Frequency Control of Unstable Disturbances in a Two-Dimensional Jet by Means of an Artificial Acoustic Loop*

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The frequency of acoustic sound emanating from the trailing edge of a two-dimensional airfoil is known to exhibit a ladder-like variation, displaying discontinuous jumps between discretely identifiable states as the free stream velocity varies. In order to reveal the underlying causes for this behavior, a two-dimensional jet issuing into still air with no aerodynamic sound emission is used as a model platform to study this phenomenon, because prescribed aero-acoustic sound may be readily introduced into the flow at the jet exit. When unstable disturbances growing in the shear layer of the jet are excited by a loudspeaker, an acoustic feedback loop automatically selects one frequency from the unstable frequencies present in the shear layer, and the resulting ladder-like variations are found to be similar to those present in airfoil trailing-edge noise. In addition, the observed slope of each rung of the ladder in the selected frequency behavior, and the observed jump frequency between ladder steps, show good agreement with existing empirical models. It is also discovered that when the remainder of the distance between the speaker and jet divided by the wavelength of the selected acoustic sound is equivalent to one-half wavelength of the accepted sound, the selected frequency jumps to another state.

Key Words: Trailing-Edge Noise, Ladder Structure, 2-D Open Jet, Acoustic Feedback Loop

1. Introduction

The noise generated by flying aircraft is spawned from a variety of sources and is known to be a problem in residential areas located close to airports. Although engine noise can be considerable, it is typically mitigated at 10 dB per decade and engine thrust is normally reduced during landing which also tends to moderate the problem of engine noise. Airframe noise however, due to high-lift devices such as flaps and slats employed on aircraft flying at moderate Reynolds number, is selectively discrete. Paterson et al.7) examined variations of the frequency of acoustic noise emanating from the NACA0012 airfoil over a wide velocity range. As a general trend, tonal-noise frequency follows a power law form; i.e., \( U^{1.5} \) for uniform velocity \( U \). However, Paterson reported the noise frequency to be locally proportional to \( U^{0.8} \) with a ladder-like functional variation. Arbey and Bataille8) observed similar results using three kinds of symmetric airfoils with different cross-sections and extended the acoustic feedback mechanism proposed by Tam.9) Arbey and Bataille assumed that acoustic noise is internalized at the location where the flow velocity over the airfoil is maximum. Based on this hypothesis, they proposed an acoustic feedback model, wherein a fundamental frequency is defined by the reciprocal of one cycle period, with this period consisting of the propagation time from the sound source at the trailing edge to the internalized location, plus the convective time from the location of internalized velocity fluctuation to the trailing edge. Using this concept, they found that the accepted frequency is given by an \((\text{integer} + 1/2)\) times the fundamental frequency. This model was observed to show good agreement with their experimental results and the data of Paterson. The distance between the accepted location and sound source divided by the cycle time previously defined, follows a power law variation of the form \( U^{0.85} \).

A wind-tunnel experiment by Nash et al.10) carefully conducted with anechoic treatment, showed that a separation bubble near the trailing edge on the pressure side, plays an
important role in the formation of a spurious feedback loop and the determination of feedback frequency. They found the feedback frequency to be without the ladder-like variations observed by Paterson and others, and observed a variation with free stream velocity proportional to $U^{0.8}$. McAlpine et al. performed stability analyses using the boundary layer profiles measured by Nash et al., and showed the acoustic frequency to be close to the most unstable frequency. In another set of wind tunnel experiments, Makiya and Konishi investigated slat noise in combination with the boundary layer profiles at the suction side and the resulting acoustic noise. For these cases, the accepted acoustic frequency was found to be proportional to a power formula of $U^{0.85}$. Furthermore, Takagi and Konishi investigated the trailing-edge noise of an NACA0012 model with a very small angle of attack and observed the frequency of the T-S wave in the boundary layer to be identical to that of the acoustic sound. They also succeeded in suppressing trailing-edge noise using a thin plate attached to the trailing edge of the model, and observed naturally growing T-S waves with broadband characteristics, showing the existence of a feedback loop between unstable T-S waves in the boundary layer and trailing-edge noise. These observations also exhibit good agreement with the analytical results of McAlpine et al. The existence of a feedback loop is also supported by several numerical simulations, namely those of Desquesnes et al. and Ikeda et al., both of whom further pursued the idea that the most amplified wave is responsible for causing tone generation.

