# Oscillations of Impinging Shear Layers

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## Introduction

COHERENT oscillations of impinging shear layers, giving rise to unsteady loading of the respective impingement edges/surfaces as well as associated noise radiation, occur in a variety of configurations, including: aircraft weapon bays and wheel wells; supersonic intakes; cavities in gasdynamic lasers; flaps of STOL aircraft; cavities/depressions in submarine and ship hulls; adjacent tall structures; leading tubes in tube bundles of heat exchanger and reactor equipment; steam regulation and control valves; and hydraulic gates.[1]

For most of these oscillations to be self-sustaining, a chain of events must occur, as schematically depicted in Fig. 1: impingement of organized vorticity fluctuations upon the edge/surface (i.e., leading-edge interaction); resultant upstream influence (interpreted as Biot-Savart induction or upstream pressure waves); conversion of disturbances incident upon the region of the shear layer in the vicinity of the separation edge to velocity fluctuations within the shear layer (i.e., trailing-edge interaction); and amplification of these fluctuations in the streamwise direction (represented in Fig. 1 by the streamwise evolution of the integrated fluctuation enegy of the $\tilde{u}$ component, $E_{\tilde{u}}$). This description accounts for neither adjacent resonators/reflectors nor fluid-elastic effects. Even without these complicating influences, the rich nature of the flow-surface interactions and the evolving shear layer have provided us with major challenges. In this review attention will first be given to the character of self-oscillations of nonimpinging flows, emphasizing the role of upstream influence. Then, the central thrust of this work, the essential aspects of impinging flows, involving leading-edge interaction, the nature of the upstream influence, disturbance-instability wave conversion at the separation (trailing) edge, and disturbance growth in the shear layer, will be addressed. This will be followed by an assessment of various models for predicting the nature of these oscillations, the effects of resonators, certain features of lower frequency impinging flows that distinguish them from the classical, highly coherent oscillations, and oscillations associated with supersonic flow.

### Apparent Length Scale for Nonimpinging Flows

Even in the absence of an impingement surface, communication between unsteadiness (e.g., changes in concentrations of vorticity) in downstream regions of the flow and the sensitive region of the shear layer near separation involves an "apparent" streamwise length scale $\ell$ (see Fig. 2); of course, in a typical shear layer, there may be a number of values of $\ell$. This downstream unsteadiness acts as the origin of upstream influence (induced velocities/pressure waves) schematically shown by dashed lines in Fig. 2. It has been attributed to vortex formation and pairing in mixing layers,[2,3] lateral oscillations of a wake,[4,5] and change in jet structure at a wall termination.[6] In addition, a somewhat different, but relevant, mechanism generating substantial upstream influence in underexpanded jets, involves shear-layer/shock cell interaction.[7-11]

Some consequences of the upstream influence, associated with these various mechanisms of downstream unsteadiness, are relatively organized amplitude modulation,[12] as well as less organized amplitude and frequency modulation,[2,3] of velocity fluctuations in upstream regions of the shear layer. Such modulation, most effective in the sensitive region of the shear layer near separation, has important consequences for downstream evolution of the unsteady shear layer. In addition, in many of the aforementioned cases, a strikingly similar consequence of the upstream influence is control of the frequency ($f$) of the oscillation as flow speed ($U$) is changed, such that the variation $f$ vs $U$ (see Fig. 2) exhibits a "ladder-like" behavior, the frequency jumping to successively higher "stages" of oscillation,[4,5-9,13] and in at least one case[13] highly accentuated, if not dominated, by acoustic resonance within the approach flow ducting. To model this sort of frequency control, Tam,[4] Laufer and Monkewitz,[12] and Powell[9] propose, in essence, the criterion

$$\ell/u_p + \ell/c_0 = n/f$$

in which $\ell$ is the aforementioned length scale, $u_p$ the phase speed of the downstream traveling wave, and $c$ the speed of sound associated with the upstream traveling disturbance. Moreover, $f$ is frequency, and $n=1,2...$ the stage of oscillation, whereby $n/f$ represents, for example, the period of lateral wake oscillation, vortex pairing, or shear-layer/shock cell interaction. The ladder-like behavior of the $f$ vs $U$ variation and associated frequency jumps is accommodated by successively higher values of $n$. Remarkable is the similarity between these features and those for shear layers impinging upon solid surfaces.[14] Clearly, care is required in attributing the character and location of sources of upstream influence in impinging flows to flow-surface interaction!

