressure oscillations it can be seen that the mean pressure was increased considerably which resulted from the burning rate augmentation caused by the instability. When

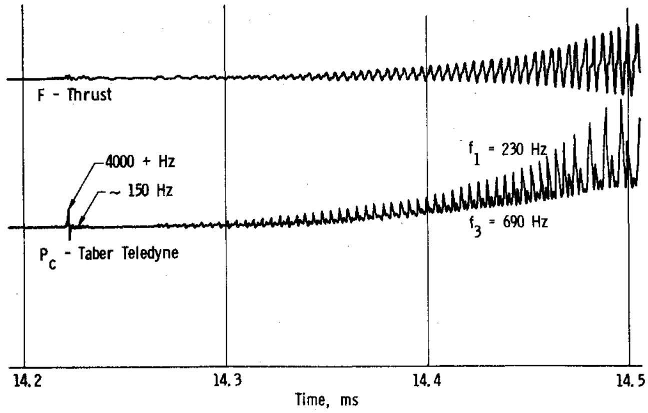

Fig. 6 Growth of instability caused by plug ejection.

the third plug was launched, the chamber pressure had already decreased to ambient, hence measurements were meaningless.

The sequence of mechanical events that occurred to launch the plug into the freestream shall not be described in detail here. Briefly, however, a squib was used to initiate red dot powder: the ensuing pressure rise ruptures a burst diaphragm and drives a piston forward until it reaches its mechanical stop or snubber plate. This, in turn, drives a plug into the gas stream at an initial velocity (muzzle velocity) considerably greater than the local stream velocity at the forward end of the chamber. The average plug velocity in passage through the chamber may be calculated from the measured time delay between the first indication of pressure rise following squib initiation and the start of pressure oscillations. Plug performance is summarized on Table 1.

The oscillograph record was used to obtain measured values of plug performance in the motor test at 10.2 and 14.2 sec after start. These values were also shown on Table 1 as well as measured and calculated values for the initial pressure rise. These appear to be in good agreement. The average grain diameter, at each of the burn times, was back calculated using the chamber inside diameter, the average burning rate of the sustain propellant and the time remaining until burnout. From this and knowledge of the nozzle throat diameter, bore exit velocities were estimated. The average plug velocity was calculated from the measured time delay of 45.5 and 47.5 msec for the 0.375 and 0.750-in. diam plugs, respectively. This time delay was assumed to consist of the time it takes the plug to reach and constrict the nozzle throat and the time required for the pressure wave to travel back to the forward dome where the transducer is located (estimated as $1/2f$). The calculated longitudinal mode fundamental frequency for the known chamber and nozzle length was 226.8 Hz. The measured fundamental frequency was 230 Hz. It should be noted that the first, second, and third harmonics are also present. These are evident from the pressure trace shown.

Chamber oscillations begin after the quiescent period following plug ejection corresponding to a total elapsed time (time delays) of 45.5 and 47.5 msec as shown on Table 1. This

Table 1 Plug performance in motor test

Launch time, sec	Aver. diam., in.	Plug length, in.	Aver. grain i.d., in.	Exit bore velocity, fps	Plug velocity, fps	Time delay, msec	Forward end pressure rise Measured, psia	Calculated psia
10.2	0.375	0.375	11.024	119.5	171	45.5	1	0.9
14.2	0.75	0.75	11.527	109.2	167	47.5	3	3.0
a	1.375	1.50	12.783	92.2	*a*	...	...	5.3

[a] Launch time after motor burnout.

