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Metastable Jet-Tone States of Jets from Sharp-Edged, Circular, Pipe-Like Orifices

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Characteristics of spectra from relatively thick orifices differ from those from relatively thin. In a given range of Reynolds number, in many cases the jet may exist in any one of several reproducible jet-tone states (metastable states) characteristic of the orifice. The dependence of the component frequencies of the jet-tone spectra (expressed in terms of the orifice-number $fd/(\Delta p/\rho)^{\frac{1}{2}}$) on Reynolds number $[\rho d(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ is shown, where d is diameter of orifice; f, frequency; Δp, pressure difference across orifice; ρ, density; and μ, viscosity of gas. The orifice numbers of the components of the jet-tone spectra generally tend to fall on a single array of equally spaced orifice-number levels. Jet-tones from the same orifice plate, characteristic of both thin as well as thick orifice plates, are found to coexist over a small transition range of orifice thickness-diameter ratio. If the orifice number of the head of the most probable spectral mode for a given orifice thickness-diameter ratio is noted, the same will be found again for the head of the most probable mode at approximate orifice thicknesses $t\pm nd$, where n is a small integer.

INTRODUCTION

A DISTINCT tone suddenly appears at a definite Reynolds number Re when the Re of the flow of air through a sharp-edged, circular, cylindrical orifice of *small thickness-diameter ratio* is gradually increased from zero. With increase of Re, the apparent acoustic frequency of this tone continues to increase until the tone merges into the turbulent noise background emitted by the jet.[1] The tone is created aerodynamically by the periodic shedding of vortices from the orifice, which gives rise to a sound field in the surrounding medium.[2–4] Generally the tone is composed of a number of eigenfrequencies. Basically the same functional dependence of frequency f (expressed in the form of the nondimensional orifice number, $ft/(\Delta p/\rho)^{\frac{1}{2}}$, where t is thickness of orifice plate; Δp, pressure difference across orifice; and ρ, density of gas) on flow conditions (expressed in form of $\mathrm{Re}=[\rho t(\Delta p/\rho)^{\frac{1}{2}}]/\mu$, where μ is viscosity of gas) is found for a relatively wide range of orifice diameters and orifice-plate thicknesses.

Jet-tones from orifices of *large thickness-diameter ratio* differ from the foregoing, as will be shown, in that their amplitudes generally are much smaller, the expressions for Re and the orifice number are different, and a given jet under the same flow conditions may have a choice of several possible metastable states for its existence.

Visualization studies using colored liquid tracers have been made of the nature of the generation and decay of vortices in the flow of water into and through a pipe from a large reservoir. Since they were carried out in the same Re range as the present studies with air, and since the flow conditions at the entrance of a long pipe should have points of similarity with that in an orifice of large thickness-diameter ratio, the results merit consideration. In the following, pipe diameter is the characteristic length in Re.

At small Re, below 600, for a sharp-edged pipe entrance, the flow is laminar throughout.[5,6] A colored liquid filament tracer in the boundary transition layer is very smooth and uniform in cross section (Fig. 1a). It is completely undisturbed and has a straight-line course throughout the entire pipe except for a Borda mouthpiece[7] (or a vena contracta if pipe has a large flange at entrance) in the flow at the pipe entrance at $300<\mathrm{Re}<600$.

Around Re 600 and somewhat above, disturbances are sent into flow (Fig. 1b) causing a slight waviness and snake-like trace of the colored filament.[8] These extend downstream from the edge of the pipe entrance. They eventually attenuate downstream so that the

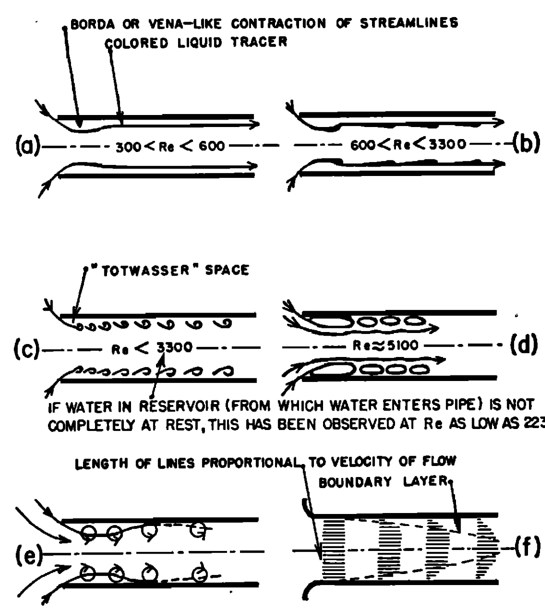

FIG. 1. Nature of the generation of circulation in the flow at a pipe entrance, and the periodic downstream shedding of this in the form of vortices.

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flow of the colored filaments finally becomes smooth and even. The greater the Re, the further the waviness extends downstream before attenuation and resumption of smooth laminar flow. With further increase of Re above 600, but below 3200 or 3400, the stronger waviness finally leads to the appearance of a periodic rolling-up of the colored filament,[9,10] i.e., a rolling-up of the boundary layer into small vortex nodules. In cross section (Fig. 1c), these take on appearance of closed vortices (and a vortex street downstream of the *Totwasser*) approaching rather quickly the walls of the pipe along a small arc at the same time that their separation increases to approach a constant value. The *Totwasser* in corner between Borda mouthpiece and pipe walls shows slight unrest but no characteristic form of flow.

