SOUND RADIATION FROM SURFACE CUTOUTS IN HIGH SPEED FLOW

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ABSTRACT

In an experimental investigation of subsonic and supersonic flows of air past rectangular cavities cut into a flat surface it was discovered that the cavities emit a strong acoustic radiation.

The frequency of the sound-producing oscillations measured by a hot wire in the cavity was found to be inversely proportional to the breadth for fixed depth. For fixed breadth the frequency was found to increase, though not systematically, with a decrease in depth.

A non-dimensional frequency S is defined in terms of the frequency of emission, the gap breadth, and the free stream velocity. The dependence of S on the various parameters in the problem, such as Mach number, Reynolds number and ratio of the boundary layer thickness to a dimension of the cavity, is discussed in light of appropriate experiments.

An estimate of the intensity of the radiation was obtained by means of an optical interferometer of the Mach-Zehnder type. For points located at 3 to 4 cavity breadths from the cavity, intensities of the order of 100 - 150 decibels were found for sound fields from cavities 0.1" deep and 0.1 to 0.2 inch broad at Mach numbers 0.7 to 0.85.

Possible mechanisms for the sound production by the cavities are discussed.

SYMBOLS

a	local speed of sound
b	width of cavity
d	depth of cavity
f	frequency
I	intensity
k	Gladstone-Dale constant
ℓ	span of model
M	Mach number
P	maximum amplitude of pressure wave
S	non-dimensional frequency of Strouhal number
s	condensation, $\Delta\rho/\rho_e$
s^*	maximum amplitude of condensation wave
T	temperature
U	flow velocity
V	relative velocity of wave propagation
x	fringe spacing, distance between two consecutive fringes
Δx	fringe shift
α	constant of proportionality between f and l/b
δ	boundary layer thickness
λ	wavelength
ρ	instantaneous local density
$\Delta\rho$	$= \rho - \rho_e$
ρ_e	equilibrium value of local density

Subscripts

db	decibel
m	maximum
o	stagnation conditions
ref	reference
w	wedge
1	conditions just ahead of cavity
∞	free-stream conditions

1. INTRODUCTION

The study of air flow past cavities in a solid surface is interesting both from fundamental and practical considerations. These involve, for instance, questions regarding a) aerodynamic properties like drag and heat transfer, b) non-stationary flow effects, c) generation of vortices and their mechanics, d) aerodynamic production of sound.

The effect of cavities on the drag and heat transfer properties of aerodynamic surfaces is an obvious point of interest. The question of whether the presence of a cavity would cause any non-stationarity of the flow in and around it is important in connection with flows over bomb bays, open cockpits, escape hatches, and so on. Experience on these has shown that the flow in the cavities is often violently unsteady leading to severe cases of buffeting.

The problem of the cavity flow is particularly suited for studies on the formation and maintenance of vortices. Experiments at low subsonic speeds show that a stationary vortex or a system of vortices is obtained inside the cavity for certain flow configurations. Such a captive vortex will facilitate experimental attempts aimed at investigating the structure of a vortex and the mechanics that maintain it.

In addition to these aspects, production of sound, if any, by these cavities will constitute a typical example for the study of aerodynamic generation of sound.

Investigations in the past on the problem of flow past cavities were attempted only as a part of other major studies. Some quantitative results about the drag coefficients of cavities were given by

Wieghardt (ref. 1) and Tillmann (ref. 2). These results were reported as a part of their larger study of the drag of surface irregularities. The drag coefficients were obtained by subtracting the measured drag values of an aerodynamic surface with and without the cavity. It was also found that a systematic variation of the depth-breadth* ratio of a given cavity gave a periodic variation of the cavity drag coefficient showing definite peaks. Wieghardt obtained also some aluminum powder pictures of the flow in a water tank (ref. 1). The pictures showed the existence of a vortex or a system of vortices in the cavity. Besides these observations, no further studies were made to explain the drag variations and to gain some fundamental understanding of the flow.

In light of the above considerations, at the suggestion of Professor Liepmann, an investigation of aerodynamic cavities in low and high speed flows was undertaken at GALCIT (Guggenheim Aeronautical Laboratory, California Institute of Technology). Experiments in low subsonic speeds were made by Dr. Anatol Roshko, and reported in Reference three. Experiments in high speed flow were undertaken by the author and the description and discussion of these form the subject of this thesis.

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*Depth and breadth are the dimensions, normal and parallel to the flow, of the cavity section in the plane of the flow.

3. EXPLORATORY OBSERVATIONS IN HIGH SPEED FLOW

Exploratory experiments on cavities in high speed flow consisted of schlieren observations of the flow field. A small rectangular groove was made in a flat plate that spanned fully the wind tunnel. The cavity extended across the whole plate. When this plate was exposed to a uniform stream in a wind tunnel and the stream Mach number was gradually increased, it was found that starting at a rather definite subsonic Mach number a beam of sound waves was emitted from the cavity. Such sound emission or radiation is, for instance, shown in fig. 1, which is an instantaneous schlieren picture of the flow field. The cavity was 0.05 inch deep and 0.1 inch broad. The Mach number was 0.855. The sound beam appeared to be very intense and directed. The wave length of the radiation, (i.e., of the sound field) was noticed to be of the order of the dimensions of the cavity. Consequently, it was concluded that the frequency of the radiation should be very high. It was estimated, as discussed below, to be about 99 kilocycles per second. The boundary layer upstream of the gap (i.e., the cavity) was laminar and it separated at the upstream edge of the cavity. Over the cavity the separated boundary layer or shear layer diffuses into it. Deflection of part of this separated layer occurred at the downstream edge of the cavity. Downstream of the cavity the boundary layer was turbulent.

The wave fronts emitted from the cavity were swept back by the free stream and, therefore, their propagation in the moving stream would accordingly be affected. This sweeping effect of the free stream on the wave fronts can be seen in the following discussion which gives a method for obtaining the wave length of the radiation from a schlieren picture such as fig. 1.

Assuming that the acoustic field*, as observed on the instantaneous schlieren pictures, is similar to that produced by a two-dimensional stationary source radiating into a moving stream, a simple geometric construction will enable one to estimate from such pictures the wave length of the emitted sound. This method is illustrated in fig. 2. Choosing a point P on any wave front one knows that this point propagates with a velocity vector $\vec{V}$ given by

$$\vec{V} = \vec{a} + \vec{U} \tag{1}$$

where $\vec{a}$ = the local velocity of sound directed normally to the wave front at the point considered, and $\vec{U}$ = the velocity of the flow at P. Taking $\vec{U} = \vec{U}_\infty$, the free stream velocity, and dividing the above equation by $|\vec{a}|$, the local speed of sound, one obtains

$$\frac{\vec{V}}{|\vec{a}|} = \vec{n} + M_\infty \cdot \vec{U}_i \tag{2}$$

where $\vec{n}$ is a unit vector in the direction of the normal to the wave front at P, and $\vec{U}_i$ is a unit vector in the direction of the free stream velocity. Hence, it is simple to construct the velocity vector $\vec{V}$ at the point P, knowing only the Mach number M_∞ and choosing any scale for the local speed of sound $|\vec{a}|$. The point P_1 where the relative velocity vector $\vec{V}$ intersects the next wave front then corresponds to P. A line drawn from P_1 parallel to $\vec{U}_i$, and intersecting vector $\vec{n}$ from P determines

*The name "acoustic radiation" or "acoustic field" will be used for the sound field. It should be noted, however, that the words "acoustic" and "sound" are not used to convey the usual notion of small amplitudes.

to scale the wave length λ of the waves as shown on the figure. The absolute value of λ is obtained from the scale determined by the gap breadth.

In the above discussion it is assumed that the propagation velocity normal to the wave fronts is equal to the local speed of sound, a, in the streaming fluid. On the basis of this assumption we can also estimate the frequency of the acoustic radiation, for the propagation velocity is related to the frequency, f, and the wave length λ of the waves by

$$a = f\lambda \tag{3}$$

Thus, if the local velocity of sound in the medium is known and the wave length is measured, as described above, from the pictures, the frequency is obtained from the relation

$$f = \frac{a}{\lambda} = \left(\frac{a}{a_o}\right) a_o \frac{1}{\lambda}$$

where a_o is the stagnation speed of sound for the flow, and $\frac{a}{a_o}$ is a function of the Mach number. a_o is obtained from the stagnation temperature of the wind tunnel.

In this way the frequency of the radiation shown in fig. 1 was found to be 99 kilocycles per second.

Similar observations were made of high speed flow over cavities of different sizes. It was established that the intense directed acoustic radiation of high frequency was an essential feature of such flows. A study of this phenomenon was accordingly made and the present thesis is an account of these investigations.*

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*A part of this work has been published by the NACA (ref. 4).

3. EXPERIMENTAL EQUIPMENT AND SET UP

A. Wind Tunnel

The investigations were made in the GALCIT 4 x 10 inch transonic wind tunnel which can be continuously operated over a Mach number range of 0.25 to 1.6. The tunnel is provided with a flexible nozzle.

The optical methods used were a conventional Toepler's schlieren system and a Mach-Zehnder interferometer. These were equipped with short duration light sources. A source consisting of a spark discharge between magnesium electrodes and an interference filter for the 5170 °A magnesium line, was added to the existing interferometer set up. The effective duration of the spark was of the order of 3 to 4 micro seconds.

B. Models

Observations were made with various models, which will be described in their appropriate situations. However, a great part of the data was obtained by using a single model in which the breadth of the cavity could be continuously varied. Different arrangements of the cavity, as will be described later, could be effected by suitably modifying this set up.

Figs. 3 and 4 show the general features of construction and installation of this model. It was made in two parts. The bottom part was a flat plate supported in the movable windows of the tunnel, where its angle of attack could be changed easily. Its nose was formed by a

3^o wedge. A step 0.1 inch deep was cut in the upper surface of the plate.

The top part of the model was a rectangular plate 0.1 inch thick. This was constrained, by means of two thin rails, to slide over the bottom part behind the step. The movement was provided by a rack and pinion arrangement, which made it possible to continuously vary the breadth of the gap while the tunnel was operating. Another rack carrying a needle indicator recorded the breadth of the gap on a 0.01-inch scale. The gap breadth could be varied from 0 to 2 inches.

The maximum thickness of the model was 0.3 inch. It was not possible to increase the thickness and thus obtain a deeper gap without lowering the subsonic choking Mach number below 0.8.

The top surface and the leading edge of the model were maintained very smooth, in order to obtain a laminar boundary layer ahead of the cavity.

C. Hot-wire Setup

The variable-breadth model, described above, was used for hot-wire measurements of the frequency of the acoustic fields.

A tungsten wire, 0.00015 inch in diameter and 3/16 inch long, was carried by two steel needles fixed in a bakelite plug, which was inserted into a suitable recess cut into the model (fig. 4). The electrical leads were carried out through one of the model supports. The wire was heated by a constant current of 25 milliamperes, its signal being fed into an amplifier with a total gain of approximately 4000 and a constant frequency response up to 70 k.c. The hot wire was not compensated up to this frequency. But it was found that a signal, sufficiently strong for frequency measurements, could be obtained. The output of the amplifier was examined on an oscilloscope and two wave analyzers, one with a frequency range of 15 k.c. to 500 k.c. and the other with a range of 30 cycles to 16 k.c.

D. Flow Reynolds Number at the Cavity

In all experiments, except in a few specific cases which will be described in their natural context, the cavities were located at a constant distance of 3.5 inches from the leading edge of the plate they were situated in.

When the model was set with its upper surface parallel to the free stream direction, flow with laminar boundary layer ahead of the gap was obtained (a slight negative angle of attack was found beneficial). The Reynolds number at the gap, based on the distance of its upstream edge from the leading edge of the plate, varied approximately from 0.75×10^6 to 1.1×10^6 for Mach numbers of 0.45 to 0.8, respectively.

To obtain turbulent boundary layers, a trip wire was attached close to the leading edge of the model.

3. DESCRIPTION OF PHENOMENON

Two-dimensional rectangular cavities cut into an aerodynamic surface gave rise to acoustic radiation both in subsonic and supersonic flows (figs. 5, 6, and 7). Such radiation had been observed for cavities of varying dimensions and for flows with either laminar or turbulent boundary layers ahead of the cavity. The character of the acoustic field was found to depend upon the type of boundary layer, the gap dimensions, and the free stream velocity or Mach number.

In all cases, for a given gap at a particular Mach number, the radiated field was weaker with a turbulent boundary layer ahead of the gap than with a laminar layer. For the laminar case the waves were well defined and could be observed very clearly with the spark, while for the turbulent case they appeared weak and diffused.

It was observed in experiments on the variable gap (where the depth was fixed while the breadth was varied) that the minimum breadth at which sound emission was first noticed depended on the Mach number, being smaller for the higher Mach numbers than for the lower. No precise measurements of the minimum breadths were made. It was noted, however, that for the same Mach number, emission in the case of the turbulent layer seemed to commence at a slightly larger breadth than in the laminar case. For instance, for a gap width of 0.1 inch and at a Mach number of 0.75, neither discrete frequencies nor any sound waves were observed in the case of the turbulent boundary layer, contrary to the laminar case.

For breadths smaller than the minimum, the shear layer leaving the upstream edge of the gap bridged across the gap to the downstream edge.

The waves at the minimum breadth for any given Mach number appeared weak and were of the shortest wave length for that Mach number. Schlieren pictures and interferometric studies showed that as the breadth was gradually increased, the wave length correspondingly became larger, while the intensity increased initially and then decreased gradually. The wave length of the emitted acoustic field was directly proportional to the breadth of the gap. Figs. 5a to 5d are spark Schlieren photographs of the phenomenon for increasing gap breadths at a Mach number of 0.82 and with a laminar boundary layer ahead of the gap. The turbulent case is shown in Figs. 7a to 7c. (The dark projection in the gap in some of these pictures is the hot-wire needle.)

No precise determination was made of the minimum Mach number at which acoustic radiation from a given gap was first detectable. For gap widths greater than 0.3 inch, approximately 0.4 was the minimum Mach number at which discrete frequencies were measured. For these gap sizes waves in the external flow were observed for Mach numbers 0.45 and above. For Mach numbers below 0.4, neither frequencies related to the gap breadths nor waves were noted for any of the gap sizes.

At low Mach numbers, up to 0.65, the radiation was not very directional or strong (figs. 6a and 6b). As the Mach number increased, the radiation became more and more intense and directional. The radiation pattern for the intense fields could be observed with the Schlieren system and continuous light source. Examples of such continuous light pictures, showing the directed beams at $M_\infty = 0.8$ for the laminar case, are given in figs. 8a and 8b for gap breadths of 0.1 and 0.2 inch, respectively. In both cases radiations in three directions are noticeable, the downstream one being the strongest. As the breadth was increased, the upstream radiations became weaker and even at b = 0.3 they were not visible on the continuous Schlieren. The directions of the radiation for the cases shown are given in the following table. The direction for each beam is given in degrees, measured from the downstream surface of the flat plate.

Gap, in.	Direction of Radiation, deg.		
	Upstream	Middle	Downstream
0.1 by 0.1	107.5 to 167	93	77.5 to 72
0.1 by 0.2	106.5 to 160	106.5 to 102	76.5 to 75

Larger gap widths or lower Mach numbers did not produce any directed beams that one could observe with the continuous Schlieren, because the radiation was weaker and not strongly directional. For the same reasons, with a turbulent boundary layer ahead of the cavity it was hard to obtain any continuous light pictures of the beam even for small gaps at high subsonic Mach numbers.

The non-stationary flow in the cavity was not necessarily stable in all instances. It was observed, for instance, that for some combinations of Mach number and gap breadth the phenomena in the gap were unstable in the sense that two intermittent frequencies could be measured. These frequencies were related as a fundamental and its harmonic (this will be illustrated in the next section). In general the processes in the gap appeared much more violent in the case of turbulent boundary layer than in the laminar case.

The above description applies to observations on the variable gap in which the depth was fixed at 0.1 inch for all breadths. Radiation from cavities of smaller depths, and from cavities situated in the top wall of the tunnel was also observed and a discussion of it is presented in later sections.

5. FREQUENCY MEASUREMENTS

The frequencies were measured in the gap by using a hot wire at constant current, and examining the output of two wave analyzers, one for the ultrasonic range and the other for the audio range.

The wave analyzer was connected across the signal to be measured, and was tuned over its entire frequency range. The frequency components of the input signal were determined by noting the peaks in the output of the analyzer. Typical plots of the analyzer output for the gap widths 0.095 inch and 0.31 inch and at a Mach number of 0.81 are shown in figs. 9a and 9b.

Measurements of frequency were made by varying the gap breadth gradually while maintaining the flow at a constant free stream Mach number, M_∞, and at a constant stagnation temperature, T_o. The frequency, f, at a given M_∞ and T_o was found to be inversely proportional to the breadth, b of the gap with its depth fixed at 0.1 inch:

$$f = \alpha \frac{1}{b} \tag{4}$$

α was different for laminar and turbulent layers and it was found that for the same Mach number α turbulent was nearly half of α laminar.

A. Laminar Case

As an example of the measured frequencies in the laminar case, a plot of f against 1/b at a Mach number of 0.82 and a stagnation temperature of 117° F. is presented in fig. 10. The dominant frequency and the first harmonic are shown. The harmonic frequency is twice the corresponding dominant frequency. The range of gap breadths covered for the measurements was from 0.1 inch to 0.5 inch. It may be noted that most of the frequencies measured for this case were in the ultrasonic range.

The results of the frequency measurements at different Mach numbers for the laminar case are shown in fig. 11. Only the dominant frequencies are included. The solid portions of the lines indicate the range of gap widths covered for the measurements. Except for gap widths around the minimum (when acoustic radiation begins) and around 0.5 inch, the dominant and its harmonic were generally the only frequencies that were observed. For breadths around the minimum an additional frequency of about half the dominant was usually observed. For breadths near 0.5 inch and above, more than one higher harmonic could be noted.

Measurements in supersonic flow showed similar linear relationships between f and 1/b. Fig. 12 shows the results of measurements at $M_\infty = 1.5$.

