Preferred Frequency Oscillatory Combustion of Solid Propellants

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Two systems were used for the study of low-frequency oscillatory combustion. The first was a small end-vented burner that employed end-burning grains and produced nonacoustic pressure oscillations. The second system was a side-vented, double-end burner of suitable lengths to produce low-frequency (5 to 120 cps) acoustic pressure oscillations. The propellant tested most extensively (a metallized double base) exhibited oscillations only over a very restricted pressure-frequency region. This region was similar for each type of burner. From these results it was inferred that the response function of the combustion zone showed a marked peak when plotted as a function of frequency at low pressures. Similar behavior was shown by a highly aluminized composite propellant; however, other propellants did not reveal the phenomenon.

Introduction

THE phenomenon known as oscillatory combustion is frequently encountered in the course of rocket motor development programs. When the combustion process couples with and supports acoustic pressure fluctuations in the combustion chamber of the motor, acoustic oscillatory combustion is observed. Generally, the acoustic oscillatory combustion encountered in solid propellant rockets shows a broad frequency band in which oscillations may occur. Experiments with burners of different sizes have shown that, for a given propellant, oscillations may be present at frequencies ranging from 9 to 55,000 cps, and there seem to be no unique stable or unstable areas in this region.[1,2] Of course, each motor oscillates in its unique acoustic modes, but these are fixed more by the acoustic characteristics of the motor than by the propellant combustion. Acoustic oscillations are generated whenever the acoustic gains in the system exceed the acoustic losses.

A different type of oscillatory combustion has been reported by several investigators.[2–6] This type of oscillatory combustion has occurred at relatively low frequencies (below 100 cps), which were characteristically lower than the lowest acoustic mode of the combustion cavity in which they were observed. The frequency of this type of oscillatory combustion seems to be fixed more by the mean chamber pressure than by the chamber geometry.[4] Clemmow and Huffington[7] explained this type of oscillatory combustion as being caused by periodic thermal explosions of the heated propellant surface layer. On the other hand, Akiba[5] and Sehgal[6] found that their data could be correlated by a theory that dealt with the interaction between the heated zone in the solid propellant and the mass discharge characteristics of the combustion chamber. Angelus[4] found that the behavior was intimately related to the metal content of the propellant tested. Although he did not seek to explain his data theoretically, he discussed them in relation to Huffington's theory.

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In the experimental work reported here, the oscillatory behavior of a propellant was first examined by the use of a small burner. The oscillations observed in this small burner were of the type described in the previous paragraph. That is, their frequencies were an order of magnitude smaller than the lowest acoustic mode of the combustion chamber. Second, the propellant was tested in a large burner whose first longitudinal modes matched the nonacoustic frequencies previously observed in the small burner. Then a comparison was made between the oscillatory combustion observed in the two burners.

Experimental Procedure

Two burners were employed in this investigation. These were the end-vented, end burner (EVE burner) and the large end burner (LE burner). In order to investigate nonacoustic combustion oscillations, the EVE burner, shown in Figs. 1 and 2, was used. It employed two 0.25-in.-thick, 1.6-in.-o.d. propellant disks press-fitted into opposite ends of a Pyrex glass tube. Steel endplates were used to support this glass tube, which served as the burner body. Ignition was accomplished by means of an electrically heated hot wire

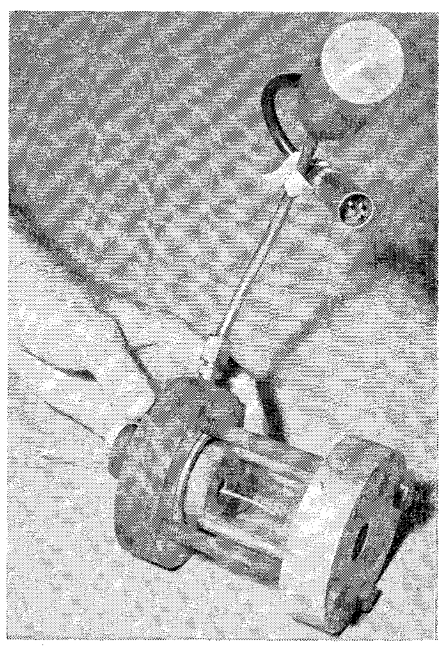


Fig. 1 Picture of the EVE burner.

that ignited a pyrotechnic paste spread on the propellant surface and coated on the wire. A small hole was drilled through the center of one grain so that the combustion gases could flow out to the nozzle. The pressure was measured by a low-frequency response pressure transducer, mounted in the side of the burner near the propellant surface, and a high-frequency response radiation transducer sensed (through the glass wall) the light emitted by the combustion process. The signal from each transducer was recorded by a galvenometer oscillograph.

