SOME EXPERIMENTAL RESULTS OF GENERATING HIGH FREQUENCY OSCILLATING SHOCK-WAVES AND OSCILLATING SHOCK-WAVE BOUNDARY-LAYER INTERACTION AT SUPERSONIC SPEEDS*

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Summary—The behaviour of axisymmetric and two-dimensional cavity type oscillating shock-wave generators, with a frequency range of 700 to 4000 cps. has been investigated and some of their peculiarities noted.

The two-dimensional oscillating shock-wave generator was used to investigate experimentally the existence of an eigenvalue of the shock-wave boundary-layer system, as predicted theoretically by Professor Trilling. A resonance frequency of the above system, close to the theoretical value, was found.

The reported results may be of some help to explain certain oscillations caused by shock-wave boundary-layer interaction.

1. INTRODUCTION

SHOCK-WAVES encountered in wind tunnels or in flight often oscillate about some mean position. These oscillations may be small as e.g. in the case of shock-waves formed on underslung stores, or large as in the case of normal shock-waves occurring on wings at transonic velocities. These shock-waves interact with the boundary-layers formed on neighbouring surface and may produce harmful or unpleasant oscillations.

Professor Trilling⁽¹⁾ has shown theoretically the possibility of existence of an eigenvalue of the system formed by a two-dimensional oscillating shock-wave of appropriate strength interacting with a laminar boundary-layer.

The aim of the reported investigation was to find means of producing oscillating shock waves of frequency in the region of the expected resonance in the experimental set-up i.e. about 1500 cps. and to prove, in the case of two dimensional flow the existence of a resonance frequency of

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the system formed by the oscillating shock-wave interacting with the laminar boundary-layer.

The experiments were performed mostly in the 8″ × 8″ continuous-flow Gas-Turbine Laboratory's wind tunnel with the boundary-layer flat plate used for other investigations (2, 3, 4).

2. CAVITY-TYPE OSCILLATING SHOCK-WAVE GENERATORS

As the theory predicts an eigenvalue of about 1500 cps. it was necessary to use high frequency shock-generators. Mechanical oscillating shock-wave generators were ruled out because of the difficulty of avoiding their own lower resonances and cavity resonator type sound generators were chosen. To obtain data on the performance of cavity type sound generators in supersonic flow, axisymmetric and two dimensional generators were tested.

2.1. *Tubular Shock-wave Generator*

The axisymmetric tubular shock-generator was formed of a $^1/_2$ in. internal diameter tube of adjustable cavity depth l_{SG}, shown schematically on Fig. 1. The oscillating pressure was measured by a transducer, placed at the base of the cavity, connected to appropriate electronic equipment permitting the harmonic analysis of the pressures(3).

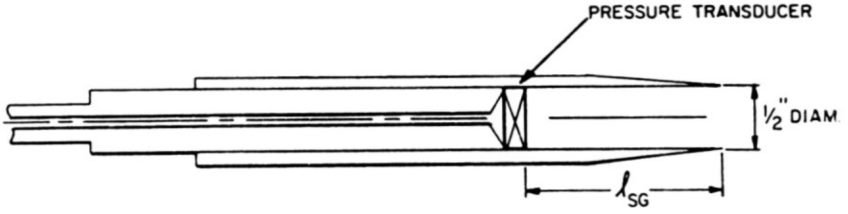


FIG. 1. Tubular oscillating shock-generator.

It was found that the tubular generator produces a main oscillating shock of frequency lower than the frequency corresponding to quarter-wave resonance, the difference increasing with the frequency. The relation between the main frequency and the cavity depth is indicated in Fig. 2. Besides this main frequency, there are higher harmonics corresponding roughly to two and three times the fundamental frequency, but their amplitude is below one-third of that of the fundamental. A typical oscillograph pressure-time record is reproduced in Fig. 3.

The amplitude of the pressure oscillation is not constant with cavity depth, but varies within a factor of one to three, as shown in Fig. 4. At the higher frequencies the amplitude is greatly reduced.

