ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013
Musical Acoustics
Session 2aMU: Aeroacoustics of Wind Instruments and Human Voice I

2aMU2. Aerodynamical sounding mechanism in flue instruments: Acceleration unbalance between the jet vortex layers
Shigeru Yoshikawa*

*Corresponding author's address: Graduate School of Design, Kyushu University, 4-9-1 Shiobaru, Minami-ku, Fukuoka, 815-8540, Fukuoka, Japan, shig@design.kyushu-u.ac.jp

According to PIV (Particle Image Velocimetry) measurement applied to the sound production in organ flue pipes and flutes, the vortex sheddings at the pipe edge proposed by Howe (1975) are not observed but the formation of the vortex layer is clearly observed along both sides of the jet flow. This has been confirmed in various sounding conditions with different blowing pressures and resulting pitches. The acceleration unbalance is generated from an incomplete cancellation of the aeroacoustical source term ($\omega \times U$) between both sides of the jet, where $U$ is the jet velocity and $\omega$ ($= \text{rot} U$) the vorticity. In addition, the vortex layer is essentially unstable because it is formed along the inflection point of the lateral jet-velocity profile. Therefore, the acceleration unbalance and inflection instability of the vortex layer activates the jet wavy motion to reinforce the inward or outward acoustic velocity $u$ at the pipe mouth. Phase relations between acoustic quantities approve conventional acoustical models based on the volume-flow drive and momentum drive. Since $\omega \times U$ can also activate the jet movement in edge-tone generation, the vortex-layer formation may be regarded as the fluid-dynamical mechanism common to the edge-tone generation and the pipe-tone generation.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

About 15 years ago, N. Fletcher explained the role of vortices in flue instruments as follows in his textbook:\textsuperscript{1}

“...... the jet introduces a very large vorticity component through its shear layers, and this in turn leads to complex flow behavior and the formation of macroscopic vortices. The interaction of these vortices with the acoustic field then either adds energy to, or takes energy away from, the pipe oscillation. While sophisticated flow visualization techniques make the vortices and their time evolution visible, it is a long step from this qualitative observation to a theory that will actually predict the sounding behavior of the instrument.” (Sec. 16.5 Rigorous Fluid-Dynamical Approaches). At present, owing to the drastic advancement of computer technology, we have excellent tools for numerical simulations based on computational fluid dynamics and more quantitative flow visualization techniques such as LDA (Laser Doppler Anemometry) and PIV (Particle Image Velocimetry).\textsuperscript{2-4} The time is ripe for the aerocoustics of musical wind instruments involving human voice, singing, and virtual instruments.

In this paper the role of vortices is considered based on experimental investigations and a new aerodynamical model for sound production in flue instruments such as the flute, recorder, shakuhachi, and organ pipes is proposed. First, the vortices shedding from the edge are reviewed. The acoustically-induced vortex (simply, the acoustic vortex) yields nonlinear loss mechanism which determines the final saturated amplitude of sound production.\textsuperscript{2, 5, 6} On the other hand, Howe\textsuperscript{7} proposed another type of vortex shedding which generates acoustic energy from the interaction with the acoustic velocity at the mouth of the instrument. Also, when the jet is thick and the condition (the flue-to-edge distance $d$)/(the jet thickness $h$) $< 2$ is satisfied, a discrete vortex shedding from the flue exit edge controls sound production in flue instruments.\textsuperscript{8-10} These discrete vortices relevant to sound absorption or generation are macroscopic and may be visible with our naked eyes if flow visualization is appropriately applied.

Next, experimental results based on PIV are introduced to demonstrate that a macroscopic discrete vortex relevant to sound generation never be observed in the flute and organ flue pipes where thin jets satisfying $d/h > 2$ are usually used.\textsuperscript{11-15} Instead of such a discrete vortex, vortex layers are observed along both sides of the jet flow. Since these vortex layers with opposite signs of the vorticity $\omega = \text{rot} U$, where $U$ denotes the jet flow velocity) are formed along the inflection point of the lateral jet velocity profile and the inflection point may yield any instability such as the Kelvin-Helmholtz instability, the aeroacoustical source term (the acceleration) $\omega \times U$ is not completely cancelled out between both sides of the jet. As the result, an acceleration unbalance derived from the vortex-layer instability can be responsible for the jet oscillation and then supplies acoustic energy to the resonant pipe.