By suitable variation of the nozzle diameter and burner length, the mean chamber pressure and the residence time of the combustion gas in the burner were controlled. With variation of these parameters, most propellants in this system may be made to burn stably, oscillate with a nonacoustic frequency, or chuff (nonacoustic, nonsinusoidal oscillations whose troughs are essentially at atmospheric pressure). Figure 2 illustrates these types of behavior.

In order to investigate further low-frequency behavior, the propellant was burned in a system (see Figs. 3 and 4 and Ref. 8) whose acoustic modes corresponded to the nonacoustic frequencies seen in the EVE burner. This burner (called the LE burner) was a 5.5-in.-i.d., cylindrical steel tube, which was segmented so that it could be used in lengths of 12, 24, 36, 48, or 60 ft. Propellant grains 5.4-in. o.d. and usually 1-in. thick (about 2 lb) were used in the burner. The grain was cemented firmly into the end of the burner with epoxy resin. In a given test a single grain was used in one end of the burner, or grains were placed in both ends of the burner. Ignition was accomplished by means of an electrically heated bridgewire that ignited a pyrotechnic paste spread on the propellant surface and coated on the wire. Placed in one end of the burner were a high-frequency response pressure transducer, a low-frequency response pressure transducer, and a high-frequency response radiation transducer that "saw" the propellant surface through a small window located in the side of the burner wall. A galvanometer oscillograph was used to record the signal from each of the transducers.

So that regions of spontaneous combustion oscillations might be found and investigated, the system was ignited at atmospheric pressure and allowed to pressurize itself with combustion gases. The rate of pressure rise was controlled by means of a small bleed located midway between the burner ends. By the use of this technique[8] and all the burner lengths, the frequency-pressure region in question could be examined for regions of self-excited instability.

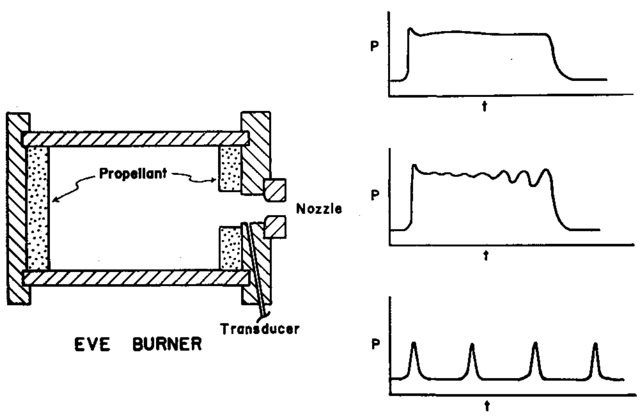


Fig. 2 Schematic of EVE burner. Dimensions: 1.6-in. i.d., 1- to 6-in. length. Typical pressure-time records are sketched at right.

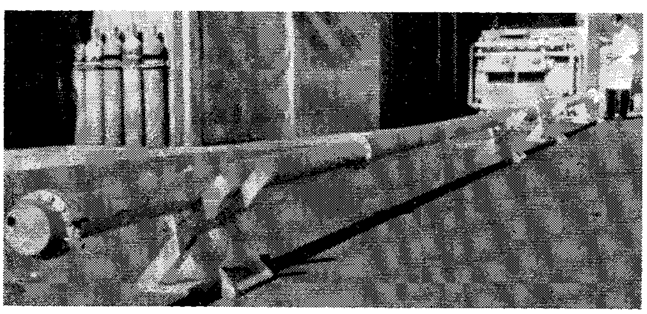


Fig. 3 Picture of LE burner.

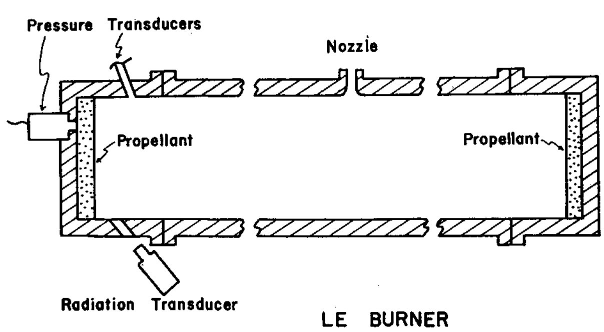


Fig. 4 Cutaway sketch of LE burner.