The preponderance of existing evidence seems to support the notion that the frequency of trailing-edge noise is selectively determined from a restricted feedback distance between an acoustic receptivity location in the boundary layer and the noise source location. Under this condition, the acoustic frequency changes in a step-like manner against the free stream velocity as observed by Paterson. However, non-vortical disturbances are generally prone to be internalized in the boundary layer developing on the airfoil, at locations where curvature (curvature radius) is geometrically discontinuous or where surface roughness changes character. It seems that such a general property of aero-acoustic disturbances does not agree with the model of Arbey and Bataille, which proposes that acoustic disturbances are accepted at the location where maximum velocity over the airfoil is attained. Thus, further experimental investigations to unravel the acoustic receptivity problem are essential. In order to examine the conditions which trigger the step-like jump in selected frequency as the velocity varies, it is instructive to find a method to artificially control the feedback distance. As mentioned before, the most essential factor for the frequency-selection mechanism of airfoil trailing-edge noise is the acoustic receptivity.

In order to identify the relationship between the acoustic feedback system and the step-like behavior, the present paper focuses on a two-dimensional laminar jet issuing into still air with no sound emission from the jet flow. Because the location for the reception of acoustic disturbances in the jet is fixed at the jet exit, an artificial feedback loop is formed if unstable velocity fluctuations growing in the shear layer of jet flow are returned as acoustic disturbances via a loudspeaker directed at the jet exit, using a power amplified feedback of the measured disturbance signal to drive the speaker. Although broadband components are naturally amplified in jet flow, it is expected that a discrete frequency will be selected through acoustic resonance between the external sound from the speaker and the unstable disturbances growing in the shear layer. In order to investigate precisely how the frequency jump is triggered, two cases are examined. The first is for a varying jet velocity with fixed distance between the jet exit and loudspeaker, and the second holds the jet velocity fixed, while varying the distance between the jet exit and loudspeaker, as described below.

2. Experimental Arrangement

2.1. Wind tunnel

A small compact wind tunnel is employed to create the two-dimensional jet flow used in the present study, shown schematically in Fig. 1. Apart from the jet nozzle itself, all wind-tunnel walls are constructed of stainless steel. The jet nozzle consists of a stack of twenty acrylic plates each with a thickness of 5 mm, which are cut by a laser-carving machine to form the desired contraction curve. The cross-section upstream of the contraction is 100 mm square, the axial length of the contraction is 120 mm and the width of the nozzle exit is 6.5 mm, with an aspect ratio of 15.4. The jet is blown out into still air by a centrifugal blower (Oriental Motor Model: MB8Z-B2) driven by an AC motor, whose rotation is varied to set the desired jet velocity by varying the AC supply voltage. The maximum mean velocity in the middle of the jet reaches approximately 13 m/s for the maximum input AC voltage of 100 V.

![Fig. 1. Two-dimensional jet flow apparatus (all dimensions in mm).](image)
2.2. Mean and fluctuating velocity measurements
Profiles of the mean and fluctuating velocities across the jet flow are measured by a constant-temperature hot wire anemometer (CTA) on a two-dimensional traversing mechanism. The CTA sensor is made from a 5-μm copper-plated tungsten wire with a sensing length of 1 mm. Both ends of the copper-plated wire are softly soldered onto phosphor-bronze prongs set at 10 mm apart. The response to small external velocity fluctuations is flat up to 10 kHz, as determined using a conventional square wave test. The CTA bridge output is fed into an analog linearizer to provide an output voltage proportional to velocity. The linearizer output is calibrated by means of a Pitot static tube connected to two digital pressure transducers (REM 21 supplied by Halstrup walcher) with a full scale range of ±50 Pa and ±500 Pa. All analog signals are digitally acquired using the LabVIEW software, with a sampling frequency of 10 kHz and a 20 s sampling period. Stored data are post-analyzed using the Excel spreadsheet software.

2.3. Acoustic excitation and noise measurements
Acoustic forcing allows for the introduction of artificial disturbances into the shear layer of the free jet, and this acoustic excitation is accomplished through the use of a loudspeaker. The experimental arrangement is as shown in Fig. 2. For artificial forcing, two different methods are applied as illustrated in the figure. The first method uses a function generator to introduce sinusoidal disturbances, from which the frequency of the most unstable disturbance in the shear layer can be examined.

The second is to emit unstable disturbances detected by a hot-wire sensor in the shear layer of the jet, resulting in the natural selection of one frequency from the broad-band of unstable disturbances, where components lower than 2 Hz are excluded. The loudspeaker characteristics are: an impedance of 8 Ω, a rated power of 8 W and a woofer diameter of 150 mm.