VORTEX-SHEDDING MODELS

Since basic aerodynamical theory on the acoustic energy absorption or generation from a discrete vortex is given by Howe,\textsuperscript{7} his theory is briefly described at first. Then, both the acoustic vortex dissipating acoustic energy and Howe’s vortex-shedding model for sound generation are explained in more detail.

**Howe’s Formula on Acoustic Dissipation or Generation**

According to Howe,\textsuperscript{7} the power density supplied from the acoustic field (specified by reciprocating potential flow $u$ crossing the fluid flow $U$) to the vortical field (specified by the flow field $v = U + u$) is given by

\[
(1/2)(\partial / \partial t)(\rho_0 v^2) = \rho_0 (\omega \times v) \cdot u, \tag{1}
\]

where $\rho_0$ is the mean fluid density. In other words, the Coriolis force

\[
f_c = -\rho_0 (\omega \times v) \tag{2}
\]

acts as an external force on the acoustical flow field $u$.\textsuperscript{4} Howe\textsuperscript{7} then proposed the *acoustic dissipation formula*:

\[
\Pi \approx \int_V \rho_0 (\omega \times U) \cdot u dV \tag{3}
\]
where total velocity \( v \) is simply approximated by fluid flow velocity \( U \) and the vorticity \( \omega \) is defined as \( \text{rot} \, U \). Also, \( V \) denotes a volume enclosing the vorticity formed in the flow field. This Eq. (3) determines the rate of dissipation of acoustic energy. The sign of Eq. (3) can be negative in oscillation system: If the phase of vorticity production enables a steady transfer of energy from a mean flow to the oscillation, the self oscillation can be maintained.

Hence, the acoustic generation formula may be proposed:

\[
\Pi_c(t) \approx - \int \rho_0 (\omega \times U) \cdot u \, dV = \int \vec{f}_c \cdot u \, dV,
\]

(4)

where Eq. (2) is used. If the time average \( \langle \Pi_c(t) \rangle \) is positive, the vorticity production from the jet flow supplies the acoustic power to the resonant pipe.

**Acoustic Vortex Shedding from the Pipe Edge**

The acoustically induced vortex shedding at the labium is a key damping mechanism to determine the final amplitude of the steady-state organ-pipe or flute tone.\(^2\)\(^5\)\(^6\) The modeled flow condition when the sounding amplitude is almost saturated and the associated acoustic vortex is generated in an organ pipe is illustrated in FIG. 1.\(^6\) The velocity field is approximated as \( v = (U, 0, 0) \) using the jet flow velocity \( U \) in positive \( x \) direction. An acoustic vortex formed above the edge rotates clockwise as shown in Fig. 1(a), that is, the vorticity \( \omega \) tends to the positive \( y \) direction. Therefore, \( \omega \times v = \omega \times U \) is in the negative \( z \) direction. When the acoustic vortex is formed above the edge, the jet deflects toward the exterior of the pipe. Hence, the acoustic particle velocity \( u \) around the edge must flow from the exterior to the interior of the pipe to sustain sound production. This situation makes \( (\omega \times U) \cdot u \) positive and leads to the absorption of acoustic energy by the vortex. Half a period later an acoustic vortex rotating anticlockwise is formed below the edge, and \( \omega \times U \) as well as \( u \) are in the positive \( z \) direction (upwards). Hence, \( (\omega \times U) \cdot u \) is positive again as illustrated in Fig. 1(b). These acoustic vortices were clearly visualized\(^2\)\(^5\)\(^6\).

![FIGURE 1. Modeled flow condition when an acoustic vortex is formed to lead the saturation of organ-pipe sound.\(^6\)](image)

**Howe’s Theoretical Model of Vortex Shedding for Sound Generation**

Howe\(^7\) assumed that a compact vortex core appearing alternately just above and beneath the edge was created by the interaction with the acoustic cross-flow velocity \( u \) at the mouth opening (see FIG. 2(a)). That is, instead of the jet oscillation over the mouth that has been assumed in conventional acoustical models,\(^1\) a point vortex is produced at the edge. Then, this vortex core is assumed to drive the air column in the pipe. A discrete-vortex model for thick jets assumes that a discrete vortex is generated from the flow separation at a flue exit corner,\(^8\)\(^9\)\(^10\) while Howe attached greater importance to the flow separation (vortex shedding) at an opposing sharp edge of the pipe due to the acoustic cross flow.