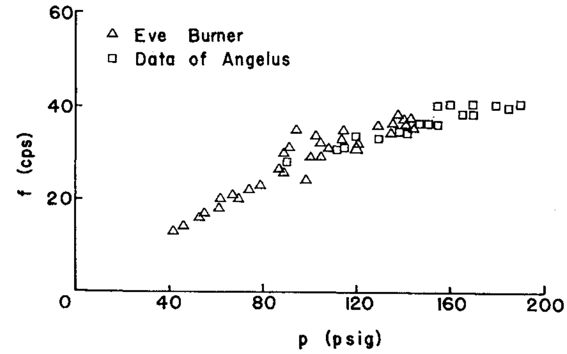


Fig. 5 Nonacoustic data with propellant *A* (EVE burner) and Angelus' results.

Results

In the investigation, the propellant tested most extensively was a cast double-base propellant (designated as propellant *A*) which contained 4.25% of 65/35 Mg-Al alloy. This propellant, which was tested also by Angelus,¶ produced nonacoustic oscillatory combustion when tested in the small EVE burner. Furthermore, the frequency of the oscillations was found to be a function of the pressure level in the chamber. As Fig. 5 shows, the frequency-pressure relationship was identical with that observed by Angelus,[9] who obtained his data from motor firings of slotted, cylindrical grains. Angelus, however, observed a different frequency-

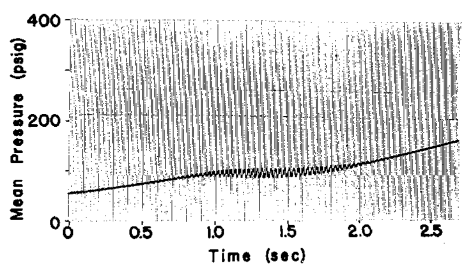


Fig. 6 A portion of a typical test record obtained by using propellant *A* in LE burner. Note the narrow pressure range over which oscillations exist.

¶ The authors are indebted to Hercules Powder Company, which supplied the propellant.

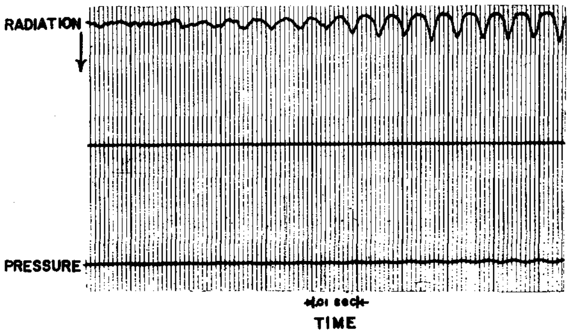


Fig. 7 A portion of a test of propellant *A* in LE burner showing both radiation and pressure traces. Note that the pressure and radiation oscillations appear simultaneously.

pressure relationship during rising and falling mean pressures, and the preceding agreement exists only for his rising pressure data.

The results with propellant *A* in the LE burner are rather complicated. In a typical test, such as that shown in Fig. 6, the system is stable as the mean pressure rises until a pressure is reached where acoustic oscillations appear. As the mean pressure continues to rise, the osicllations grow in amplitude, reach a maximum, begin to decay, and finally disappear altogether. With the onset of detectable pressure oscillations, the radiation transducer shows that (see Fig. 7) there occur periodic fluctuations in the intensity of the light emitted by the combustion process. These fluctuations, which are inferred to represent combustion variations, persist until the pressure oscillations are no longer seen and then shortly thereafter disappear. Figure 8 shows the phase relationship between the combustion (radiation) and pressure oscillations on one test, and in Fig. 9 are plotted all of the combustion oscillation data as a function of mean chamber pressure.

In addition to propellant *A*, four composite propellants were tested. A summary of the results and propellant compositions is shown in Table 1.