Around Re = 3200 to 3400 (if the reservoir water is not disturbed initially, and as low as 2230 if it is disturbed), a new form of flow arises at the entrance[5,9] where, in place of the discontinuity surface and the sequence of small discrete vortices, a seemingly greatly elongated vortex appears showing vigorous rotation. Figure 1d, for example, shows the presence of a large vortex at the pipe entrance at around Re 5100, followed by smaller ones shed from the larger, and in the process of moving downstream. These disturbances no longer attenuate downstream; laminar flow has given way to turbulent flow downstream. In reality, according to the results of high-speed photography, the seemingly large elongated vortex is composed of a number of smaller ones. Smearing out of details of the smaller vortices is accounted for by the fact that the downstream translational velocity of the vortices has a minimum near the pipe entrance causing a bunching of several vortices. Also, there is a pronounced fluctuation in the frequency at which the vortices are formed, and therefore, in their intervals of separation. This is not true in flow regime where downstream flow is laminar. Fluctuation in the strength of the vortices is associated with fluctuation in the frequency of vortex shedding. This gives rise experimentally to vortex coalescence since the stronger overtake and coalesce with the weaker.

Distinction exists between the interaction of separate vortices in a perfect fluid and that of eddies in a viscous medium.[11] In the former, a system of vortices during their interplay will always retain their separate identities irrespective of their relative strengths and signs. In the latter, experiment shows that an eddy may change in strength apparently by absorbing any number of others.

Vortex separation approaches a constant value in 3 to 5 pipe diameters downstream[5,6,8,12–14] due to vortex coalescence. Vortices formed adjacent to the entrance edge (referred to as *Kanten Wirbel*) differ from those found downstream (referred to as *Körper Wirbel*). *Kanten Wirbel* in their form, frequency, and separation, depend only on the nature of the edge, the flow velocity, and the fluid kinematic viscosity, and do not depend on the size of the pipe or object through which the flow occurs. *Körper Wirbel* (which result from eventual coalescence of *Kanten Wirbel*) in form, frequency and separation do depend on the size of the pipe or object.

The nature of the rolling up of the discontinuity surface into vortices according to visualization studies[5] is shown schematically (Fig. 1e). It is difficult and sometimes impossible to generate vortices in pipes having rounded entrance edge (Fig. 1f). If it is possible, it will always require a higher Re than if the edge is sharp.[15,16] Although the flow in the jet inside the orifice may be laminar, it cannot have the Poiseuille parabolic velocity distribution.[15–17] Visualization studies have been made of the geometrical form of the flow pattern of a singing jet upon emergence from a circular orifice, some have been made with liquids,[12,18–23] others with gases.[2–4,24–26] All agree that a periodic succession of circular vortex rings are shed from circular orifices, and not spirals or distorted loops as in flows past disks.[27–31] Some theoretical interpretation of the observed relation between vortex ring diameter and separation has been made[2,3,32,33] and of the mean time average, velocity distribution throughout the jet.[34–38]

There is little unanimity as to whether diameter or thickness of the orifice plate is the appropriate geometrical parameter defining the jet-tone among early studies of jet-like tones.[39–43] Recent studies[1,2,3,44] indicate orifice plate thickness to be the appropriate parameter. Generally, however, the latter studies were made on relatively thin orifices (relatively small thickness diameter ratio).

APPARATUS

The experimental equipment and precautions used have been described elsewhere.[1,45,46] Care was exercised to avoid the presence of Pfeifentöne and cavity resonances in the jet-tones.[47]

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EXPERIMENTAL RESULTS

For relatively thin orifices the functional dependence of the jet-tone frequency on flow conditions[1] is described by

$$F\left[\frac{tf}{(\Delta p/\rho)^{\frac{1}{2}}}, \frac{\rho t(\Delta p/\rho)^{\frac{1}{2}}}{\mu}, \frac{t}{d}\right]=0 \qquad (1)$$

where orifice thickness t is the pertinent geometrical variable involved in both Re and the orifice number. As the thickness-diameter ratio is increased, it will be shown that a transition gradually occurs in the nature of the jet-tone phenomena so that the pertinent geometrical variable becomes the orifice diameter d, and not t. According to dimensional analysis,[46] the functional dependence for relatively thick orifices should, therefore, be

$$F\left[\frac{fd}{(\Delta p/\rho)^{\frac{1}{2}}}, \frac{\rho d(\Delta p/\rho)^{\frac{1}{2}}}{\mu}, \frac{t}{d}\right]=0. \qquad (2)$$

In a small transition range of t/d both functional dependencies apply simultaneously to jets from the same orifice. Here, some of the jet-tones from a given orifice will be described by one and some by the other of the foregoing. In the present study attention will chiefly be confined to the range of t/d where the second applies. Only enough will be presented at the lower range of t/d to indicate briefly how the two jet-tone domains tie together.

