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COUPLED VORTEX SHEDDING AND ACOUSTIC RESONANCES IN A DUCT*

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ABSTRACT

Undesirable sound generation in the combustion chambers of solid propellant rocket motors previously has been attributed to vortex shedding from obstructions that are uncovered as the propellant burns back. An experimental investigation of the phenomenon has re-confirmed this observation and extended the understanding of the mechanism by which the process is self-sustaining.

A pair of aluminum baffles within a lucite duct through which air is drawn models the important aspects which enable the sound generation mechanism to operate. The baffles form an edgetone system which interacts with the longitudinal acoustic modes of the chamber. Pure acoustic tones occur spontaneously, at frequencies equal to the acoustic resonances, when the spacing between the baffles satisfies certain criteria. Flow visualization using smoke and a strobe light triggered by the pressure oscillation indicates that vortex shedding occurs at the upstream baffle in phase with the acoustic velocity oscillation there.

Based on the results of the present experiments and others reported in the literature, a mechanism is postulated which explains the observed behavior. It is suggested that pressures induced on the downstream baffle by the vortices convected past by the freestream drive the acoustic resonance. In turn, the acoustic velocity at the upstream baffle serves as the perturbation triggering the formation of vortices in the shear layer growing from the separation point at that location. The amplitude is limited by the nonlinearity in the growth of the vortices in the shear layer.

A model based on the proposed mechanism is formulated and written as a computer program. The results predict the behavior of the experimental apparatus well, confirming that the postulated mechanism is correct.

INTRODUCTION

Undesirable spontaneous acoustic oscillations have been observed in segmented solid propellant rocket motors at frequencies equal to the longitudinal acoustic organ pipe modes of the combustion chambers. Since the cause was not known, limiting amplitudes could not be predicted. Such oscillations occurred in the space shuttle boosters at 15Hz. While it is unlikely that the pressure amplitude could grow to a level that could cause failure of the motor case, previous experience has shown that vibrations of this sort could cause other structural damage or failure of equipment with a mechanical resonance at a nearby frequency. This frequency is also close to the resonant frequency of the human eyeball and although the amplitudes have never reached sufficiently high levels to impair reading of instruments, the vibrations have been noticeable to the astronauts. Further increases in the amplitude could cause difficulties.

These oscillations occur in a class of rockets which are constructed with the solid propellant in large segments which are loaded into the case individually. This procedure is mainly for ease of casting and handling the large blocks of propellant. A large retaining ring is installed between each segment and bonded to the ends of the propellant grain segments to inhibit burning other than on the lateral surfaces. This configuration is depicted schematically in Figure 1. These inhibitors are made of a material that burns more slowly than the propellant and thus they protrude into the mean flow as the propellant burns back.

In 1975, Flandro and Jacobs (1) first suggested that vortex shedding from these protrusions may be driving the acoustic resonances to produce the unwanted oscillations. This finding now appears correct but the actual mechanism by which the vortex shedding interacts with the acoustic resonances was not well understood at that time.

The aim of the present investigation has been to understand this interaction mechanism by performing laboratory experiments. Based on the understanding gained from these experiments and from the work of others, a mechanism has been proposed and is described below. Since the proposed mechanism does not involve the burning processes, a cold flow apparatus is used. Difficulties associated with instrumenting hot flows are thus avoided. Other experimental investigations of this type of oscillation confirm that the mechanism operates in the absence of burning (2,3,4,5,6,7,8,9). It is believed that this explanation of the behavior in a cold flow apparatus which apparently has little in common with a solid rocket motor in fact applies in both cases. The important aspects pertaining to the self-generation of acoustic standing waves, as elucidated by this work, are simulated by the experimental apparatus.

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From the postulated mechanism, a model is developed which predicts the behavior observed experimentally. Although some of the assumptions made in the model are crude, the real aim is not to calculate precise numerical values, but rather to confirm that the physical explanation is correct. With a true understanding of a process, future investigators are more likely to make correct assumptions in their models, which may well include more details than the present model. No matter how much detail is included, if false assumptions are made about fundamental aspects of a process, then a model based on those assumptions must fail. Thus, the aim here has been to strive for a true understanding of the principals of operation that allow the self-excited oscillations to occur.

This paper is a condensation of the PhD thesis by the first author under the guidance of the second. Details omitted here can be found in this thesis (10).

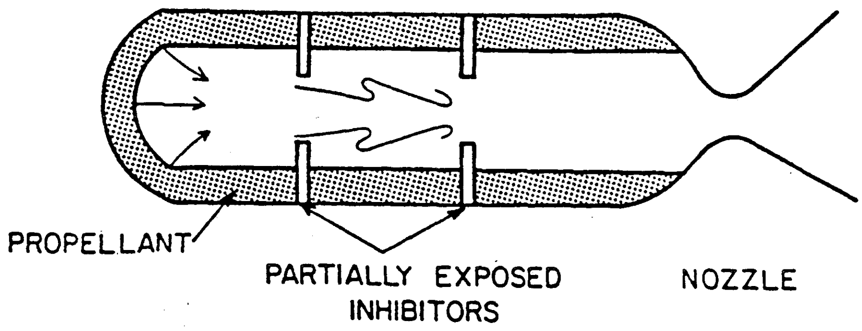

Figure 1. Segmented Solid Propellant Rocket Motor

POSTULATED MECHANISM

The postulated mechanism is as follows. The protruding inhibitors act as separation points resulting in the formation of shear layers. In such a shear layer, vortices grow due to the instability of the flow as investigated by Freymuth (11) and Michalke (12,13,14). The vortices initially grow exponentially in the streamwise direction, but eventually their strengths reach a saturated value. This saturation process is the amplitude limiting aspect of the entire interaction. As the vortices are convected downstream by the mean flow, they pass another protruding inhibitor resulting in a fluctuation of the drag force acting on this obstacle. By Newton's second law, since the fluid is applying a fluctuating force on the obstacle, the obstacle applies an equal and opposite force on the fluid. This oscillating force drives the acoustic resonance of the chamber at a frequency equal to that of the passage of the vortices. The acoustic velocity at the location of the separation point acts as a perturbation which triggers the formation of new vortices in phase with the acoustic response. Thus, there is a closed feedback loop and the whole process can be self-excited. This is the main idea to be investigated and has not been advanced in previous investigations of oscillations in rocket motors.

