Oscillations of the Supersonic Flow Downstream of an Abrupt Increase in Duct Cross Section

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Abstract

THE flow in a duct following a sudden change in section is described herein. Sonic flow through a convergent nozzle expands into a larger cross section to produce a mixed supersonic flow, and a low base pressure in the upstream corners. Under certain pressure conditions, oscillations occur in the duct and excessive externally generated noise results. These self-excited oscillations are caused by a boundary-layer/shock-wave interaction, and can exist in both circular and rectangular ducts. Many types of oscillations have been observed in different test arrangements, and a complete description of the flow may be found in the full paper.[1]

Contents

Most of the tests were carried out in a duct through which atmospheric air was induced by means of a downstream vacuum. A schematic diagram, characteristic of all the ducts tested, is shown in Fig. 1. Figure 2 shows typical interferograms for the different flow regimes obtained with a Mach-Zehnder interferometer in a rectangular duct, as the downstream receiver pressure p_e increased. The base pressure typically varies with the ratio of p_e to input stagnation pressure p_a, as shown in Fig. 3. The flow structure can either be dominated by a series of reflected oblique shock waves or, when the base pressure p_w increases, a single normal shock wave (Mach disk) close to the nozzle exit.

For very low values of p_e/p_a, the reflected oblique shock waves are repeated in the stable structure shown in Fig. 2a. With higher values of p_e/p_a, flow separation occurs in the presence of oblique shock waves, as is shown in Figs. 2b and 2c, where the flow separates in the region of the third and second oblique reflections, respectively. In both cases the separation points oscillate through a small distance. The oscillations represented by Figs. 2b and 2c may be called the downstream and midstream oscillations, respectively. A further oscillation type occurs with the higher p_e/p_a values when the main flow structure changes from an oblique to a normal shock during a cycle. Figure 2d shows an instant during the oscillations which are of large amplitude and have been called the shock-pattern oscillations.[2]

As the pressure ratio p_e/p_a increases further the flow becomes stable with a normal shock wave in the duct (e.g., Fig. 2e for a pressure ratio p_e/p_a of 0.314). After a pressure range of stable flow an instability occurs in which the normal shock wave oscillates through a small distance; Fig. 2f is an example of an interferogram taken at an instant during a cycle. In this type of oscillation, which has been referred to as a base pressure oscillation,[2] the fluctuations exist throughout the entire duct length.

With higher pressure ratios the flow becomes asymmetrical. Base pressure oscillations of an asymmetrical kind can exist (Fig. 2g) with a single normal shock wave moving in a flow attached to one wall surface only. Separation and attachment of the asymmetrical flow to one side of the duct occurs at different pressure ratios, hence the hysteresis which is exhibited in Fig. 3. Much higher frequency oscillations can exist in a flow characterized by a cellular shock wave structure, and Fig. 2h illustrates this type of flow. The frequencies are of the same order as those of the screeching oscillations of supersonic jets observed by Powell.[3]

The interferograms in Fig. 2 present the patterns at instants in time. Interferogram sequences with time of complete oscillation cycles obtained with a high-speed drum camera may be seen in the main report.[1]

The frequencies of the different oscillations are shown in Fig. 4. The oscillation described in Fig. 4 as the downstream type has predominant frequencies at 250 and 750 Hz. The symmetrical base pressure oscillation, as represented by Fig. 2f, has a fundamental at 308 Hz and strong harmonics. The frequencies have not been normalized in any way, because oscillation type is controlled by a different parameter. The base pressure oscillation depends upon duct length, and to a lesser extent on nozzle height, the Powell-type oscillation on nozzle height h alone, and it is not known what factor controls the shock pattern oscillations. The frequency of the base pressure oscillations depends upon the duct length and can be estimated approximately from acoustical theory and one-dimensional gas dynamics theory. The frequency f for longitudinal oscillations in a duct of length L closed at one end is given by

$$f(2n-1)(1-M^2)(c/4L) \quad \text{for} \quad n=1,2,3, \text{etc.}$$

where c is the average velocity of sound in the duct and M the mean Mach number.