The nature of the upstream influence has been interpreted in terms of Biot-Savart induction associated with changes in concentrations of vorticity due to pairing[2,12] or upstream pressure waves emanating from the region of pronounced unsteady activity.[4,9] If the length scale $\ell$ is much smaller than the corresponding acoustic wavelength $\lambda_a$, as in several recent

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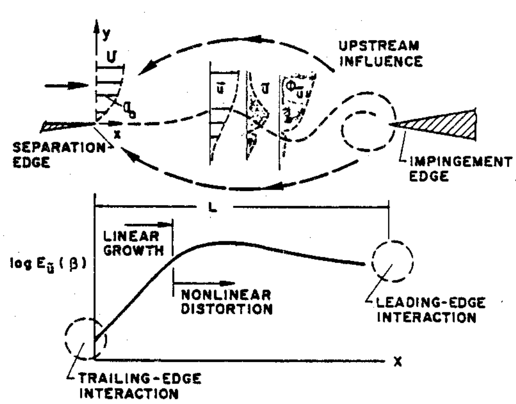


Fig. 1 General features of a self-oscillating shear layer impinging upon a solid surface.

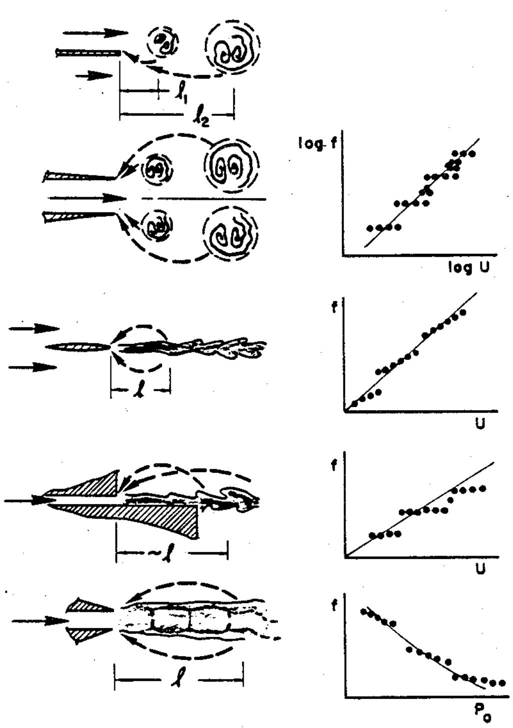


Fig. 2 Apparent streamwise length scales for a variety of nonimpinging flows, and typical variation of frequency $f$ vs velocity $U$.

experiments,[2,3,12] then the sensitive region of the shear layer lies in the "pseudosound" domain of the origin of upstream influence (e.g., location of vortex pairing). In this limit, it is straightforward to demonstrate the equivalence between interpretations of Biot-Savart induction and unsteady pressure field, both driven by the downstream regions of vorticity.[15] Since $\ell/\lambda_a \ll 1$, and if mean flow effects are *not* considered, the sensitive region of the shear layer lies in the nonpropagating pressure field, and it experiences pressure fluctuations of order $\rho\tilde{u}^2$, where $\tilde{u}$ is the local velocity fluctuation; on the other hand, if $\ell$ becomes a significant fraction of $\lambda_a$, the sensitive region sees real sound having fluctuations of order $\rho\tilde{u}c_0$. However, if a fixed frame at the separation edge is considered, as well as the limit $\lambda_a \to \infty$, the unsteady Bernoulli equation shows that terms $U\tilde{u}$ and $\rho\partial\phi/\partial t$ make substantial contributions to the local pressure amplitudes. Such consideration of amplitude is important because the perturbation exerted upon the sensitive region of the shear layer dictates the very mechanism by which the developing shear layer responds[12]; for example, at sufficiently high amplitude, a number of small vortices become embedded within very large-scale vortices[16,17] having, in turn, important consequences for the upstream influence.