Discussion

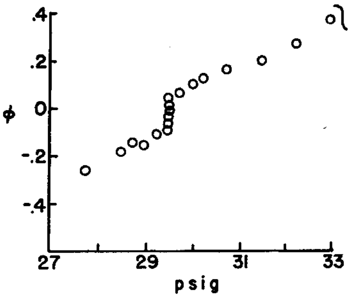
As generally observed,[10] the driving of oscillatory combustion is not overly sensitive to either pressure or frequency. That is, the response function of the combustion zone as defined in the Hart-McClure theory[11] is rather constant, both experimentally and theoretically. This constancy causes the familiar broad frequency bands in which oscillatory combustion is observed.

Figure 10, which is a combination of all oscillatory data from propellant *A*, shows that the self-excited oscillatory combustion seems to take place in a rather narrow frequency-pressure band. A further illustration of this narrow band is illustrated by a portion of a typical test record (Fig. 6). Note that first-mode, acoustic pressure oscillations are driven

Table I Summary of results

Propellant designation	Composition	Oscillatory behavior
A	Moderately metallized (65/35 MgAl alloy) cast double base.	Oscillated in same regime in both LE and EVE burners.
B	Heavily aluminized polyurethane-ammonium perchlorate composite.	Oscillated in same regime in both LE and EVE burners.
C	Heavily aluminized polybutyl acrylic acid-ammonium perchlorate composite.	Nonacoustic oscillations in EVE burner, stable in LE burner.
D	Lightly aluminized polyurethane ammonium perchlorate composite containing LiF.	Nonacoustic oscillations in EVE burner, nondiscriminatory oscillations in LE burner.
E	Lightly aluminized polyurethane ammonium perchlorate composite containing copper chromite.	Nonacoustic oscillations in EVE burner, marginally discriminating oscillations in LE burner.

Fig. 8 Phase relationship between pressure and radiation frequencies. Phase difference may pass through many cycles. ϕ is the fractional cycle by which the combustion oscillations lead the pressure oscillations.



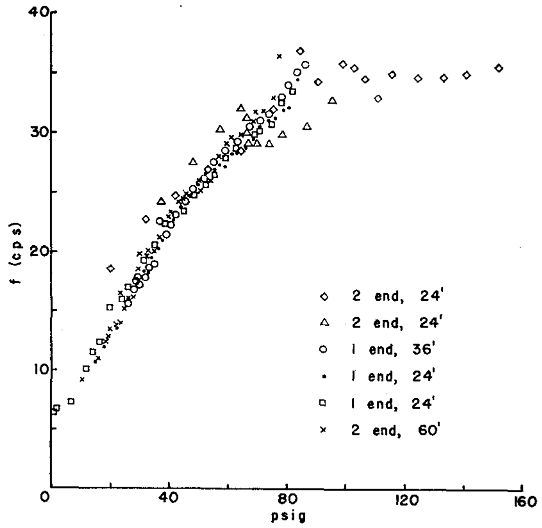


Fig. 9 The results of all tests of propellant *A* in the LE burner. The results show the preferred frequency-pressure relationship.

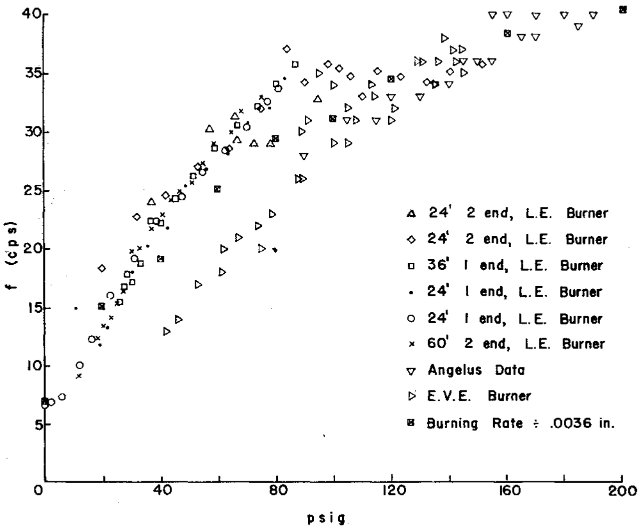


Fig. 10 Compilation of all oscillatory data gained with propellant *A*.

only over a small mean pressure interval. The existence of this isolated region of instability indicates that, at a given pressure, the response function-frequency curve must show a sharp peak. The frequency at which this peak exists for a given mean pressure will be referred to as the "preferred frequency" of the combustion process.