However, Howe’s conceptual vortex core is not observed experimentally, at least in the present author’s PIV experiment.\(^11\) If such a macroscopic large vortex can be involved in sound generation, the resulting acoustic energy might be tremendous. This is a naive question to Howe’s model. Probably much smaller vortex may be involved in sound generation in musical instruments. Therefore, Howe’s vortex-shedding model should be carefully examined experimentally. Also, his model is based on the irrotational potential flow of \( u \), but actual \( u \) may be different from such an idealized condition when we consider large-amplitude nonlinear sound conditions.
FIGURE 2. Conceptual sketches of aerodynamical models based on the vortex generation in organ pipes and other jet-driven musical instruments: (a) the vortex shedding at the edge proposed by Howc; (b) the vortex layer along both sides of the jet flow; (c) the generation and cancellation of the aeroacoustical source term (the acceleration) $\omega \times U$. The dashed line in (b) and (c) depicts a lateral profile of the jet velocity.

Discrete Vortex Shedding from the Flue Exit

Meissner\textsuperscript{10} proposed a model of aerodynamic source when a cavity resonator is driven by the 2-D jet (see FIG. 3). It is assumed that vorticity generation begins immediately downstream of the nozzle edge due to flow separation and the shear layers roll up into discrete vortices because of nonlinear effects. Vortices travelling in an area of the resonator opening cause force fluctuations, which excite an acoustic oscillation. The oscillation, in turn, triggers the periodic formation of new vortices.\textsuperscript{10} In his experiment $h$ and $d$ were 2.7 and 8 mm, respectively. This discrete-vortex model was successfully applied to flue instruments by Dequand \textit{et al.}\textsuperscript{14} According to their visualization experiments, the conventional jet-drive model is valid for thin jets ($d/h > 2$) which are typically present in musical instruments, but their discrete-vortex model is much more relevant to the sound production by thick jets ($d/h < 2$). In their experiment $d/h = 0.8$ (for $h = 30$ mm) and 1.7 (for $h = 14$ mm).

FIGURE 3. Discrete vortex formation at lower flow-separation edge of the flue exit (after Ref. 10).

VORTEX-LAYER FORMATION MODEL

The formulation of Eq. (4) provides another physical image as illustrated in FIG. 2(b): Since an actual jet has a velocity profile as indicated by the broken line, the vorticity can be formed along the boundary between the jet and the surrounding fluid. As the result, a layer of vorticity is organized along an immediate vicinity of the jet. The upper layer consists of the positive vorticity (the counterclockwise-rotating vortices), and the lower layer consists of the negative vorticity (the clockwise-rotating vortices). This physical picture of the vortex-layer formation was first proposed by Bamberger\textsuperscript{12} and then experimentally confirmed by his subsequent research\textsuperscript{13, 14} and our research\textsuperscript{13} both based on PIV measurements.

PIV-Based Experiment

Measurement Procedures

Our experiment to visualize the vortex-layer formation and evaluate the vorticity distribution over the mouth area between the flue and the pipe edge (labium) is introduced in this section. Our method is based on the particle image velocimetry (PIV), which can yield global and quantitative information on the flow-acoustic interaction.\textsuperscript{16, 17} The outline of our PIV is given in Ref. 11 and our system to measure $U$ and $u$ is shown in FIG. 4.
Since $|\mathbf{u}| \ll |\mathbf{U}|$, it is very difficult to measure both velocities simultaneously when driving the pipe by the air jet. Therefore, both velocities should be separately measured. Of course, $\mathbf{U}$ cannot be measured without using the jet. On the other hand, $\mathbf{u}$ can be measured by resonating the pipe externally, for example by using an inverse exponential horn.\textsuperscript{11} The loudspeaker is driven by an oscillator to generate a sinusoidal wave in the pipe with the same frequency and amplitude as those when the jet drives the pipe. In order to experimentally examine the generation of the vortex sound based on Eq. (4), both measurements of $\mathbf{U}$ and $\mathbf{u}$ must be carried out at the same condition as exactly as possible. That is, these vectors must be measured at the same phase of the generating sound and at the same measurement area by using the same organ pipe. The phase-locked PIV measurement on $\mathbf{U}$ and $\mathbf{u}$ is essentially important to evaluate Eq. (4). Also, the jet drive and the loudspeaker-horn drive must be switched as quickly as possible while maintaining the same sounding condition and the same measurement condition.