Direct comparison of the aforementioned nonimpinging flows with their impinging counterparts has received little attention. However, it is clear, for the limiting cases of $\ell/\lambda_a$ and $L/\lambda_a \ll 1$, that the upstream influence (in terms of induced velocity at shear-layer separation) and overall coherence of impinging mixing-layer configurations can substantially exceed corresponding nonimpinging cases.[3,18] In the following, the source(s) of upstream influence associated with unsteady flow-surface interaction will be addressed.

## Leading-Edge Interactions—Edge Loading and Source of Upstream Influence

In discussing the origin of the upstream influence in terms of the unsteady pressure field, associated with loading of the leading edge, it is helpful to draw upon Lighthill's wave equation in presence of a solid boundary $S(x,t)$:

$$\left(\frac{\partial^2}{\partial t^2} - c_0^2\nabla^2\right)[(\rho-\rho_0)H(S)] = \frac{\partial^2}{\partial x_i^2 x_j}[T_{ij}H(S)] - \frac{\partial}{\partial x_i}[F_i\delta(S)] + \frac{\partial}{\partial t}[Q\delta(S)]$$

in which the terminology of Crighton[19] has been employed; $H$ and $\delta$ denote Heaviside and delta functions. Outside the boundary $[H(S)=1;\ \delta(S)=0]$, this equation becomes Lighthill's classical wave equation, the source term on the right-hand side representing a quadrupole distribution, where $T_{ij}(x,t) \simeq \rho_0\tilde{u}_i\tilde{u}_j$ if $M=U/c_0 \ll 1$ and viscous effects are negligible. At the boundary, $F_i$ signifies dipole strength (stress by surface on fluid) and $Q$ monopole strength (mass displaced by boundary) per unit area of an impermeable surface. Now if the vortex or eddy of scale $\ell$ adjacent to the surface is compact $(m=\tilde{u}/c_0 \ll 1)$ and the surface of length $b$ is also compact $(mb/\ell \ll 1)$, then it can be shown, for example, that the far field intensity corresponding to the dipole of the surface is a factor of $m^{-2}$ greater than that produced by a single vortex or eddy. In general, these conditions of vortex and surface compactness allow determination of the acoustic field if the flow adjacent to the surface, and surface pressures and velocities are known, though a more direct means of solving Lighthill's equation is normally possible. In other words, if the local hydrodynamics is known, the resultant sound field follows. In the event that the surface is not compact, but $T_{ij}$ is specified, the resultant surface pressures and velocities can be calculated keeping in mind that $T_{ij}$ itself will be influenced by acoustic contributions.[19,20]

Since the class of flows under consideration usually involves interaction of relatively coherent concentrations of vorticity with solid surfaces, attention will be focused on methods of simulating the corresponding hydrodynamic aspects. Concerning the acoustic features of unsteady flow-surface interactions, the reader is referred to the insightful overviews of Goldstein[20] and Crighton.[19]

In examining models of leading-edge/corner/surface interaction, it should be kept in mind that, in some instances, excitation of a normal mode of, for example, an adjacent cavity is often considered to exert a predominant influence, little attention being given to the interaction region. In any case, by aiming toward an understanding of the local hydrodynamics, features that influence the amplitude and phasing of the upstream influence (at least for compact surfaces) can be brought forth, and attenuation techniques optimized. Categories of simulation, or modeling, encompass: acoustic sources, vortex sheet interactions, single-point vortex interactions, multiple discrete vortex interactions, distributed vorticity/leading-edge interactions, and finally, the conversion process between an incident disturbance and an instability wave downstream of the edge.