For acoustic forcing, the signal is power-amplified through the use of a power operational amplifier LM12 supplied by National Semiconductor. The speaker woofer is mounted on a linear slider (Suruga Precision Model KXL06300-C2-FA) oriented perpendicular to the jet axis. The distance between the jet exit and speaker is varied parametrically, with speaker position managed by either manual, or LabVIEW software control. To define the coordinate system, the streamwise, transverse and spanwise directions are taken as X, Y and Z, respectively. The axis origins are located at the jet exit, the vertical middle of the jet, and the jet center in the spanwise direction.

3. Experimental Results
3.1. Basic flow characteristics
Profiles of mean and fluctuating velocities at X = 1 mm downstream of the lateral center of the nozzle exit are shown in Fig. 3. Outside the shear layer, the mean velocity profile is observed to be almost flat with a center velocity U₀ = 13 m/s, and therefore this flat center velocity U₀ is used henceforth to represent the jet exit velocity. In the figure, the profile of rms values denoted by u’ of fluctuating velocity u is also illustrated, showing that the intensity level in the flat-top region is 0.5% of U₀, while the maximum intensity in both shear layers reaches approximately 1% of U₀. The latter may be ascribed to residual fluctuations in the boundary layer along the contraction nozzle wall. These basic characteristics of the mean and fluctuating velocity profiles provide a two-dimensional, laminar nozzle flow of the so-called top-hat type. This laminar, two-dimensional character to the flow, especially the fluctuating quantities, is of essential importance for comparison with theoretical findings.

In reality, spectral analyses of the fluctuating velocity at the maximum intensity locations in the shear layers for two streamwise cross-sections, namely X = 1 mm and 10 mm, in two spanwise directions of Z = 0 mm, and also Z = ±25 mm, reveal that although the flow is primarily two-dimensional, some deviation from this condition does exist. Therefore, in order to minimize this influence, measurements are made in the middle cross-section of the jet.

Figure 4 depicts the power spectra of the fluctuating velocities, acquired at X = 1 mm and 10 mm, as identified above. As indicated, all frequency components, especially in the 0.5–2 kHz range, are amplified in the downstream direction. Higher harmonics of the amplifying components

![Fig. 2. Experimental layout for the artificial acoustic feedback loop.](image)

![Fig. 3. Profiles of mean and fluctuating velocities in the axial direction at X = 1 mm.](image)
are also clearly evident. Although the growth of velocity fluctuations in the 0.5–2 kHz range is most likely attributable to the shear-layer instability, it is difficult to determine the most unstable frequency due to numerous line components and narrow-band peaks in this frequency range of the spectrum. Therefore, the most unstable frequency is identified using artificial acoustic forcing with a loudspeaker driven by a constant amplitude, variable frequency signal. With the hot-wire sensor placed in the shear layer at $X = 10$ mm, the speaker is located at a distance $L = 1.1$ m away from the flow axis and vertically perpendicular to it. The measured amplitudes denoted by $u'_f$ for artificial forcing obtained from spectral analysis are also plotted in Fig. 4, as indicated by the square symbols. Since the data exhibit considerable scatter, a parabolic curve is fitted by use of the least-squares method. A peak at 1.2 kHz is evident, thus identifying the most unstable frequency. The presence of data scatter of this nature is expected, and is an artifact of the acoustic receptivity problem, as discussed in greater detail below.

Because the spectra in Fig. 4 all show a number of narrow-band peaks and spikes, it is important to identify their origin, and therefore a spectral decomposition of the acoustic noise, measured above the blower, is also shown in Fig. 4. The spectral shape of the acoustic noise in the 0.5–2 kHz range bears resemblance to that of the streamwise velocity component, so it can be concluded that the presence of these frequency components contaminating the streamwise velocity fluctuations, arise from the fan noise and mechanical vibration due to the motor or its fan. To confirm this speculation, similar experiments are repeated in the anechoic chamber, and no noticeable difference between echoic and anechoic environments is observed. This result also suggests that the observed acoustic noise is not due to reflection of acoustic noise from the walls surrounding the apparatus. Examination of the 1,176 Hz line spectral component under natural forcing from external noise is instructive, and the maximum amplitudes measured along the flow axis are plotted in Fig. 5. These amplitudes are normalized by $U_0$, and the two symbols $\square$ and $\times$ represent measurements taken in the shear layer, in the positive and negative $Y$ directions, respectively. Figure 5 shows that the most unstable components in both shear layers are evenly amplified. In addition to the 1,176 Hz component, many narrow-band and line components are visible in the 0.5–2 kHz range, indicating that one of these components might be due to an absolute instability\(^{16}\) in the top-hat-type jet flow. However, this possibility has been excluded under the present experimental conditions, and to document this, a comparison of the observed growth rate with linear stability analysis is provided in the next paragraph.