In order to experimentally examine the vortex-sound generation based on Eq. (4), the acoustic cross-flow $\mathbf{u}$ must satisfy the theoretical hypothesis: $\mathbf{u}$ is an irrotational potential flow. In addition, the PIV cannot evaluate the contribution from the harmonics but only estimate the instantaneous flow magnitude on a plane sheet illuminated by the laser. Hence, the acoustic cross-flow $\mathbf{u}$ should meet the requirement as an \textit{irrotational potential flow reciprocating sinusoidally}. In our experiment this requirement was practically satisfied based on a dive at \textit{piano} level (at the blowing pressure of about 60 Pa).\textsuperscript{11} A metal organ pipe used for the measurement has the main geometry as follows: the flue-to-edge distance $d = 8.8$ mm, the jet thickness (the flue width) $h = 0.75$ mm, the pipe inner diameter $2a = 43.6$ mm, and the physical pipe length $L = 793$ mm. The sounding frequency is about 192 Hz.

**FIGURE 4.** Experimental setup based on the phase-locked PIV system. The blower and loudspeaker-horn system (indicated by the broken line) are alternately used for the jet dive to measure the jet velocity and for the horn drive to measure the acoustic cross-flow velocity, respectively.\textsuperscript{11}

The two-dimensional velocity vectors at about 4000 discrete points, which corresponds to the spatial resolution of about five discrete points per one millimeter, can be gained on a pictured frame in our PIV measurement. If the 2-D velocity vectors of tracer particles are estimated on the $x$-$z$ plane as $\mathbf{U} = (U_x, 0, U_z)$, the vorticity $\omega = (0, \omega_y, 0)$ at a discrete point is given from the velocities at four points surrounding the point of interest based on the finite difference approximation.

**Measurement Results**

The phase-locked velocity measurement was carried out at the interval of $(1/12)T$, where $T$ denotes the tonal period. Therefore, the measurement results of $\mathbf{u}$ and $\mathbf{U}$ are given at the specific phases (Phase 0, Phase 1, Phase 2, ..., Phase 11). The results at Phase 4 and Phase 7 are illustrated as examples in FIG. 5.\textsuperscript{11}

The measurement plane was set at the middle of the mouth breadth ($y = 0$). The flue exit and the pipe edge are located at $(x, z) = (2.0$ mm, $2.2$ mm) and $(x, z) = (10.5$ mm, $3.8$ mm), respectively. The flow fields applied to PIV signal processing are surrounded by the solid line. The outflow of $\mathbf{u}$ was observed at phase 4, and the inflow was
observed at phase 7. The maximum velocity of the outflow (+1.1 m/s) was measured at phase 3 and that of the inflow (-1.2 m/s) was measured at phase 9. The measurement of \( \mathbf{u} \) demonstrated the following characteristics:

1. The maximum velocity is observed just in front of (about 1 mm before) the edge.
2. The velocity rapidly decreases toward the edge tip from the position giving the maximum.
3. The velocity near the flue is much less than half the maximum velocity.

These characteristics can be inferred from the theory on the potential flow and the edge singularity. Also, it was confirmed by drawing \( \text{rot} \mathbf{u} \) that the cross-flow \( \mathbf{u} \) was almost irrotational except the regions around the edge, flue, and lower boundary in our experiment.

The jet flow was not exactly laminar (the Reynolds number was about 500), and the jet slowing and spreading were observed. The jet velocity was not always constant but fluctuated during a period: the maximum initial velocity near the flue (9.8 m/s) was observed at Phase 8; the minimum initial velocity (7.5 m/s) was observed at Phase 11. Jet velocity fluctuation like this is rather common in organ flue pipes because it is probably caused by the difference in flow resistance between the pipe exterior (free space) and the pipe interior (enclosed space). Although the detailed structure of the jet velocity is not easily understood from FIG. 5(b), the entrainment from the upper or lower side of the jet as well as the rotation of the velocity vectors around the portion where the jet shows larger curvature are clearly observed if the frames are fully magnified. A large-scaled vector rotation around point \((x, z) = (8 \text{ mm}, 7 \text{ mm})\) is observed at Phase 7, and similar rotation around point \((x, z) = (9.5 \text{ mm}, 7 \text{ mm})\) and the entrainment from the jet upper side are observed at Phase 10. These rotation yield the vorticity, but these large vortices are insignificant because their positions are far from the edge and the acoustic cross-flow velocity over there is very weak.