Some additional, independent measurements in the supersonic case are available from the work of Vrebalovich (ref. 5) who used an a.c. glow anemometer to measure the frequency of the sound emitted in supersonic flow from a cavity cut into a wedge. Fig. 13, which is reproduced from this reference, shows these measurements.

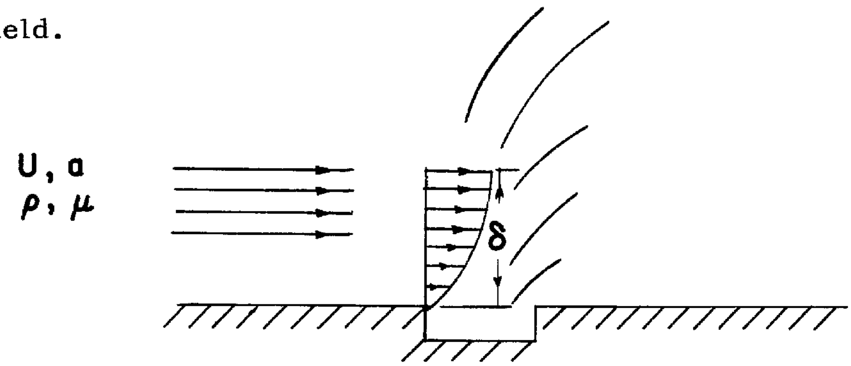
B. Turbulent Case

Measurements of frequency with turbulent boundary layer were made for Mach numbers of 0.8, 0.75, 0.7, and 0.65 only. The results of these measurements differed from those of the laminar case mainly in one respect. While in the laminar case only a single dominant frequency was observed at a given gap width and Mach number, in the turbulent case two frequencies of nearly equal strength were recorded. The higher of these frequencies, which shall be referred to as the "high", was nearly twice the other, which shall be referred to as the "low". When at any particular setting of b and M_∞, frequencies besides these were measured, it was found that all the observed frequencies were usually harmonically related to the low as fundamental. The variation of high and low frequencies with l/b at different Mach numbers is shown in fig. 14. Comparing this plot with that of fig. 11 it may be noted that the fundamental frequencies for the turbulent boundary layer case are nearly half of the fundamental frequencies for the laminar case.

For some combinations of U_∞ and b, the phenomena in the gap were unstable and the radiation intermittent. As an example, intermittency observed for b = 0.5 inch at $M_\infty = 0.75$ and $T_o = 117^\circ$ F is shown in fig. 15, which is a plot of f against l/b for $M_\infty = 0.75$. The high frequency component B (equal to 13.9 k.c.) was present when the components A and C (equal to 6.6 k.c. and 19.2 k.c., respectively) were absent, and vice versa. When A and C were present a note could be heard (A is in the audible range) which momentarily disappeared when component B was present. Slight change in temperature T_o, or the gap width b would cause this instability to disappear. This behavior, which apparently results from the coexistence of two stable states in the gap, was observed to be a typical feature of flow past gaps of breadths around 0.5 inch and greater, with a turbulent boundary layer.

6. NONDIMENSIONAL FREQUENCY

The variables influencing the phenomenon are the geometry of the gap given by its shape, breadth b and depth d, the velocity U, the local speed of sound a, the density ρ, the viscosity μ, and the boundary layer thickness δ, of the fluid stream just ahead of the cavity (see sketch below). The frequency f and intensity I describe the acoustic field.



(Intensity of the radiation is defined as the rate at which energy is transmitted across a unit area of a plane parallel to the wave front.) Dimensional analysis shows that the physical dependence of the frequency on the variables is expressed by the relation

$$S = \frac{fb}{U} = \psi\left(M, Re_\delta, \frac{d}{\delta}, \frac{b}{d}\right) \tag{5}$$

where S is a nondimensional frequency or as usually called a Strouhal number, and Re_δ is Reynolds number based on the boundary layer thickness.

In the experiments either the frequency was measured by the hot wire or the wave length λ of the radiation was determined, as discussed previously, from spark Schlieren pictures. The nondimensional frequency is then obtained by the following relations: in subsonic flow, the characteristic velocity U is taken equal to U_∞ the free stream velocity while a_∞ the free stream speed of sound is taken for the propagation velocity of the wave fronts. Thus one obtains, for subsonic flow

$$S = \frac{fb}{U_\infty} = \frac{fb}{M_\infty \cdot a_\infty}$$

or, since $f\lambda = a_\infty$ (6)

$$S = \frac{1}{M_\infty} \cdot \left(\frac{b}{\lambda}\right).$$

In supersonic flow, U is taken equal to U_1 the velocity immediately ahead of the gap, and the total speed of sound a_1 there is taken as the propagation velocity of the wave fronts. Thus one obtains for supersonic flow

$$S = \frac{fb}{U_1} = \frac{fb}{M_1 a_1}$$

or, since $f\lambda = a_1$ (7)

$$S = \frac{1}{M_1} \cdot \left(\frac{b}{\lambda}\right)$$

7. DEPENDENCE ON $\frac{b}{d}$

A. Variable Gap with Fixed Depth

In experiments on the variable gap, the cavity was always situated at the same distance from the leading edge of the plate so that at a fixed Mach number it was possible to keep the parameters Re_δ, δ, $\frac{d}{\delta}$ constant while $\frac{b}{d}$ could be changed by varying the breadth of the cavity. The measurements of frequency under these conditions determine the explicit variation of S with $\frac{b}{d}$. We have seen that fb remained a constant and equal to α when measurements were done at a fixed M_∞. For a given M_∞ and T_o, S is proportional to fb and hence it follows that S remains a constant when $\frac{b}{d}$ is varied at a given value of M_∞, Re_δ, δ and d. Such is the nature of the dependence of S on $\frac{b}{d}$ in the experiments on the variable gap whether the boundary layer ahead of the gap is laminar or turbulent (note that α turbulent is only half α laminar). Figs. 11 and 14 illustrate this conclusion.

The various values of S obtained for the different Mach numbers in these experiments are displayed in fig. 16. We will come back later to a discussion of this plot.

B. Shallow Cavities with Fixed Breadth

Practical difficulties prevented systematic investigation of the dependence of S on $\frac{b}{d}$ by varying the depth at a fixed breadth while maintaining the other parameters constant. Also, the depth of the model could not be increased over that of the variable gap without effectively lowering the choking Mach number of the tunnel. However the question whether shallow cavities in high speed flow would give rise to acoustic radiation and if radiation was present what would be its properties were compelling to undertake some experiments. Accordingly, cavities at two fixed values of the breadth, viz. 0.1 and 0.2 inch respectively, but with different depths were examined. All the cavities were located at 3.5 inches from the leading edge of the plate just as in the case of the variable gap. Thus at a given Mach number, the Reynolds number Re_{δ}, and the boundary layer thickness δ were maintained the same for both the experiments. It should be noted, however, that when the depth was changed at a fixed b, not only $\frac{b}{d}$ but also the parameter $\frac{d}{\delta}$ changed. For instance, at a Mach number of about 0.82, $\frac{d}{\delta}$ varies from 5.5 to 0.44 while $\frac{b}{d}$ changes from 1 to 12.5 for a 0.1 inch broad gap and from 2 to 25 for a 0.2 inch broad gap. The experiments were all done with a laminar boundary layer ahead of the cavity.

It was observed that emission of sound occurred also from these shallow cavities and that it persisted even for very shallow ones. Fig. 17 shows some typical pictures of such radiation. The general features of the acoustic field are the same as those described for the variable breadth cavities. The radiation, however, gets weaker as the depth is decreased more and more. At a Mach number of about 0.82, the 0.1 inch broad cavity did not exhibit any radiation for a depth of 0.0085 inch, while the 0.2 inch broad cavity did show clearly radiation even at 0.008 inch depth. For the latter cavity no emission was observed at the depth of 0.004 inch.

With each gap size, the Mach number was varied from 0.2 to about 0.82 the choking Mach number, and instantaneous schlieren pictures were taken. From these records, values of $\frac{b}{\lambda}$ were obtained and the non-dimensional frequency S for each flow configuration determined. The values of S thus obtained for the different $\frac{b}{d}$'s in these experiments are shown in Tables 1 and 2. The blank spaces in the tables indicate that the corresponding schlieren pictures were not clear enough to determine $\frac{b}{\lambda}$'s from them.

We notice that S does not seem to vary (within the limits of estimating the $\frac{b}{\lambda}$'s from the pictures) a great deal with $\frac{b}{d}$ at any Mach number and also over the Mach number range covered. However, no definite conclusions can be drawn with regard to the trends of variation of S with $\frac{b}{d}$ and M from these data, which are purely qualitative. Comparing these values of S with those for the variable gap with a fixed depth of 0.1 inch (fig. 16), we notice that the non-dimensional frequencies for the shallow cavities with b = 0.1 inch fall near and below the values for the variable gap while those for the 0.2 inch broad cavities are considerably higher. The shallowest cavity (viz. d = 0.008 inch) of 0.2" b group seems to give the highest S.

8. DEPENDENCE ON M

A. Variable Gap

The non-dimensional frequencies obtained for the cavities at different Mach numbers are shown in fig. 16. It is noticed that in these experiments when the Mach number is changed, changes in S, and consequently in Re_δ and $\frac{d}{\delta}$ are simultaneously produced. However, these changes are not very large. For instance, when M is changed from 0.45 to 0.82, δ changes from 0.02" to 0.018" causing $\frac{d}{\delta}$ to change from 5 to 5.5. Thus, we may consider fig. 16 as showing the dependence of S on M.

B. Shallow Cavities

Tables 1 and 2 show that S for these cavities does not exhibit any considerable variation over the Mach number range shown. The average variation (excluding the 0.008" d by 0.2" b gap) in S is about 10 % for the b = 0.2" group and about 6 % for the b = 0.1" group. However, no conclusions can be drawn with regard to the trend of the dependence of S on M. It should be born in mind that at any Mach number, the parameter $\frac{d}{\delta}$ is influenced noticeably whenever d is changed.

The values of S for these cavities at different Mach numbers are shown in fig. 18 which contains also data for some other experiments soon to be described. On this plot, some values of S for the variable gap as determined from schlieren photographs were included for comparison. It is to be noticed that the 0.1" cavity shows a value of S = 0.88 at a depth of 0.05".

9. EFFECT OF δ OR OF Re_δ

With laminar boundary layer ahead of the cavity, the only way to change δ or Re_δ in these experiments at a given Mach number was to change the location of the cavity with respect to the leading edge of the plate. Accordingly a few values were chosen for the distance x from the leading edge of the plate to the upstream edge of a 0.05" deep by 0.1" broad cavity, and schlieren observations of the acoustic radiation were made for these conditions. The features of the radiation were the same as observed before. The non-dimensional frequency obtained at a Mach number of about 0.85 and the different experimental situations are summarized below.

Gap = 0.05" deep by 0.1" b					
Gap distance from leading edge of plate x	M	δ	Re_δ	$\frac{d}{\delta}$	S
1/4 inch	0.855	0.0048	1578	10.4	0.877
7/8 inch	0.852	0.009	2940	5.55	0.862
3.5 inch	0.855	0.0182	5940	2.75	0.878

The boundary layer thickness δ is obtained from the relation

$$\delta = (5.2 + 0.412\, M^2)\ \frac{x}{Re_x}$$

as given by L. Howarth for compressible laminar boundary layer.

We notice that changing the boundary layer thickness by a factor of four has practically no effect on S at this Mach number. The values of S shown in the table are included in fig. 18.

10. EFFECTS OF TURBULENT BOUNDARY LAYER

A. Variable Gap

The acoustic radiation resulting from cavities made in the variable breadth model when the boundary layer ahead of the cavity was turbulent has been already described. Also hot-wire measurements of the frequency were reported. The non-dimensional frequency S was found to be a constant at any Mach number when $\frac{b}{d}$ was varied by varying the breadth with depth fixed at 0.1 inch. S depends on Mach number and decreases as M increases (figs. 14 and 16).

No experiments were done on the shallow cavities with turbulent boundary layers.

B. Cavities in the Wind Tunnel Wall

In order to determine if there is any sound production for flow over large cavities with thick turbulent boundary layers ahead of them, gaps 0.5 inch deep and 0.25 to 2 inches wide were arranged in the top wall of the tunnel and were studied at Mach numbers from 0.2 to 1.4. Acoustic radiation did result from such flows. No frequency measurements were made and hence schlieren observations were the means of these studies. It was found that the radiation from these cavities generally appeared at the high subsonic Mach numbers and supersonic Mach numbers and was usually not well defined. Fig. 19 shows the radiation from two cavities 0.25 inch and 1.0 inch broad respectively. The depth is 0.5 inch for both of them. The waves seen in the picture of the 1.0 b cavity are the reflection at the tunnel bottom of the waves emitted from the cavity. The non-dimensional frequency as determined from the schlieren records and the corresponding experimental conditions are summarized as follows:

d = 0.5 inches

b	0.25	0.578	0.578	1.0
M	1.3	1.2	1.13	0.8
S	0.578	0.451	0.51	0.656

These values of S are also shown in fig. 18.

11. OTHER DATA FOR S

The non-dimensional frequencies computed from the data of Reference five have been plotted in fig. 18. Also the results of some additional measurements made at J.P.L. on the radiation from a 0.16" deep cavity are shown in fig. 18. This cavity was situated at 6.5 inches from the leading edge of the plate and three breadths, 0.3, 0.4, and 0.5 inch respectively, were used. The free stream Mach number in these experiments was 2.55.

It should be noted that the cavity used in Reference five was of 0.1 inch depth.

12. INTENSITY OF THE ACOUSTIC RADIATION

The intensity of radiation is the rate at which energy is transmitted across a unit area of a plane parallel to the wave front. For a simple harmonic wave of frequency f the intensity I is given by the relation

$$I = \frac{1}{2} \frac{P^2}{\rho_e a} \tag{8a}$$

or

$$I = \frac{1}{2} \rho_e a^3 s^{*2} \tag{8b}$$

where a is the local speed of sound, and P and s^* are the maximum amplitudes of the pressure and condensation waves, respectively. ρ_e is the equilibrium value of the local density of the medium. I is expressed in ergs per square centimeter per second.

In the decibel scale the intensity is given by its level relative to the reference level 10^{-9} ergs per square centimeter per second. Thus,

$$I_{db} = 10 \log_{10} \frac{I}{I_{Ref}}$$

where I_{db} = intensity in decibels and I_{Ref} = reference intensity = 10^{-9} ergs per square centimeter per second. Hence,

$$I_{db} = 90 + 10 \log_{10} I \tag{9}$$

An optical interferometer of the Mach-Zehnder type is very suitable to measure intense sound fields. One measures the maximum amplitude of the condensation at any desired point in the acoustic field by means of "no-flow" and "with-flow" finite fringe interferograms (of very short duration) of the field. The fringe shift and the "condensation" are related by:

$$\frac{\Delta x}{x} = \frac{\ell}{\lambda_v} \cdot k \Delta\rho$$

or

$$s^* = \frac{\rho - \rho_e}{\rho_e} = \frac{\Delta\rho}{\rho_e} = \frac{\Delta x}{x} \cdot \frac{\lambda_v}{\ell} \cdot \frac{1}{k\rho_e} \qquad (10)$$

where

ρ = instantaneous local density

Δx = fringe shift (measured as distance)

x = fringe spacing: distance between two consecutive fringes

λ_v = wave length (in vacuum) of light used = 5170 A (Mg. line)

k = Gladstone-Dale constant = 0.0017 cm^3/gm (table 349, ref.6)

ℓ = span of model = 3.996 inches

Thus an instantaneous "with-flow" interferogram of the field is a measure of the wave form of the condensation and one can simply obtain the maximum amplitude of the condensation by measuring the corresponding fringe shift. Thus,

$$s^* = \left(\frac{\Delta x}{x}\right)_m \cdot \frac{\lambda_v}{\ell} \cdot \frac{1}{k\rho_e} \qquad (11)$$

where $\left(\frac{\Delta x}{x}\right)_m$ = maximum amplitude of the fringe shift.

From relations 8b and 11 one obtains

$$I = \frac{1}{2} \rho_e a^3 \left[\left(\frac{\Delta x}{x}\right)_m \cdot \frac{\lambda_v}{\ell} \cdot \frac{1}{k\rho_e}\right]^2$$

which may be rewritten,

$$I = \frac{1}{2}\left(\frac{a}{a_o}\right)^3 a_o^{\,3} \frac{1}{\left(\frac{\rho_e}{\rho_o}\right)\rho_o} \frac{\lambda v}{\ell} \frac{1}{k^2} \cdot \left(\frac{\Delta x}{x}\right)_m^2 \qquad (12)$$

if a and ρ_e are expressed in terms of the stagnation conditions a_o and ρ_o, respectively.

This relation is the basis for the evaluation of the intensity of the acoustic radiation. At a Mach number of 0.7 or 0.8 and for $T_o = 110^\circ$ F, a unit fringe shift (that is, $\left(\frac{\Delta x}{x}\right)_m = 1$) corresponds to an intensity of 163 decibels. Fringe shifts equal to and greater than 1 have been observed for the radiation from the cavities.

A few typical finite-fringe interferograms of the acoustic field are presented in fig. 20. It may be observed that the intensity of radiation from a gap of 0.3-inch breadth at $M_\infty = 0.82$ is greater with laminar boundary layer than with turbulent flow. Further, the intensity for a gap 0.2-inch wide at $M_\infty = 0.7$ is comparable to that for a gap 0.3-inch wide at $M_\infty = 0.82$. Detailed quantitative studies of the intensity were not done.

Fig. 21 shows infinite-fringe interferograms of the radiation in laminar flow from a gap 0.3-inch wide for $M_\infty = 0.82$. These pictures were taken under identical free stream conditions. They are indicative of the changes taking place within the gap and in the field, and could prove to be of value in studies of the mechanism of the radiation.

13. POSSIBLE MECHANISM OF THE SOUND EMISSION

In this section is presented a qualitative discussion of some ideas suggestive of the physical factors underlying the acoustic radiation from cavities in high speed flow. Some of the important characteristics of the radiation in light of which these ideas have to be examined are summarized as follows.

For a fixed velocity of the stream, i.e., for a fixed M and T_o, there is a minimum value of the breadth of the cavity at which sound emission begins. Then as b is increased the frequency of the sound field decreases and in fact is inversely proportional to b.