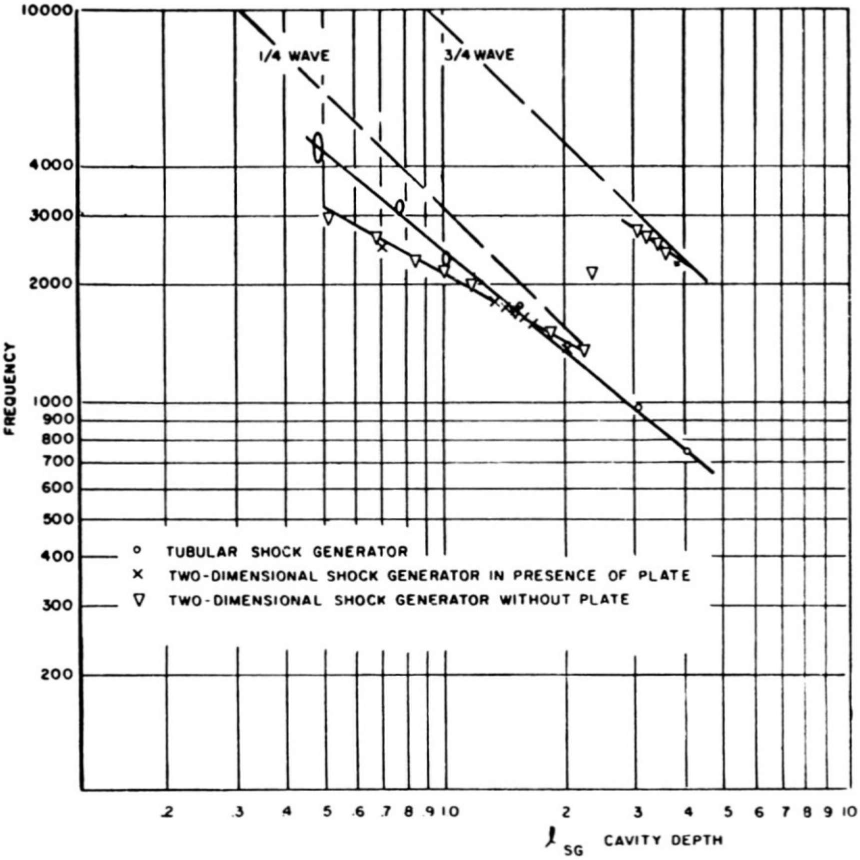


FIG. 2. Relation between cavity depth and shock wave frequency.

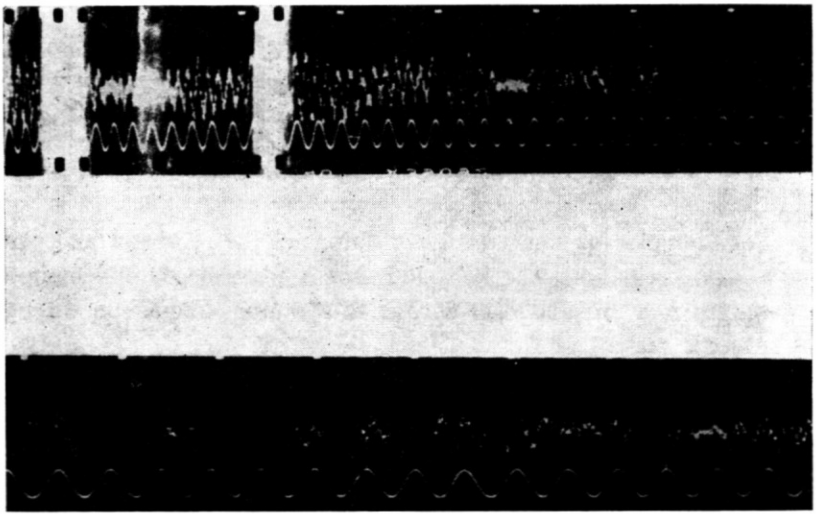


FIG. 3. Sample of shock-generator pressure oscillations.

With the flat plate also installed in the tunnel, the tubular oscillating shock-generator showed an unexpected behaviour, shown in Fig. 5. The peak-to-peak pressure amplitude inside the shock-generator depended strongly on the relative position of the tubular shock-generator and the plate. For example, for some relative positions of the generator and plate there was no oscillation. The behaviour appeared to be dependent upon the Reynolds number, and may be due to a mutual interaction through local subsonic regions of flow.