**Calculation of the Acoustic Generation Formula**

The PIV can derive the vorticity map from the jet velocity distribution. Therefore, the aeroacoustical source term \( \omega \times \mathbf{U} \) and the acoustic power generation term \( (\omega \times \mathbf{U}) \cdot \mathbf{u} \) can be calculated from the measurement of velocity fields \( \mathbf{U} \) and \( \mathbf{u} \).

**Jet Vortical Field and the Resulting Aeroacoustical Source Term**

The vorticity map is illustrated in FIG. 6(a). Since 2-D velocity \( \mathbf{U} \) was measured in \( x-z \) plane \( [\mathbf{U} = (U_x, 0, U_z)] \), the vorticity vector has only \( y \)-direction component \( [\omega = (0, \omega_y, 0)] \); \( \omega_y(x, z) = \partial U_z / \partial x - \partial U_x / \partial z \). It is well recognized that the vorticity is formed along the upper and lower boundaries of the jet and any significant vortex shedding from the edge is not observed. The upper layer possesses the positive vorticity (the counterclockwise rotation of small vortices) and the lower layer the negative vorticity [cf. FIG. 2(b)]. These layers may be called *vorticity layers* or simply *vortex layers*. Our experimental result implies that Howe’s vortex-shedding model may not be applicable to the sound generation in organ flue pipes that are usually driven by thin jets.
FIGURE 6. Aerodynamical quantities derived from the phase-locked PIV measurement at the organ-pipe mouth:
(a) vorticity \( \omega \); (b) aeroacoustical source term (acceleration) \( \omega \times U \); (c) acoustic generation term \( (\omega \times U) \times u \).11

Also, it should be stressed that the formation of the vortex layer has been widely confirmed on the flute and organ pipes in different sounding conditions.12-15Strong blowing pressures of about 325 and 680 Pa applied to produce a D6 tone (1150-1170 Hz) on the flute, mediate blowing pressure of about 240-265 Pa applied to produce a D4 tone (290 Hz), and strong blowing pressure of about 430 Pa applied to produce a G1 tone (195 Hz).

The resulting aeroacoustical source term \( \omega \times U \) is displayed in FIG. 6(b). The upper and lower layers of the vorticity yield the positive \( z \) and negative \( z \) components of \( \omega \times U \), respectively. The maximum magnitude of \( \omega \times U \), which is about \( 2 \times 10^5 \) (m/s^2), can be observed near the flute. The opposing vectors of \( \omega \times U \) along both layers seem to almost cancel each other. However, since \( \omega \times U \) has a very large acceleration, an imperfect cancellation (or a slight unbalance) between \( \omega \times U \) vectors along both layers yields a significant effect in acoustical events.

**Generation of the Acoustic Power from the Vortical Field**

The acoustic generation term \( (\omega \times U) \times u \) appearing in Eq (4) is illustrated in FIG. 6(c). Since \( u \) indicates the outflow at Phase 4 and the inflow at Phase 7, \( (\omega \times U) \times u \) takes the opposite sign along the vortex layer between these phases. The maximum magnitude of \( (\omega \times U) \times u \) appears near one to two millimeter downstream from the flute at Phases 3 and 8 as about \( 4.2 \times 10^6 \) (m^2/s^3). The jet crosses the edge from the inside at Phase 3 and from the outside at Phase 8 as inferred from FIG. 6(c). Although the magnitude of \( (\omega \times U) \times u \) is relatively small near the edge, it should be noted that \( (\omega \times U) \times u \) originally has very large values in acoustical sense.

