APPROXIMATE ANALYSIS AND STABILITY OF PRESSURE OSCILLATIONS IN RAMJETS

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ABSTRACT

This paper summarizes work accomplished during the past five years on analysis of stability related to recent experimental results on combustion instabilities in dump combustors. The primary purpose is to provide the information in a form useful to those concerned with design and development of operational systems. Thus most substantial details are omitted; the material is presented in a qualitative fashion.

A major part of the work at Caltech and the University of California, Berkeley, has been supported under the ONR Research Initiative on Pressure Oscillations in Ramjets, the remainder being supported by AFOSR (Caltech) and by the Air Force Aero Propulsion Laboratory (California State University, Sacramento). It is convenient to divide this summary into a brief résumé of recent experimental work followed by a summary of the analyses.

EXPERIMENTAL WORK

The experimental work at Caltech [Smith and Zukoski (1985)] has been carried out in the duct shown in Figure 1. It is a two-dimensional configuration in the form of a dump combustor, or half of a blunt-body flameholder. The characteristics of the flow have been determined over broad ranges of conditions, as summarized in Figure 2.

Large amplitude oscillations have been found to occur at several frequencies. Figure 3 shows shadowgraphs of the flow downstream of the rearward facing step when conditions are stable and when significant pressure oscillations are present. In the latter case, large vortices are shed periodically at the same frequency as the pressure oscillations. One cycle of the motion is shown in Figure 4, with a trace of the pressure.

There seems to be no doubt that the mechanism for the instability is associated with vortex shedding and periodic pulses of energy released by combustion in the vortices. Smith and Zukoski have proposed the following mechanism. A vortex is initiated at the edge of the step at a time determined partly by the local acoustic velocity. The vortex propagates downstream, releasing energy at a rate that seems to reach maximum when the vortex impinges on the wall. In order for the time of impingement to be at a favorable time during the acoustic oscillation, the propagation rate and hence strength of the vortex must increase with frequency. Because the vortex strength depends on the magnitude of velocity fluctuation initiating the motion of the lip, it is necessary that the steady amplitude of the acoustic field increase with frequency. That behavior is observed. Moreover, numerical calculations by Hendricks (1986) have shown quite similar behavior for the unsteady flow induced by an abrupt change of velocity past a rearward facing step. Figure 5 is a sketch taken from Hendricks' work showing the development of a vortex calculated for those conditions.

Somewhere similar findings have been made at Berkeley by Daily and co-workers. Keller et al (1982) had earlier observed vortex shedding in the turbulent reacting shear layer shed from a step, Figure 6. In a different configuration, a conical dump combustor, Yu et al (1987) have investigated unsteady flows of the sort illustrated in Figure 7. A major difference from the case illustrated in Figures 3 and 4 is that the shed vortices now tend to fill the chamber and interact strongly with the exhaust nozzle. Differences between the flows in axisymmetric and two-dimensional configurations must of course be expected.

Although these flows bear certain obvious similarities, the connection cannot presently be made quantitatively: each device has to be treated as a special case. What is clear from these observations is that vortex

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shedding from steps or bluff bodies is likely a dominant mechanism for combustion instabilities in ramjet engines and probably afterburners as well. The earliest examples of this phenomenon were reported by Kaskan and Noreen (1955) and by Rogers and Marble (1956). Taken all together those works illustrate why much of the analytical work has taken the course it has in recent years.

ANALYTICAL WORK

Vortex shedding may cause unstable pressure oscillations via four routes: direct coupling between the velocity field of the vortex and the acoustic velocity field; impingement of the vortex and a solid surface, causing a pressure pulse; convection of vorticity into a choked exhaust nozzle, generating a pressure pulse; and periodic combustion of reactants entrained by the shed vortices.

The work on vortex shedding as a mechanism for instability discussed here has been based largely on the assumption that the last two processes are likely dominant in ramjet combustors. Direct coupling of the velocity fields and impingement of vortices on obstacles have been investigated in connection with oscillations in solid propellant rockets. It appears that those mechanisms are unlikely to sustain unsteady pressure fluctuations of large amplitudes, i.e. greater than a few percent of the mean pressure.

There are of course other possible mechanisms not associated with the presence of vortices. An unstable motion may occur if a process is sensitive to the motion in such a fashion as subsequently to cause transfer of energy to the motion. In liquid-fueled systems, the formation of liquid droplets, their vaporization, and subsequent combustion of the gaseous reactants involve many processes that may contribute to combustion instabilities. The subject was intensively investigated for more than two decades during the development of liquid rockets, particularly for application to engines used in the Apollo vehicle, special attention being required for man-rated machines.