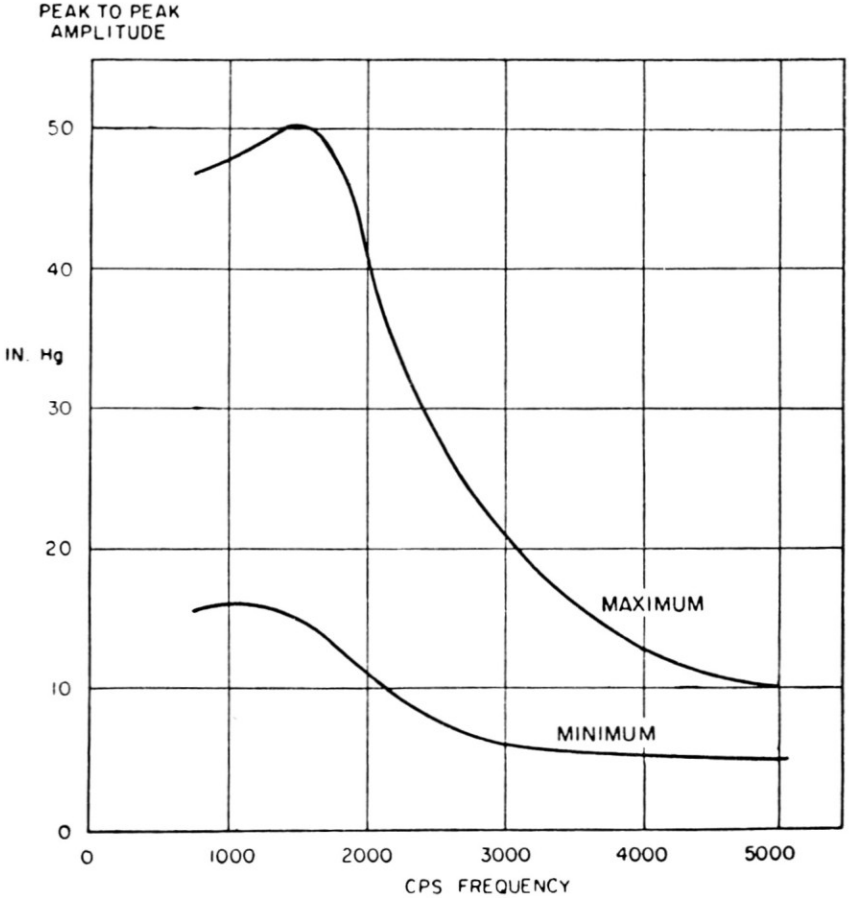


FIG. 4. Tubular shock-generator pressure oscillations.

2.2 *Two Dimensional Oscillating Shock-wave Generator*

The two dimensional shock-wave generator consists of two $^1/_8$ in. plates placed $^1/_4$ in. apart spanning the wind tunnel. The gap between the two plates is blocked by a plate which can be moved to change the depth of the two dimensional cavity Figs. 7 and 8. A miniature pressure transducer is imbedded in the end of the plate.

The relationship between cavity depth and frequency is given in Fig. 2, and the pressure amplitude vs. frequency curve is given in Fig. 8.

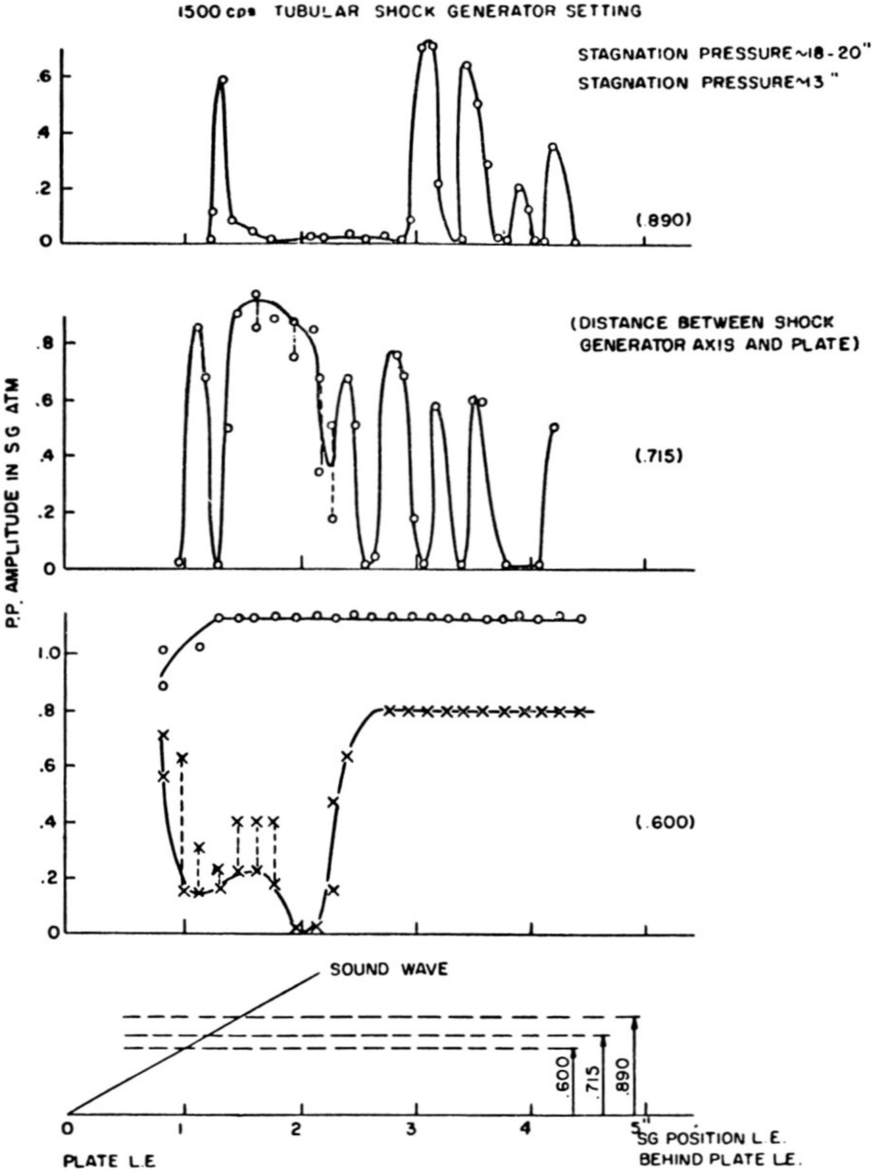


FIG. 5. Variation of shock-generator pressure amplitude with position relative to the boundary-layer plate.