For a fixed breadth, there is a minimum velocity or Mach number at which sound emission commences. As the velocity is increased, the frequency of the sound field increases.

With turbulent boundary layer ahead of the cavity the fundamental frequencies are half of those obtained with a laminar layer, when the Mach number and gap size are maintained the same for both cases.

Even before we consider the mechanisms that may give rise to the sound production with the above characteristics, we have to recognize at the very outset the important part played by the back edge of the cavity. It is an essential factor of the whole phenomenon that the back edge should be placed so that the separated boundary layer or the free shear layer will impinge on the edge as the layer deflects and diffuses downstream. If no edge is present in the path of the shear layer, no sound production takes place. These conclusions are well illustrated in fig. 22, which shows the effect of the back edge on the sound field emitted by a cavity in a stream of Mach number 0.8. We know that at this Mach number sound emission occurs from a 0.1" broad by 0.1" deep cavity. When the back edge of the cavity is completely removed the sound field disappears. In this case the shear layer leaving the step diffuses gradually as it moves downstream. In picture a of fig. 22 the back edge is only half as high (0.05") as the front edge. With b = 0.1" the shear layer does not hit the edge and no sound production takes place. Now in picture b the back edge, still 0.05" high, is moved further downstream so that b = 0.02"; at this position the shear layer has diffused enough to impinge on the edge, and sound emission results. It is of interest to note that the non-dimensional frequency in this case, as obtained from the schlieren picture, is about 0.84, which compares with the value obtained for the edge of full height (0.1") at this breadth (0.2"). (The result for the half-height edge is denoted as the "stepped trailing edge" in the plot of fig. 18.)

A most important factor connected with the phenomenon is the nature of the flow processes occurring at the back edge. So far this process is not understood. The impinging shear layer creates locally at the edge a high pressure region which fluctuates periodically as the shear layer oscillates. This local variation of pressure constitutes a source of sound emission from the cavity. The lack of understanding of the process here is comparable to the situation in the case of vortex shedding from bluff bodies, and, similarly, probably holds the key to the problem.

Bearing in mind the above observations, we may now examine some of the mechanisms that are likely to determine the characteristics of the sound field from the cavity. These are: a) an acoustic mechanism, involving standing waves in the cavity, b) filling and expulsion of fluid from cavity, c) formation of an unstable vortex or system of vortices in the cavity, and d) the instability of the free shear layer.

(a) In the acoustic idea it is assumed that standing waves are set up in the cavity and that the frequency of the observed sound field from the cavity is simply equal to the frequency of these waves. For a longitudinal mode of oscillation between the front and back of the cavity, the fundamental frequency of the standing wave is given by

$$f = \frac{c}{2b}$$

where b is the breadth of the cavity and c is some average speed of sound in the medium of the cavity. This speed of sound is given in terms of the square root of some average temperature, say T_c, in the cavity. Thus we obtain

$$fb = \text{const} \sqrt{T_c}$$

where T_c is in absolute units. This shows that any variations in fb should be accounted for by variations in T_c only.

From experiments we know that at a fixed M and T_o, fb is constant while b is varied. This is possible if the flow in the cavity remains quiet enough. However, experiments indicate that the flow is fairly violent in the cavity.

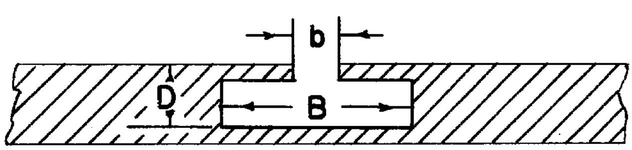
Secondly, from experiments we know that at a fixed b and T_o, fb increases with M. This means that at a given b and T_o, $\sqrt{T_c}$ should increase with M in the same way as fb does. In other words, for a given cavity the average temperature in the cavity at low Mach numbers should be considerably lower than that at high Mach numbers. As a specific example, consider the sound emission from a 0.2" broad by 0.1" deep cavity. The frequency of emission (as measured by hot wire) at M = 0.8 and $T_o = 47^o$ C, is 36.5 kilocycles per sec, which makes the average temperature in the cavity to be $T_c = 70^o$ C. At a Mach number of 0.6 and $T_o = 47^o$ C, the frequency of emission from the same cavity is 30 kilocycles per sec. giving the cavity temperature to be $T_c = -43^o$ C. Thus, in order to explain the measured frequency of emission in the two cases on the basis of standing waves in the cavity, the average temperature in the cavity should change from 70^o C to -43^o C when the Mach number is changed from 0.8 to 0.6 and the stagnation temperature is maintained for both cases at 47^o C. It is unreasonable to expect such a temperature variation.

We may similarly consider another experimental result, viz. that for the same M and T_o, fb for a given cavity but with a turbulent boundary layer ahead of the cavity is about half of that with a laminar layer. This means that T_c in the turbulent case should be nearly one-quarter of its value in the laminar case. Again, as a specific example let us consider the case of the 0.2" broad by 0.1" deep cavity with a turbulent boundary layer, at M = 0.8 and $T_o = 47^o$ C the measured frequency of the sound field from the cavity is 15.8 kilocycles per second. This requires that the average cavity temperature be nearly 65^o K or -208^o C, which is about one-fifth of the temperature required in the laminar case.

From such considerations it does not seem likely that acoustic standing waves are the governing mechanism in the sound production by the cavity.

b) The second possibility is concerned with the idea that the deflected shear layer feeds fluid into the cavity at the back edge. When the volume of the cavity is filled up and a certain pressure difference is set up across the layer the layer deflects up from the cavity thus allowing fluid to escape from it. This creates a low pressure in the cavity and the layer returns into it thus starting again a new cycle. The period of oscillation is determined by the timing of filling up of the cavity volume and hence the frequency depends on the volume of the cavity. This means that the depth should influence the frequency in the same way as the breadth. But experiments do not show such influence. Observations on cavities in the tunnel wall indicate that an increase of depth over a certain value has no effect on the sound field.

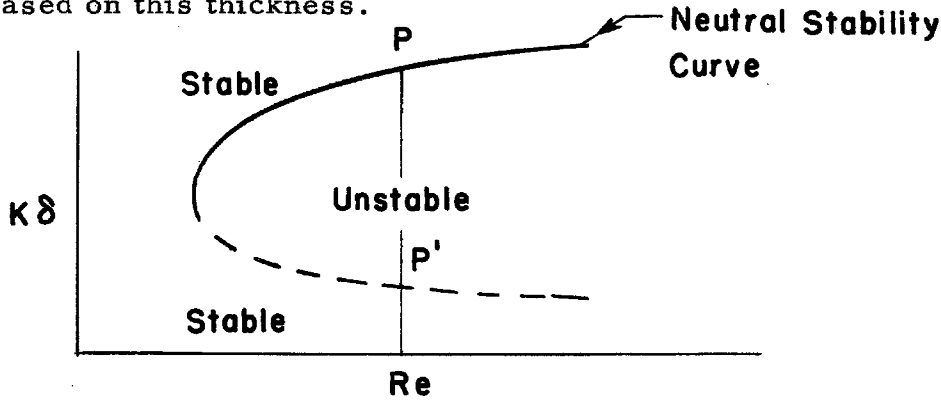
Observations on resonator type cavities, as shown in the sketch below, indicate that the principal factor governing the frequency of radiation from them is the distance b between the cavity lips and not the dimensions B and D of the lower cavity (see section 15 and fig. 26).



c) The third possibility is based on the idea that an unstable vortex or system of vortices is formed in the cavity and that the sound field is connected with periodic changes of the vortex configuration. From experiments (refs. 1, 2, and 3) in low speed flow we know that a very stable vortex is formed in a square cavity while a series of vortices is formed in a larger cavity. Changes in the vortex configuration, for instance from a one- to a two-vortex system, are accompanied by fairly abrupt changes in flow parameters, e.g. pressure on the wall. If the vortex system were the governing factor in sound production by the cavities, these adjustments in the vortex configuration should produce similar abrupt changes in flow parameters, e.g. pressure on the wall. If the vortex system were the governing factor in sound production by the cavities, these adjustments in the vortex configuration should produce similar abrupt changes in the sound field. But experiments do not show such effects. For instance, sound emission starts for values of $\frac{b}{d} < 1$, and the frequency decreases linearly as b increases to large values of $\frac{b}{d}$, namely to $\frac{b}{d} \simeq 5$. Thus a mechanism based on the instability of a vortex system in the cavity does not appear to be a possible explanation for the sound production.

d) We have next to consider the role of the instability of the shear layer. We know that sound production is accompanied by oscillations of the free shear layer. This produces fluctuations of the pressure at the back edge of the cavity, which intercept the fluctuating layer, and these pressure fluctuations in fact are probably the main source of sound production. What causes the shear layer to oscillate and what maintains its oscillations ? Further, what determines the frequency of the oscillations ?

A possible explanation for the occurrence of the shear layer oscillations is in the natural instability of the free shear layer. Such a layer is unstable to a certain range of wave lengths (or equivalently frequencies) of disturbances. This range is obtained by calculations of the stability characteristics of the shear layer. The results of the calculations are usually represented by a curve of neutral stability on a plot of the disturbance wave lengths (or frequencies) against Reynolds numbers for the shear layer. A qualitative idea of such a plot for a laminar free shear layer (fig. 7, ref. 7) is shown in the sketch below, where the disturbance wave number $k = \frac{2\pi}{\lambda}$ is made non-dimensional by a boundary layer thickness, δ, of the shear layer and the Reynolds number is based on this thickness.*



The points along the curve represent neutral disturbances while the region within the curve corresponds to unstable disturbances and that outside it contains stable points. To each point on this plane there exist a corresponding pair of values of C_r and C_i which are respectively the velocity of propagation of the disturbance wave and the factor determining its amplification. For points on the neutral curve $C_i = 0$. Now, at any particular value of Re, there is a definite range of disturbance wave lengths (or alternatively frequencies), such as PP' on the curve above, which is dangerous to the free shear layer.

The question then is, in the case of sound production by the cavities, what causes the shear layer to oscillate with a certain particular frequency selected out of the band of unstable frequencies ? Due to the os-

*This curve can be alternatively given on a plot of the disturbance frequencies versus Reynolds numbers, since the circular frequency is equal to $C_r \cdot k$, where C_r is the speed of propogation of the disturbance.

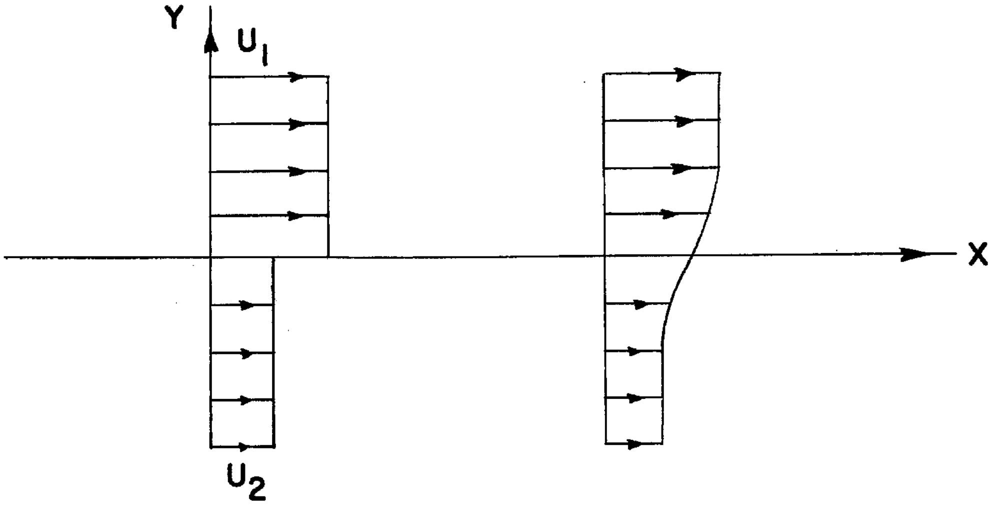
cillations of the shear layer the pressure at the back edge fluctuates and this in turn affects the motion of the layer. The coupling must be such as to select a definite frequency from the available range. One may assume that there exists some kind of phase relation between the pressure fluctuation at the back edge and the motion of the shear layer, say at the front edge. If this phase relation is to be always the same, then it is reasonable that the frequency decreases linearly with increase in the separation distance between the front and back edges of the cavity.

An important factor that comes out of the above discussion on the shear layer instability is the question of the minimum breadth for sound emission. Referring to the above sketch of the neutral stability curve for the shear layer the smallest unstable wave length at a given Re is given by a point such as P on the curve. Now as the breadth of the cavity is gradually increased from zero, the shear layer remains undisturbed untill the breadth assumes a value suitable to the smallest disturbance wave length whence oscillations of the shear layer commence leading to sound emission from the cavity. Thus the minimum breadth for sound emission is determined by and given in terms of the smallest unstable disturbance wave length.

An idea of the order of magnitude of the minimum breadth in case of a laminar boundary layer ahead of the cavity can be obtained by using the results given by Lessen (ref. 8) for the stability of an incompressible laminar boundary layer between parallel streams.* Lessen's analysis, based on the theory of small disturbances, concern the plane flow con-

*Detailed studies into the stability of free shear layers, either compressible or incompressible are not available at present.

figuration sketched below.



The solution of the problem is, however, carried out only for the case of flow in which the stream U_2 is at rest. The results for this case are shown in fig. 23 which is reproduced from Reference eight. On this plot $R = \frac{U_1 \delta}{\nu}$ where $\delta = \sqrt{\frac{\nu x}{U_1}}$. The lower branch of the neutral curve is not obtained. We notice that for large Reynolds numbers (i.e., for the so-called "inviscid solution") the smallest unstable wave length is given by

$$\lambda_{d\ min.} \simeq \frac{2}{0.395}\ \delta \quad \text{(fig. 23)}$$

In our experiments on the cavity the Blasius boundary layer thickness $\delta_B = 5.2\sqrt{\frac{\nu x}{U_1}}$ of the shear layer at the cavity leading edge is approximately 0.02 inches. Using this value we have for the above relation $\delta = \frac{0.02}{5.2}$ inches, which gives for the shortest wave length

$$\lambda_{d\ min.} \simeq 0.061 \text{ inches}$$

Thus, if $\lambda_{d\ min}$ is assumed equal to the minimum breadth, the latter should be of the order of 0.06 inches for large Reynolds number flow. Experiments show that at a Mach number 0.82 (which is about the maximum Mach number for the experiments), b minimum is of the order of 0.08 inches.

Lessen's results can be used further to get an estimate of the non-dimensional frequency for the sound emission at minimum breadth. Lessen shows that for large Reynolds numbers, the wave speed of the neutral disturbances approaches a value $C_R = 0.587\ U_l$. This gives, for large Reynolds number, the frequency of oscillation of the shortest wave length to be

$$f = \frac{C_R}{\lambda_{d\ min}} = 0.587\ \frac{U_l}{\lambda_{d\ min}}$$

With respect to the cavity problem, this relation gives the order of magnitude of the frequency of sound emission for minimum breadth and for large Reynolds number. If we assume $b_{minimum} \simeq \lambda_{d\ min.}$ we obtain

$$S \equiv \frac{fb_{min}}{U} \simeq 0.587$$

That is, the non-dimensional frequency or the Strouhal number of the sound field for large Reynolds numbers is of the order of 0.6. Experiments show that at $M \simeq 0.82$, (the maximum Mach number in experiments) $S = 0.68$.

The free shear layer involved in Lessen's analysis is not in the vicinity of any solid boundaries. Thus considerations based on this situation are applicable to the free shear layer in the case of flow over a cavity only if the depth of the cavity is large compared to the boundary layer thickness of the shear layer. For shallow cavities, i.e., when the depth is of the order of the boundary layer thickness and less, the depth of the cavity will be an important factor influencing the characteristics of the stability of the free shear layer and consequently the characteristics of the sound radiation from the cavity. Experiments on shallow cavities, where the depth is varied at a fixed breadth, indicate that the frequency shows an increase while the depth is decreased (see section 7.b and fig. 18).

The stability characteristics of a turbulent free shear layer are not known at present. Thus the order of magnitude considerations given above for the case of a laminar layer cannot be extended to the case of a turbulent free shear layer over the cavity.

It should be noted that even with a laminar boundary layer ahead of the cavity, the free shear layer over the cavity becomes turbulent as the breadth is increased and sound emission occurs. This means that the role of the instability of the free shear layer for production of sound by the cavities is only in making available a range of unstable frequencies of disturbances. The actual selection of the frequency of oscillation of the shear layer is determined by the phase relation between the pressure fluctuations at the back edge and the motion of the shear layer.

14. "EDGE TONES" - A RELATED PHENOMENON

Similar to our problem of sound production by the cavities is the old phenomenon of "edge tones" where a pure tone of sound is produced by allowing a thin jet of air (or water) issuing from a slit to impinge on a wedge-shaped edge placed at a short distance from the slit. The most important characteristics of the edge tones are:

a) When the mean velocity of efflux of the jet is maintained constant, there is a minimum edge distance (i.e., from edge to the slit) at which sound production commences.

b) At fixed jet velocity, the frequency of the edge tone is inversely proportional to the edge distance. As this distance is increased, jumps in frequency occur at certain edge distances.

c) For a fixed edge distance, the edge tone frequency increases as the velocity of the jet is increased; the frequency jumps occur at certain velocities.

Various theories have been proposed to explain the edge tone production, but none so far seem to be completely satisfactory. The main difficulty is again the lack of understanding of the flow processes at the edge and of their reaction on the jet issuing from the slit.

For further discussion on the edge tone problem reference may be made to papers by Brown (ref. 9), Nyborg (Ref. 10), and Curle (ref. 11) where other references on the problem may be found.