Since the mean velocity distribution of the jet flow at the exit is of the top-hat type, the instabilities present in the two shear layers near the exit are hydrodynamically independent. The mean velocity distribution in the shear layer may be approximated by a hyperbolic tangent curve of the form $U/U_0 = 1 + \tanh(\sigma Y)$ as proposed by Michalke.\(^{17}\) Using this function, the parameter $\sigma$ obtained from the best fit curve, may be used to compute a value of the momentum thickness $\theta$ from the relation $\theta = 1/(2\sigma)$, as is readily verified by direct integration in the definition of $\theta$.

As shown in Fig. 6, the best fit $\sigma$ for the present velocity distribution at $U_0 = 13$ m/s is found to be $\sigma = 4$, which
corresponds to a momentum thickness \( \theta = 0.125 \text{ mm} \), and a Reynolds number based on this thickness of approximately 100. Linear stability analyses are conducted for this Reynolds number, and Fig. 7 compares the measured spatial growth rate (Fig. 5) with the analytical result, for a value of the non-dimensional frequency \( 2\pi f/\theta U_0 = 0.071 \). The figure also includes existing experimental results from Sato\(^{18}\) and Freymuth,\(^{19}\) as well as the analytical result at an infinite Reynolds number by Michalke.\(^{17}\) The effect of Reynolds number on the range of unstable components appears to widen the unstable frequency domain, while no Reynolds number dependence is seen at lower frequencies. The experimental results lie within the lower frequency regime of the spatial-growth-rate curve, and show that the present data are in good agreement with the stability analysis. Because of this agreement with two-dimensional analytic results, it may be inferred that the experimental jet flow with measured mean and fluctuating velocity distributions of the top-hat type, does indeed exhibit a sufficiently two-dimensional character.

3.2. Frequency selection in the acoustic loop

The region between the jet exit and the streamwise location \( X = 10 \text{ mm} \) lies in the linear growth portion of the laminar shear layer under natural forcing conditions because unstable fluctuations grow exponentially there. Velocity fluctuations are detected at the location with maximum amplitude in the shear layer, and are subsequently power-amplified for feedback into the loudspeaker, which projects into the flow from the vertical direction. Figure 8 depicts the spectra from the anemometer data, for cases where the distance between the flow exit and the speaker is kept constant at \( L = 1.13 \text{ m} \). The figure includes a spectrum with no acoustic forcing, denoted by the broken line. Remarkably, only one frequency, namely \( f = 1.125 \text{ Hz} \), is selected in the artificial acoustic loop. Additionally, the second harmonic of the selected frequency is perceptible, showing the onset of impending laminar-turbulent transition.

A comparison of the spectra with and without forcing reveals that the amplitudes of both line frequencies (e.g., \( f = 1.176 \text{ Hz} \)) observed in natural flow near the selected frequency and broad-band components near the selected frequency are suppressed. Furthermore, a subharmonic component of the selected frequency is also observed, which is representative of a separated laminar shear layer, comprised of broad-band components even for a discrete fundamental.\(^{20}\)

Once an artificial acoustic loop is established with parameters \( U_0 \) and \( L \) both given, the flow automatically selects only one frequency in a stable configuration. Since these two parameters play such an important role in the frequency-selection mechanism, the underlying cause for observed jumps in the frequency-selection process is studied by independently varying them. Frequency jumps at velocities of approximately 12.7 and 10.2 m/s are clearly evident. The figure includes curve fits of the data to the form \( f = kU_0^m \), where determination of \( k \) and \( m \) is described below. A curve \( f = 0.026U_0^{1.5} \) denoted by a dashed line, is also plotted in the figure.

3.3. Frequency selection in acoustic loop: varying \( U_0 \)

For variable jet exit velocity with fixed speaker distance \( L = 0.46 \text{ m} \), the frequency automatically selected in an artificial acoustic loop is determined. Figure 9 shows results from a case for which the jet velocity is decreased gradually.