Frequency components of a given jet-tone spectrum in the following will, therefore, be expressed in terms of the nondimensional orifice number $fd/(\Delta p/\rho)^{\frac{1}{2}}$. Thus, orifices having geometrically similar shape, but varying in size, will be found to show basically the same or like functional dependence on Re. For example, when two jet-tones having the same orifice number were produced by two geometrically similar orifices A and B, but such that A was four times B in size, then the frequency of the jet-tone from A was $\frac{1}{16}$ and the pressure difference across orifice A was $\frac{1}{16}$ that across B.

Figures 2 and 3 present the jet-tone spectra obtained from 31 orifices whose diameters vary from 0.0625 to 0.375 in., and orifice plate thicknesses from 0.219 to 2.00 in. They undoubtedly do not include all of the self-excited jet-tone spectra that might conceivably arise from these orifices. They do, however, include all those observed during the present study, which was carried out in considerable detail. Since jet-tones were never observed below Re≈1600, the Re range, zero to 1400, has been omitted in all graphs.

As Re is gradually increased, several jet-tone states frequently appear in succession. Even in a given Re range under suitable circumstances, the jet may exist in any one of several reproducible jet-tone states (metastable states) characteristic of the orifice. This explains why several graphs are frequently shown for the same orifice. For example, graphs 1A, B, and C present different jet-tone states in the same Re range for orifice plate No. 1. The same is true of all other orifices for which several graphs are shown.

It is not to be presumed that the different jet-tone spectra for a given orifice will, with change of Re, always occur in the same sequences shown in the graphs. In most cases, the jet-tone spectra in any given graph were obtained on different days, in some cases, separated more than six months. The spectra in the graphs have been strung together over the Re range like beads for economy of space in presentation.

Circumstances surrounding the transition of a given jet-tone spectrum to another, at the same Re, will be considered later.

Results presented for each orifice were generally obtained by superimposing, on the same graph, the two sets of experimental results obtained by passing the gas through the orifice in opposite directions. The graphs of the cases where this occurred in Figs. 2 and 3 are indicated by the number alone, of the orifice plate, placed in the upper left-hand corner or by the number followed by a single letter. Generally, with exceptions to be noted, excellent reproducibility and coincidence of results for a given jet-tone state were obtained. Usually where the jet-tone modes found by passing the air through the orifice in one direction were not quite identical with those found by passing the air through the orifice in the other direction, the spectral components agreed in general arrangement.

In some instances, however, jet-tone spectra obtained when passing the air through the orifice in one direction were found to be quite different from those obtained when passing the air through the orifice in the opposite direction. Graphs in which this occurred in Figs. 2 and 3 are designated by the number of the orifice plate followed by a letter, and then followed by a number one or a number two, depending upon which direction the gas passed through the orifice.

When jet-tone spectra especially rich in components appeared, they seemed to occur within approximately the same range of Re for all orifices. The components in most cases tend to arrange themselves on an array of equidistant orifice number levels. This has been emphasized in the graphs by the arrays of horizontal lines drawn through the points. Generally for any considerable change of Re, these spectra change their pattern of equally spaced orifice number intervals, e.g., graphs 9A, 10, etc. In a given Re range at widely different times in successive observations of the same jet-tone spectrum, the spectral components seem to preserve the same basic pattern of arrangement although the actual presence or absence of any one particular component may change.

In the majority of instances, the orifice numbers of the components of a given jet-tone spectrum appear independent of Re. A very few, however, rise with increase of Re, e.g., the orifice number around 1.00 in