15. OBSERVATIONS ON MISCELLANEOUS CONFIGURATIONS

1. Non-Rectangular Crossections.

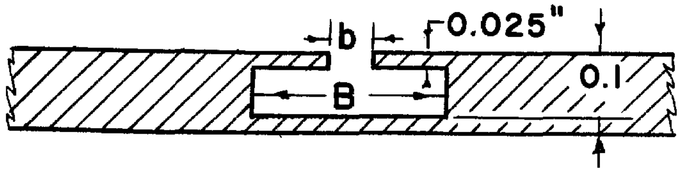
To see whether any sound emission would result from arbitrary configurations, cavities of different shapes were observed in high speed flow. The geometry of the sections used is shown in fig. 24. They were all arranged with the same breadth to depth ratio (viz. 0.2" by 0.1"). Each configuration was observed as the Mach number of the flow over it was gradually increased from 0 to 0.86. In these experiments, the boundary layer ahead of the cavity was laminar. Sound emission occurred in all cases. The radiation from these cavities in a flow of Mach number 0.86 is shown in fig. 25. The cavities exhibit radiation of roughly the same wave length and equal to that from a rectangular cavity of the same breadth and depth dimensions. For the triangular cavity shown in picture b fig. 24 notice that the radiation consists of a single rearward beam. In case of the cavity with a large rounding of the back edge (picture c) three sources seem to be involved in the sound emission.

The sound field from these cavities of different shapes is weak compared to that from a rectangular cavity.

Thus it appears that the intensity rather than the frequency of the radiation is affected by the shape of the cavity.

2. Resonator type cavities of rectangular section.

The following sketch and table illustrate the configurations observed.



Dimension	Case			
	a	b	c	d
b	0.1	0.2	0.1	0.3
B	0.2	0.4	0.3	0.5

Each configuration was observed as the Mach number was increased from 0 to 0.85. The boundary layer ahead of the cavity was laminar in all cases. For configuration (a), no sound emission was observed till M is about 0.4. Between M = 0.4 and 0.45, the emission was intermittent and weak. At M = 0.48, a directionally uniform pattern was observed as shown in fig. 26.1. The emission almost disappears between M = 0.55 and 0.75 while a weak beam started again around M = 0.8 which finally developed into the characteristic sound field, as in the case of a rectangular cut-out, at M = 0.85 (fig. 26.2). The wave length of the emission is roughly equal to that from a 0.1" broad by 0.1" deep rectangular cavity.

The sound field from the other configurations (viz. b, c, and d) followed the usual pattern observed for rectangular cut-outs. Typical pictures for these configurations are shown in fig. 26. The wave length of the radiation in each of these cases is roughly equal to that for a rectangular cavity of the same b under the same flow conditions.

From these observations one can conclude that the frequency is principally governed by the distance between the front and back lips of the cavity and not by the dimensions B and D of the lower cavity.

3. Baffles in the cavity.

Various arrangements involving partitions in the cavity were observed. Thick and thin baffles some of full height and some of half height of the cavity were used. Sound emission was noticed in almost all cases.

The phenomenon assumes a complex nature when the back edge of the cavity is moved backward and forward while a fixed partition is located in the cavity. Intermittencies and resonance effects characterize the sound field from such configurations. A typical case is shown in fig. 27.

16. CONCLUDING REMARKS

The main features of sound radiation by cavities in high speed flow are:

For a given velocity (or rather Mach number) of the flow there is a minimum breadth below which no sound emission occurs.

At a fixed velocity, the frequency of the sound field decreases linearly as the breadth increases.

At a fixed breadth, the frequency increases with velocity.

The radiation exhibits characteristic directional properties.

The intensity of the radiation is high (about 160 decibels or more).

With turbulent boundary layer ahead of the cavity, the frequency is nearly half of that with a laminar layer. Also the intensity for the turbulent case is weaker.

To explain the production of the sound fields, the mechanisms considered are, a) an acoustic mechanism involving standing waves in the cavity, b) filling and expulsion of fluid from cavity, c) formation of an unstable vortex or system of vortices in the cavity, and d) instability of the shear layer. None of the first three possibilities appears to be the governing factor in the sound production. The instability of the shear layer makes available a certain range of frequencies of disturbances to which the layer is susceptible. Oscillations of the layer are accompanied by pressure fluctuations at the back edge of the cavity. These fluctuations in turn react on the motion of the shear layer. It is this coupling that determines the particular frequency with which the layer actually oscillates. Thus the key to the problem lies in an understanding of the flow processes at the back edge and their reaction on the motion of the shear layer. In this respect, the present problem is similar to that of vortex shedding from bluff bodies and that of edge tone production.

Future experimental studies on the problem should be directed mainly at clarifying the mechanism of sound production. High speed motion picture studies of the flow in the cavity, especially at the back edge, hot-wire surveys and transient temperature measurements will be fruitful. Quantitative experiments to determine the influence of parameters such as $\frac{d}{\delta}$, Re_{δ} on the sound field are needed. A systematic investigation of the intensity of the radiation is to be done. Experiments to precisely determine the minimum breadth for sound emission at different values of the boundary layer thickness just ahead of the cavity will throw light on the considerations involving the instability of the free shear layer. The question of the stability characteristics of turbulent free shear layer, is brought up and is a problem that has not been looked into.

Sound production by the cavities is a typical example of the conversion of aerodynamic shear energy into acoustic energy. Small cavities are likely to prove successful as efficient and cheap sources of intense ultrasonic sound for aerodynamic applications such as measurement of local fluid properties and production of turbulence by interaction of sound with shock waves.

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TABLE I

$b = 0.1$

S for

M						
$d =$	0.05	0.04	0.03	0.02	0.014	0.0085
$\frac{b}{d} =$	2	2.5	3.3	5.0	7.15	11.75
0.82	0.624	0.686	0.666	0.676	0.675	NO
0.75			0.687	0.64		EMISSION
0.70		0.65	0.671	0.658		
0.60			0.693	0.666		

TABLE 2

b = 0.2 inch

	d =	0.04	0.03	0.02	0.008	0.004
M	$\frac{b}{d}$ =	5	6.66	10	25	50
0.82		1.09	1.035	1.178	1.26	No
0.75			1.042	1.061		Emission
0.7		1.18		1.081		
0.65		1.09	1.04	1.02		
0.60				1.008		

Fig. 1. Sound radiation due to high speed flow over a cavity.

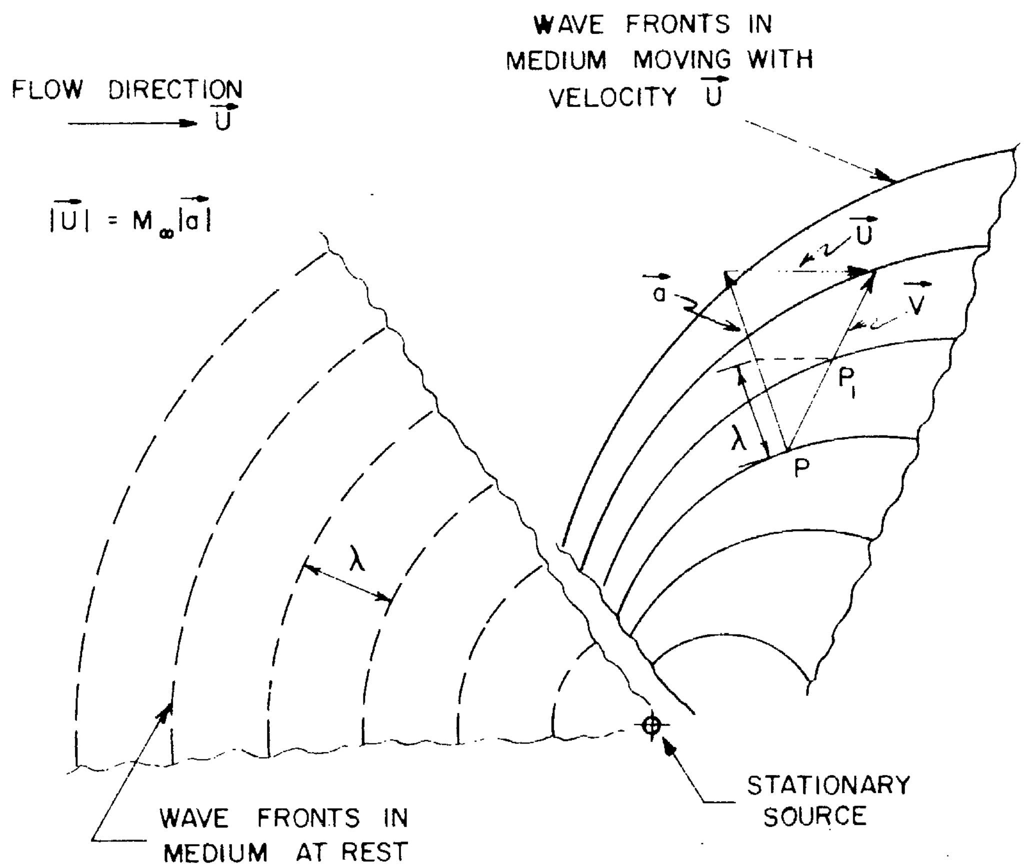


Figure 2. Acoustic field due to a stationary source radiating into a moving stream.

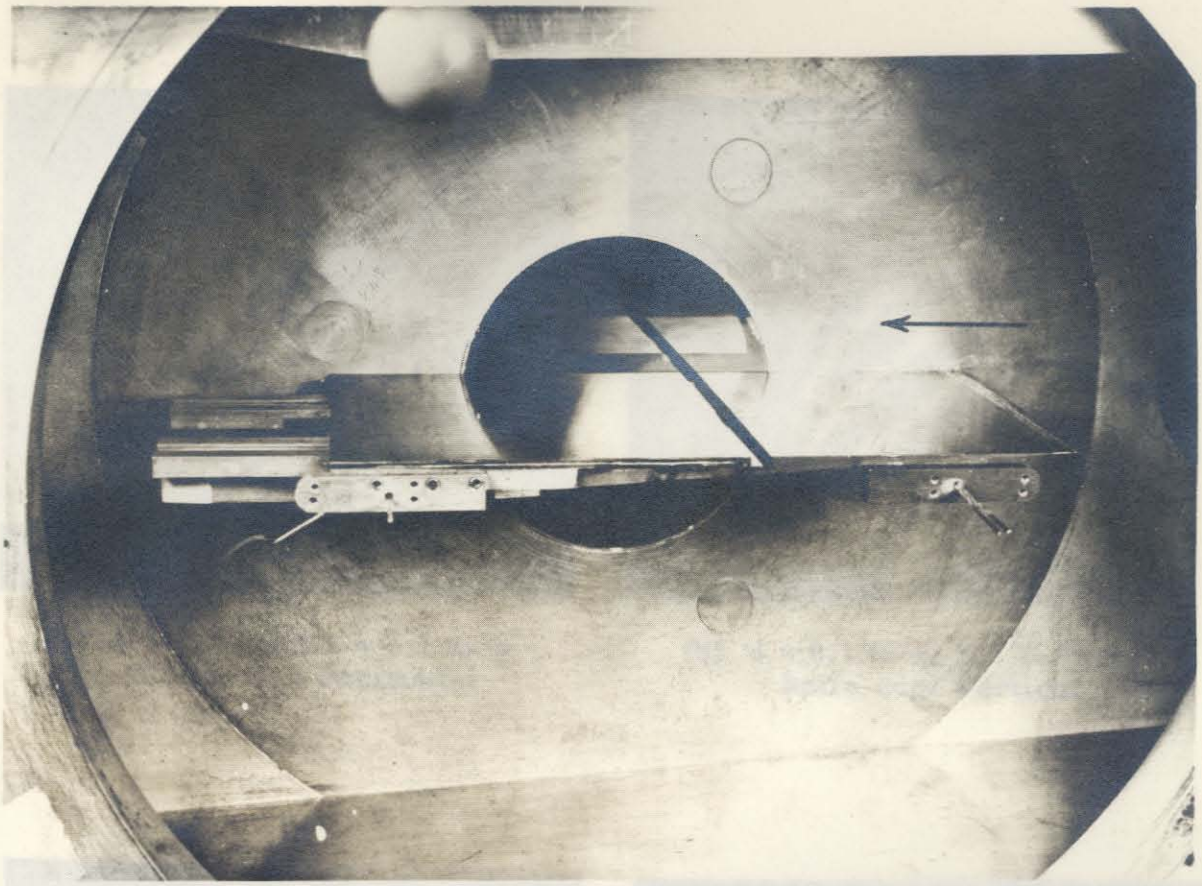


Fig. 3. Variable breadth model in test section.

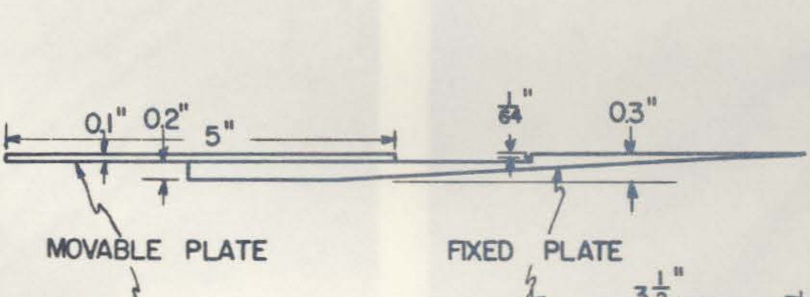
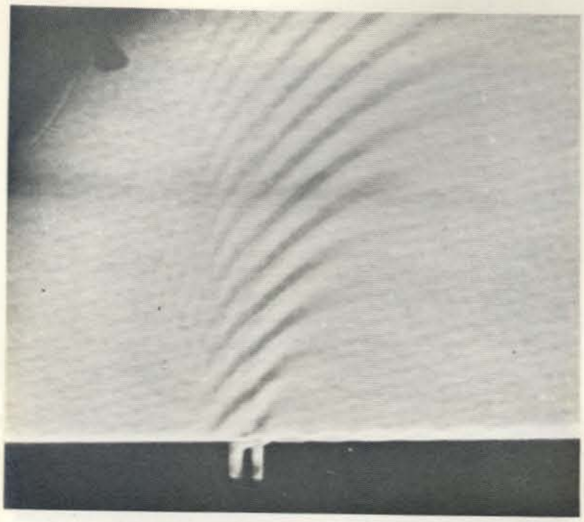
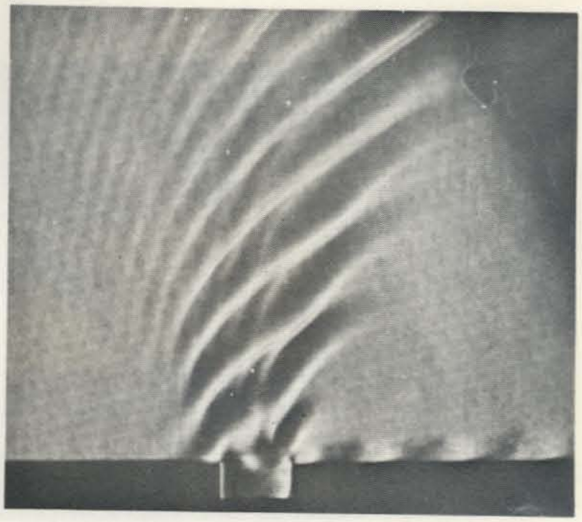


Fig. 4. Dimensional sketch of model.



(a) d = 0.1 inch; b = 0.1 inch
knife edge horizontal



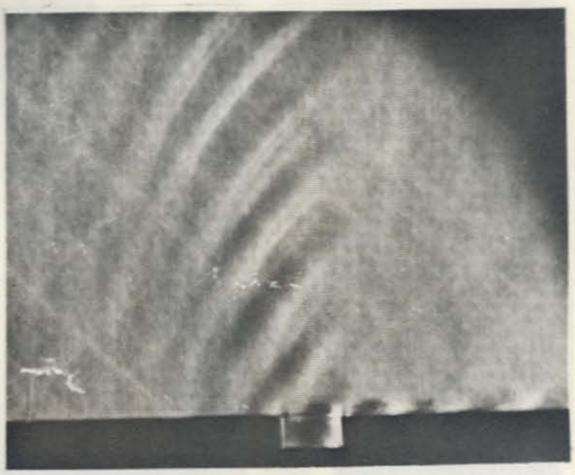
(b) d = 0.1 inch; b = 0.2 inch
knife edge vertical

(c) d = 0.1 inch; b = 0.3 inch
knife edge horizontal

(d) d = 0.1 inch; b = 0.4 inch
knife edge horizontal

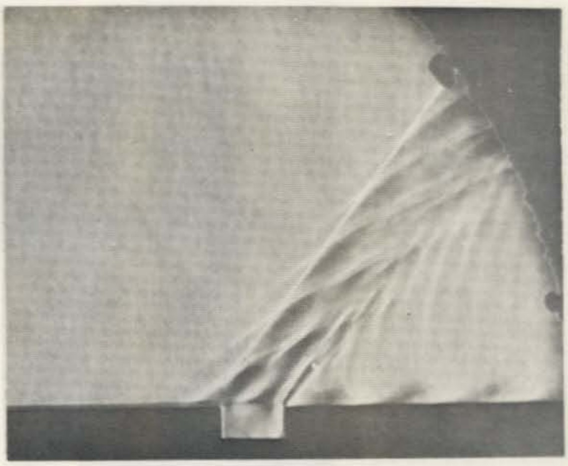
Fig. 5. Sound emission for increasing gap breadths with laminar boundary layer. $M_\infty = 0.82$.

(a) $M_\infty = 0.5$
knife edge vertical



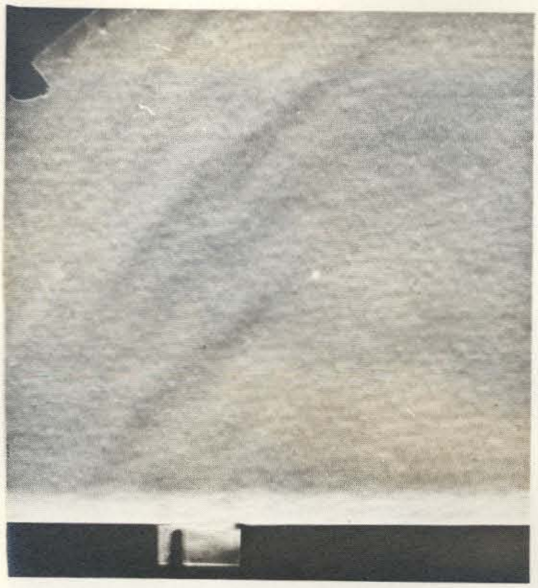
(b) $M_\infty = 0.64$
knife edge vertical

(c) $M_\infty = 0.7$
knife edge horizontal



(d) $M_\infty = 1.38$
knife edge vertical

Fig. 6. Sound emission for gap 0.1 inch deep and 0.2 inch wide with laminar boundary layer at different Mach numbers.