### Sources

In general, this type of model relates the source-like nature of the interaction region to gross deflections of the incident

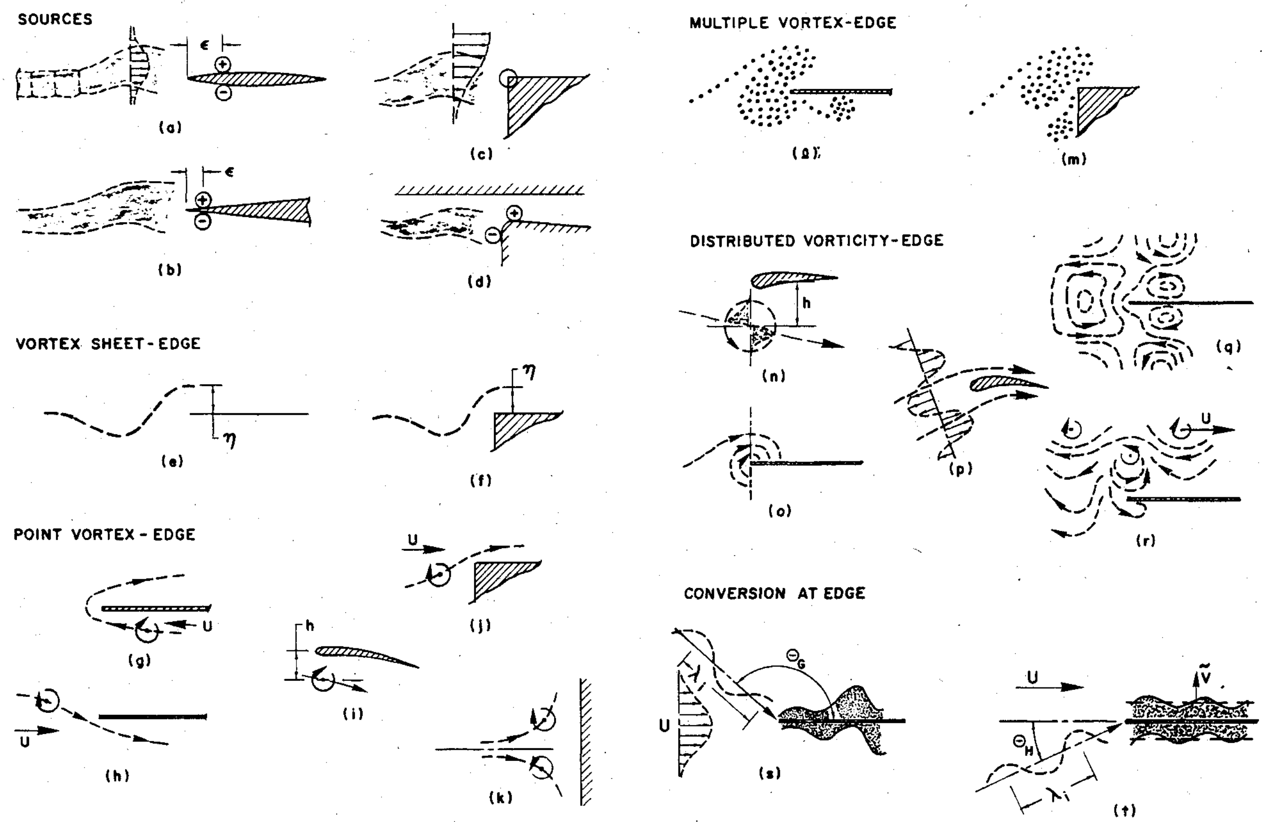


Fig. 3 Simulations of leading-edge interaction.

shear layer (see Figs. 3a-3d). Powell[9,21,22] interprets the unsteady field in the vicinity of an edge (wedge), associated with transverse undulations of an impinging planar jet, in terms of either simple or dipole sources. Based on schlieren photos and microphone measurements of an initially underexpanded jet impinging upon an airfoil (Fig. 3a), he suggests that, at these high speeds, there exist equal and opposite simple sources on either side of the (approximately) quarter-chord location of the airfoil. At low jet speeds (Fig. 3b), the impedance of the jet is viewed to be relatively low, allowing the simple sources to take on a dipole character (small $\epsilon$) near the tip of the edge, evidenced by corresponding microphone traverses. The strength of this dipole (i.e., force on the wedge) is taken to be proportional to annihilation of the transverse momentum of the incident jet. Moreover, in a related investigation of jet-edge oscillations, both in absence and presence of an adjacent organ pipe, Coltman[23] asserts, on the basis of somewhat limited microphone measurements, that the center of the dipole is located not at the tip of the edge, but downstream of it (i.e., $\epsilon > 0$).