LITERATURE REVIEW

From investigations made during the past decade, it is now known that the phenomenon termed the edgetone is one source of acoustic oscillations in solid rocket motors. Although edgetones have been observed for more than a century, their connection with unexpected oscillations in combustion chambers was not made until quite recently. As previously mentioned, the first suggestion that vortex shedding from discontinuities within the chamber could couple with acoustic resonances came from Flandro and Jacobs (1) in 1975. They did not make the direct association with the edgetone at that time, however. In their paper, a model is suggested in which vortices form at geometric disturbances and then interact with the acoustic resonances of the chamber. In their formulation, there is no downstream impingement point critical to the operation of an edgetone system. We quote from reference (1), "acoustic waves are produced in a manner analogous to the well-known Aeolian tone resulting from a Karman vortex street." This implies that the resultant acoustic disturbances are due to reaction forces on the body from which the vortices are shed rather than from some other body that the vortices pass later. Their model correctly assumes, based on experimental results, that the shedding of vortices is dominated by the acoustic waves present and therefore that they form at the same frequency. It incorrectly assumes that the strength of the vortical disturbance is proportional to the amplitude of the acoustic pressure. This leads to the conclusion that greater growth rates will occur if the geometric discontinuity is near a pressure antinode. This has since been shown to be incorrect by the experiments of Dunlap and Brown (6) described below, and also in the present work. In fact the strongest response occurs when the edges are near a velocity antinode, the point at which the pressure amplitude is minimum. This observation has since been incorporated into Flandro's model as indicated by his contribution to the recent paper by Dunlap et al. (7).

It was first demonstrated by Culick and Magiawala (2) that two discontinuities are necessary for the existence of spontaneous oscillations with any significant amplitude. For a very restricted range of baffle location near the midpoint of the duct they observed weak oscillations with a single baffle. Their apparatus consisted of a lucite tube containing a pair of annular baffles through which air was forced by a blower. Only frequencies at resonant modes of the tube were observed and the corresponding Strouhal numbers ranged from 0.4 to 1. They found that the location of the baffle pair within the duct was important in determining whether or not oscillations would occur but it seems they did not recognize that the strongest response would occur if the baffles were placed at a velocity antinode.

In response to the findings of Culick and Magiawala (2), a more realistic cold-flow scale model of a solid rocket motor was studied theoretically and experimentally by Brown et al. (4,5). Spontaneous oscillations occurred only at frequencies corresponding to longitudinal resonant modes of the combustion chamber of the Titan rocket modeled, confirming that coincidence between vortex shedding and resonant frequencies is required. Strouhal numbers in the range of 0.5 to 2 were measured. Conventional stability calculations for the configuration modeled predicted strongly negative growth rates ($\alpha < -10$ for most of the burn) implying that the observed oscillations should not have arisen. Brown et al. (5) report without reference that similar discrepancies between predicted and actual behavior have been observed for the Space Shuttle Booster and by ONERA in one of their large solid propellant motors. They concluded that vortex shedding is indeed a significant source of acoustic energy not included in the stability prediction. While they conclude that feedback from the acoustic field to the growing vortices occurs, the effect of feedback is ignored in the analysis developed. They confirmed experimentally that at least two restrictors are necessary for sustained oscillations and assume that the effect of the downstream baffle is to disrupt the vortices in the shear layer, preventing their driving the acoustic field further. The same assumption is made by Flandro and Finlayson (15). While it is very unlikely for vortices to collide with a solid object and not be disrupted, it seems that the interaction itself will produce a much larger driving force than the weak interaction of the growing vortices upstream with the acoustic field.

In a much simpler apparatus, Dunlap and Brown (6) then demonstrated that with nitrogen flowing past a pair of restrictors within a tube, only acoustic modes with velocity antinodes (pressure nodes) near the location of the restrictor pair were excited. Modes with a pressure antinode there did not respond at all. Their apparatus consisted of a tube with a small inlet and an exhaust port at the ends which otherwise were closed. Restrictors made of two washers mounted close together, near the midpoint of the tube, constituted the edgetone part of the system. Both the fundamental resonance and the third mode have acoustic velocity antinodes at that point, but the second mode has a node there. They were unable to excite the second mode at all, but could easily observe the first and third modes at appropriate mean velocities. In order to cause the third mode to oscillate spontaneously they had to triple the mean velocity at which the first mode was excited. This is consistent with the idea that, since the period of a cycle of the third mode is one third of the period of the fundamental, the vortices must travel with three times the speed to cover the distance between the baffles.

The apparatus used in the present investigation was first designed by Nomoto in order to perform experiments for his Engineer's thesis (3). His results are discussed in a more readily available article by Nomoto and Culick (8). By synchronizing a strobe light to flash at the same frequency as the oscillation, Nomoto was able to take photographs of the vortices, made visible using smoke, which clearly demonstrate that vortex shedding is associated with the oscillation. The frequencies of operation were observed to be almost constant over large velocity ranges and were dictated by the organ-pipe resonances of the duct.

Following the analysis of Rossiter (16) dealing with flow over cavities, Nomoto (3) assumed that the acoustic disturbance generated by the collision of a vortex with the downstream baffle travels upstream and directly triggers the formation of another vortex as in an isolated edgetone. He was thus unable to explain why oscillations occur at essentially constant frequencies equal to the duct resonances over ranges of velocity and baffle spacing rather than at the frequency the edgetone system alone would select. He suggested that some interaction between the two systems was occurring and that the location of the baffles with respect to the acoustic modes may be important, but was not more specific than that.