This curve is derived from the non-dimensional form \( 2\pi f/\theta U_0 = 0.071 \) for the most unstable frequency \( f = 1.176 \text{ Hz} \) in the shear layer at a velocity of 13 m/s. In
addition, it is assumed that the momentum thickness \( \theta \), is proportional to \( \theta = C/\sqrt{U_0} \), based on the presence of a laminar boundary layer right upstream of the jet exit, with the constant \( C \) determined from the observed \( f \) at the known \( U_0 \). The figure shows that the selected frequency over restricted ranges of \( U_0 \) (i.e., the local variation) appears to be proportional to \( U_0 \) to the power of 0.65, whereas over the entire range of jet velocity (i.e., the global variation) the selected frequency roughly varies as \( U_0^{0.5} \). Although such a trend is qualitatively consistent with the results of Paterson, the slope \( m \) of the step-like structure in the local variation is smaller than that observed in previous studies (i.e., \( m = 0.8–0.85 \)), so full understanding of the underlying causes for this discrepancy is warranted.

A sound wave with a frequency \( f \) emanated from a location \( L \) away from the jet exit, takes a time \( L/a \) to the jet exit, where \( a \) is the sound speed. An internalized velocity fluctuation traveling at phase velocity \( c \), advects to the hot-wire probe located at \( X \), taking a time \( X/c \). One cycle of the acoustic loop is equal to the sum of the above two time intervals and for such a resonant loop, Arbey and Bataille proposed the following model

\[
f = (n + \delta n)/(X/c + L/a) = kU_0^m.
\]

where \( n \) is an integer showing the degree in the resonant mode and \( \delta n \) is an arbitrary number representing the deviation in the phase when the acoustic wave is accepted at the jet exit. Linear stability analysis shows that the convective velocity \( c \) is nearly independent of Reynolds number, and is roughly 51% of \( U_0 \). Since \( X \) and \( c \) are constant, the two parameters \( U_0 \) and \( L \) in Eq. (1) are the relevant variables. Substituting the experimental data of Fig. 9 into Eq. (1), yields the result shown in Fig. 10. The variation of \( n + \delta n \) is almost constant in three distinct velocity ranges, over which the selected frequencies change in a piecewise continuous manner, indicating that the above model is reasonable. From each of the three distinct velocity ranges, the degree \( n \) is seen to be the integers 2, 3, and 4, respectively, and \( \delta n \) corresponds to values of approximately 0.53, 0.43 and 0.18. For the lower two velocity ranges, \( \delta n \) is roughly a value of 0.5, showing that sound is accepted at one-half wavelength of the acoustic wave at the jet exit. For the highest velocity range, however, \( \delta n \) deviates considerably from a value of 0.5. One plausible explanation for this may be that the higher velocity range is exhibiting some characteristics of non-linear disturbance growth, due to the onset of laminar-turbulent transition. As shown in Fig. 5, the location \( X = 10 \text{ mm} \), at which the hot-wire probe is placed, lies in the linear-growth stage for natural forcing. Once the artificial loop is formed, the transition process at the hot-wire location may be from the linear stage to a nonlinear one, because the higher harmonics have already grown there as evidenced by Fig. 8. The transition process in the shear layer is promoted by the acoustic loop, and the velocity distribution spreads in the transverse direction and eventually the convective velocity \( c \) becomes slower than that in the linear region. For example, when \( c \) is reduced from 51% of \( U_0 \) to 46% in Eq. (1), \( \delta n \) reaches a value of 0.5, indicating that \( \delta n \) is very sensitive to the convective velocity. If the parameters \( X, L \) and \( c/U_0 \) in Eq. (1) are held constant, the frequency \( f \) is a function only of \( U_0 \). Therefore, Eq. (1) may be rewritten as

\[
f = (n + \delta n)/(X/c + L/a) = kU_0^m.
\]

For three velocity regions in Fig. 9, the coefficient \( k \) and power \( m \) are determined for the best fit to the experimental data. This fit yields coefficients \( k \) of 0.172, 0.229 and 0.277, respectively, and the power \( m \) is determined to be 0.65, independent of the velocity range involved. It is found that \( k \) and \( m \) in the acoustic feedback loop are determined by the streamwise location \( X \) of the hot-wire sensor, and the speaker distance \( L \).

Of additional interest is the difference \( \Delta f \) between frequency jumps and how it relates to the jet velocity at the exit. These jumps are equivalent to the reciprocal of one cycle period of the acoustic feedback loop as confirmed in Fig. 10. Two jumps occur at 10.2 and 12.7 m/s, and the jump frequencies correspond to changes of 0.27 and 0.26 kHz, respectively, while Eq. (2) gives 0.3 and 0.34 kHz, respectively. At 10.2 m/s there is good agreement between the observed jump frequency and Eq. (2). However, at 12.7 m/s the deviation is not small, but could also be attributable to the fact that the convective velocity for the fluctuations in the shear layer are under the influence of non-linear disturbance growth.