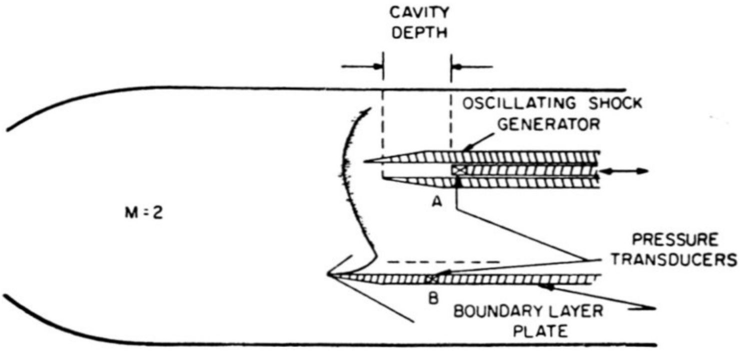


FIG. 6. Experimental arrangement with two-dimensional shock-generator.

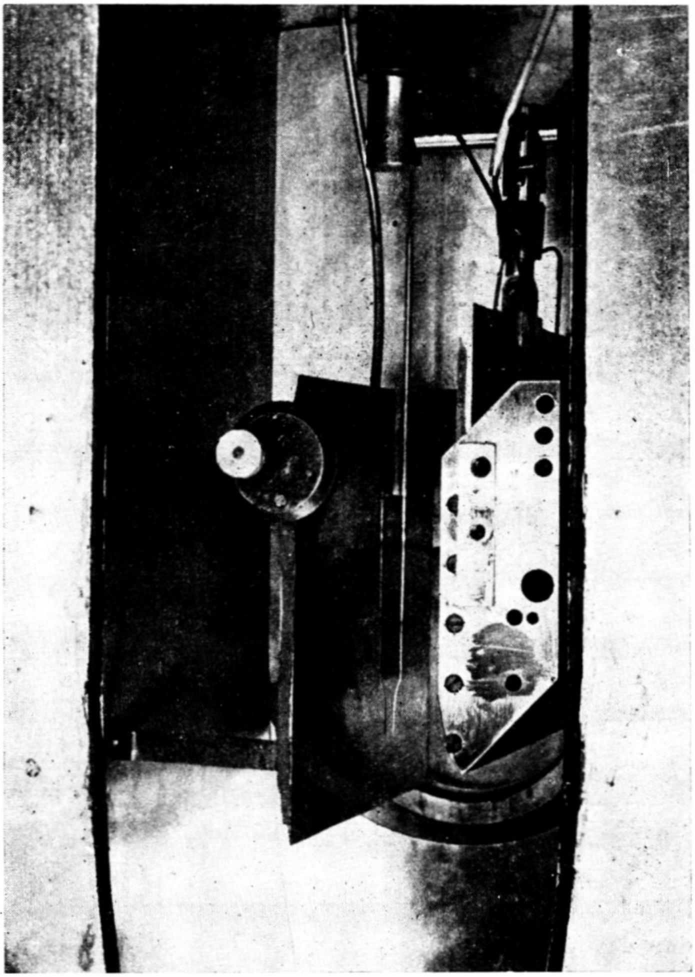


FIG. 7. Experimental two dimensional wind tunnel set-up of the plate variable frequency shock-generator and boundary-layer probe.