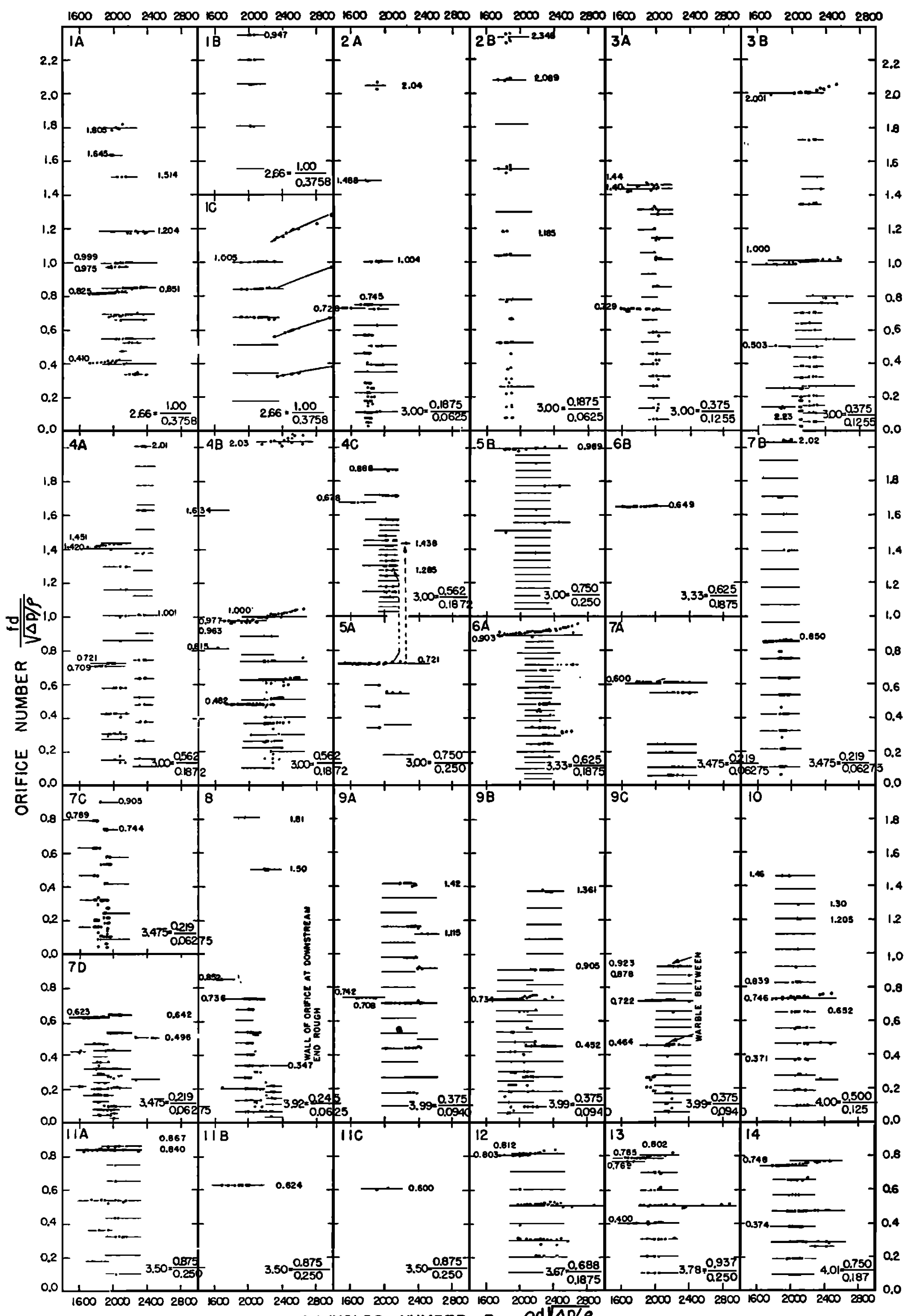


FIG. 2. Jet-tone spectra from orifices of relatively large thickness-diameter ratio expressed in the form, orifice number as a function of Reynolds number Re. Number in upper left-hand corner of graphs, either alone or preceding a letter, denotes the number of the orifice plate. Meanings of letters and other numbers that may follow letters are described in text. Equation at lower right-hand corner of each graph gives numerical value of thickness-diameter ratio of the orifice and the ratio of the actual values of the thickness and the diameter, expressed in inches. Numbers associated with points in main body of graphs denote the orifice numbers of the heads, or of an harmonic of the heads, of the jet-tone spectra.

