LINEAR THEORY OF PRESSURE OSCILLATIONS IN LIQUID FUELED RAMJET ENGINES

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ABSTRACT

Low frequency pressure oscillations in ramjet engines are treated within the one-dimensional approximation. The engine is treated in two main parts: the inlet-section, containing relatively high speed flow, and the combustion chamber. A linearized analysis of a normal shock exposed to acoustic waves provides the upstream boundary condition. Most of the work reported here has been concerned with the combustion chamber. A simple model of the steady flow in a dump combustor has been worked out, comprising three regions: the flow of unburnt reactions; the region containing products of combustion; and the recirculation zone. Combustion is assumed to occur in an infinitesimally thin sheet; an infinitesimally thin shear layer separates the recirculation zone from the remainder of the flow field. Acoustic fields in the inlet and the combustion chamber are formed separately and joined at the dump plane to provide a transcendental equation for the computer wave number. Results for the frequencies of oscillations and the pressure distributions compare well with experimental data taken at the Naval Weapons Center, China Lake.

Some preliminary results are given for the unsteady behavior of a normal shock wave in a diffuser, calculated with a modified form of a computer program obtained from the Air Force Rocket Propulsion Laboratory.

DESCRIPTION OF THE ANALYSIS

Suppression of pressure oscillations is a fundamental problem in the design of high performance ramjet engines. Disturbances of this type, generically called combustion instabilities, are a consequence of the sensitivity of combustion processes to local pressure and velocity fluctuations. For low frequency pressure oscillations, this sensitivity is mainly associated with fluid dynamic processes, rather than chemical kinetics. Recent investigation of the low frequency pressure oscillations in ramjet engines[1-7] prompted the work discussed in this paper.

The basic ramjet configuration, shown schematically in Figure 1, includes a shock wave system at the entrance, an inlet diffuser, a dump combustor, and an exhaust nozzle. Air is delivered to the dump combustor where fuel is injected and burned in the presence of a flame stabilizer.

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The combustion processes in the dump combustor is extremely complicated, involving turbulent mixing, flame propagation, shear layer, recirculating flow, and finite-rate chemical kinetics. Attempts to model these complicated phenomena have been made for over three decades, but still remain poorly understood. Most of the past work has concentrated on investigation of the mean flow fields in the combustor; information available on the treatment of the unsteady flow fields is limited. An excellent review paper concerning the computer modeling of the steady combustion in ramjet combustor has been given by Lilley.[8]

Combustion instabilities in ramjet engines may usually be characterized by several well-defined frequencies. These are close to the frequencies of the natural acoustic modes for the internal cavity of the system. For convenience the oscillatory behavior is classified as bulk, longitudinal, and transverse modes according to the frequency range and spacial structure.

For contemporary liquid-fueled ramjets, the most serious problem seems to be low frequency instabilities closely related to longitudinal modes. A very important consequence is the loss of inlet stability margin due to the effect on the inlet shock system. Experimental investigation of this subject has been recently conducted by several organizations. The results obtained have provided information about the effects of combustor configuration, fuel type, and fuel-to-air ratio on the overall instability processes.

Rogers[2] summarized the features of the pressure oscillations in two liquid-fueled engines having very different geometrical configurations. One had an axial dump with a single inlet, and the other had two inlets with a side dump arrangement. Significant differences appear in the structure of the oscillations excited in the combustion chamber. Schadow and coworkers have studied[5-7] oscillations in a research dump combustor with special attention focused on the inlet shock/acoustic wave interaction. The entire device was extensively instrumented during testing. Two kinds of data have been taken under various operational conditions: the acoustic wave structure and the properties of the inlet shock.

So far as analysis of longitudinal pressure oscillations in ramjets is concerned, Culick and Rogers[3] have constructed an one dimensional linear acoustic model. The combustion processes were accommodated in a general fashion, but not treated in detail. As examples, data were discussed for the two liquid-fueled engines mentioned above. Later, they studied[4] the frequency response of normal shock to downstream disturbances in an inlet diffuser. Two limits of a linearized analysis were discussed; one represented isentropic flows on both sides of a shock wave, and the other might be a crude approximation to the influence of flow separation induced by the wave.

Because observations of the unsteady behavior suggest that the low frequency oscillations do not involve significant transverse motions anywhere in the engine, the analysis here is based on a quasi one-dimensional model. The engine is treated in three parts; the inlet section, the combustion zone, and the region containing combustion products. Each region is handled separately and then matched with adjacent regions. The unsteady motion of the shock wave is characterized by an acoustic admittance function, providing the necessary upstream boundary condition. The acoustic field in the inlet is represented by the superposition of two simple waves running downstream and upstream.