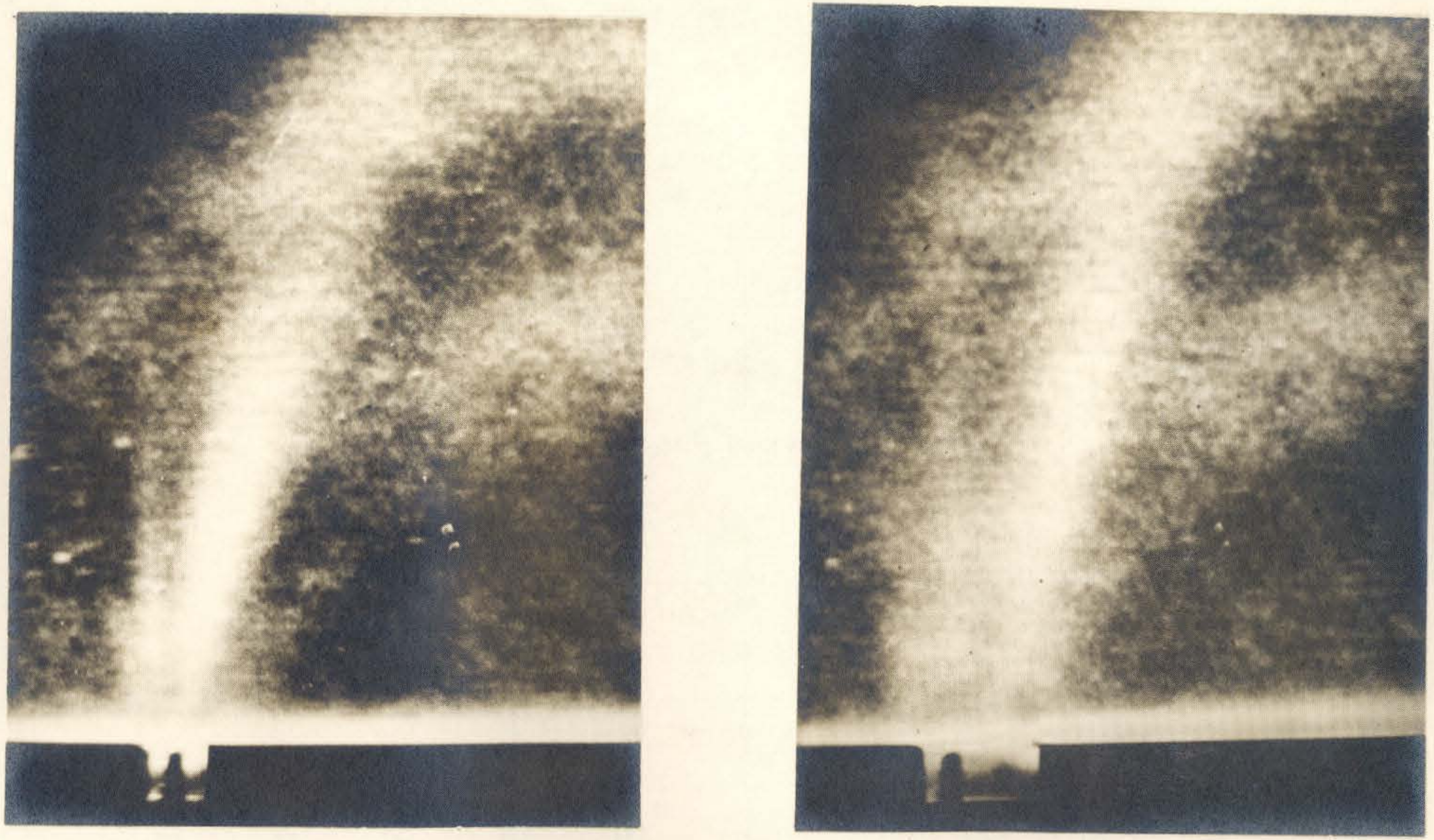


(a) d = 0.1 inch; b = 0.2 inch
knife edge horizontal

(b) d = 0.1 inch; b = 0.3 inch
knife edge vertical

(c) d = 0.1 inch; b = 0.5 inch
knife edge vertical

Fig. 7. Sound emission for increasing gap breadths with turbulent boundary layer. $M_\infty = 0.8$.



(a) d = 0.1 inch; b = 0.1 inch

(b) d = 0.1 inch; b = 0.2 inch

Fig. 8. Continuous-light schlieren photographs of sound emission. $M_\infty = 0.8$.

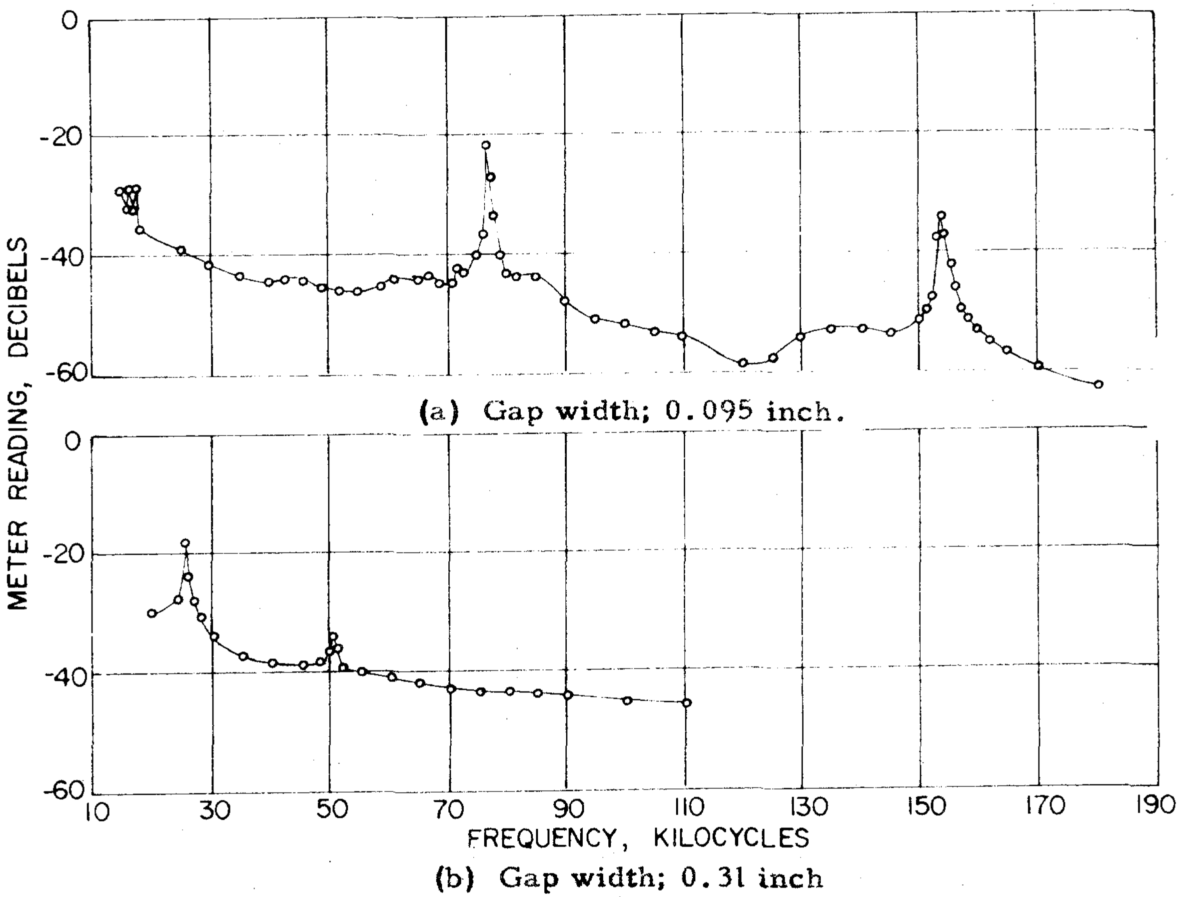


Figure 9. Typical frequency distribution of analyzer-meter readings. $M_\infty = 0.81$; laminar flow.

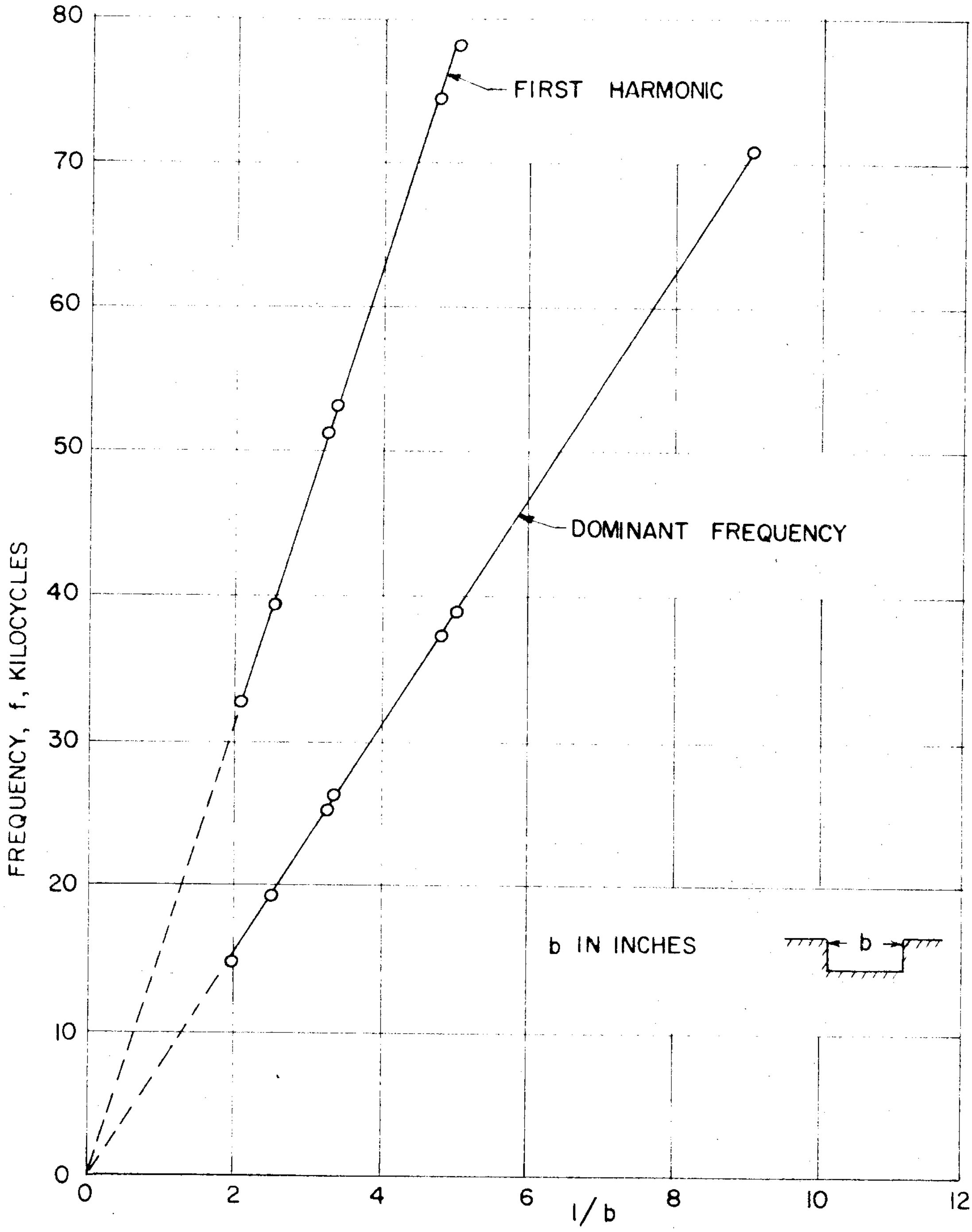


Figure 10. Results of frequency measurements for laminar case for range of gap breadths from 0.1 to 0.5 inch. $M_\infty = 0.82$; $T_o = 117^\circ$ F.

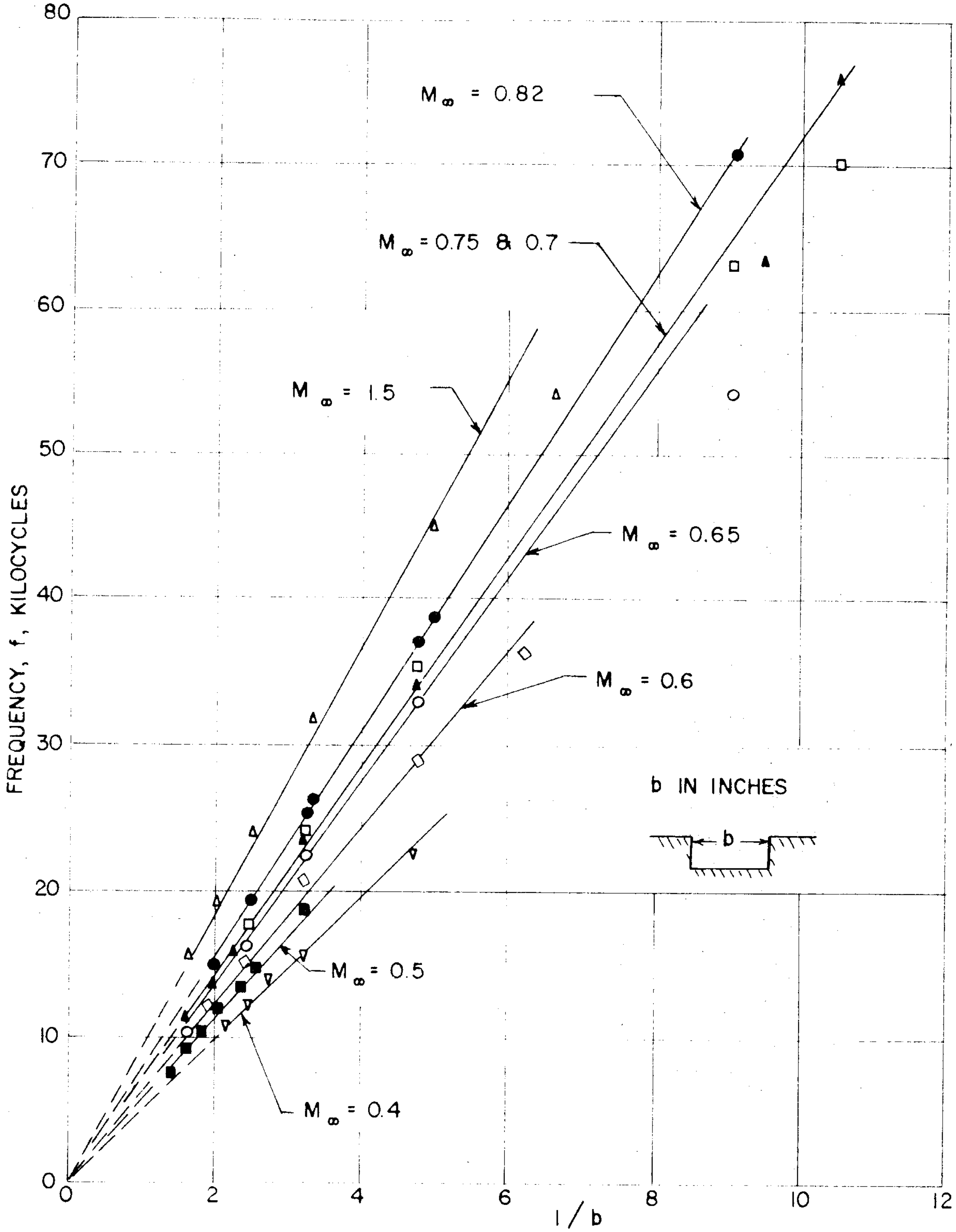


Figure 11. Results of frequency measurements for laminar case at different Mach numbers.

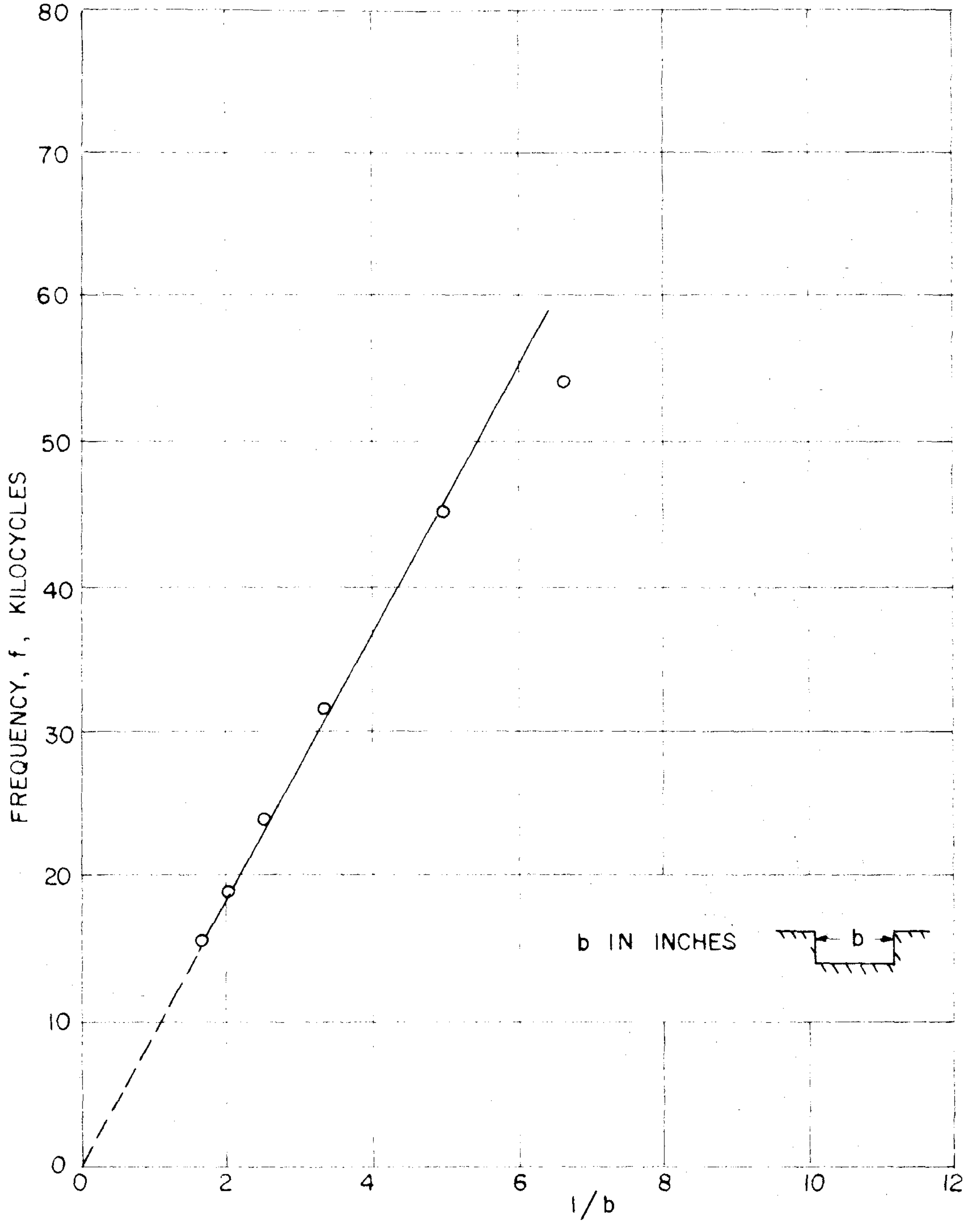


Figure 12. Results of frequency measurements for laminar case in supersonic flow. $M_\infty = 1.5$; $T_o = 123^\circ$ F.