A similar flow was investigated by Schachenmann and Rockwell (17,18,19). In their apparatus, air is blown through a long tube terminated by a hole-tone cavity which interacts with the organ pipe resonances of the tube. The mean flow rate and distance from separation to the edge are variable. As in Nomoto's apparatus (also used in the present work) the oscillations occur predominantly at the resonant frequencies of the resonator. They find that the resonance is strongest when there is a phase difference of $2n\pi$ between the fluctuating velocities at separation and impingement, meaning that there is an integral number of wavelengths or vortices between the two points. As the mean velocity or spacing is changed, this phase difference varies up to 50° according to the results reported (18). This is in agreement with the model postulated here.

MODEL

Based on the postulated mechanism, a model is developed to predict the behavior of the combined acoustic resonator duct and edgetone system. By demonstrating that the model agrees well with the experimental observations, it is verified that the proposed mechanism is correct.

The model consists of several blocks linked together. Each is considered separately then combined to produce a system with characteristics similar to those of the experimental apparatus.

One major component is the acoustic duct resonator. Its response can be modeled quite well using one-dimensional acoustics, which neglects any variation across the width of the duct. The response to localized sinusoidal forcing at an arbitrary location in the duct (equal to the location of the downstream baffle) is calculated. The entrance and exit of the duct are modeled as complex impedances which are calculated using piston functions after Kinsler and Frey (20). These impedances serve as losses necessary to obtain finite amplitudes. Formulations for other systems should include appropriate losses.

Another major section is the shear layer which forms at the upstream baffle. Velocity fluctuations at the separation point, calculated using the acoustic response mentioned above, are taken to be the perturbation which are amplified in the streamwise direction by the shear layer instability studied by Freymuth and Michalke (11,12,13,14). A similar matching assumption is made by Flandro in his model (7). The growth of the velocity fluctuations is initially exponential, with a growth rate dependent on the Strouhal number, as predicted by Michalke and confirmed experimentally by Freymuth. The Strouhal number, or non-dimensional frequency, is determined using the acoustic response and the experimental shear layer momentum thickness which is found by integrating the hotwire velocity profile numerically.

Freymuth's data concentrate on the initial region of the shear layer for which the linear instability theory of Michalke holds. However, this data also indicate a saturation of the amplitude downstream. The saturated amplitude is independent of the initial perturbation amplitude and appears to depend only on Strouhal number. A plot of the maximum amplitude versus Strouhal number is given in Fig. 2 along with a logarithmic least squares fit to the data. This saturation phenomenon is the amplitude limiting aspect of the overall mechanism.

The velocity fluctuations are assumed to remain constant downstream once they have reached the saturation value corresponding to the initial Strouhal number. The circulation corresponding to the velocity fluctuation is replaced by a point vortex which convects at a velocity which also depends on the Strouhal number according to Freymuth.

As the vortex is convected past the downstream baffle, the pressure acting on its surface is calculated using potential flow theory and integrated to yield the total force acting on the baffle for each position of the vortex. Since the fluid applies a force on the baffle, the baffle must apply an equal and opposite force on the fluid. Therefore, there is a jump in pressure from the upstream side to the downstream side of the baffle equal to the force divided by the cross-sectional area. The approximation is made that this jump in pressure acts across an infinitessimally thin region at the location of the downstream baffle. Since a vortex passes the baffle each cycle, the pressure varies periodically. This pressure is replaced by its Fourier component at the acoustic frequency and is used as the driving force to determine the acoustic response of the duct.

Determination of the frequency and initial perturbation amplitude is an eigenvalue problem which is solved in the computer program using an iterative scheme. Since the response velocity at the upstream baffle is assumed to be the perturbation, the correct solution is that which yields the same response velocity there. This equality includes both amplitude and phase. It is found that varying the frequency while the amplitude is kept fixed mainly affects the phase difference between the perturbation and the response. Similarly, changing the initial amplitude changes the response amplitude while leaving the phase difference relatively constant. The iteration scheme, therefore, alternates between the two variables. One time the frequency yielding zero phase difference is determined, the next time the amplitude that results in the same amplitude is found. After a few times through this procedure, it is generally found that both equalities are satisfied simultaneously within the desired tolerance.