Tam and Block[24] summarize source-like models of unsteady shear-layer/corner interactions occurring in cavity-type geometries. Their own formulation involves a simple line source at the corner (Fig. 3c), justified by the schlieren visualization of Krishnamurty[25] (i.e., Karamcheti) and the water table observations of Heller and Bliss[26]; these studies show that upstream traveling compression waves generated at the corner, by (downward) shear-layer deflection at the corner, are in phase on upper and lower sides of the cavity shear layer (before being distorted by the mean flow difference). This contrasts with the mass inflow/outflow concept at the corner reasoned by Bilanin and Covert[27] which, in essence, gives rise to out-of-phase acoustic waves above and below the shear layer, i.e., dipole radiation behavior. Dipole behavior at a confined impingement corner has been hypothesized by Keller and Escudier[28]; the corner is bounded by an adjacent (parallel) wall, thereby constricting the flow in this region. In general, it would be insightful to carry out detailed pressure correlations at the impingement edge, or corner, in conjunction with one of the aforementioned visualization techniques,[25,26,28] to move toward a clearer resolution of the nature and location of the sources.

### Vortex Sheets

Impingement of an infinitesimally thin vortex sheet upon a leading edge (Fig. 3e) or corner (Fig. 3f) is addressed by Moehring,[29] Howe,[30] and Crighton and Innes[31] in conjunction with their studies of unstable flow past a slit and by Howe[30] and Covert,[32] for flow past a cavity. Moehring and Covert assume that the sheet remains attached at the leading edge/corner for all time [i.e., $\eta(L,t) = 0$]; however, Crighton and Innes show that the condition of Moehring can lead to no nontrivial solution of the slit oscillation if the flow is incompressible. In their analysis, they allow the vortex sheet displacement to have a "simple finite time-harmonic jump discontinuity" at the leading edge, compared with the "infinite jump" of Howe. However, Howe points out that such a singularity in his linear model is in sympathy with the actual nonlinear and discontinuous behavior at the edge. As yet, a direct experimental assessment of these assumed interactions at the edge is lacking; it is complicated by the highly distributed vorticity of the laboratory shear layer. Instead of shear-layer deflection, a more meaningful comparison may well involve theoretical and experimental pressure fields at the impingement surface.

### Single Point Vortices

For those self-sustained oscillations involving impingement of highly coherent vortices upon a leading edge, some insight may be gained by examining the hydrodynamics of highly concentrated vorticity impinging upon solid surfaces. Interaction of point (line) vortices with leading edges, corners, and plates has been examined with the objective of corroborating calculated results for sound scattering by solid surfaces (e.g., Figs. 3g, 3k), facilitated by exact solution of the corresponding hydrodynamic fields (reviewed by Crighton[19]); gaining insight into the "competition" between the mean potential- and (vortex) image-induced flows and the resultant sound radiation[33] (Fig. 3g); relating blade lift fluctuations to the acoustic far field[34] (Fig. 3i); illustrating "vorticity segregation" (Fig. 3h), whereby an incident vortex can be swept above or below a leading edge, depending on its dimensionless circulation[35]; and predicting time-averaged spectra associated with amplitude modulation of pressure fields at an impingement corner (Fig. 3i) due to variation in impingement location of successive vortices.[36] These simplified models involving highly concentrated vorticity cannot be expected to effectively simulate most features of an impinging shear layer in the laboratory,[38,39] where vorticity tends to be distributed over the entire distance (i.e., wavelength) between adjacent vortices as modeled by Stuart.[37] However, in certain cases, trajectories of laboratory vortices (Fig. 3j) can be approximated by assigning a sufficiently weak strength to point vortices, even though the phase between induced surface pressure and vortex position is not well predicted.[36] Moreover, by employing a novel means of representing the viscous core of a vortex such as defining an effective distance ($h$) of a vortex below the blade[34] (Fig. 3i), the form of the induced lift and the radiated noise are shown to be in agreement with experiment.