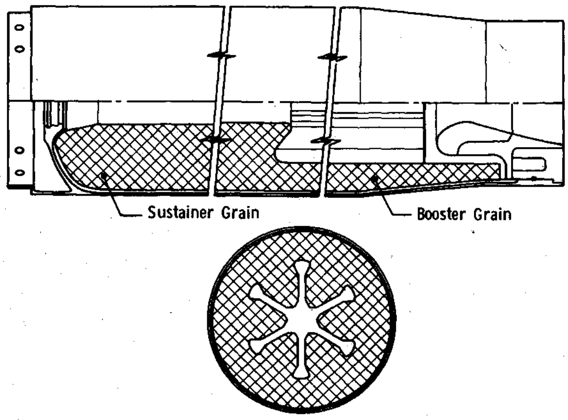

Fig. 7 Dual thrust single grain tactical motor.

unstable combustion was triggered by the pressure rise that occurs as the plug passes through and partially constricts the nozzle throat. The measured values of approximately 1.0 and 3.0 psia, on Table 1, compared very well with calculated values using an existing ASPC computer program. This program utilized the method-of-characteristics for unsteady one-dimensional flow to trace the pressure wave along the length of the chamber upstream of the throat to the forward dome. Given the velocity of the plug, its trajectory through the throat was calculated based on the drag force exerted on the plug by the accelerating gas flow. The average plug velocity of 167 fps (0.75-in. plug) was used for all plug sizes in this calculation. The magnitude of the pressure wave was determined by the change in area ratio at the nozzle entrance due to the blockage of the throat area. The method-of-characteristics program assumed a constant velocity chamber flow and this did not account for mass addition effects. However, for the chamber velocity conditions existing at these burn times, mass addition effects are small. It should be noted that at the launch times of approximately 10 and 14 sec, respectively, the calculated gas velocity in the chamber was considerably less than the measured plug velocity, hence the plug could not be accelerated by the gas as originally assumed, until it was well inside the nozzle region. Therefore, the same assumptions were used for all three plug sizes. By using this program, the pressure disturbance at the forward head, for the nominally 1.5 in. diam plug, would have been 5.3 psia.

Accelerometer response measurements were reviewed to obtain a qualitative assessment of stability along with the pressure and thrust traces. Accelerometers located on the same side of the motor (in line), were used to confirm the postulation (made earlier) that the pressure wave originated at the aft end of the motor (as the plug passed through the throat) and takes approximately 2.2 msec ($t = 1/2f$) to travel forward and record on the forward dome where the pressure transducer is located. Both the pressure amplitude peaks and forward and aft accelerometer disturbances were approximately 2.2 msec out of phase.

The motor history described above provides a typical example of combustion instability during development and the reoccurrence of instabilities in production. The pulse tests firmly established the sensitivity of the motor to transient pressure pulses and that the motor could be triggered into instability by the ejection of material through the nozzle throat. The pressure coupled instability that occurred in this motor was eventually eliminated by a change in the propellant formulation. Velocity coupling instability in the sustain phase may be avoided by an adequate design to preclude the ejection of any significant size material during the firing.

Dual Thrust, Single Grain Motor

The previous motor discussed was a dual thrust bipropellant (dual grain) motor which experienced instability. The next motor to be reviewed is a dual thrust single propellant motor nominally 8 in. diam. The dual thrust levels are achieved by the interior grain geometry as shown in Fig. 7. The fore end of the motor is a circular bore and the aft portion contains large surface area radial fins. The high thrust portion of the ballistics is obtained by the propellant finned surface in the aft end. These burn out in a few seconds leaving only the cylindrical bore of propellant in the forward end for the sustain phase of motor operation.

The instabilities which occurred were both pressure-coupled and velocity-coupled with an associated change in mean ballistics as shown in Fig. 8 and an adverse pressure oscillation. The instabilities were unacceptable from the standpoint of the missile and their elimination was approached from a cut and try process. The changes made in motor design included minor grain geometry changes, propellant formulation variations including oxidizer particle size and aluminum particle size changes, as well as various attempts to utilize Helmholtz resonators. This motor development took place before the acceptance of the *T*-burner as a laboratory tool to evaluate propellants for combustion instability. Stability was eventually achieved for the motor after approximately 35 motor tests using various combinations of grain design and propellant changes. Velocity coupling was eliminated from the boost phase and pressure-coupled instabilities eliminated from the sustain phase.