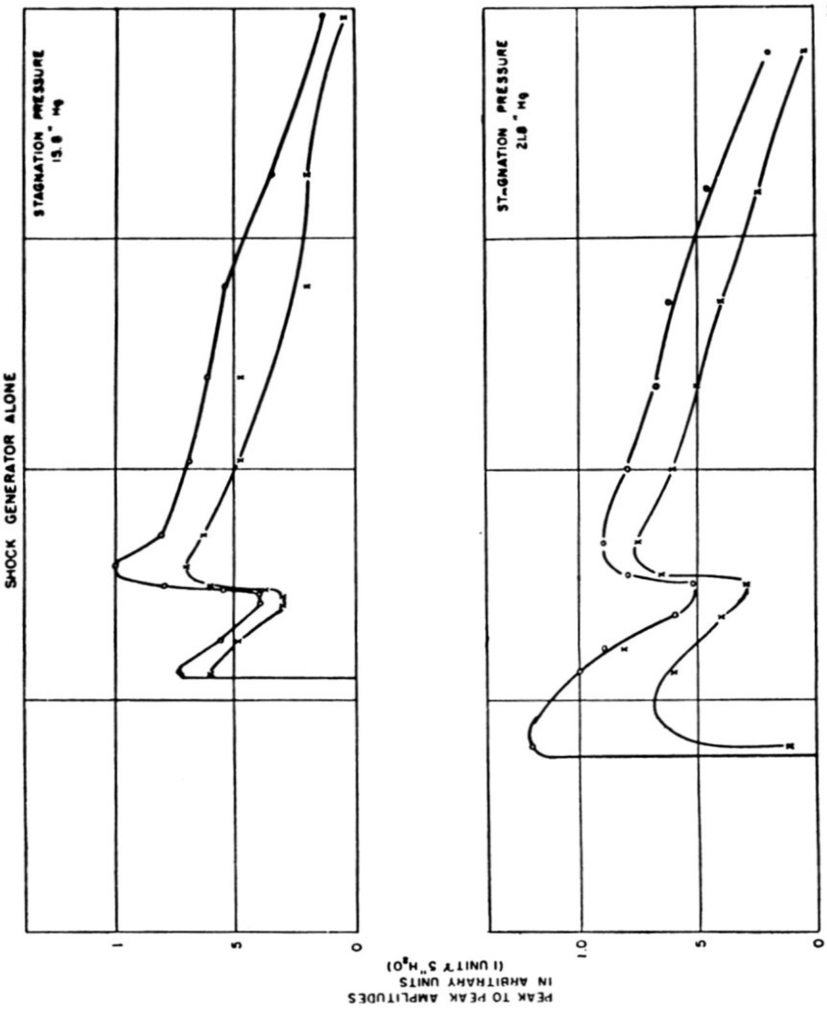


FIG. 8. Shock-generator pressure oscillations.

Experimental evidence indicates that when the distance between the plate and shock-generator is 2·5 in. the presence of the plate does not affect practically the performance of the oscillating shock-wave generator. It should be noted, however, that for a distance of 1·5 in. between the plate and generator chocking occurred and there was no oscillation.

As can be seen on Fig. 2 the frequency curve has two branches: one for depths between about 0·5 in. and 2·2 in., corresponding to frequencies of approximately 3000 and 1400 cps., and another for depths larger than about 3 in. Between 2·2 in. and 3 in. the general level of pressure oscillation inside the shock generator is low and there is no predominant frequency except at 2·3 in.

The two frequency branches correspond roughly to one quarter and three quarter-wave-length cavity depths, but their slopes are smaller than the corresponding slopes for the theoretical resonator and for the tubular shock-wave generator.

Comparing the pressure amplitude frequency curves in Fig. 8, we notice a dip in amplitude at about 1720 cps.

The behaviour of the cavity-type oscillating shock-wave generators is not understood, and more thorough investigations would be recommended to explain their features and to improve their performance.

3. TWO-DIMENSIONAL OSCILLATING SHOCK-WAVE BOUNDARY-LAYER INTERACTION

The experimental set-up is shown in Figs. 6 and 7.

It should be noticed that the noise level of the wind tunnel, as assessed by pressure measurements at the plate in the absence of the shock generator, is appreciable, particularly at about 11,000 cps. The random pressure oscillations at other frequencies were much smaller than the excited pressure.

The measurements consisted of two parts: one, to establish the effect of the pressure oscillations around 2000 cps. on the static boundary-layer characteristics, and hence to substantiate the linearization assumptions of Trilling's theory; two, to find experimentally whether an eigenvalue existed or not.

3.1 *Effect of Oscillating Shock-wave on Static Boundary-layer Characteristics*

The effect of the shock-wave oscillation on the velocity distribution in the boundary-layer is practically non-existent. This is illustrated in Fig. 9 showing the velocity distribution in the boundary-layer, for a section 1·5 in behind the leading edge and a stagnation pressure of 20 in. Hg, measured while the oscillating shock-wave generator was set to produce different frequencies indicated on the figure.

The pressure distribution along the plate with an oscillating and a non-oscillating shock-wave was measured for different values of the stagnation pressure, and the results are given in Fig. 10. Comparing these results with Schlieren photographs (Fig. 11), it may be noticed that the slope change at about 1·5 in. behind the plate leading edge is due to the transition from laminar to turbulent flow in the detached boundary-layer. The change of slope at about 2·4 in. occurs not far after the shock-wave detached boundary-layer interaction. Until this second change of slope, the difference in the pressure distribution along the plate, for the two cases considered, is practically absent. The pressure gradient aft of about 2·4 in. behind the plate leading edge is smaller and persists for a longer distance in the case of the oscillating shock-wave.