An integral scheme has been developed to study the flow fields in the combustion zone. It has been our intention to develop a suitably simple and realistic model accommodating the fundamental features of the flow field, including the flame front, the shear layer, and the recirculating flow. For low frequency oscillations, the flame front and the shear layer can be adequately represented by a flame sheet and an infinitesimally thin vortex sheet, or dividing streamline, respectively. The flow field is, accordingly, decomposed into a flow of reactants, a region containing combustion products, and a recirculation zone as shown in Figure 1. The three zones are then matched at the flame sheet and the dividing streamline by taking into account conservation and kinematic relations. Determination of their shapes is part of the solution. The unsteady flow fields are considered within linear acoustics and approximated as one-dimensional motions in each of the three zones.

Downstream of the combustion region, the flow consists entirely of products of combustion; the flow is nearly uniform except near the nozzle. The analysis of the acoustic field in this region is similar to that for the inlet section. The simple result for the admittance function of a compact nozzle is used as the downstream boundary condition.

The analysis is completed by matching the acoustic fields found for the three main regions.

SOME RESULTS

Figures 2-4 show some results for the steady flow field in the combustor. No experimental data is available for checking the accuracy, but the qualitative features appear reasonable. The technique developed here has also been used to give a good comparison with the shape of a flame sheet in a duct, computed and reported in reference 9.

Several cases of unsteady motions have been calculated for comparison with data given in references 5-7. An example of the acoustic pressure distribution in the inlet is shown in Figure 5. Although the wave system is stationary, there is no fixed mode. Hence the pressure distribution changes periodically, a node oscillating about its average position. An example of the amplitude distribution through an engine, at one instant of time, is given in Figure 6.

The analysis is presently incomplete. Most significantly, the flow of energy from the combustion processes to the acoustic field has not been accounted for. As a result, all unsteady motions are predicted to be stable. Work is in progress to correct this deficiency.

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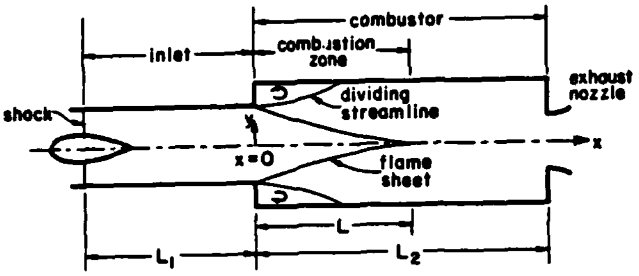