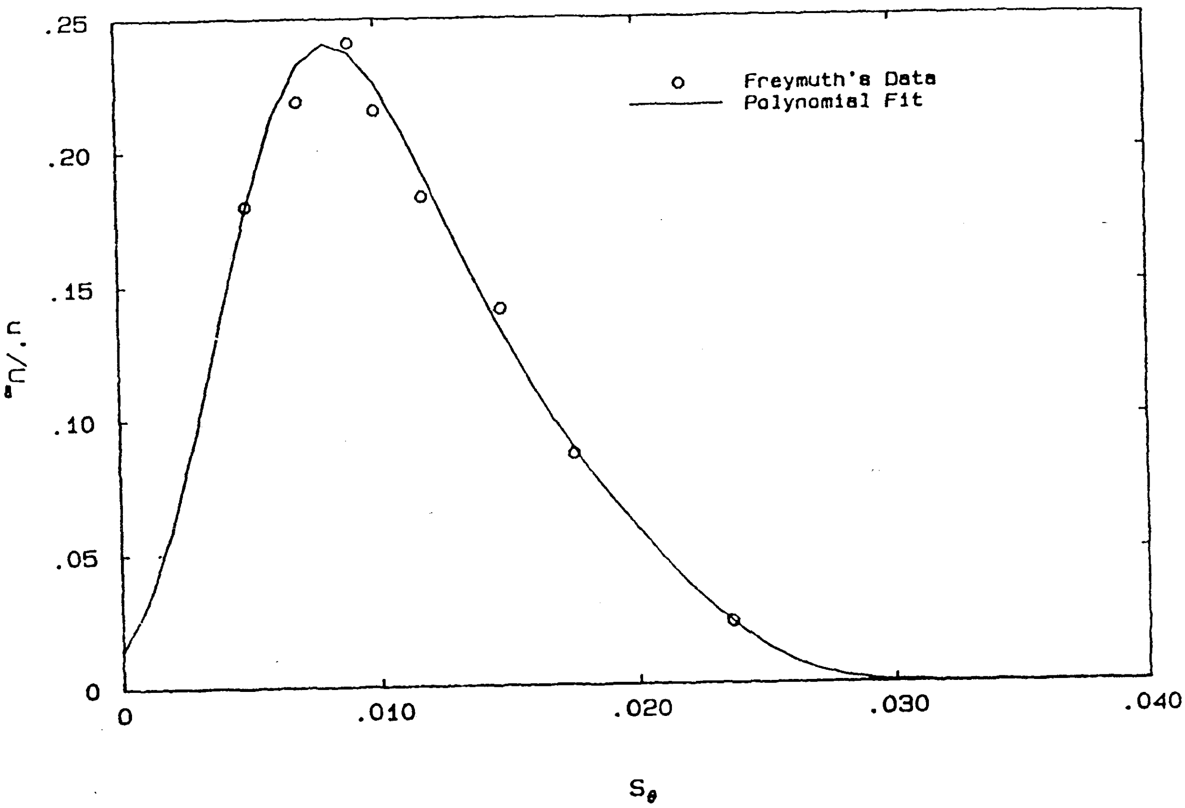

Figure 2. Maximum Saturated Velocity Amplitude in Shear Layer

APPARATUS

The test section of the apparatus is a rectangular lucite duct 50cm (20") long with a cross-section 5cm x 15cm (2" x 6"), as illustrated in Fig. 3. Two pairs of aluminum baffles can be placed at almost any location inside the duct and are connected by brass bars which fit in four grooves in the walls of the duct. The baffles act as separation and impingement points to form an edgetone on either side of the chamber. The baffles are modeled after the geometry that occurs in the combustion chamber of a solid propellant rocket when inhibitors protrude into the flowfield as the propellant burns back. The rectangular cross-section is to facilitate flow visualization using smoke and a strobe light. Air is drawn through the duct by a centrifugal blower downstream. A rectangular box and flexible hose acoustically isolate the test section from the blower. A loudspeaker mounted on top of the acoustic isolater is used to drive the acoustic field externally for some tests.

Velocity measurements are made using a TSI 1210 hotwire in the constant temperature mode with a Caltech designed Matilde bridge anemometer. The hotwire is calibrated using a pitot-static probe and a Barocel 570 strain gauge differential pressure transducer. Acoustic pressure measurements are accomplished using Bruel and Kjaer 4133 and 4134 capacitance microphones. In addition to mounting ports at the midpoint and three quarter point of the duct, the acoustic pressure can be measured at any point along the length of the duct using a B&K 4002 trolley containing a microphone with a tube extension.

RESULTS AND DISCUSSION

The measured natural frequency of the duct is 295Hz, which is exactly the value predicted by the model, demonstrating that the end conditions are approximated well using the piston function approach. When baffles are installed, the effect of the blockage is to reduce the natural frequency about 20Hz, an effect predicted theoretically by El-Raheb and Wagner (21) but not included in the acoustic part of the model

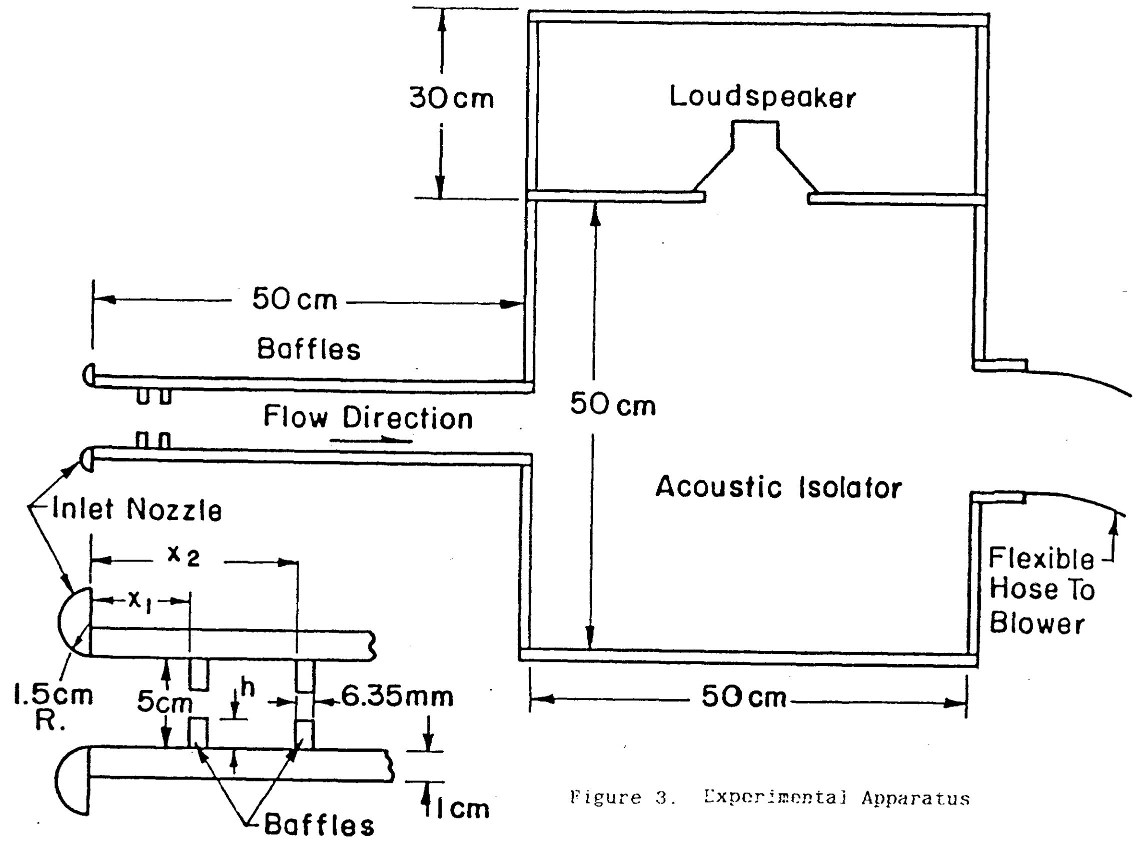

Figure 3. Experimental Apparatus

The predicted mode shape fits the measured distribution well as shown in Fig. 4. The curve and data are both normalized using the maximum value. The agreement at the extremities again shows that the end conditions are well modeled. From Fig. 5, it can be seen that there is little change in the mode shape for different size baffles. Again, the amplitudes are normalized using the peak values.