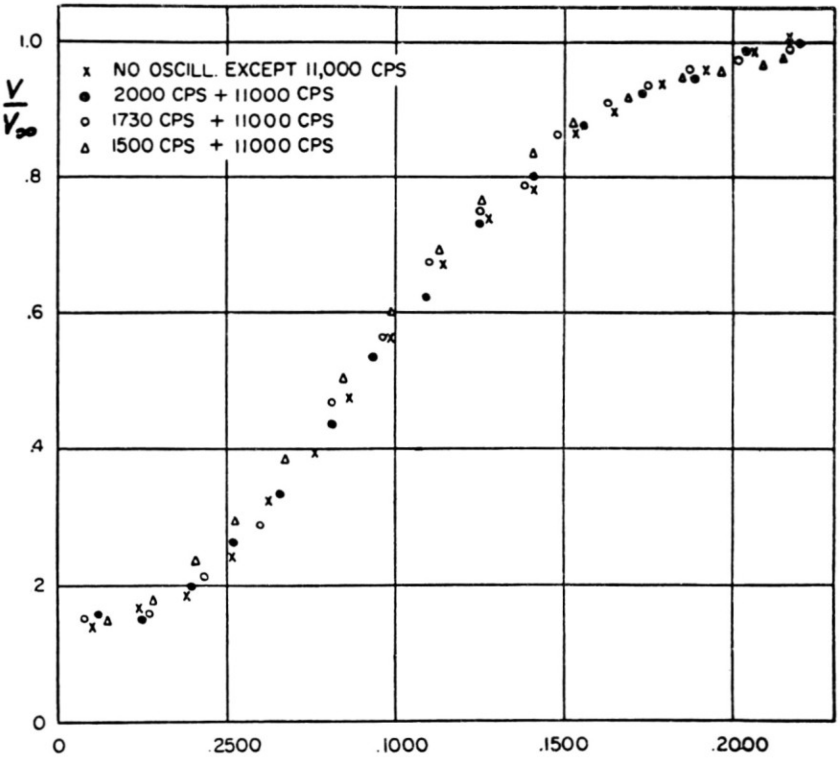


FIG. 9. Effect of shock-generator frequency on boundary-layer velocity distribution.

On the whole the boundary-layer behaves more like a turbulent one.

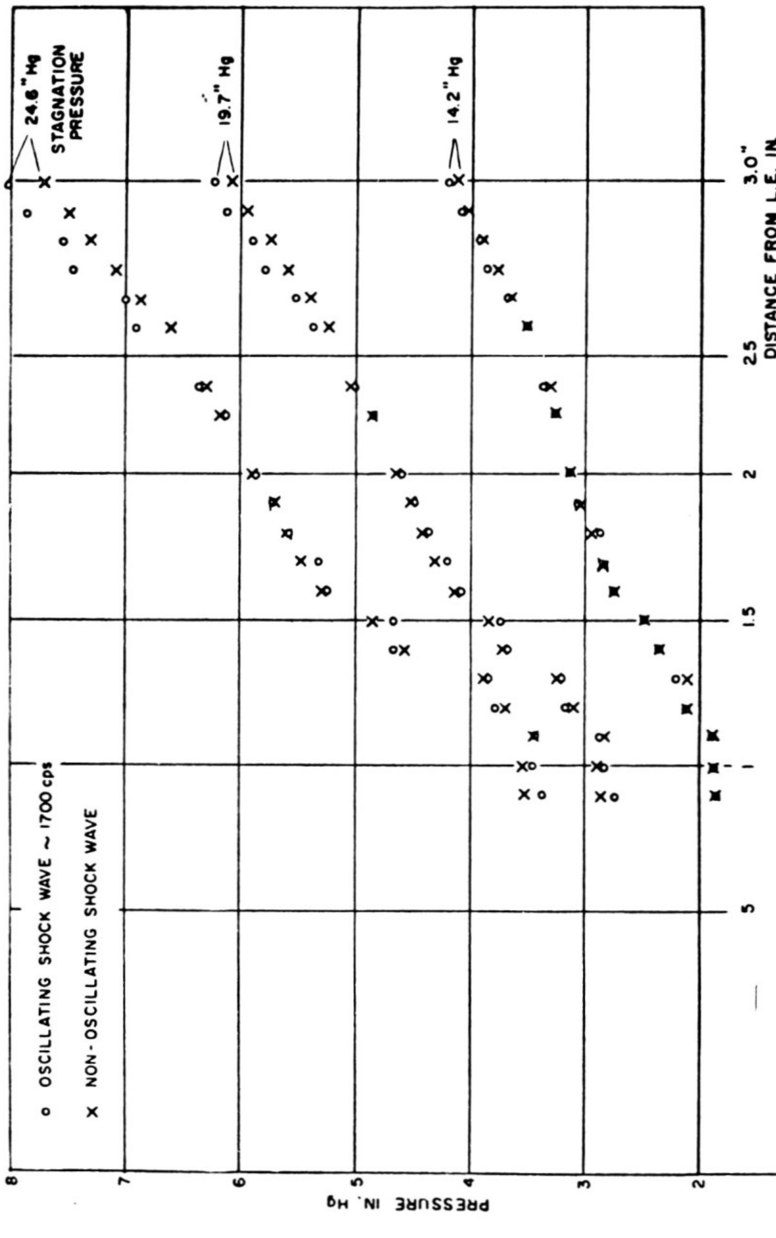
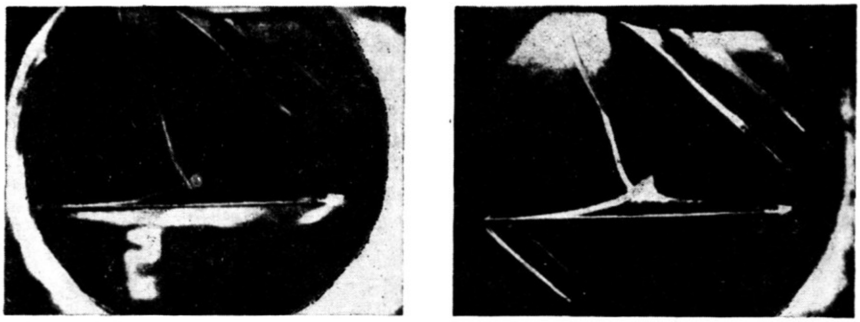
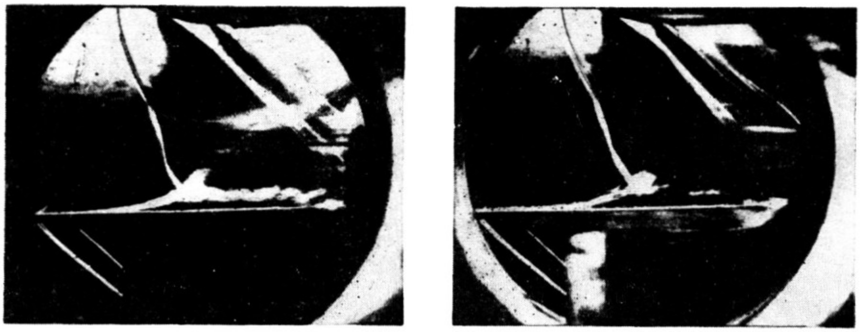