Figure 1. Schematic Diagram of a Ramjet Engine

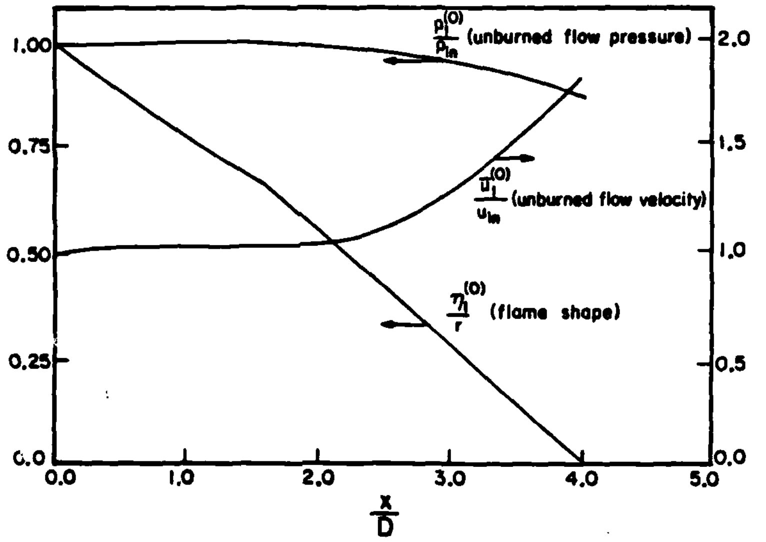

Figure 2. Distributions of Mean Flow Variables

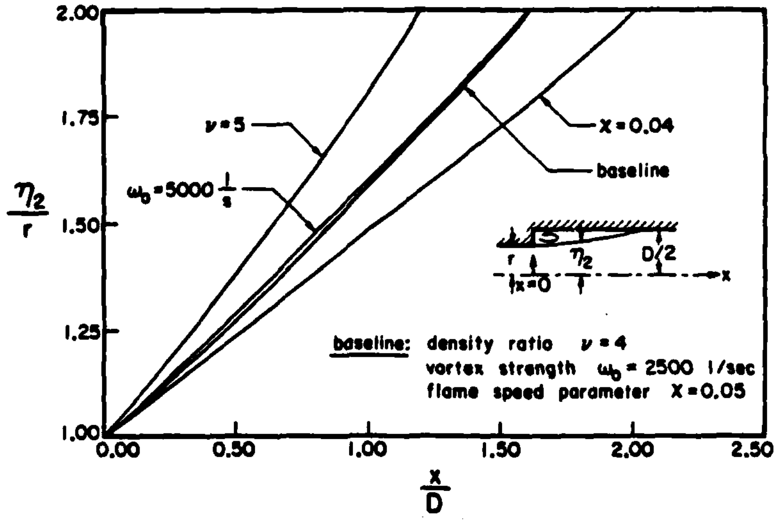

Figure 3. Shapes of Mean Dividing Streamline

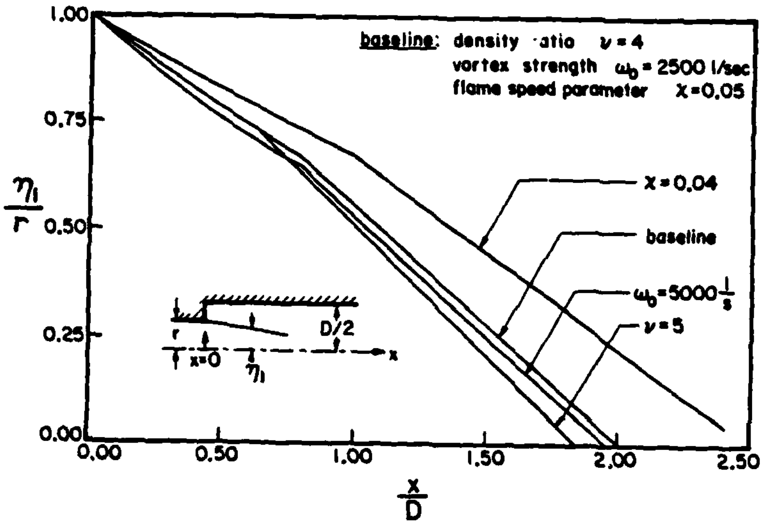

Figure 4. Steady Flame Envelopes

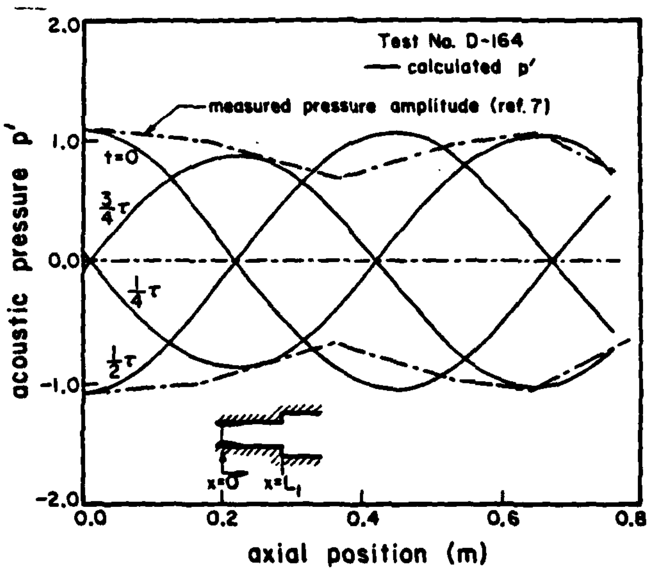

Figure 5. Measured and Calculated Acoustic Pressure Distributions in the Inlet

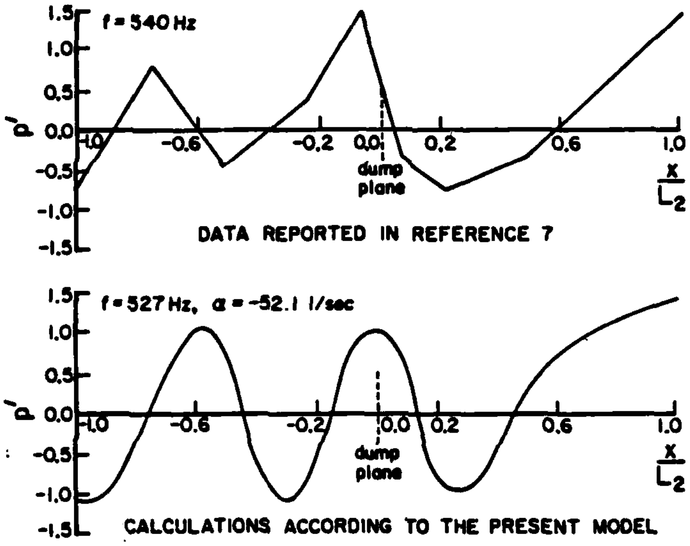

Figure 6. Measured and Calculated Acoustic Pressure Distributions in the Entire Engine

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