The momentum thickness, found by numerically integrating the hotwire mean velocity profiles, was found to be about 0.5mm (.02"). With a velocity difference across the shear layer of 13 m/s and a frequency of 275Hz, the corresponding Strouhal number is about 0.010 which falls very close to the value of the Strouhal number for which Freymuth obtained the maximum saturated amplitude in his shear layer measurements. This confirms that the amplitude is determined, to a large extent, by this saturation process which occurs in the shear layer.

As the spacing between baffles is changed with the mean velocity fixed, the amplitude passes through a maximum while the frequency remains essentially constant and equal to the resonant frequency of the duct. This is depicted in Fig. 6 along with the prediction of the model. The conditions, which are the same for the experimental data and the prediction, are that the upstream baffle is located very close to the inlet to the duct and the mean velocity between the baffles is 17.4 m/s. This location for the baffles is used since the fundamental acoustic mode has a velocity antinode there and the greatest response occurs when the baffles are located at a velocity antinode, as indicated earlier. The mean velocity and the condition of the shear layer are such that the Strouhal number corresponding to the fundamental frequency of the duct is about 0.008, the value for which the vortices saturate with the greatest strength. The dashed curve also plotted in this figure is a prediction based on the same mechanism, but with many simplifications. This simple theory does not predict actual amplitudes, so it is matched to the data at the peak, however, it models the trend extremely well. This simple model will not be presented here, but details can be found in Aaron (10). The peak of the predicted curve for the more complete theory occurs at close to the correct baffle spacing, confirming that the model exhibits the right behavior, although the shape is not correct away from the peak. The maximum amplitude is predicted within a factor of two. This agreement is probably fortuitous since the prediction of absolute acoustic levels is generally very difficult due to the extreme sensitivity to apparently minor geometrical changes, such as a small hole through the wall, perhaps for the insertion of a probe of some kind. Furthermore, some of the assumptions made in the model are rather crude. Nonetheless, agreement within an order of magnitude can safely be claimed. The corresponding frequency variation is shown in Fig. 7. It is noted that the frequency remains essentially constant throughout and that the slight trend is well predicted. The shift is due to the effect of the baffle blockage on the natural frequency of the duct, as explained earlier.