The dominant method of analysis used in those works was based on the idea of a time-lag, introduced in the 1940's and developed principally by Crocco and his students and co-workers at Princeton. That method does not provide predictive results based on first principles but rather offers a means of correlating and interpreting experimental results. The correlations may then be used for design work, provided the new devices have geometries similar to those tested and in some sense operate under comparable conditions. Professor Reardon, using his experience with liquid rockets, has applied the time-lag method to analyze extensive data taken at the Air Force Wright Aeronautical Laboratories. He has restricted his attention to cases in which the oscillations in the combustion chamber were evidently bulk modes for which the pressure is closely uniform in space but pulsates in time. His work has been reported previously at JANNAF meetings [Reardon (1981, 1983, 1984, 1985)] and has most recently been summarized for presentation at an AGARD meeting [Reardon (1985)].

In addition to examining possible effects of vortex shedding, Reardon has considered fluctuations of the energy release due to variations in the flow rates of reactants; influences of pressure and temperature variations in the flame zone; and convective waves, generating pressure waves as a result of regions of non-uniform entropy (temperature) carried into the exhaust nozzle by the average flow. He attempted to correlate data for the frequencies, amplitudes and incidence of oscillations in terms of geometric and operating characteristics. His chief conclusion is that oscillations in the feed rates of fuel and air seem to be dominant causes of oscillations in the cases he examined. The results are limited — it is difficult to see how they can be generalized — and are contingent upon several assumptions of the values for crucial parameters. Nevertheless, he has succeeded in bringing some order to a large set of data.

Much of the same data have also been studied by Abousief, Keklak and Toong (1984) and by Waugh and Brown (1984) using the idea that convective waves are the dominant mechanism. In these cases, acoustic wave modes are allowed in the combustion chamber. The idea is that interactions of convected entropy, or temperature, waves with the exhaust nozzle produce pressure waves as noted above. The pressure waves then propagate upsteam to be reflected (possibly with partial absorption) at the upstream end of the chamber. Superposition of the upstream and downstream waves produces a standing oscillation. Thus, the supply of acoustic energy, by interactions of the convective waves with the nozzle, compensates the energy losses in the chamber. Both groups were able to obtain some agreement between their results and observations of the frequencies and pressure distributions of instabilities. The analyses are linear and therefore cannot predict the amplitudes of instabilities.

Humphrey (1987) and Humphrey and Culick (1986, 1987a, 1987b) have also treated problems of convective waves, but with greater emphasis on the sources of the non-uniform entropy. In a ramjet engine, the two main sources are the combustion zone near the dump plane and the inlet shock system. The combustion processes were modeled as a plane flame, using results obtained many years ago by Chu (1952) and the shock system was idealized as a single normal shock, based on the analysis worked out by Culick and Rogers (1983). A modest effort was made to examine the influences of nonlinear gasdynamics. Perhaps the most important result of that work was demonstration of the existence of modes of oscillation that occur entirely because of entropy fluctuations. That is, in addition to the classical acoustic modes, there are oscillations that are not present if the entropy is uniform. Their frequencies lie between those of the acoustic modes. Although some experiments have shown instabilities not identifiable as perturbed forms of classical acoustic modes, the analysis has not been carried far enough to provide unambiguous explanation of observed results. Similar calculations apply to coupled vorticity/acoustic waves, as Jou and Menon (1988) have shown with their numerical calcualtions.

It is difficult in practice to establish unambiguously that convective waves are *the* mechanism for an instability. In fact, it is more likely that other mechanisms are always involved. The theoretical result that modes may exist at frequencies different from classical acoustic frequencies provides an initial basis for clarifying the mechanism when a problem arises. Nevertheless, the experimental results cited above demonstrate clearly that vortex shedding is a dominant feature of the flows in dump combustors. Indeed, the large vortices observed are possible sources of convective waves, both of vorticity and of entropy, due to periodic nonuniform combustion.

A comprehensive theory of combustion instabilities driven by vortex shedding and combustion has not been worked out. Rogers and Marble (1955) first proposed periodic vortex combustion as the cause of the transverse instabilities they observed in their apparatus. The idea is that if an oscillation is present, the acoustic vortex initiates a vortex at the lip of the flamehoder, entraining unburnt reactants. Sometimes later (in their case, the time was apparently due mainly by ignition delay) the reactants burn, providing a pulse of heat release which, if it occurs at the proper time during the cycle, will tend to sustain the acoustic oscillation. That is essentially the idea adopted by Smith and Zukoski (1985) to explain the occurrence of the longitudinal oscillations they found in their testing.