### 3.4. Frequency selection in acoustic loop: varying \( L \)

For a fixed jet exit velocity of \( U_0 = 13 \text{ m/s} \), the separation distance \( L \) between the speaker and jet flow exit is varied parametrically. Since the wavelength of the sound for the selected frequency is estimated at roughly 300 mm, the speaker position is moved in 30 mm intervals.

Figure 11 shows the selected frequency as a function of the separation distance \( L \). As the separation distance decreases, the frequency increases, and at a certain distance the selected frequency is observed to suddenly jump down to a lower value. In addition, the selected frequencies all lie within the 1.13 to 1.3 kHz range, which corresponds to the most unstable frequency domain as mentioned in the discussion of Fig. 4.
It is apparent that the frequency jump is related to the sound wavelength $\lambda$ and the speaker separation distance $L$ and therefore using the relation $\lambda = a/f$ with sound speed $a$ and frequency $f$, all the data of Fig. 11 are replotted in Fig. 12 with $L/\lambda$ as the ordinate.

Taking into account the sound directivity of the speaker, the frequency tends to shift from the $(n + 1/2)$-mode to the $n$-mode. This result is consistent with Fig. 10, and a similar sound receptivity mode is observed in the laminar-turbulent transition process on a 2-D airfoil emitting trailing-edge noise, where the transition is tripped by a thin tape with a width of one-half T-S wavelength, placed spanwise on the airfoil.\(^\text{21}\)

In an aero-acoustic feedback loop, there may also be the possibility of hysteresis in cases where the speaker is approaching or receding from the jet flow and the data of Fig. 13 shed some light on this possibility. The figure illustrates the presence of hysteresis, as the results clearly indicate a dependence on the direction of speaker motion and the frequency is observed to jump at one-half wavelength of the acoustic sound selected in the artificial loop.

4. Conclusion

It is well-known that the tonal noise emanating from the trailing edge of 2-D airfoils at moderate Reynolds numbers is acoustically coupled with Tollmien-Schlichting instability waves in the airfoil boundary layer. The variation of acoustic sound frequency with uniform changes in velocity evolves into a piecewise continuous, step-like dependence. Although the presence of an acoustic feedback loop is well documented, the precise location for acceptance of the tonal noise into the wing boundary layer has been difficult to establish.

The present study focused on a two-dimensional jet flow, where acoustic disturbances are internalized at the jet exit location. The jet flow was established so that sound is not radiated from the shear layers, but rather that growing fluctuations in the shear layer could be detected, power-amplified, and then emitted from a loudspeaker to create an acoustic feedback loop.

Under such flow conditions, the key parameters in the frequency-selection mechanism consisted of the distance between the speaker and the jet exit, and the velocity of the jet at the nozzle exit, for a fixed detection location of the growing fluctuations in the shear layer. By varying each parameter independently, the frequency-selection mechanism was identified. Several conclusions may be drawn from the present study:

1) Once an artificial feedback loop is established, only one frequency is selected, and the selected frequency is approximately equal to the most unstable frequency in the shear layer as determined by linear stability theory.

2) If the jet exit velocity is decreased after the artificial acoustic loop has been established, the selected frequency decreases continuously, but jumps suddenly at certain values of the jet exit velocity, resulting in a step-like functional dependence when the selected frequency is plotted against jet velocity.

3) The piecewise slope in the step-like variation is proportional to the power law $U_0^{0.65}$ and the value of the power is determined by the detection position of the unstable fluctuations in the shear layer and the distance between the speaker and nozzle exit.

4) The magnitude of the frequency jump is inversely proportional to the overall cycle time in the artificial feedback loop.

5) The slope of the step-like structure and the observed frequency ranges in the artificial loop.
frequency jump show agreement with the empirical model of Arbey and Bataille for trailing-edge noise from a two-dimensional airfoil, confirming that their model provides a good representation of the underlying physics.

6) As the distance between the speaker and flow is increased, the selected frequencies tend to decrease and when the remainder of the distance between the speaker and jet divided by the wavelength of the selected acoustic sound is equivalent to one-half wavelength of the acoustic sound, the selected frequency jumps to another state.

7) Hysteresis is present in cases where the speaker approaches or recedes from the jet flow.

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