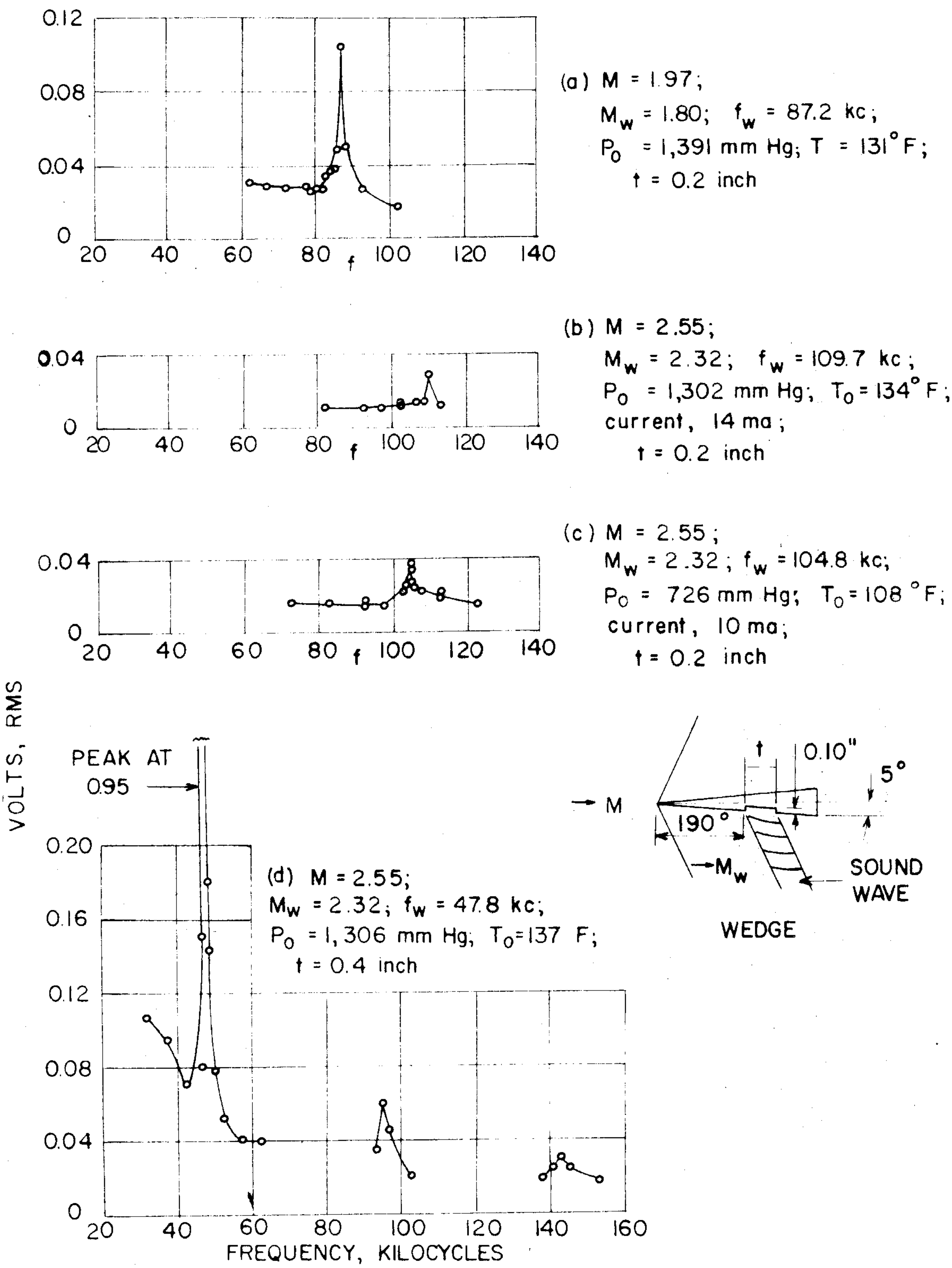


Figure 13. Disturbance frequency induced by a slot in a wedge in supersonic flow. (From ref. 5).

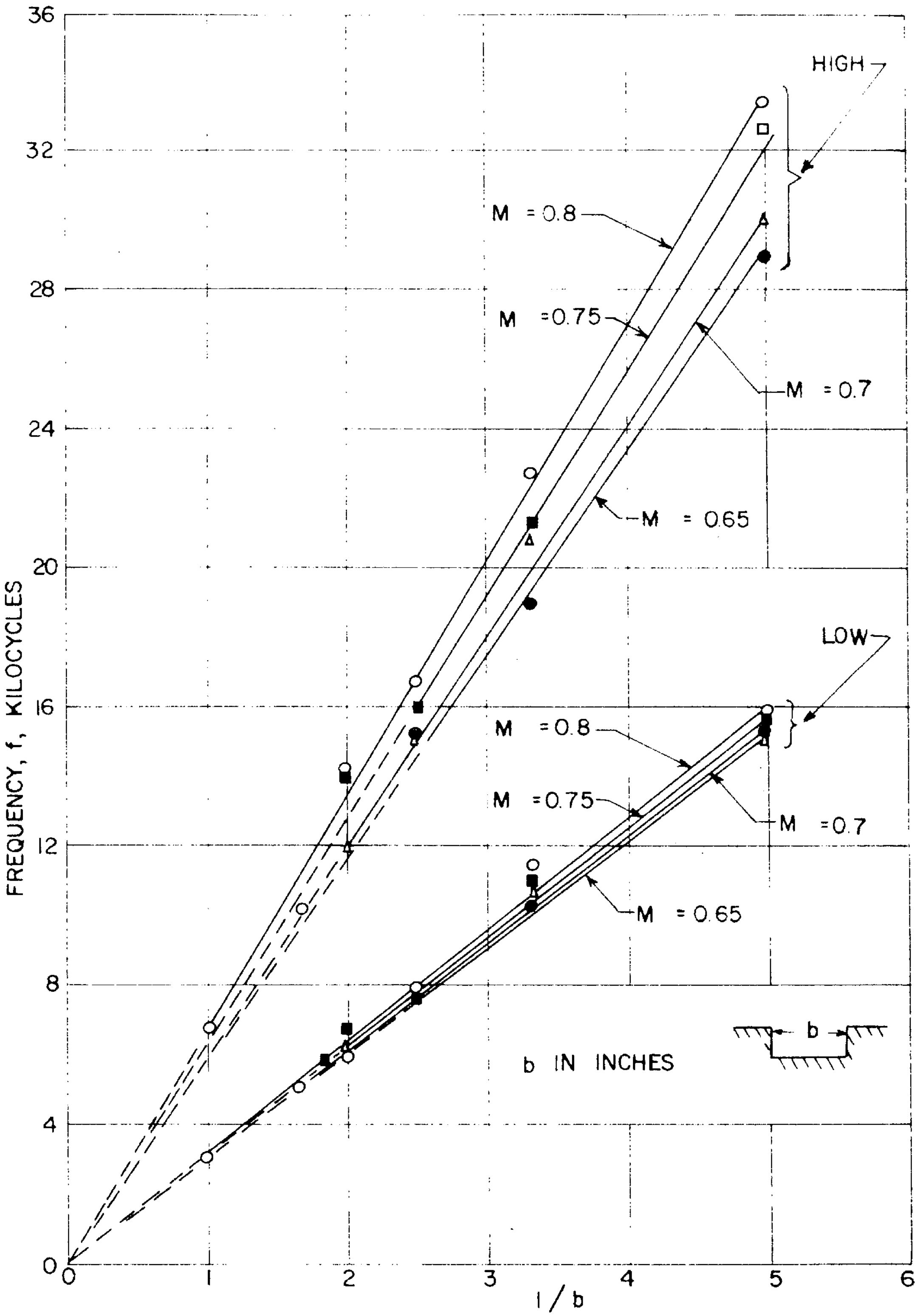


Figure 14. Results of frequency measurements for turbulent case at different Mach numbers. $T_o = 117^o$ F.

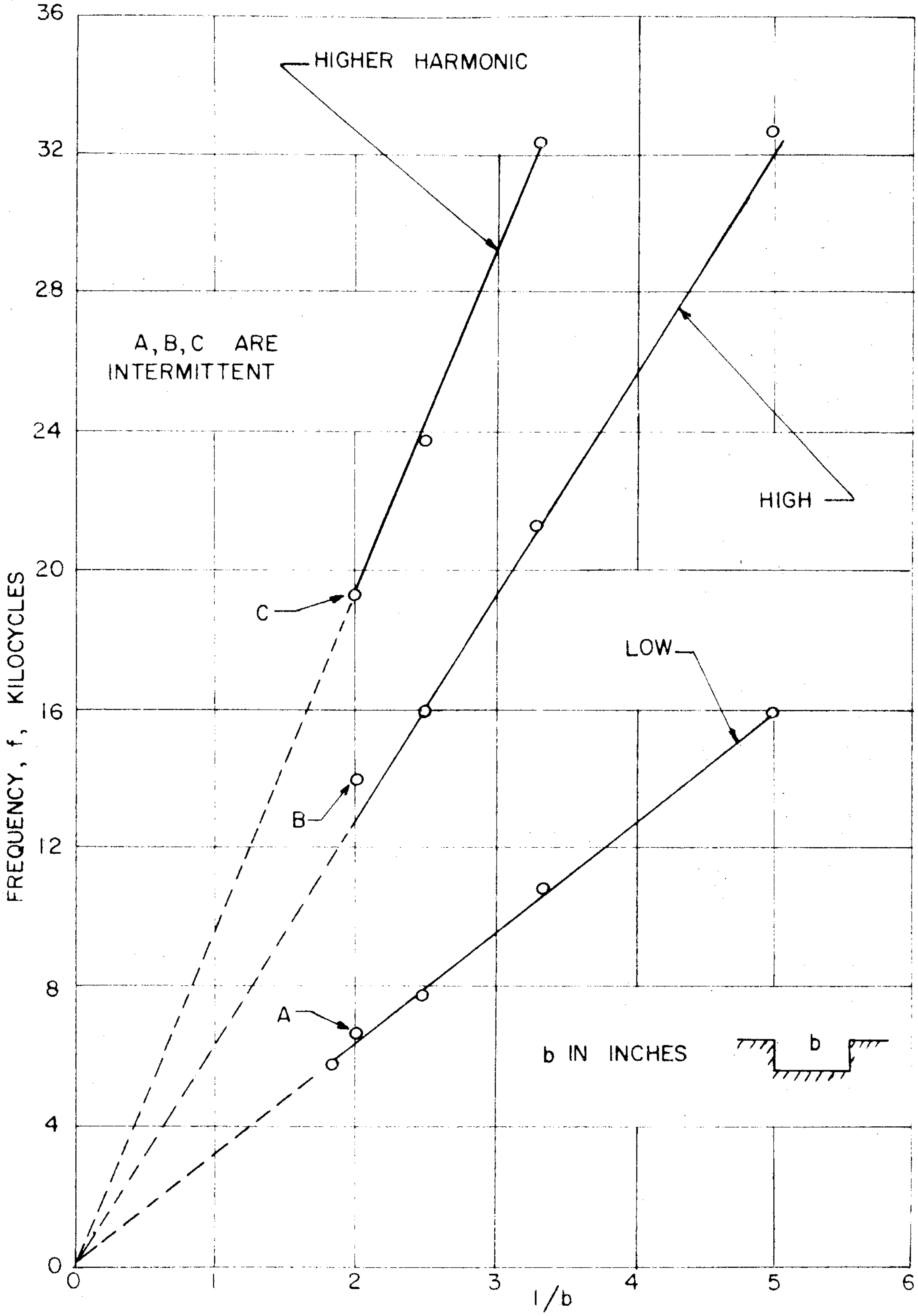


Figure 15. Results of frequency measurements for turbulent case showing intermittency observed for b = 0.5 inch. $M_{\infty} = 0.75$; $T_o = 117^{\circ}$ F.

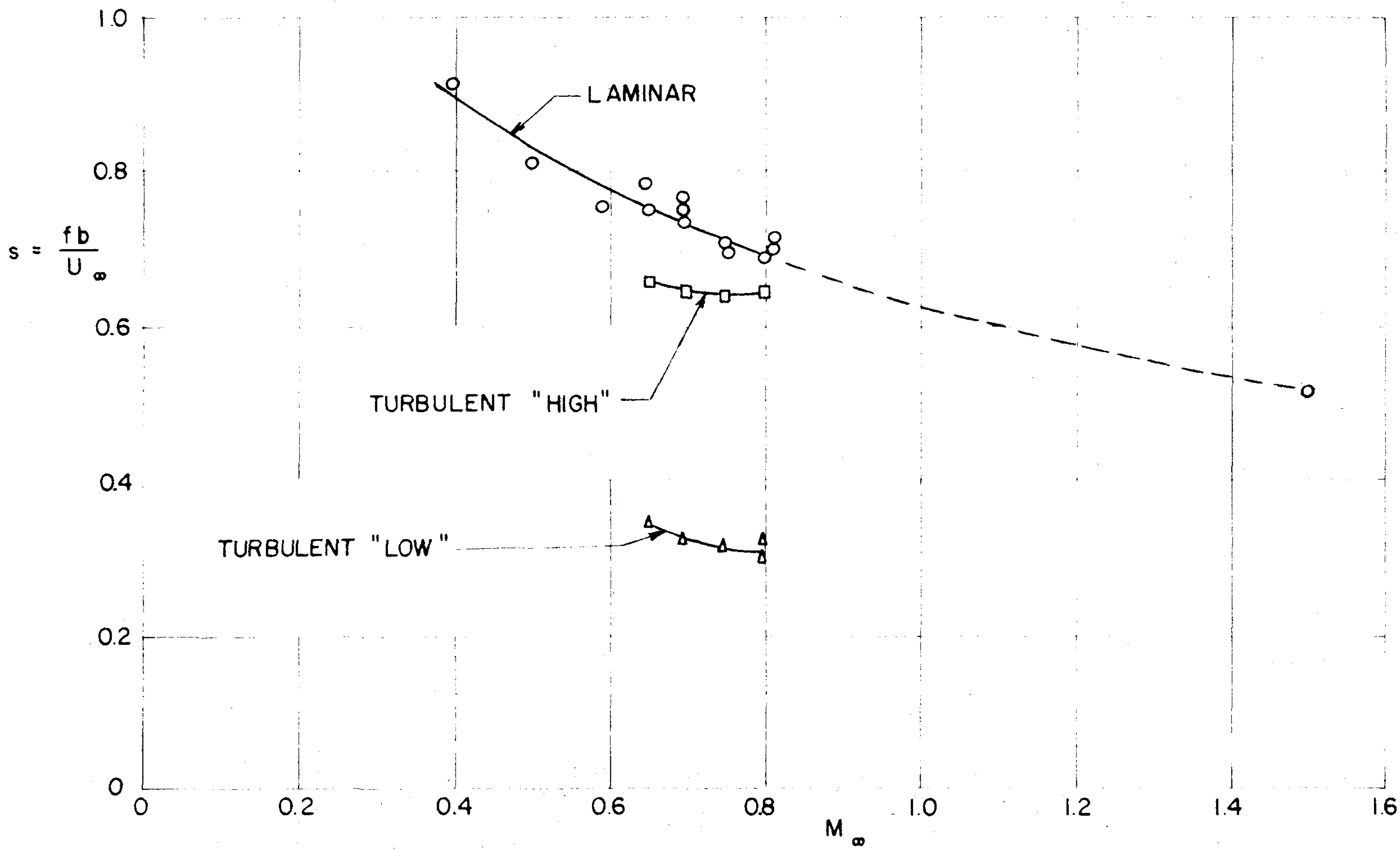
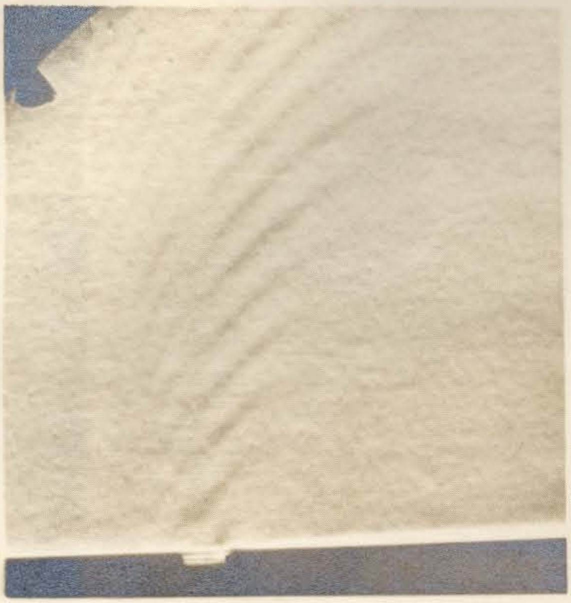
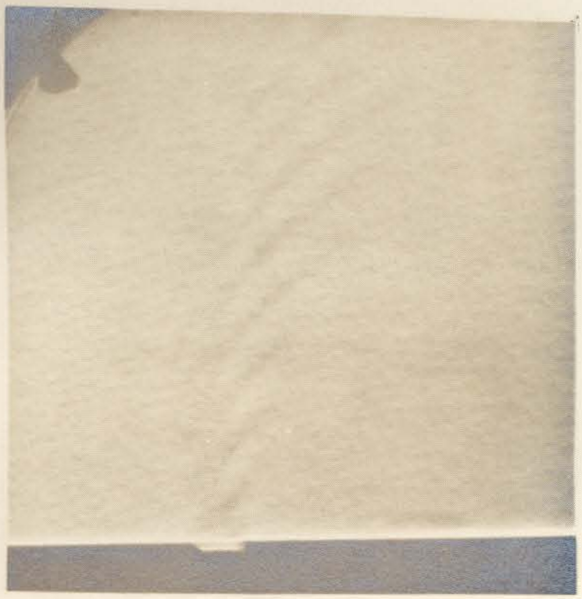


Figure 16. Nondimensional frequency. Gap with fixed depth and variable breadth.