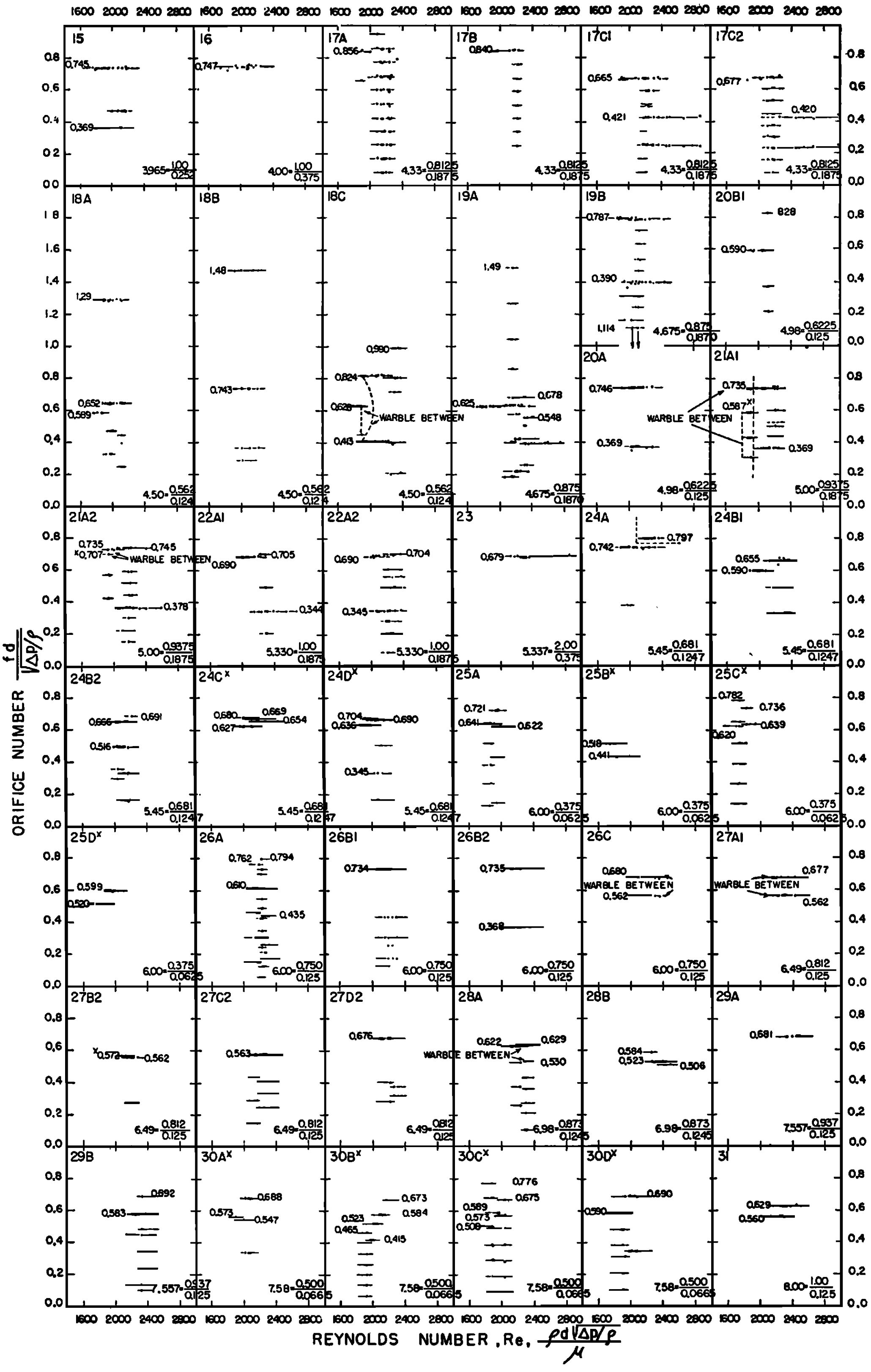
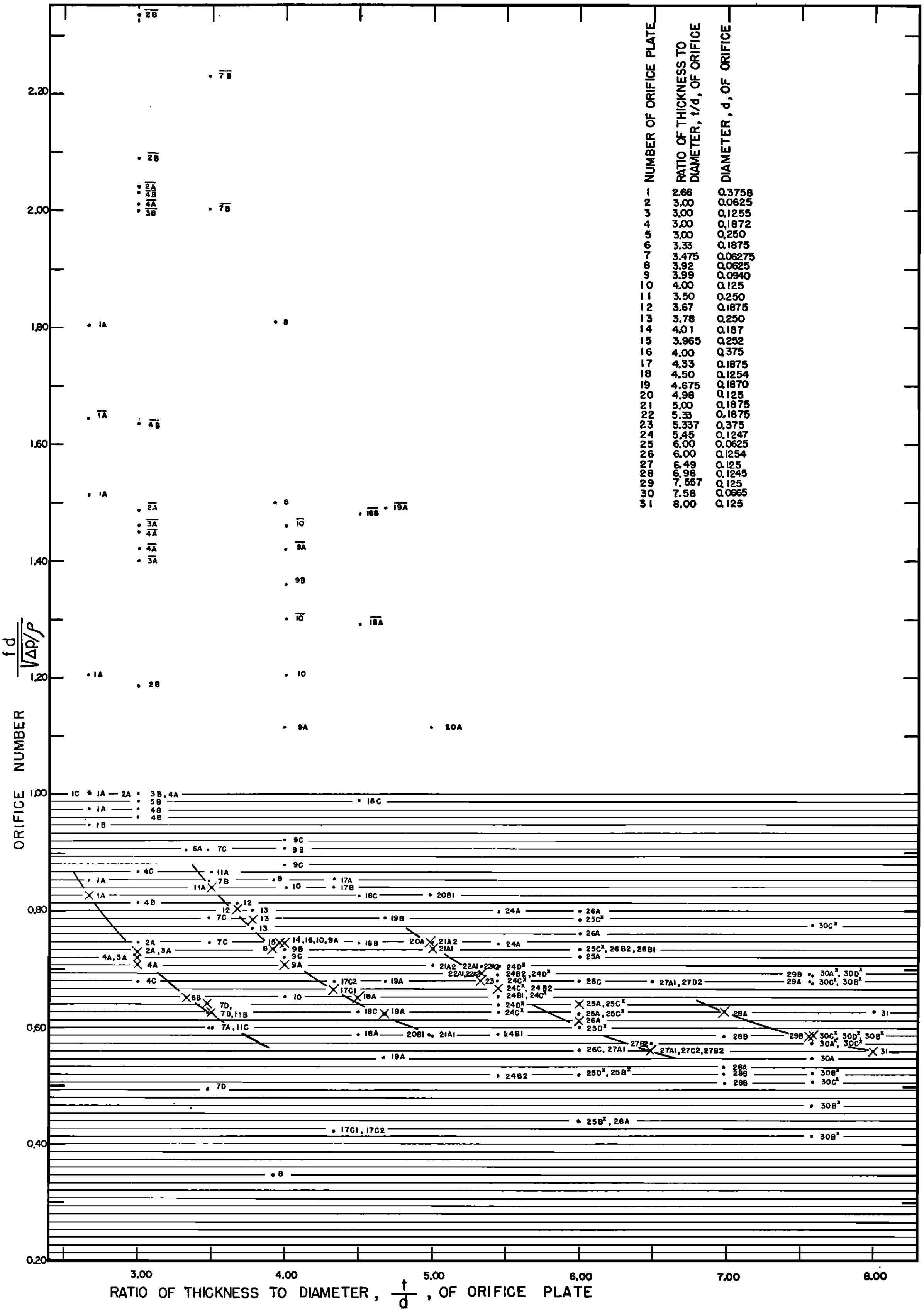


FIG. 3. Same as for Fig. 2.