A theory has also been developed which looks more closely at the originating mechanism of the self-excited base pressure

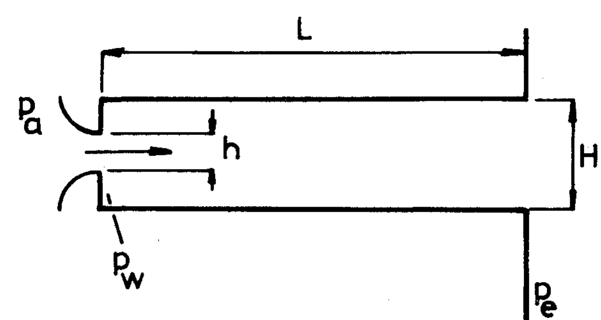

Fig. 1 Schematic diagram of the duct and nozzle.

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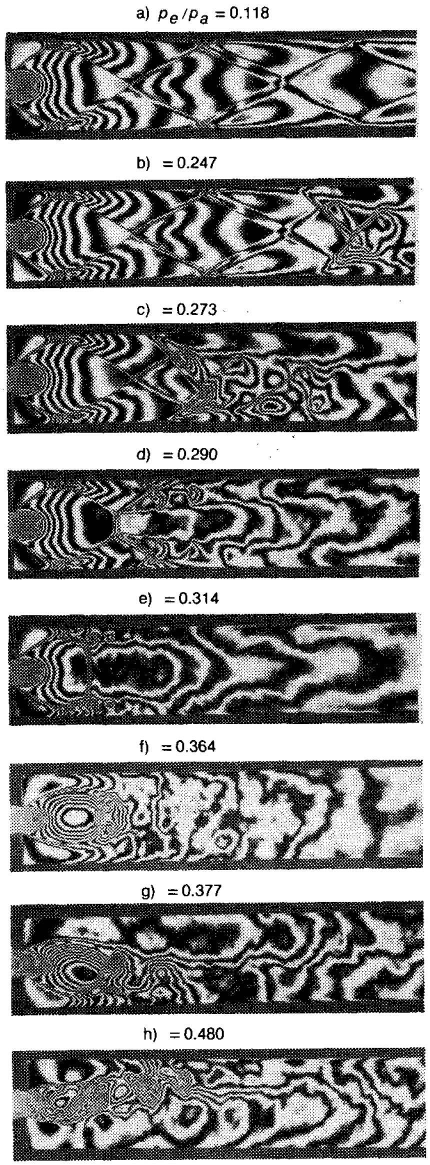

Fig. 2 Interferograms of the flow regimes; $h = 10$ mm, $H = 33.2$ mm, $L = 240$ mm.

oscillations.[4] According to this theory, an expansion region of supersonic flow from the nozzle is terminated by a normal shock wave. The equations of continuity and momentum are used in integral form and applied to the flowfield in the region bounded by the enlargement of the duct, the jet boundary, the shock front, and the axis. Linear approximations are used to solve the integrals in the basic equations. Additionally, a model equation is required to relate the feedback between the base pressure p_w and the pressure just downstream of the shock wave. For certain values of base pressure p_w the flow can be shown to be stable, but at other higher values of p_w a

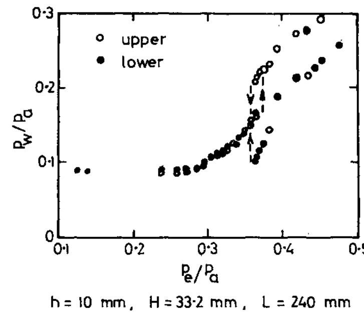

Fig. 3 Variation of base pressure with receiver pressure.

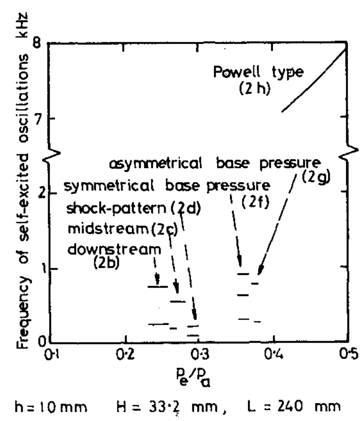

Fig. 4 Frequencies of self-excited oscillations.

disturbance in a flow parameter leads to a limit cycle oscillation at a frequency close to that measured experimentally at the same value of p_w.

Reference 1 shows how the base pressure oscillations with the normal shock waves can exist for rectangular ducts and for circular ducts fed by a wide range of nozzles, including convergent, convergent-divergent, and annular nozzles.

References

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