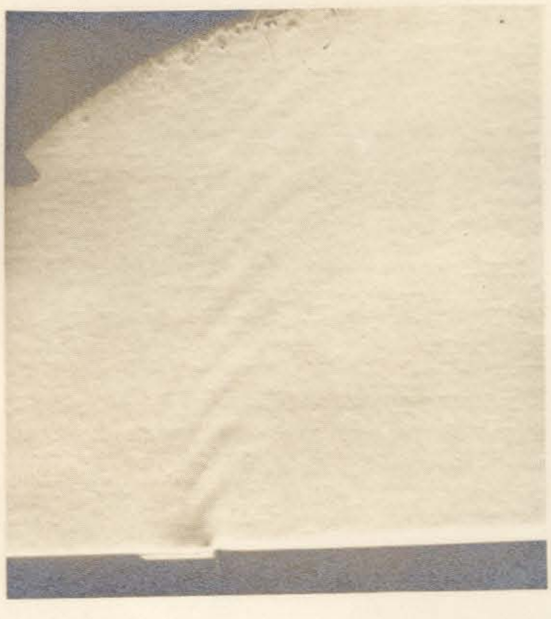


(a) b = 0.1 inch; d = 0.02 inch



(b) b = 0.1 inch; d = 0.014 inch

(c) b = 0.2 inch; d = 0.02 inch



(d) b = 0.2 inch; d = 0.008 inch

Fig. 17. Sound emission for shallow cavities with laminar boundary layer. $M_{\infty} = 0.82$.

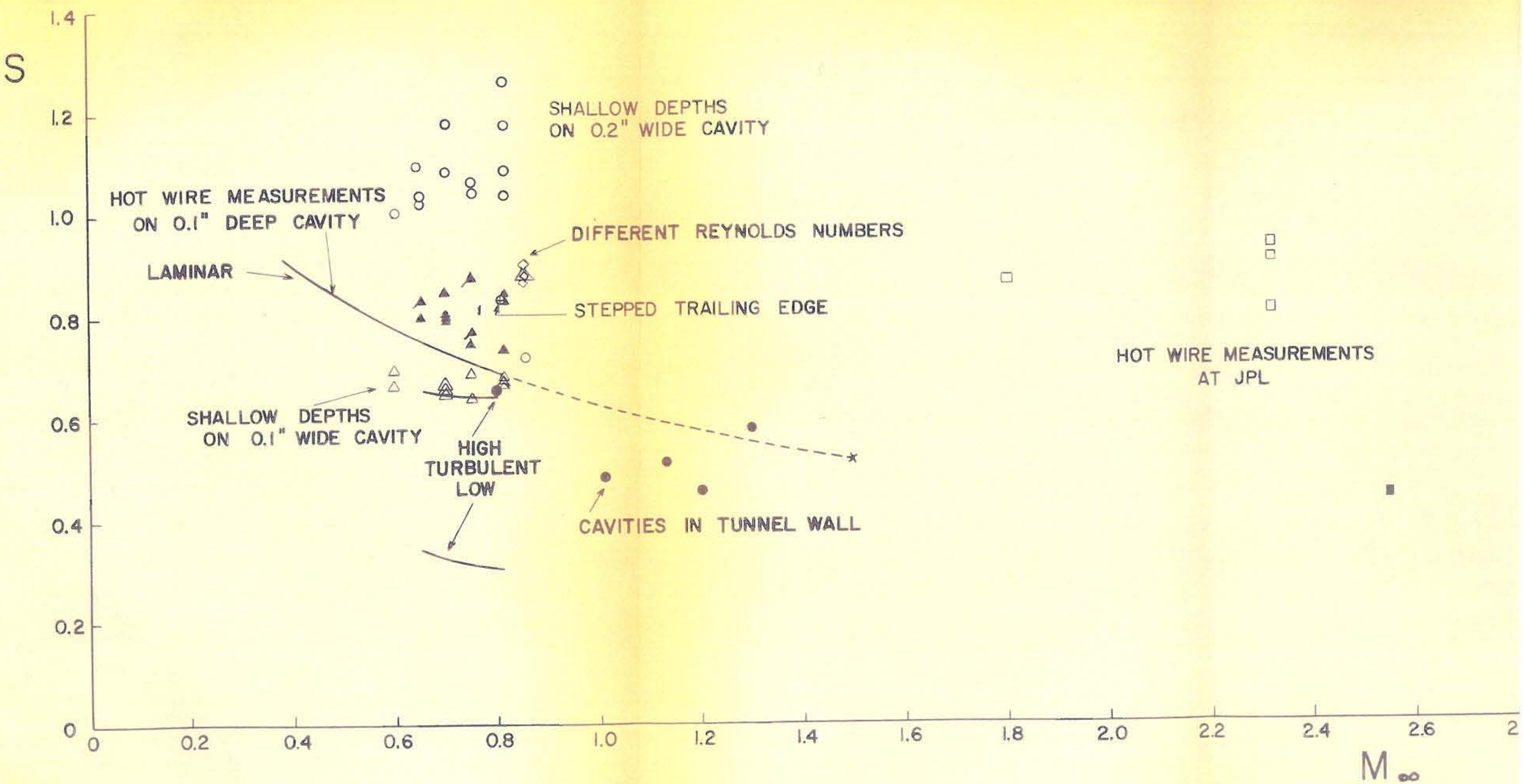
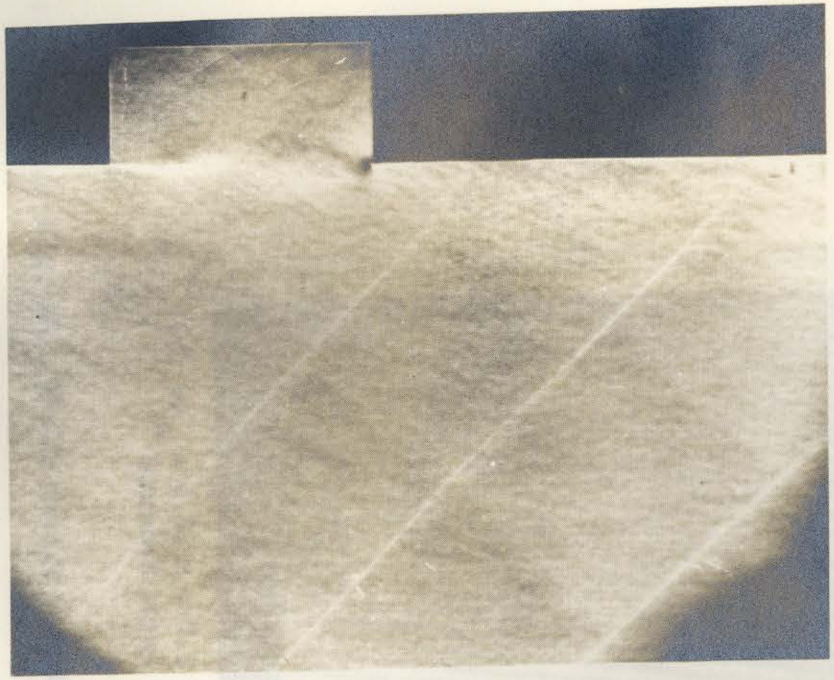
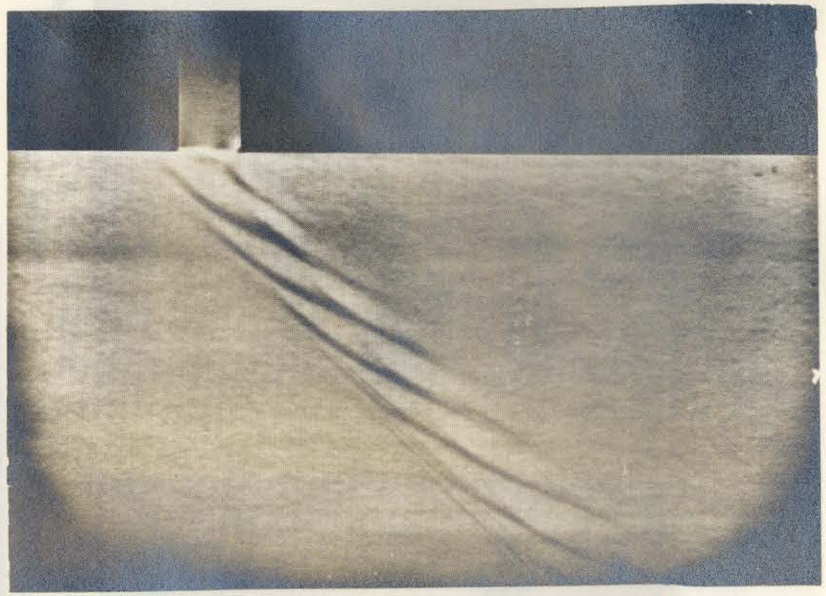


FIG. 18
NON-DIMENSIONAL FREQUENCY



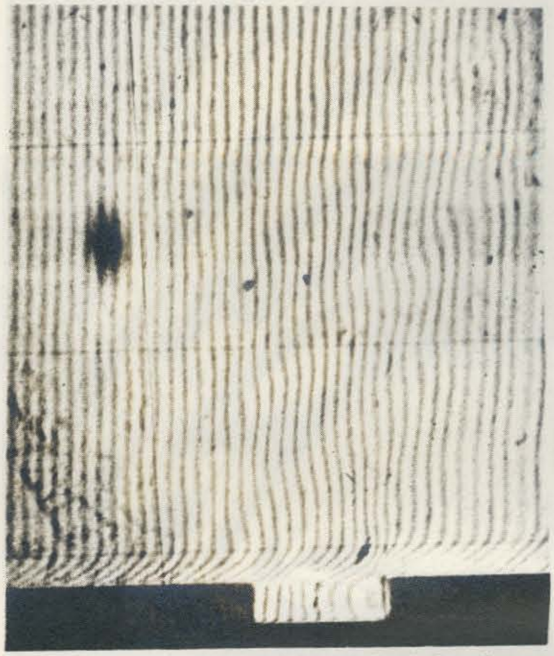
(a) d = 0.5; b = 1 inch; $M_\infty = 0.8$



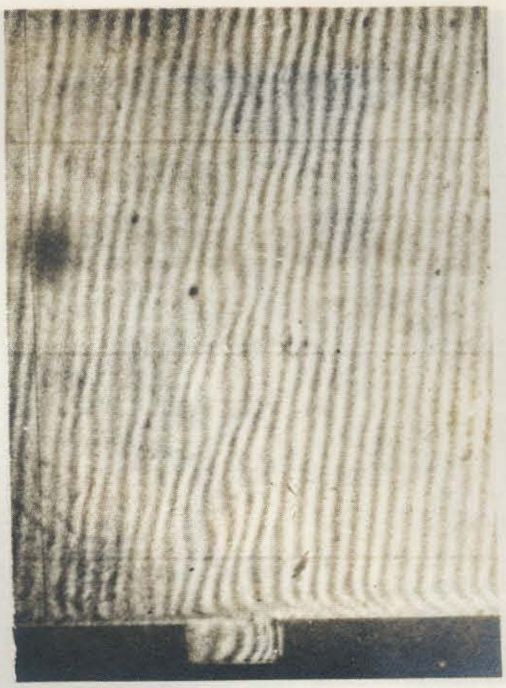
(b) d = 0.5 inch; b = 0.25 inch; $M_\infty = 1.3$

Fig. 19. Sound emission for gaps on tunnel top block with turbulent boundary layer.

(a) $M_{\infty} = 0.82$; $b = 0.3$ inch
laminar layer

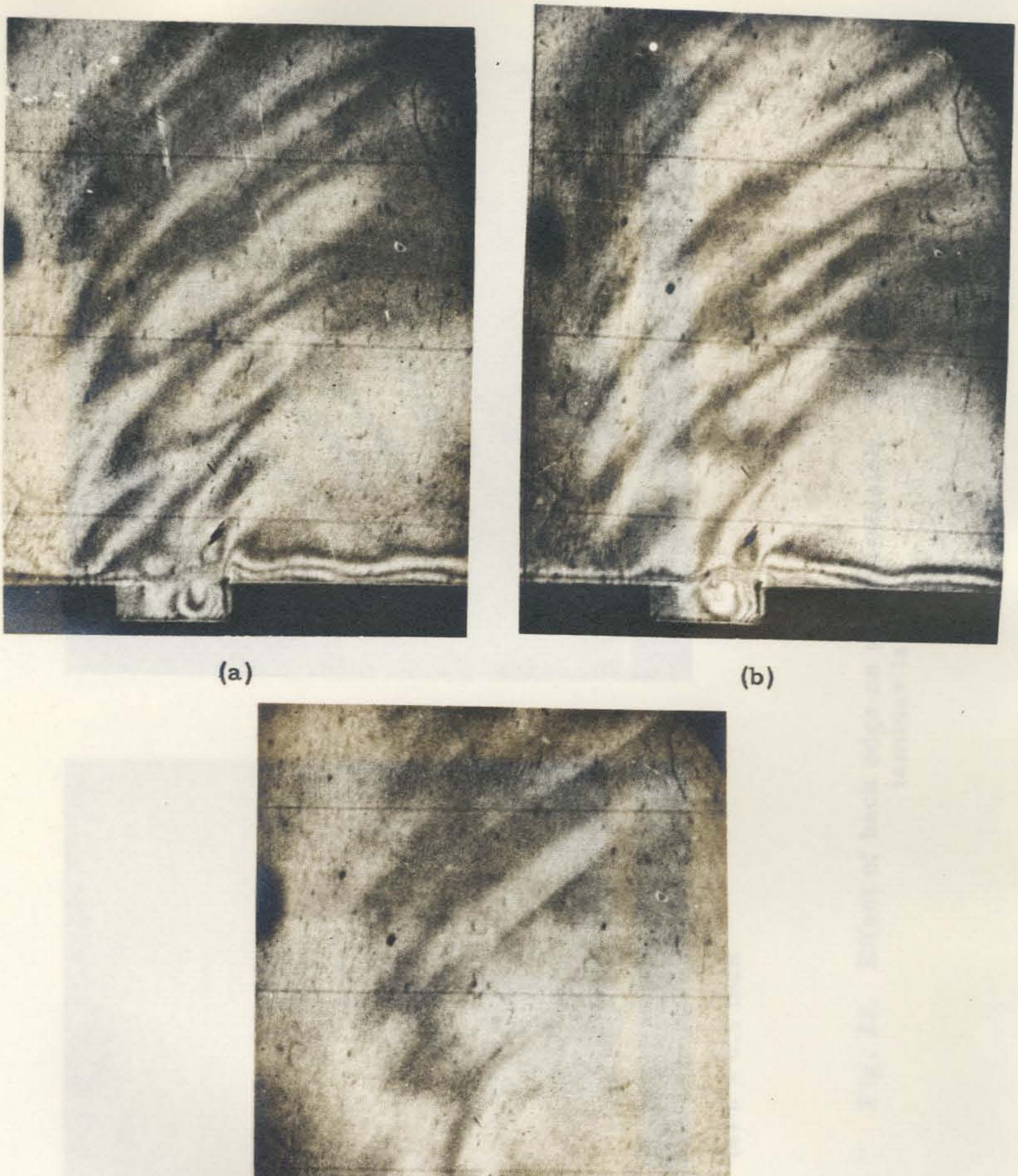


(b) $M_{\infty} = 0.82$; $b = 0.3$ inch
turbulent layer



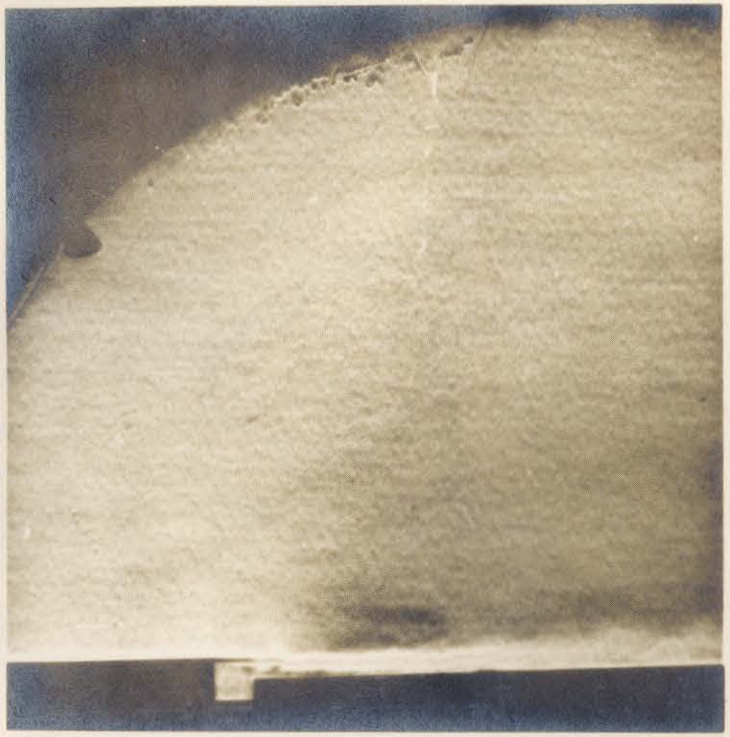
(c) $M_{\infty} = 0.7$; $b = 0.2$ inch
laminar layer

Fig. 20. Finite-fringe interferograms.