Byrne (1983) first proposed vortex shedding as mechanism for longitudinal instabilities in dump combustors. He was evidently unaware of the earlier work by Rogers and Marble, and based his interpretation on recent work concerned with large vortex structures generated in shear layers. Thus his proposal rests on direct coupling between the vortex velocity field and the acoustic field: periodic combustion is not an issue. While it is true that such a mechanism exists, as established by many recent works dealing with flows in solid rockets and in dump combustors, it seems clear that combustion processes are required to drive oscillations to the large amplitudes observed in laboratory and full-scale systems.

The problem of computing combustion in a vortex has been addressed by Marble (1985), Karagozian and Marble (1986), Karagozian and Manda (1986), Norton (1983) and by Laverdant and Candel (1987a, 1987b, 1988). The results are of course based on idealized models and so far as the problem of instabilities are concerned are perhaps best viewed as preliminary. Only the calculations by Norton suggest the appearance of enhanced burning, a small amplitude pulse, produced some time after the vortex is initiated.

Yu et al (1987) and Trouvé et al (1988) have given qualitative estimates of the possible coupling between vortex shedding and acoustic oscillations observed in their tests. They have examined the stability of shear layers, as for example discussed by Byrne (1983) and by Schadow et al (1987). A general conclusion, consistent among all these works as well as earlier results obtained for similar flows in solid rockets, is that combustion instabilities are most likely to occur under conditions when the frequency of vortex formation is closely coincident with an acoustic mode of the chamber. That result holds whether or not combustion is present, but as noted above, if burning is absent, the amplitudes are always small.

In a series of works, Yang, Paparizos, Culick and Kim (1983–1988) have studied the application of an approximate analysis based on Galerkin's method and time-averaging to explain combustion instabilities. The analysis provides a general framework for interpreting and predicting the behavior of unsteady motions generally in combustion chambers. It accommodates longitudinal and transverse modes and, because of its broad nature, any mechanism can be studied. The results are quantitative, giving formulas for linear stability as well as limited results for the existence and stability of periodic limit cycles. Moreover, explicit representations of Rayleigh's criterion have been derived [Culick (1987, 1988)].

The approximate method seems presently to provide the most convenient basis for deducing the properties of combusiton instabilities and for predicting their occurrence. According to limited comparisons with more accurate numerical calculations for simplified problems, the accuracy of the approximations involved seems to be entirely satisfactory for both theoretical and practical purposes. While any mechanism can be treated, only modest results have been obtained for convective waves, and none which include the details of vortex shedding. A simple model has been proposed for the latter [Culick (1988)] but the consequences have not been worked out.

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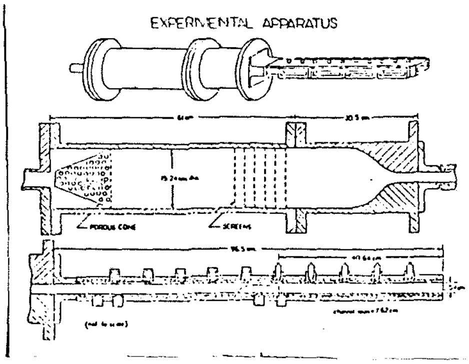