One of the trends observed from the results of this program showed that there is an effect of particle size on stability. Figures 9 and 10 illustrate the change in oscillatory amplitude and mean chamber increase as the aluminum particle size was increased and the particle size of the oxidizer decreased. The mean particle size of the ingredients is shown in Table 2.

Solution of the stability problems for this motor was both costly and time consuming. The utilization of technologies

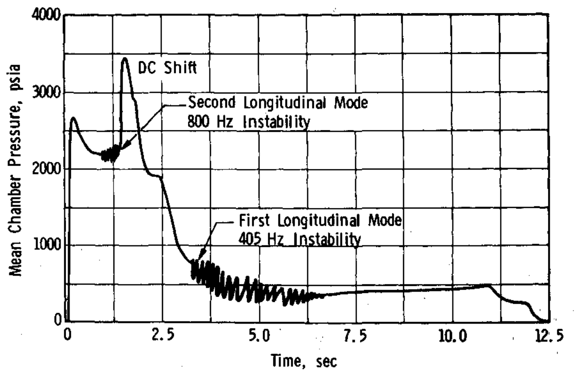

Fig. 8 Dual thrust single grain tactical motor measured chamber pressure.

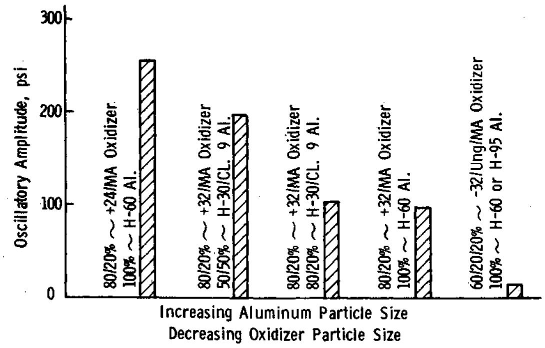

Fig. 9 Effects of various aluminum and oxidizer particle sizes on oscillating amplitude.

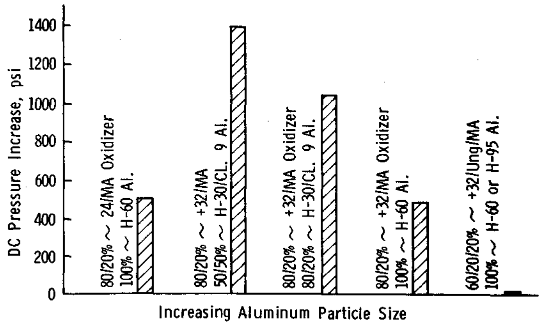

Fig. 10 Effect of various aluminum and oxidizer particle sizes on d.c. pressure increase.

Table 2 Ingredient particle sizes

Ingredient	Class	Mean particle size, μ
Oxidizer	+24 mesh	700
	+32 mesh	500
	UNG	180
	MA	5
Aluminum	H-30	30
	H-60	60
	H-95	95
	CL-9	18

such as those currently being developed[3-7] in both stability analyses and the use of the T-burner as a laboratory test device could have greatly reduced the effort expended to isolate and eliminate the motor instability.

The foregoing discussion considered instabilities in the motor cavity that have occurred in the longitudinal mode. Historically, instabilities have occurred in solid rocket motors involving both the radial and tangential modes of the gas cavity as well. For clarity, a simple description of the tangential mode is given in the next section.

Tangential Acoustic Modes

If we consider a cylindrical cavity for the rocket motor as used earlier and look at a cross-section through the cylinder then the tangential modes of the cavity can be illustrated as shown in Fig. 11.

The motion of the gas particles is similar to the longitudinal mode along the cylinder with a pressure maximum at one side and a pressure minimum at the other. The particle velocity distribution is also similar to the longitudinal mode except it now moves in a circular direction along the cylindrical wall. The tangential modes are much more complex than the longitudinal one-dimensional modes in that the circumferential pressure distribution can vary as cos $n\theta$, where θ is the angular location. The modes are further complicated because the cross sectional mode structure shown on Fig. 11 can vary along the longitudinal axis of the cavity with a modal distribution corresponding to the longitudinal modes of the cavity. The cavity, therefore, has an infinite multiple of tangential modes. The radial modes of the cylindrical cavity are similar to the tangential mode with the exception that the pressure antinode occurs at the outer periphery of the cylinder and at the center of the cylinder and the mode structure is axisymmetric.