(a) (b) (c)

Fig. 21. Infinite-fringe interferograms. $M_\infty = 0.82$; b = 0.3 inch; laminar layer.



(a) b = 0.1 inch

(b) b = 0.2 inch

Fig. 22. Effect of back edge on sound emission. $M_\infty = 0.82$; laminar layer.

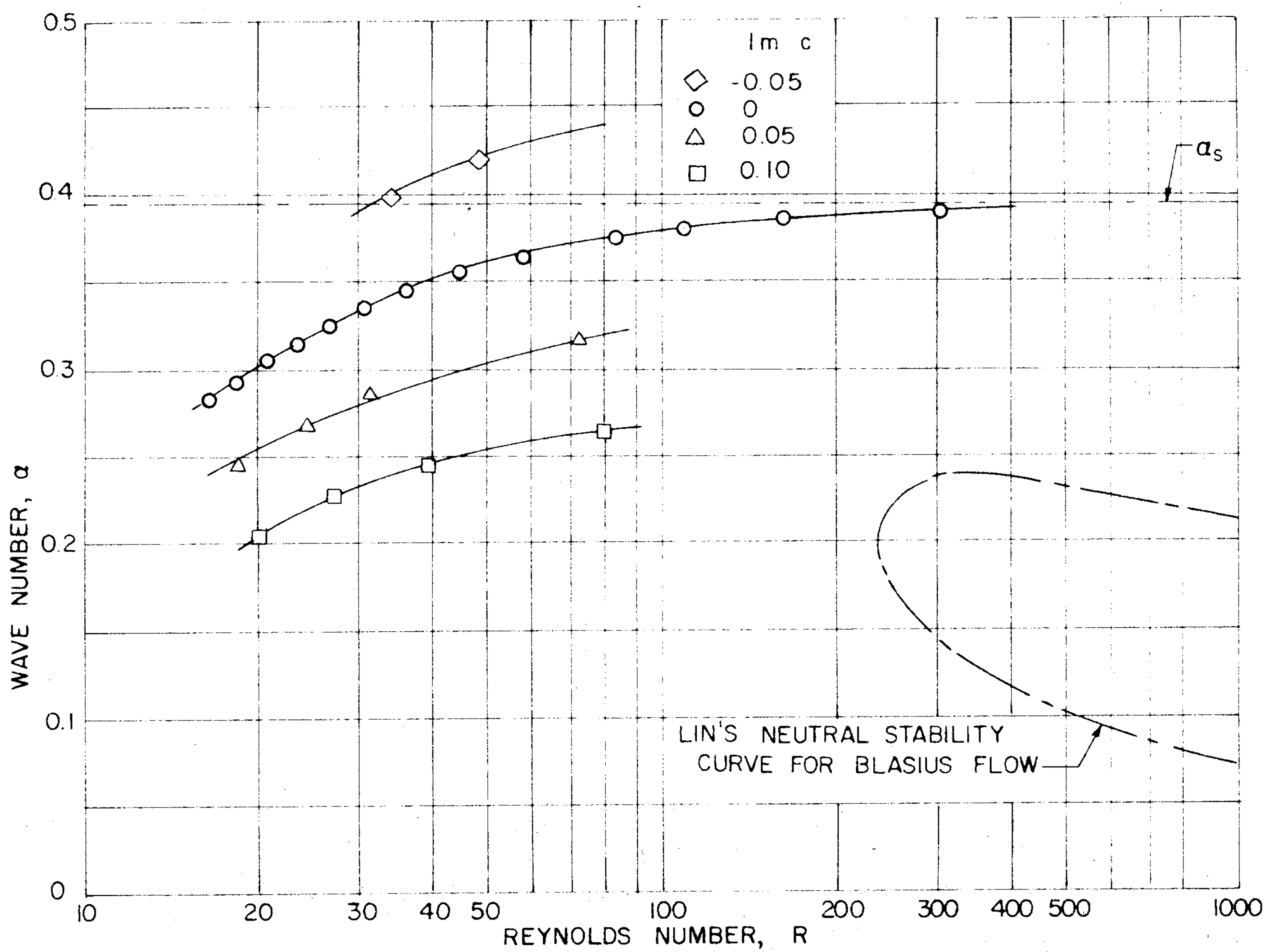


Figure 23. Curves of equivalent amplification and damping for free boundary layer. (from Ref. 8)

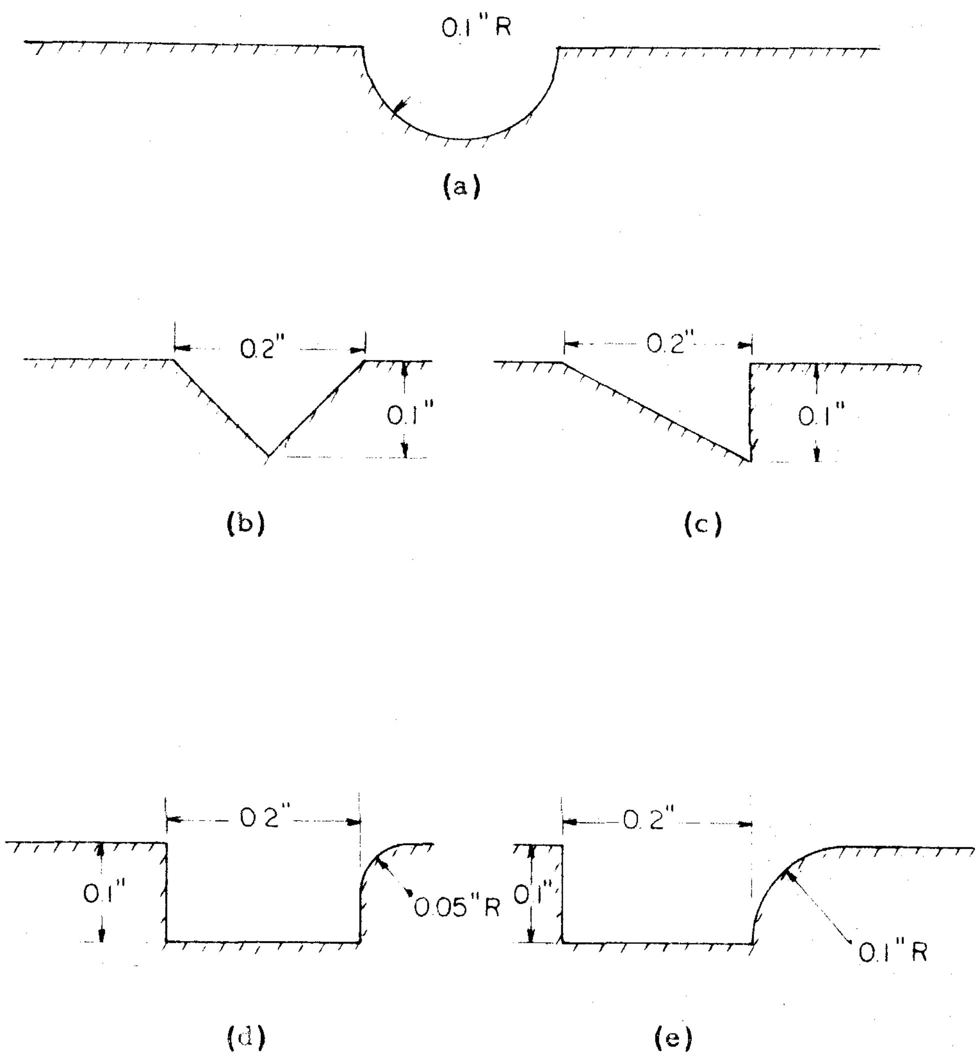


Fig. 24. Geometry of non-Rectangular Cavities.

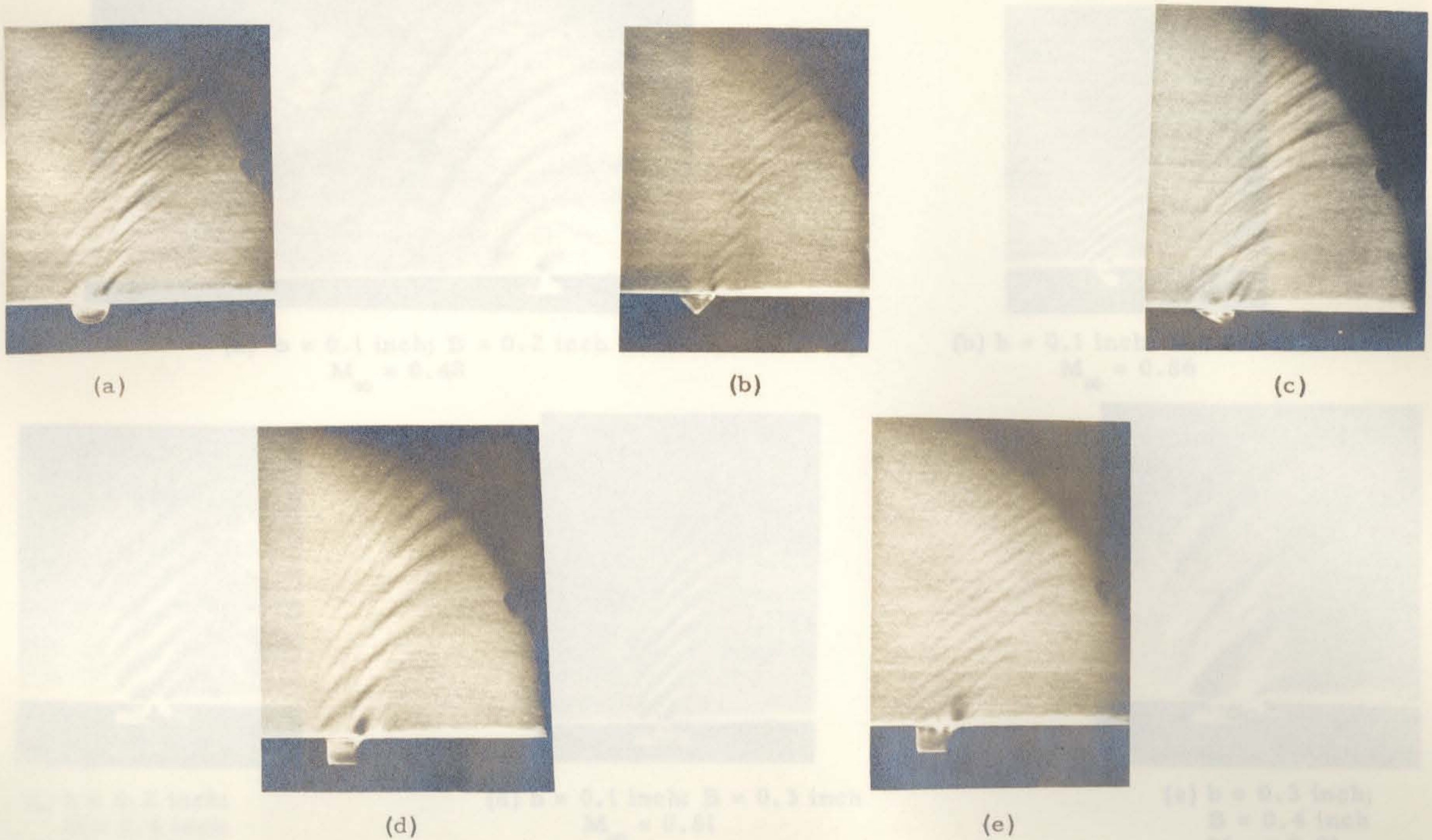
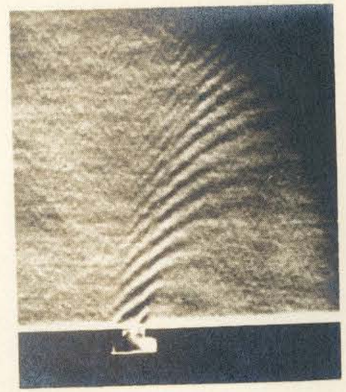


Fig. 25. Sound emission for cavities of different shapes.
$M_\infty = 0.85$; laminar layer.

(a) b = 0.1 inch; B = 0.2 inch
$M_\infty = 0.48$



(b) b = 0.1 inch; B = 0.2 inch
$M_\infty = 0.86$

(c) b = 0.2 inch;
B = 0.4 inch
$M_\infty = 0.72$

(d) b = 0.1 inch; B = 0.3 inch
$M_\infty = 0.81$

(e) b = 0.3 inch;
B = 0.4 inch
$M_\infty = 0.81$

Fig. 26. Sound emission for resonator type cavities; laminar layer.

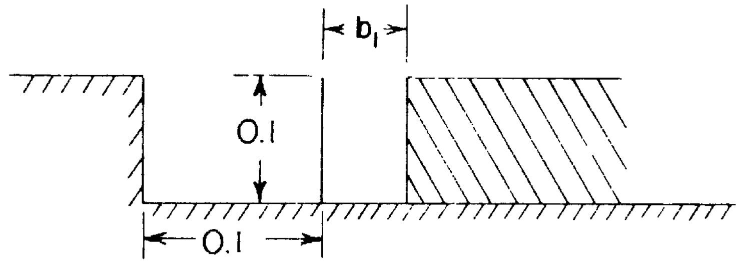
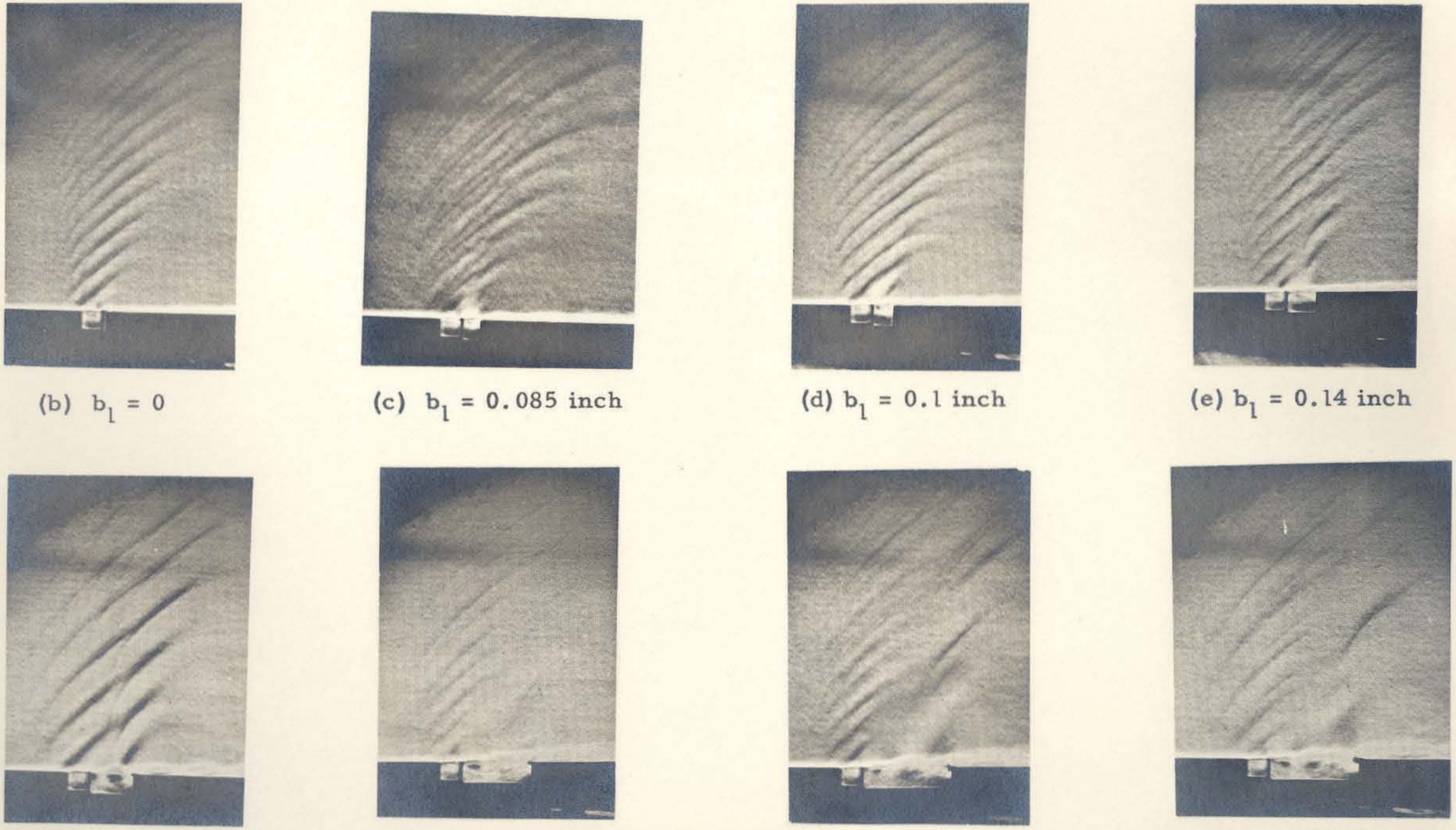


Fig. 27a. Geometry of cavity with a baffle piece.



(b) $b_1 = 0$ (c) $b_1 = 0.085$ inch (d) $b_1 = 0.1$ inch (e) $b_1 = 0.14$ inch

(f) $b_1 = 0.215$ inch (g) $b_1 = 0.355$ inch (h) $b_1 = 0.455$ inch (j) $b_1 = 0.455$ inch

Fig. 27. Sound emission for a cavity with a baffle piece; $M_\infty = 0.81$; laminar layer.