Figure 1

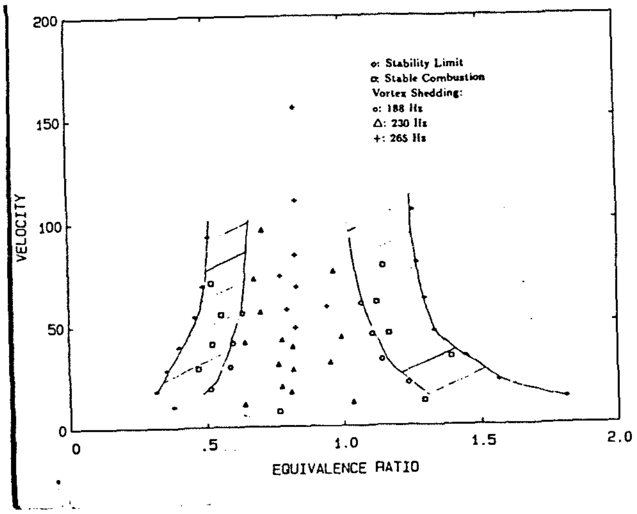

Figure 2

Stable Flow

Unstable Flow

Figure 3

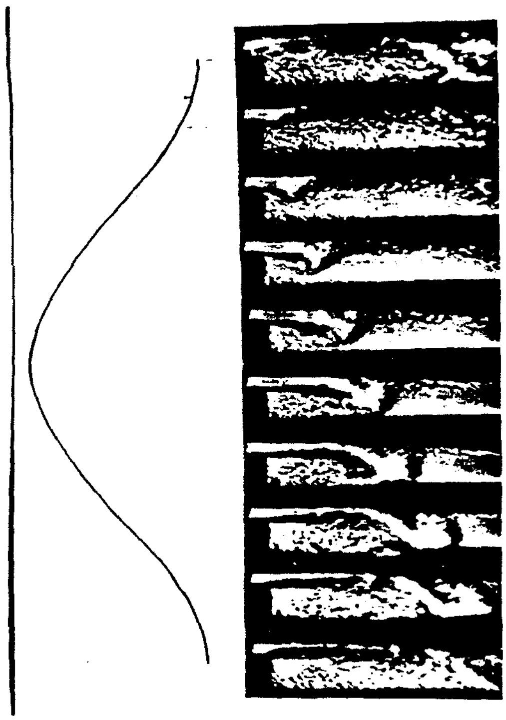

Figure 4

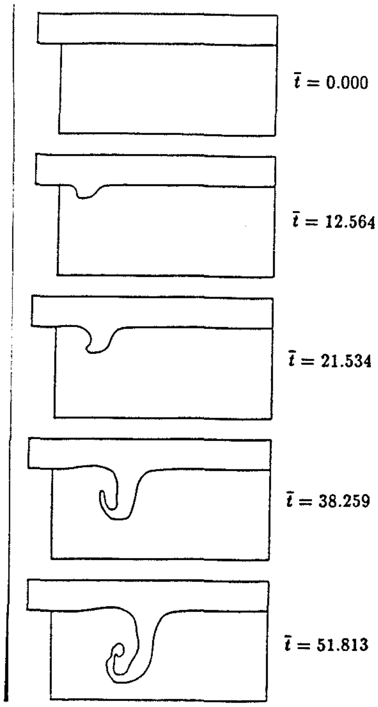

Figure 5

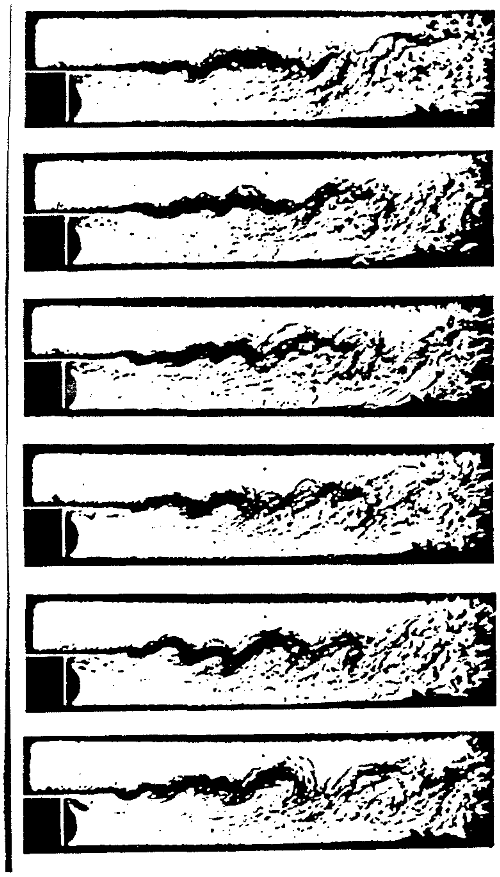

Figure 6

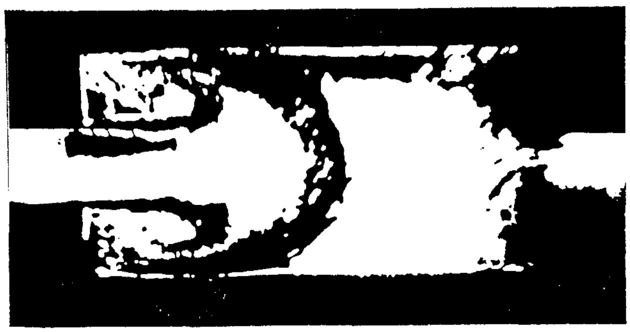

Figure 7