From the existence of this preferred frequency of oscillatory combustion, one might infer that the combustion process tended to oscillate with a frequency that was not dependent upon the oscillating pressure characteristics of the combustion system. There are theoretical grounds for suspecting that such a process might occur,[7, 12] and it is indeed conceivable that a microscopic area of propellant might spontaneously show a characteristic combustion frequency. However, before the entire combustion surface can show the synchronized periodicity necessary to generate nonrandom oscillatory gas motion, points on the surface far removed from each other must be brought into the proper phase relationship. In the absence of an external coupling or phasing mechanism, it is difficult to understand how such coherent combustion oscillations can occur.

The results from propellant *A* fired in the LE burner show that, although there seems to be a frequency at which the entire surface of this propellant "wishes" to oscillate, it cannot produce synchronized combustion oscillations in the absence of pressure oscillations. This is evidenced by the fact that gross combustion oscillations are not observed except when the pressure is also oscillating. Other confirming evidence is that the burner containing propellant in both ends oscillates much harder than when propellant is in only one end. For this to be so, the combustion in each end must be synchronized, and there is no logical synchronizing mechanism that will cause surfaces 60 ft apart to drive first-mode pressure oscillations except pressure perturbations.

To find the aspects of the combustion which may be responsible for producing preferred frequency oscillatory combustion, one may refer to the rates at which various combustion steps occur. Only those steps whose time constants are the same order of magnitude as the period of the oscillations must be considered. Those that are much faster are essentially taking place under steady-state conditions, and those that take place much slower do not respond at all to the oscillations. The gas-phase combustion processes seem to be of the "too fast" variety,[11, 12] whereas the relatively slow solid-phase processes are suitable candidates. There is, at this time, no evidence that clearly points to a particular causative agent; however, one or more of the solid-phase processes is probably involved.

One could speculate that the preferred frequency was intimately related to the cyclical appearance and subsequent depletion of some propellant ingredient upon the combustion surface. A logical consequence to such a speculation is that the preferred frequency might be directly proportional to the accumulation rate of the ingredient and hence to the burning rate of the propellant. Were this so, the combusting surface would regress by a fixed distance during each oscillation.

This speculation was examined in terms of the experimental results. It was assumed that the combustion produced a pulse with every recession of 90 μ (a number found empirically), and the experimental burning rate data were combined with this number to yield a pressure-dependent "frequency." In Fig. 10 are plotted the results of this operation, and the points agree rather well with the preferred-frequency data. Although the result is interesting, it can only be regarded as suggestive at this time.

It can be seen from Fig. 10 that the oscillatory frequencies observed at a given pressure in the LE and EVE burners are slightly different. This is probably because the oscillations occur at the frequency where the driving exceeds the damping by the greatest margin, and the damping is presumably different in the two systems. However, the frequencies observed in the two systems are similar because the preferred frequency driving of the combustion dominates over the tuning of the burners in the selection of steady-state frequencies.

The fact that propellant *A* produced acoustic oscillations of a preferred frequency in the LE burner shows that one could indeed expect acoustic oscillatory combustion in properly sized, large motors that used this propellant at low pressures. Although it would not be possible to say exactly how severe this oscillatory combustion might be, the techniques of Ref. 10 make it possible to estimate the response function of the propellant combustion zone. A conservative value for the response function is determined by neglecting the damping and considering only the growth of the oscillations. Use of only the growth rate constant of the oscillations shows that the value of the response function is a minimum of 11 at 10 cps. This approximate value may be contrasted to response function values in the range of 0.5 to 3 observed at higher frequencies.[10] The order-of-magnitude larger response function at low frequencies indicates that the low-frequency oscillatory combustion of this propellant is indeed rather severe.

Conclusions

All five of the propellants tested for preferred frequency oscillatory combustion produced unique pressure-frequency relationships in the EVE burner. However, their behaviors varied with respect to the LE burner. Two propellants showed preferred frequency oscillatory combustion, two only marginally showed it, and one failed to exhibit what has been termed preferred frequency oscillatory combustion.

Two significant results have been achieved in this study. First, it has been shown that preferred frequency oscillatory combustion exists, and, although it does not appear to be a general phenomenon, it has been observed for both composite and double-base propellants. The second finding was that there is, indeed, a real danger that the large solid boosters could experience a coupling between an acoustic mode and preferred frequency oscillatory combustion. To forestall this possibility, it would seem prudent to subject a few pounds of each candidate propellant to testing for preferred frequency oscillatory combustion at the pressures and frequencies of interest. It is possible that, by doing so, one might prevent the failure of a multiton booster test.

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