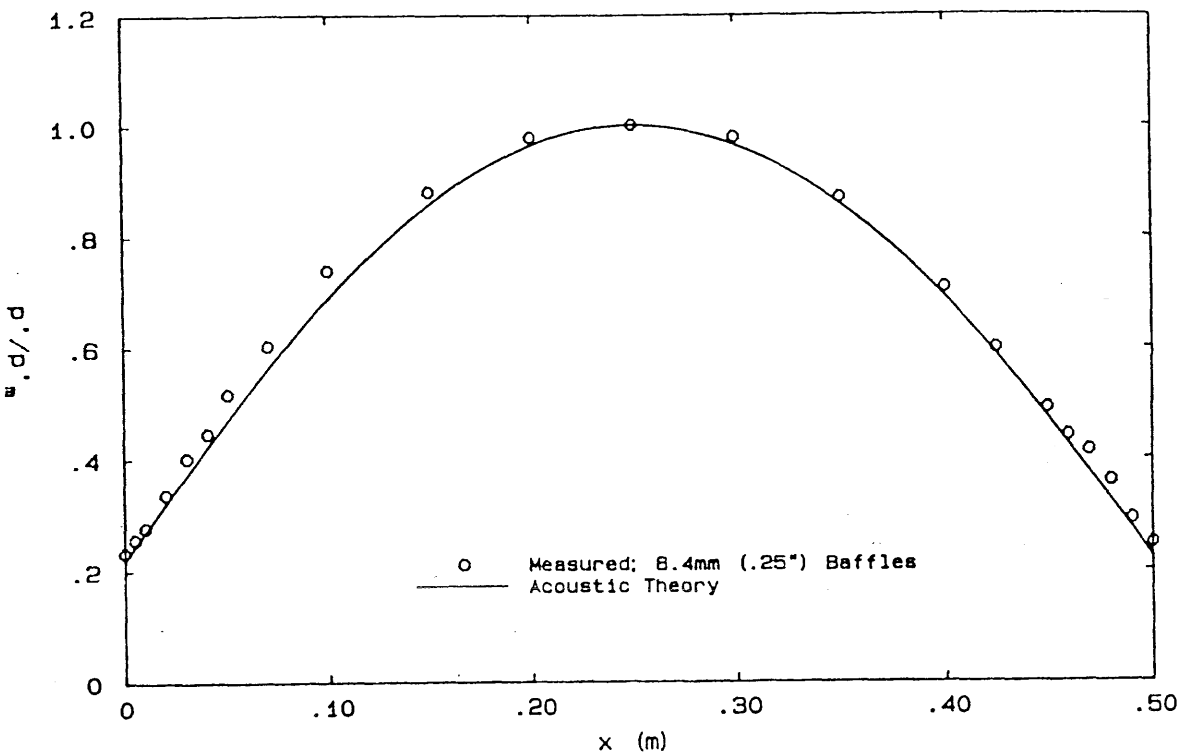

Figure 4. Acoustic Pressure Distribution with Baffles at Inlet

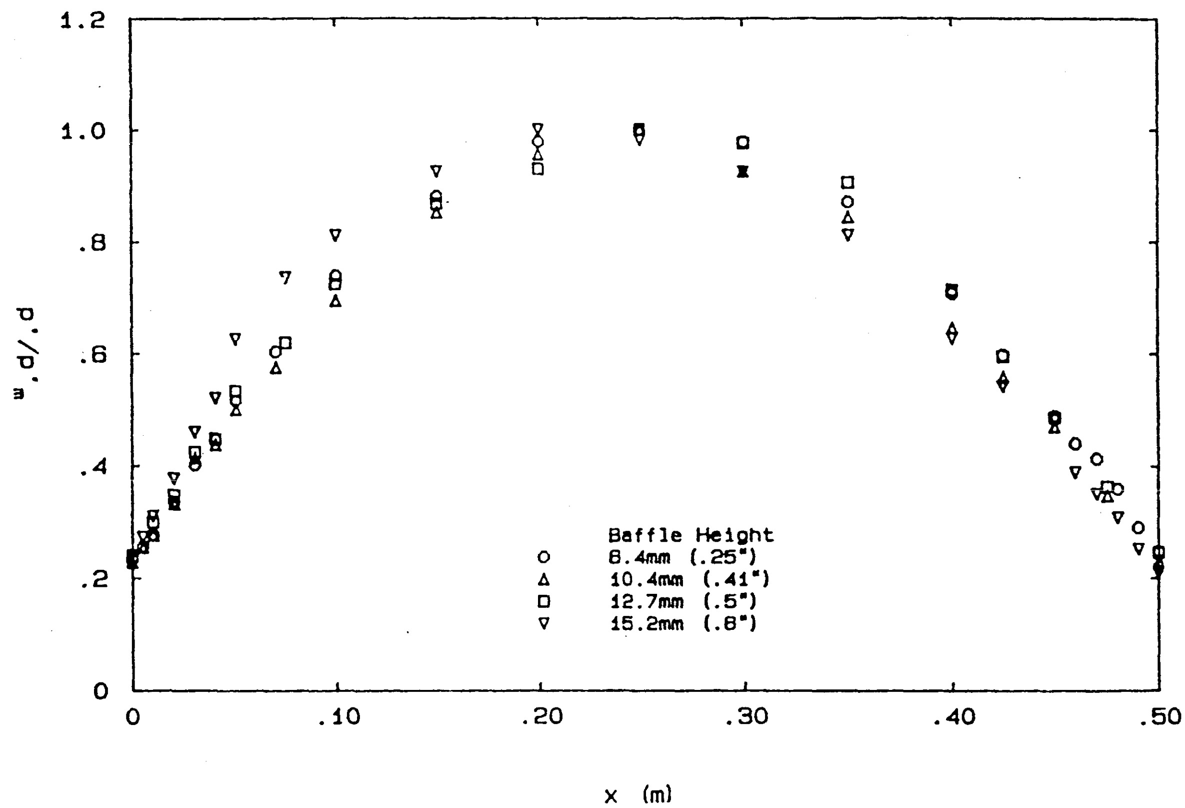

Figure 5. Acoustic Pressure Distribution with Different Size Baffles

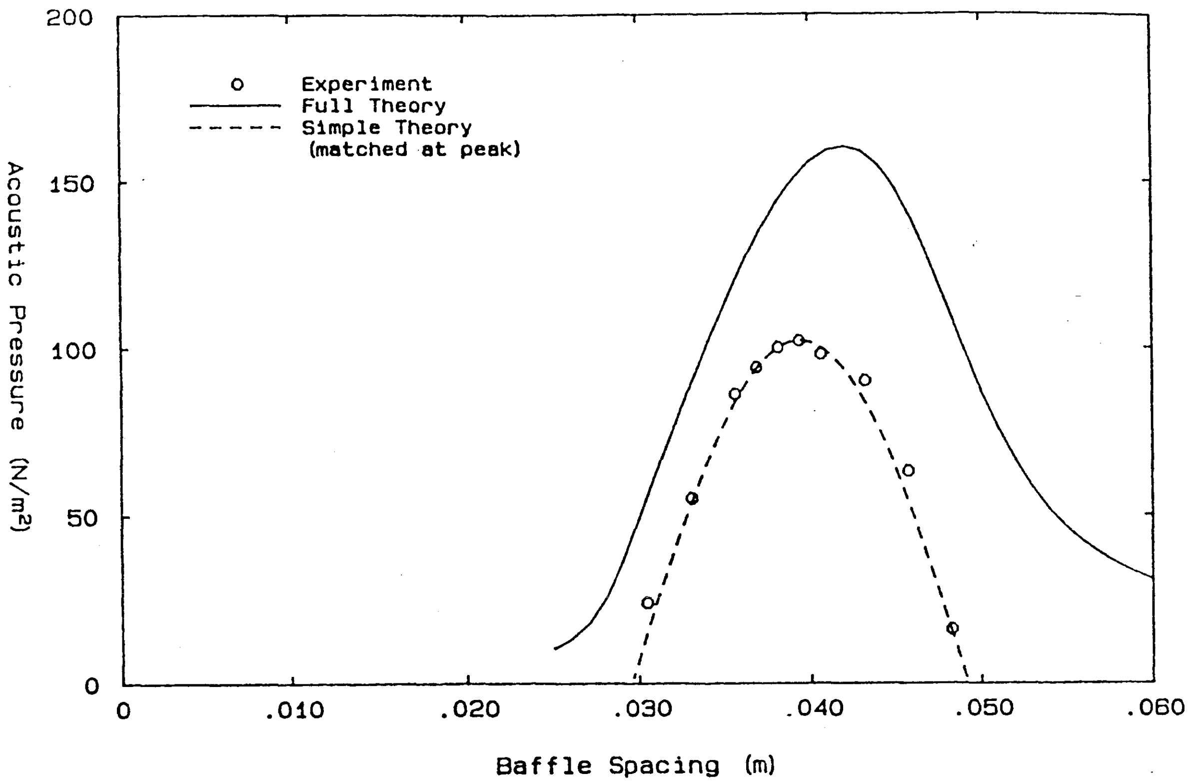

Figure 6. Effect of Baffle Spacing on Amplitude

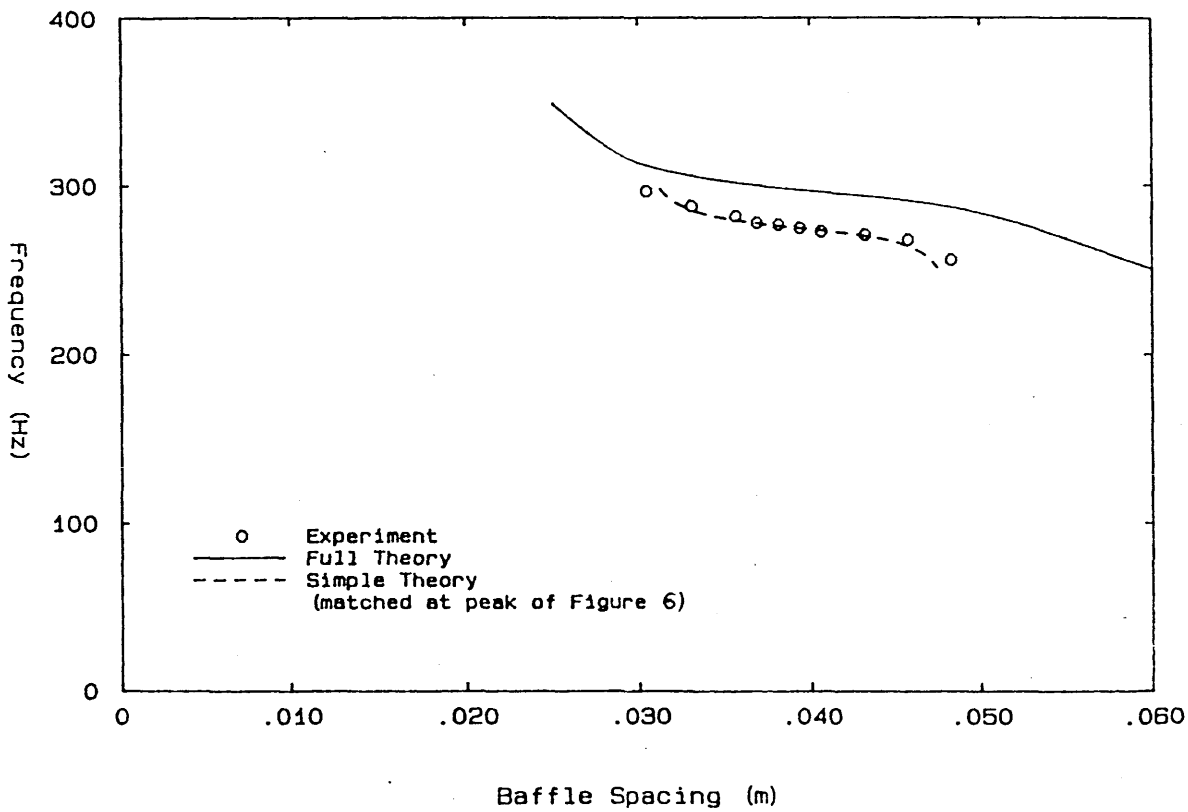

Figure 7. Effect of Baffle Spacing on Frequency

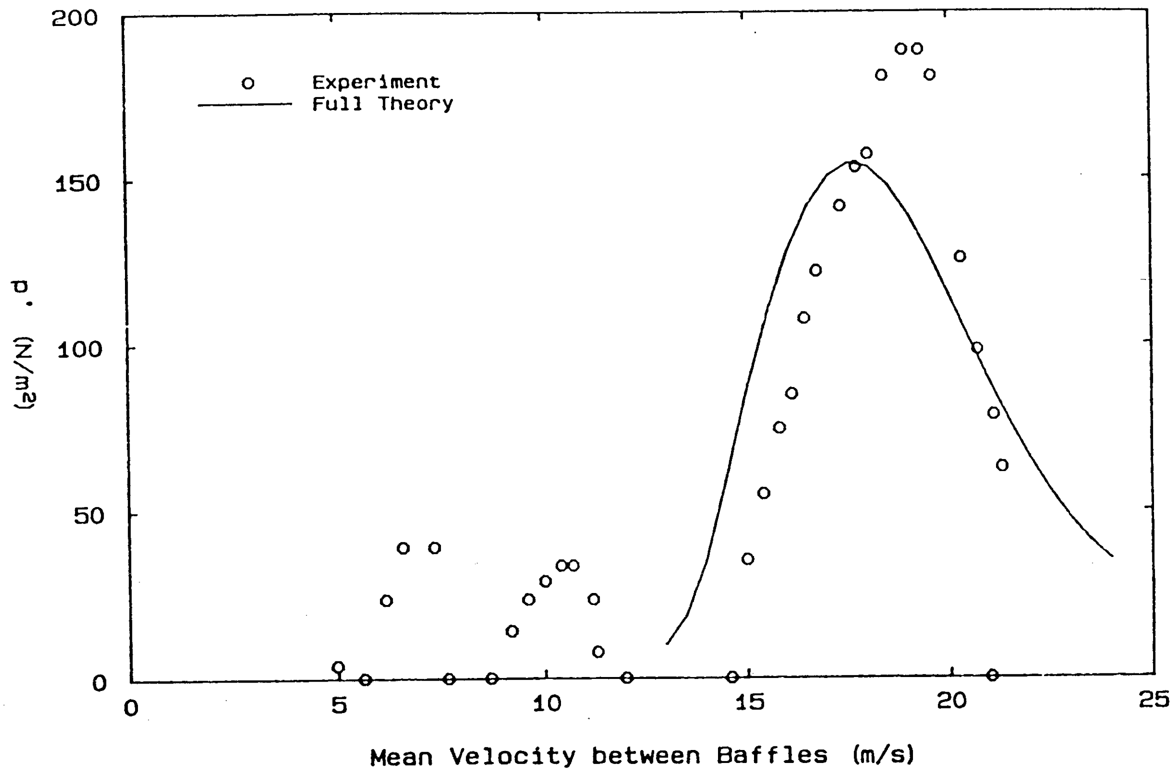

Figure 8. Effect of Mean Velocity on Amplitude

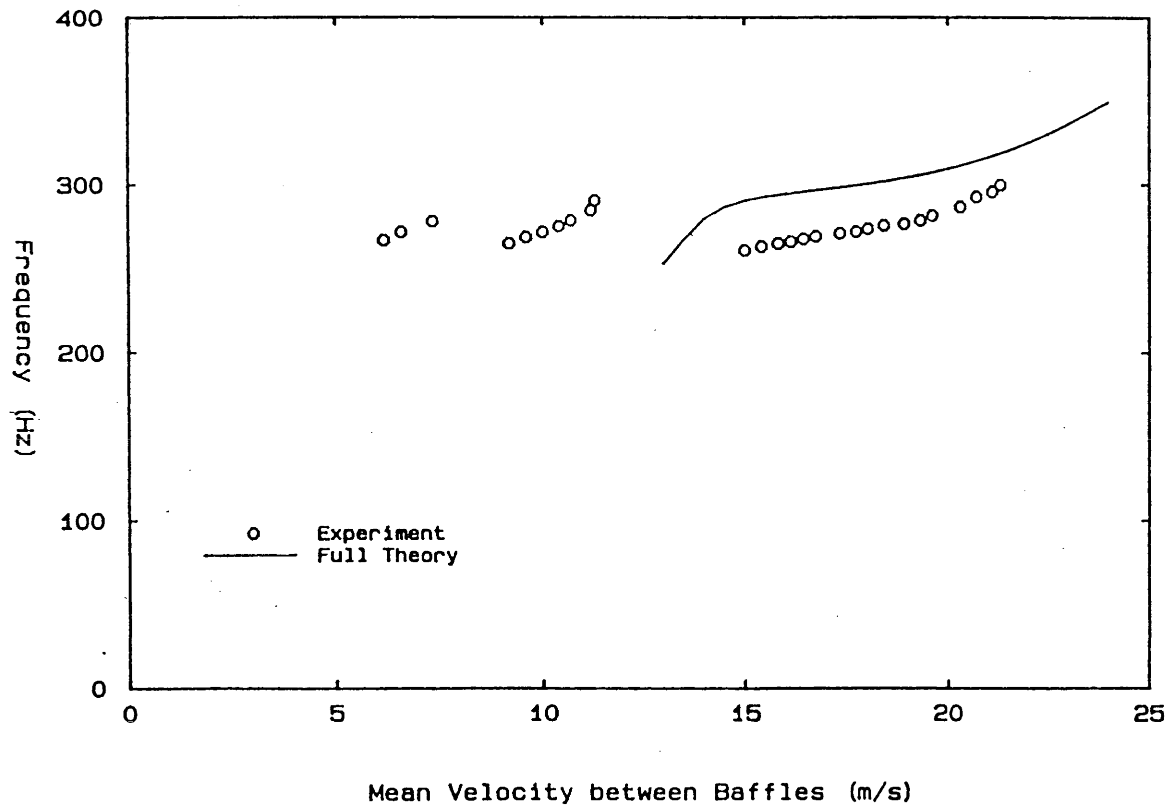

Figure 9. Effect of Mean Velocity on Frequency

In Fig. 8, the amplitude behavior with changing mean velocity is shown. The baffles spacing is fixed at 3.81 cm (1.5") and this time the location of the baffles is close to the duct exit which is also a velocity antinode. Again, the model agrees well with the experimental measurements in both magnitude and trend. This agreement confirms that the postulated mechanism is correct. The consecutive peaks as the velocity is decreased correspond to increasing stage numbers, with the number of vortices between separation and impingement increasing by one each time. It is interesting to note that the peak for stage N occurs at a mean velocity close to 1/N of that for the first stage. As shown in Fig. 9, the frequency is approximately the same for each peak. Since the vortices are formed at the same frequency, but travel at 1/N of the velocity, this suggests that there are exactly N wavelengths from separation to impingement and that the vortices arrive at the downstream baffle at the same phase in the acoustic cycle for each case. This condition must be such that the oscillating force and the acoustic velocity are in phase with one another. For this condition, the maximum energy is transferred to the acoustic field, resulting in the largest response.