The vortex-induced acoustic power, which is supplied to the pipe from the jet vortical field, is evaluated from Eq. (4). However, since the volume integral defined by Eq. (4) is not easily executed, the acoustic power generation from the vortex layer is estimated from the following surface integral by assuming the two-dimensionality of the jet flow \( U \) and the acoustic cross-flow \( u \):

\[
\frac{\partial P_0(t)}{\partial y} \approx -\iint \rho_0 (\omega \times U) \cdot u \, dx \, dz = \iint \hat{f}_c \cdot u \, dx \, dz,
\]

This surface integral, which may be called the instantaneous 2-D vortex-sound power, is carried out at each phase, and the result is represented in FIG. 7. Another scale of the ordinate is added to the right side of FIG. 7 in order to give a rough estimate of the magnitude of \( P_0 \) by simply multiplying the mouth breadth \( b = 30 \) mm. Actually, \( U \) and \( u \) are not 2-D. Therefore, an effective \( b_{d0} \) (possibly less than half the physical breadth \( b \)) should be introduced.11
Since the time average \( \langle H_{0d}(t) \rangle \) surely takes a positive value as understood from FIG. 7, the acoustic power generation is realized. However, it is not clear where the aeroacoustical interaction is most dominant. The maps of \( \omega \) and \( \omega \times U \) definitely indicate much larger magnitudes at the flue side as shown in FIG. 6. On the other hand, \( u \) takes much larger magnitudes at the edge side as shown in FIG. 5(a). It should be then discussed which side is more dominant for the acoustic power generation. A reasonable method to solve this question is to divide the integration area for Eq. (5) into two at \( x = 7, 8, \) and \( 9 \) mm, respectively. According to the result of surface integral of Eq. (5) over these six sub-areas with the same \( z \) extent, it was revealed that a small area closest to the edge (\( 9 \leq x \leq 11 \) mm) was most responsible for the acoustic power generation.\(^{11}\) This implies that the spatial distribution and the phase of \( u \) are essentially important to the acoustic power generation by the vortex-layer formation.

The phase relation between \( u \), acoustic pressure \( p \) at the mouth, and the jet displacement \( z_j \) (the upward direction was defined as positive) at the edge was then measured. The result indicated the in-phase relation between \( p \) and \( \Phi = - b z_j U_e / (U_e ; \) the jet velocity at the edge).\(^{11}\) This phase relation, which is favorable to the acoustic power generation in organ pipes, is just that observed in the volume-flow model (the Helmholtz-Cremer model)\(^{1, 2, 19}\) that was first formulated by Cremer and Ising\(^{19}\) based on the jet-wave characteristics due to the flow instability. This means that the sound generation mechanism based on the jet vortex-layer formation cannot deny the acoustical volume-flow model. On the other hand, the phase relation in PIV measurements by Bamberger\(^{12, 14}\) suggests the momentum-drive model (the Rayleigh-Colman model)\(^{1, 20}\)

The acoustical models are based on the respective activating sources for the jet wavy motion: (1) acoustic displacement;\(^{1, 2}\) (2) acoustic velocity;\(^{1, 3}\) (3) acoustic acceleration (the pressure gradient or pressure difference between the upper and lower surfaces of the jet).\(^{7, 21}\) On the other hand, our present study demonstrated that the aeroacoustical source term \( \omega \times U \) (having the dimension of the acceleration) associated with the vortex-layer formation along the jet could activate the oscillation in an organ pipe. More precisely, an incomplete cancellation (or a net unbalance) of \( \omega \times U \) between both sides of the jet can activate (oscillate) the jet.

**CONCLUSIONS**

Vorticity generations due to the flow-acoustic interaction mainly in flue instruments were reviewed. According to the phase-locked PIV measurement of velocities of thin jet flow and acoustic cross-flow, it is concluded that a jet vortex-layer formation model is more relevant to the sound generation than the vortex-shedding model.\(^{11}\) The acoustic power is dominantly generated by the flow-acoustic interaction near the edge where the acoustic cross-flow velocity is larger. Since the jet vortex-layers with opposite signs of the vorticity are formed along the inclination points of the lateral jet velocity profile and the inclination point may cause jet flow instability, the aeroacoustical source term (the vector product of the vorticity and the jet velocity) is not completely cancelled out between both sides of the jet. As the result, an acceleration unbalance derived from the vortex-layer instability can be responsible for the jet oscillation and then supplies acoustics energy to the resonant pipe. The phase relation in the jet-pipe interaction supports the conventional volume-flow model. The vortex-layer formation and acceleration unbalance may be regarded as the fluid-dynamical mechanism common to the edge-tone and the pipe-tone generations.
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