As one deviates from a circular cross section for the inner bore to more complex geometries typical of solid motors, the tangential acoustic modes still exist although they become more complex. Motor cavities with deep radial slots or fins possess tangetial acoustic modes that penetrate to the depth of the fins. These tangential modes exist in geometries with both an even and an odd number of radial slots or fins.

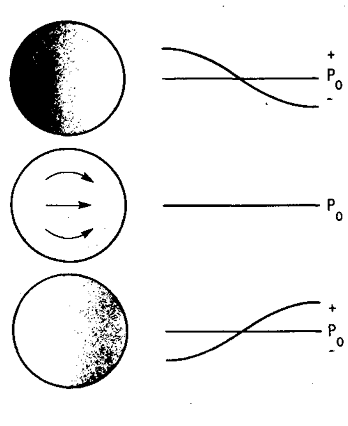

Fig. 11 Tangential modes.

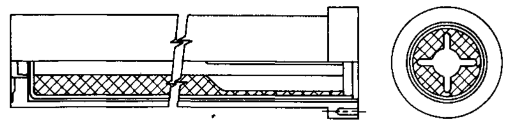

Fig. 12 Smokeless propellant test motor aft finocyl grain.

Single Grain Smokeless Motor

When metal additives were first introduced into propellants to increase I_{sp}, they also resulted in eliminating tangential mode combustion instability. With the current interest in developing solid rocket motors without primary smoke, the metal additives have been removed and it is natural to expect the reoccurrence of tangential mode combustion instabilities. This is indeed the case, as tangential mode instability has occurred in three smokeless motor development programs at Aerojet in recent years. The particular motor program to be reviewed here had not only tangential mode instability but also a longitudinal mode instability for the same propellant formulation but with different grain geometries.

The conceptual motor design shown on Fig. 12 was a four blade finocyl geometry with a cylindrical bore in the fore end and four radial slots in the aft portion of the motor. This motor had velocity-coupled instabilities midway in the firings with a large increase in mean chamber pressures. T-burner data were available for the propellant formulation used in the motor and a stability assessment of the motor geometry was made. Based on this assessment it was concluded that stability could be improved by grain geometry modification. Two grain design changes were made. First, the finocyl design was modified to extend the length of the fin slots and the depth of the slots was reduced to prevent the early burnout of propellant in the aft end. The results of this design change showed a major improvement in motor stability. Although pressure oscillations still occurred, the amplitude was reduced by an order of magnitude and the increase in mean pressure was eliminated.

An alternative motor design was developed for the motor. This design, shown in Fig. 13, consisted of a cylindrical bore with two radial slots that run the full length of the motor. Test firings of this motor configuration with the same propellant formulation used on the previous design showed no evidence

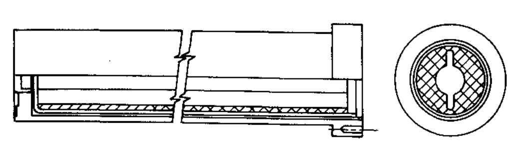

Fig. 13 Smokeless propellant dogbone grain.

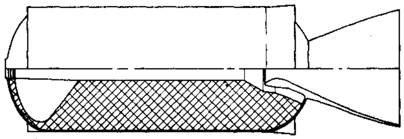

Fig. 14 Strategic missile motor.

of longitudinal mode velocity-coupled instability. Instead a tangential mode instability occurred in the motor with a large change in mean chamber pressure. The instability started midway through the motor firing and continued intermittently until tailoff.