FIG. 10. Pressure distribution along boundary-layer plate.



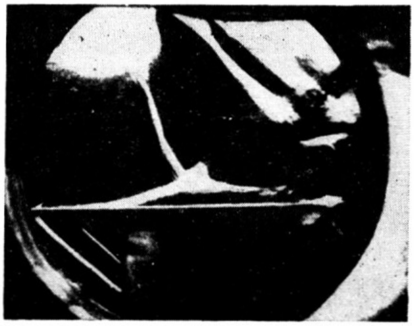
NO SHOCK-WAVE OSCILLATION

2400 CPS SHOCK-WAVE OSCILLATION



1800 CPS SHOCK-WAVE OSCILLATION

1600 CPS SHOCK-WAVE OSCILLATION



1600 CPS (4 FLASHES)

FIG. 11. Schlieren patterns of shock-wave boundary-layer interaction.

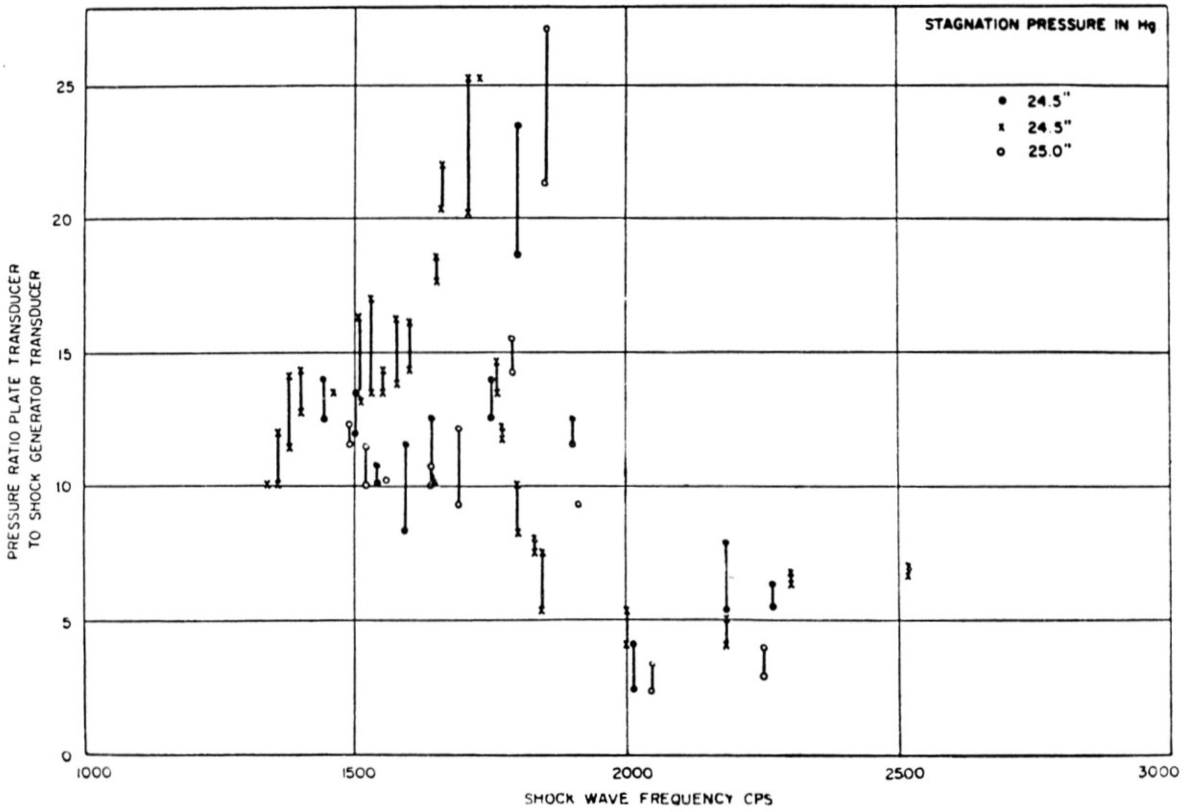


FIG. 12. Boundary-layer resonance curves.