ORIFICE NUMBER $\frac{f\,d}{\sqrt{\Delta p/\rho}}$
RATIO OF THICKNESS TO DIAMETER, $\frac{t}{d}$, OF ORIFICE PLATE
NUMBER OF ORIFICE PLATE
RATIO OF THICKNESS TO DIAMETER, t/d, OF ORIFICE
DIAMETER, d, OF ORIFICE
1 2.66 0.3758
2 3.00 0.0625
3 3.00 0.1255
4 3.00 0.1872
5 3.00 0.250
6 3.33 0.1875
7 3.475 0.06275
8 3.92 0.0625
9 3.99 0.0940
10 4.00 0.125
11 3.50 0.250
12 3.67 0.1875
13 3.78 0.250
14 4.01 0.187
15 3.965 0.252
16 4.00 0.375
17 4.33 0.1875
18 4.50 0.1254
19 4.675 0.1870
20 4.98 0.125
21 5.00 0.1875
22 5.33 0.1875
23 5.337 0.375
24 5.45 0.1247
25 6.00 0.0625
26 6.00 0.1254
27 6.49 0.125
28 6.98 0.1245
29 7.557 0.125
30 7.58 0.0665
31 8.00 0.125

graph 4*B*, and 0.903 in graph 6*A*. If the jet is observed long enough even in these cases, however, one finds an occasional transition into a state where the orifice number does not rise, but remains constant with increase of Re.

In rare instances, the orifice number of a given jet-tone was made to split into two component orifice numbers whose mean value equaled the original orifice number. Consider, for example, graph 24*B*2, and the tone having the orifice number 0.666. Owing to the proximity of the pressure probe (or some other object) to the orifice, this jet-tone orifice number was made to split into orifice numbers 0.636 and 0.690 (graph 24D^x) whose mean is very close to 0.666.

It might be said that the maximum frequency of the jet-tone spectrum characterizes the jet-tone, and is the principal one in the frequency sequence of the spectrum. Henceforth, this will be referred to as the *head* of the jet-tone spectrum. It is one of the most reproducible components of the spectrum. The relative amplitudes of the lower frequency components usually differ considerably between each other; also, the amplitude of any one of these components may vary appreciably from one observation to another.

Generally the jet-tone mode having the lowest head has the greatest sound amplitude when comparing several jet-tone modes at the same Re obtained with a given orifice and with the pressure probe placed far enough away not to affect the jet-tone.

The orifice numbers of the components of the more complex jet-tone spectra are not randomly distributed over the orifice number range. Most frequently, each appears to fall on one of a set of equally spaced orifice-number levels characteristic of the jet-tone. Occasionally, they seem to arrange themselves on a set of levels which can be built up of more than one basic orifice number interval as in graphs 2*A*, 3*A*, and 4*A*. It will be shown, however, that these intervals are usually expressible as multiples of a smaller basic orifice number interval.

Figure 4 shows an array of equally spaced orifice-number levels, below orifice number 1.00, whose separation is the basic orifice number interval Δ, and whose ordinates have been adjusted to fall at the mean orifice number values of the spectral components in graphs 7*B*, 8, 9*C*, 10, 11*A*, 12, 13, 14, and 17*A* (Figs. 2 and 3). For economy of space, the ordinate (Fig. 4) begins at 0.200, since none of the levels observed fall below 0.200. The heads of all the spectra (Figs. 2 and 3) have been plotted (Fig. 4) as function of the orifice thickness-diameter ratio.

One might expect that the points (Fig. 4) would be scattered at random with respect to the levels if the array of levels shown is not that on which the heads of the spectra (Figs. 2 and 3) tend to fall. That is, if one counts all the points falling within the limits $\pm\frac{1}{4}\Delta$ of these levels one would then expect to obtain a total equal to approximately one-half of all the points in the figure. When the count is made, however, it is found that over 5.5 times as many points fall within $\pm\frac{1}{4}\Delta$ of the levels as elsewhere. Thus, it appears that the head of each spectrum tends to fall on one of the levels of the array of equally spaced orifice number levels.

Not only the orifice numbers of the heads but also the orifice numbers of the lower spectral components of the jet-tone spectra appear to tend to fall on this array of equally spaced orifice-number levels. Over 3.5 times as many of the averages of the orifice numbers of the components also fall within $\pm\frac{1}{4}\Delta$ of the levels as elsewhere. One might therefore say that these levels are the permitted or most probable levels on which the great majority of the orifice numbers of the jet-tone spectra here investigated tend to fall.