The tangential mode instability observed in this motor occurred at frequencies starting at 16,000 Hz and decreasing to approximately 6000 Hz at burn out. The instability was first detected by the use of accelerometers mounted on the chamber o.d. Subsequent tests with high-frequency pressure measurement established a correlation between observed mechanical vibration sensed by the accelerometers and pressure oscillations measured on the chamber side wall.

The final grain selection was a dog bone geometry for this motor. Stability was finally achieved by propellant formulation modification. Special additives were incorporated to eliminate the high-frequency instability. The same propellant formulations when used in the finocyl design showed a very low level longitudinal mode pressure oscillation. The motor completed development including many successful flight tests without any recurrance of instability.

Strategic Missile Motor

The final motor to be reviewed is a large diameter strategic missile motor. The motor design for this motor is shown in Fig. 14 and consists of a finocyl grain design and a submerged nozzle. Six radial fins or slots are located in the forward dome area of the motor and the aft portion of the bore is cylindrical. The propellant used in the motor is a highly aluminized formulation.

Combustion instability occurs during two distinct time periods in the motor firing. During the first six seconds of motor operation, the fundamental tangential modes of the forward fins become unstable. This instability does not produce any measurable change in mean ballistics. Later in the motor firing during the period of 15–24 sec, low-level pressure oscillations are observed at the fundamental longitudinal mode of the motor.

This motor which is in production has always had combustion instability as described above. No attempt has been made to reduce or eliminate the instability because it does not have any adverse effect on the motor or missile system. The tangential mode instability does produce vibration amplitudes on the motor forward dome of the order of 180 g, however, motor components located on the dome are insensitive to the mechanical vibration. Further, the structural characteristics of the missile interstage are such that vibrations generated in the stage are not transmitted up stage to any significant degree. The instabilities described for this motor are typical of the types of instabilities that have occurred in large strategic missile motors. In other motors, however, the presence of the instability may result in unacceptable performance of the missile.

Conclusion

The motors reviewed were selected to illustrate the various forms of instability which have occurred in actual motor development program. As indicated by the various examples, the occurrence of instability depends on propellant formulation, motor geometry, and transient pressure perturbations. Instabilities may be tolerated in certain applications depending upon the missile and motor. Instabilities have been eliminated by geometry changes, or variations in propellant formulations.

The elimination of combustion instability from a motor during development can be very costly in both dollars and time if approached on a cut and try basis. The development of laboratory test devices for propellant evaluation and the development of analytical techniques to evaluate motor geometries is an absolute necessity. These technologies have been significantly advanced in the last few years. Continued efforts will ultimately place solid rocket motor combustion instability in a class of technology that is readily solvable by analytical and laboratory experimental techniques.

References

[1] McClure, F. T., Bird, J. E., and Hart, R. W., "Erosion Mechanism for Non-Linear Instability in the Axial Modes of Solid Propellant Rocket Motors," *ARS Journal*, Vol. 32, No. 3, March 1926, pp. 374–378.

[2] Culick, F. E. C., "Stability of Longitudinal Oscillations with Pressure and Velocity Coupling in a Solid Propellant Rocket," *Combustion Science and Technology*, Vol. 2, 1970, pp. 179–201.

[3] Micheli, P. L., "Pulsed *T*-Burner Evaluation Program," AFRPL Contract F04611-71-C-0021, Sept. 1972.

[4] Micheli, P. L. and Lovine, R. L., "*T*-Burner Motor Verification Program," AFRPL-TR-73-66, Interim Rept., Aug. 1973.

[5] Beckstead, W. M., Horton, M. D., Kraskin, M., and Butcher, A. G., "Velocity Coupling Combustion Instability," Final Tech. Rept., AFRPL–TR–73–73, Sept. 1973.

[6] Price, W. W., "Combustion Instability in Rocket Motors with Aluminized Propellants," NWC–TP–5505, June 1973.

[7] Colucci, S. E., "Status of the Suppression Devices Program for Solid Rocket Combustion Stability," presented at the 10th JANNAF Combustion Proceedings, Newport, R.I., Aug. 8, 1973.