3.2 *Effect of Oscillating Shock-wave on Boundary-layer Wall Pressure*

To determine the existence of an eigenvalue, it was necessary to find the ratio of the oscillating pressure, measured at the wall of the boundary-layer plate, to the oscillating pressure inside the shock generator for different frequencies. The pressure measurements were harmonically analysed, and only those corresponding to the frequency of the predominant shock-wave oscillation were compared at different stagnation pressures.

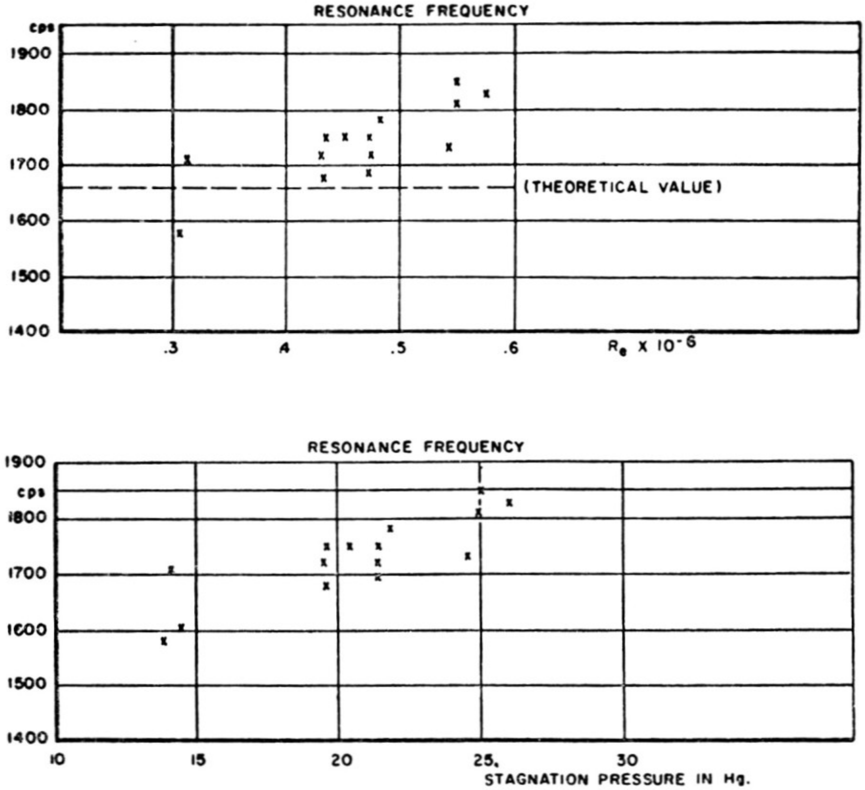


FIG. 13. Variation of resonance frequency with Reynolds number.

As the pressure amplitudes were varying constantly, the upper and lower limit was taken in each case and their ratio calculated. The scatter of the test results necessitated many measurements, and some representative results are given in Fig. 12. These curves show that between 1800 and 1850 cps. there is a definite maximum pressure ratio, indicating the existence of an eigenvalue. The scatter of eigenvalues frequencies is shown in Fig. 13 as a function of Reynolds number based on a 2 in. length which is approximately equal to the distance from the boundary layer plate leading edge to the approximate point of the shock-wave boundary-layer intersection.

3.3 *Comparison with Theoretical Calculations*

From theoretical calculations according to Trilling's theory for a strong shock-wave, using a distance of $L = 2$ in. from the leading edge to the shock-wave boundary-layer intersection, the characteristic frequency is 1660 cps. This frequency is based on the frequency parameter $k=\omega L/u$.

It may also be noted that the distance from the boundary-layer separation point to the shock-wave boundary-layer intersection is roughly equal to the quarterwave-length of the resonant frequency.

4. CONCLUSIONS

The experiments have confirmed the theoretically predicted existence of a characteristic frequency of the oscillating shock-wave boundary-layer system. The experimental value is within 10 per cent of the theoretical one in the range of Reynolds numbers investigated and a Mach number of 2. The distribution of the scatter of experimental results shows very small variation with Reynolds number, the tendency being towards a rise of characteristic value with Reynolds number. In the present experiments, the shock-wave position is constant, and theory would indiscate a characteristic value independent of Reynolds number. In any case the theory, in spite of its radical simplifying assumptions, seems fairly consistent with the experiments performed. The experiments confirmed that the non-stationary and stationary flows can be treated as nearly independent, substantiating the linearizing theoretical assumptions.

It would be very useful to extend the experimental results to a much wider range of Reynolds numbers and Mach numbers, and also to attempt to lower the wind tunnel noise level.

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