The foregoing conclusion does not rule out the possibility that a few relatively improbable components might fall between the levels indicated. Inherent experimental scattering in the orifice numbers of the present data prevents ascertaining the presence of any levels midway between those shown. The experimental accuracy required even in the present studies was very great. For example, if an orifice number whose true value is 1.000 is to fall within the limits $\pm\frac{1}{4}\Delta$ of this value, the value of the orifice number must be known to an accuracy of one part in 300. This means that if the diameter of the orifice is 0.0625 in. and all the other quantities involved in the orifice number are known precisely, the diameter of the orifice must be known to within 2×10^{-4} in. Because of the proportionately higher experimental accuracy required for a valid comparison above orifice number 1.000, no systematic attempt has been made to extend the array of orifice number levels above 1.000 and therefore to determine the coincidence of the observed experimental points with this array. The orifice numbers of a few spectral components (Figs. 2 and 3) show a slight dependence on Re. In these instances the points (Fig. 4) have been arbitrarily evaluated from data in the vicinity of Re 2000.

Even though many of the jet-tone spectra (Figs. 2 and 3) were obtained under very diverse circumstances, such as listed in the following, the heads as well as the components both tend to fall on the same array of orifice-number levels (Fig. 4):

FIG. 4. Dependence of the orifice numbers of the heads of the jet-tone spectra on orifice thickness-diameter ratio, for orifices of relatively large thickness-diameter ratio. Designation associated with each point corresponds with the graph (Figs. 2 or 3) from which the point was taken. Points designated by crosses and through which heavy lines are drawn indicate the orifice numbers of the heads of the loudest and most probable spectra of the orifices. Points above orifice number 1.000 whose designations are underlined are harmonics of the heads below orifice number 1.000. Table at upper right-hand corner gives the thickness-diameter ratios, as well as the diameters of the orifices in inches.

1. Entirely different spectra, in a number of instances, were presented by the same orifice plate when the air was passed through the orifice in opposite directions. Although all the orifices were machined with extreme care, it is surmised that the differences in these cases might be accounted for by very minor blemishes of the orifice edges or walls. Designation of the graphs where this occurred includes a letter followed by either the number one or the number two.

2. An extreme case of the foregoing is the following shown in graph 8: Owing presumably to a very small almost imperceptible roughness of part of the orifice wall of this orifice plate, practically no tones could be obtained when passing air through the orifice in one direction except a feeble wheezy unstable tone having the maximum orifice number 0.347. This and also the lower spectral components, nevertheless, fall on the array of levels (Fig. 4). When the air passed through in the opposite direction the jet-tones behaved normally.

3. A number of relatively improbable jet-tone spectra appeared only once, or at the most a very few times, even though the orifice was carefully studied many times over an extended period of time. Figures 2, 3, and 4 show a number of such spectra. Their components also tend to fall on the same array of equally spaced orifice number levels (Fig. 4).

4. From several orifice plates during the early period of the studies, very prominent and clear spectra were obtained which were never found subsequently. In these cases, it might be presumed that since the orifices were always carefully cleaned with a pipe cleaner before each run, very minor blemishes or slight burrs on the edge of the orifice were gradually and permanently removed during successive cleanings. Apparently these blemishes were not great enough to prevent the orifice numbers of the components of the spectra from falling on the array of equidistant levels (Fig. 4), although the orifice numbers of the spectra themselves were quite different from the orifice numbers found subsequently.

5. In many instances, when the jet issued undisturbed into free space without any jet-tone, a jet-tone appeared when some object such as the pressure probe was brought into the immediate vicinity (but by no means touching or overhanging) of the orifice edge. Also in many instances, if a jet-tone were already present, the close presence of the object tended to increase the richness of the jet-tone. Designations of graphs (Figs. 3 and 4) where this occurred end in superscript x.

6. Graphs 9*C* (Fig. 2) and 18*C*, 21*A*, 21*A*2, 26*C*, 27A1, 28*A* (Fig. 3) show jet-tone spectra between which warbling occurred at the same Re, that is, spectra between which sustained spontaneous periodic transitions occurred at a rate up to many times a second.

An anomaly to the foregoing occurs. The orifice numbers 0.421 and 0.420 of the jet-tones of graphs 17*C*1 and 17*C*2 do not fall closely on one of the equidistant levels of the array. The question, however, might be raised whether these jet-tones are of a different nature from all others presented in this paper. They extend to much higher Re than the others, except the following:

From the same orifice plates, jet-tones characteristic of both thin, as well as thick, orifice plates are found to coexist over a small transition range of orifice plate thickness-diameter ratio. That is, some of the jet-tones of the orifice plate follow the functional dependence described by Eq. (1); others, Eq. (2). The spectrum in graph 1*C* above Re 2300 is characteristic of relatively thin orifices and follows precisely the appropriate relation (Eq. (1)) described elsewhere[1] in detail. To avoid confusion in presentation of the present studies, thin orifice plate spectra have been omitted from the graphs of the other relatively thin orifice plates (Fig. 2). Further details on this transition region will be described in a later paper.