CONCLUSIONS

Based on laboratory experiments and results quoted in the literature, a mechanism has been postulated which explains the interaction between an edgetone and an acoustic resonator. This mechanism is believed to be a contributor to undesirable low frequency tones in segmented solid propellant rockets.

In addition to the acoustic resonator, two key elements required for the mechanism to operate are a shear layer in which vortices grow and an obstruction downstream. The most important idea leading to an understanding of the operation of the system is that the acoustic velocity acts as the perturbation which triggers the formation of the vortices in the shear layer. These vortices, in turn, drive the acoustic resonance by interacting with the obstacle downstream. The hydrodynamically induced velocity fluctuations due directly to the interaction of the vortices with the obstruction, which trigger the vortex growth in an isolated edgetone, are negligible when compared with the acoustic velocity.

Since the vortices are initiated in phase with the acoustic response, changing the distance from separation to impingement or changing the mean velocity changes the phase between the forcing and the response of the acoustic resonator. Associated with these large phase changes are relatively small changes in frequency since the operation is in the neighborhood of a strong resonant peak. Over large ranges of velocity and distance from separation to impingement, an edgetone and resonator system can produce significant spontaneous vibrations.

The amplitude of oscillation is limited by the saturation of the strength of the shear layer vortices. Generally, the level will be quite low compared with oscillations due to combustion instability. Nonetheless, the concentration of the energy in narrow bands of frequency could lead to vibration problems with components having resonant frequencies in those bands.

An important parameter is the Strouhal number based on the momentum thickness at separation. Oscillation can only occur if the resonant frequencies correspond to Strouhal numbers within the amplified range (0 to 0.04). The strongest fluctuations exist when the resonant peak corresponds to the Strouhal number with the maximum saturated amplitude (0.01).

Based on the postulated mechanism, a model has been developed which predicts behavior similar to that of the experimental apparatus. Amplitudes can only be predicted within an order of magnitude with any degree of confidence due to some coarse assumptions made in the model. The agreement in the trends is very important, however, and confirms that the proposed mechanism is correct.

Armed with an understanding of this mechanism, designers should be able to anticipate the occurrence of oscillations due to the phenomenon described, and either enhance or weaken them as desired by adjusting the geometry. The most obvious way to eliminate these self-excited acoustic oscillations is to remove the shear layer. If separation can be avoided, the mechanism cannot operate.

The ideas presented here should help future investigators of this phenomenon to understand the processes involved, allowing them to pursue the details and improve their models. Ultimately, this will lead to sufficient understanding that the associated problems can be tackled effectively.

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