The relative intensity and probability of occurrence of the different jet-tone spectra (Figs. 2 and 3) vary widely. If the Re of the flow through an orifice is gradually increased from zero (merely by increasing the flow velocity) the jet may at the same Re have the choice of one or more distinct possible modes for its existence. When the jet is thus confronted with a multiple choice of modes in which it may exist, it has been generally observed that *the jet-tone spectrum, first most likely to occur spontaneously with increase of Re, is the one having the greatest sound amplitude and the smallest orifice number of its head.* The head of the most probable spectrum from each of the 31 orifices studied (Figs. 2 and 3) has been denoted by a cross in Fig. 4. Two most probable heads are plotted for orifice No. 11 since both spectra appeared almost equally intense. One terminates the first cycle (Fig. 4), the other begins the second. Heavy lines have been drawn through all of the orifice numbers of the most probable heads. The arrangement of the lines appears to indicate that the orifice numbers of the heads of the most probable spectra of thick orifice plates tend to repeat whenever the thickness-diameter ratio t/d of the orifice changes by unity. This becomes even more apparent if the heavy lines in the upper range of thickness-diameter ratio are extrapolated. *Over the range of t/d studied*, it therefore appears that *if the orifice number of the head of the most probable mode for a given t/d is noted, the same will be found again for the head of the most probable mode at approximate orifice thicknesses $t \pm nd$*, where n is a small integer.

DISCUSSION

It appears reasonable to presume that the series of studies summarized schematically in Fig. 1, involving the generation and periodic shedding of vortices downstream from the Borda mouthpiece in a flow of water, involves an analogous vortex generating mechanism to that in the present studies of air flowing through thick orifices. The range of Reynolds number $\mathrm{Re}_w=\rho Vd/\mu$ (where V is the mean velocity of flow in the pipe) over which vortex generation in the water was observable, is the same order of magnitude as the range of $\mathrm{Re}_a=[\rho d(\Delta p/\rho)^{\frac{1}{2}}]/\mu$ over which jet-tones were observed in the present studies. Precise numerical comparison of magnitudes is at present very difficult because of difference in form of the two expressions for Re. In the present case for thick orifices, if one assumes the flow to be isentropic and the velocity distribution relatively constant over the exit cross-section of the orifices, one might expect the velocity of discharge to be given by $V=(2\Delta p/\rho)^{\frac{1}{2}}$. Thus, in this case $\mathrm{Re}_w=\sqrt{2}\mathrm{Re}_a$. If this be true, the numerical agreement between the Re_w range in which vortices in water were observed and $\sqrt{2}$ times the range Re_a in which jet-tones in air were observed, in the present studies, is remarkable.

For relatively thin orifices, on the other hand, one might expect some deviation from the foregoing relation between the two expressions for Re in that the two expressions for Re should now be roughly numerically equal. This is because the velocity of flow $(2\Delta p/\rho)^{\frac{1}{2}}$ is now the velocity chiefly in the main core of flow through the Borda mouthpiece whose cross-sectional area on the average is approximately $\sqrt{2}/2$ of the total area of the orifice cross section[5,6,8,9] for the range of Re here involved. If the flow is again assumed isentropic, the mean velocity of flow through the orifice therefore now becomes $V\approx(\Delta p/\rho)^{\frac{1}{2}}$. Thus, in this case $\mathrm{Re}_a\approx\mathrm{Re}_w$.

Whenever the entrance edge of the orifice was even slightly rounded, the intensity of the jet-tone emitted was more feeble (if not entirely absent) than when the direction of flow was reversed and the entrance edge was sharp. This agrees with observations for water summarized in Fig. 1. Rounding of the entrance edge reduces or eliminates the Totwasser space at the Borda mouthpiece where the circulation of the vortices shed downstream was observed to originate.[5,6,8–12]

The orifice number of the head of the loudest jet-tone generally is the smallest when several jet-tone spectra occurring at the same Re are compared. That is, the lower the frequency of the head of the jet-tone, the louder the jet-tone. This same trend between downstream vortex frequency and vortex strength was observed with water.[5,6,8,9,11] Coalescence of smaller water vortices into larger entailed a decrease in the downstream vortex frequency as well as an increase in the strength of each resulting vortex.

Vortex coalescence in the water studies appeared to be completed in a downstream pipe length interval of 3 to 5 pipe diameters from the pipe entrance. In the present studies, the frequencies associated with the heads (Fig. 4) also tend to approach a constant value within the same number of orifice diameters (4 to 5) from the orifice entrance. An amazing difference, however, appears between the results of the present studies using air, and the studies using water. In the present studies (Fig. 4), there is a periodic repetition of the asymptotic approach of the head frequency to a constant value as the orifice thickness is increased, for a given orifice diameter. For a given orifice diameter, a given value of the most probable head frequency is seen to repeat itself at orifice-thickness intervals of approximately one orifice diameter.

The question might, therefore, be raised as to whether there might be a periodic repetition of the same basic vortex flow pattern inside the orifice for changes of orifice thickness in multiples of the diameter d. That is, if there is a certain sequence pattern of vortices inside the orifice for a given thickness t of the orifice (such as indicated schematically in Fig. 1), then for a thickness $(t+d)$ essentially the same pattern might again appear except that an additional vortex ring will be added to the original sequence-pattern. This consideration seems related to the following observation. Circular vortices in an open air jet formed under similar circumstances prefer a vortex separation approximately equal to the diameter of the circular orifice edge generating the vortices.[2,3,12] Also the loudest jet-tones are produced by orifices whose thicknesses are approximately equal to their diameter.