#### Multiple Discrete Vortices

Simulation of vortex impingement upon leading edges/corners (Fig. 3ℓ, 3m) may be attainable using the discrete vortex technique involving sheets of point vortices or finite-core vortices (i.e., vortex blobs). Although this technique has seen remarkable success in dynamic simulation of free shear layers as well as time-averaged velocity and turbulent stress distributions of internal, reattaching flows (e.g., Clements and Maull,[40] Ashurst and Durst[41]) little attention seems to have been given to unsteady loading of impingement surfaces; of course, accurate modeling of the detailed structure of the distorted vortex incident upon the surface is essential. The schematics of Figs. 3l, 3m pose the central challenge to the predictor: a defined distribution of vorticity of the incident vortex, and shedding of vorticity of opposite sign at the edge. For both slender leading edges and corners, this secondary vortex shedding is markedly consistent (see Figs. 4-7); however, there may be difficulties in numerically treating it as a truly self-generated phenomenon arising from impingement of the large-scale distributed vorticity. Critical assessments of the multiple discrete vortex technique are given by Clements and Maull,[40] Fink and Soh,[43] Saffman and Baker,[44] Maull,[45] and Leonard.[46] In addition, consideration should be given to the technique of Christiansen[42] in modeling the "severing" of the incident distributed vorticity.

#### Distributed Vorticity

Rather than simulating the distribution of vortices by a number of discrete vortices, direct (albeit linear) representation in terms of a distributed disturbance field $[\tilde{\Omega}_z(x,y,t)]$

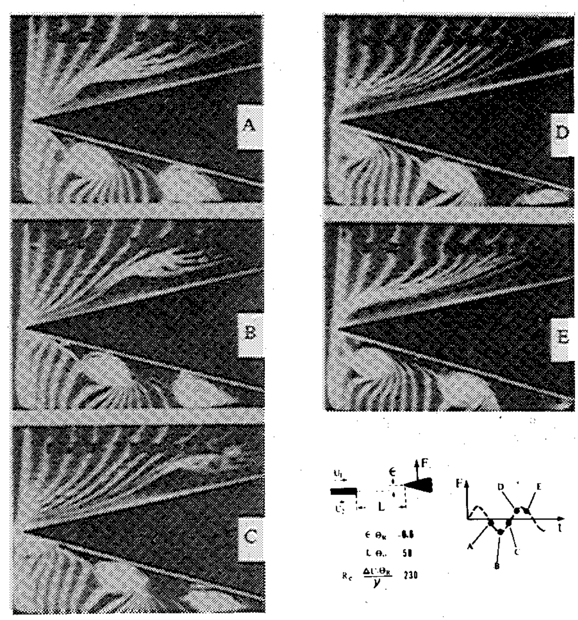


**Fig. 5 Same interaction as for Fig. 4 with hydrogen bubble wire at leading edge.**

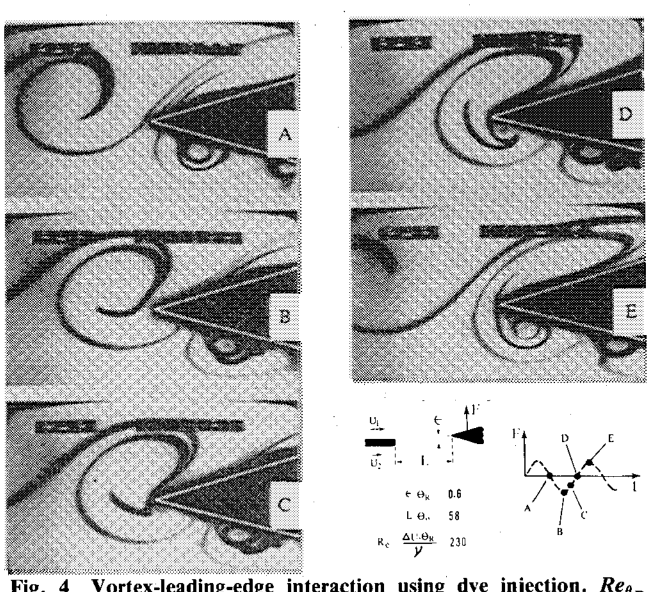


**Fig. 4 Vortex-leading-edge interaction using dye injection. $Re_{\theta_R} = 230$; $\epsilon/\theta_R = -1.6$ (Ref. 39).**

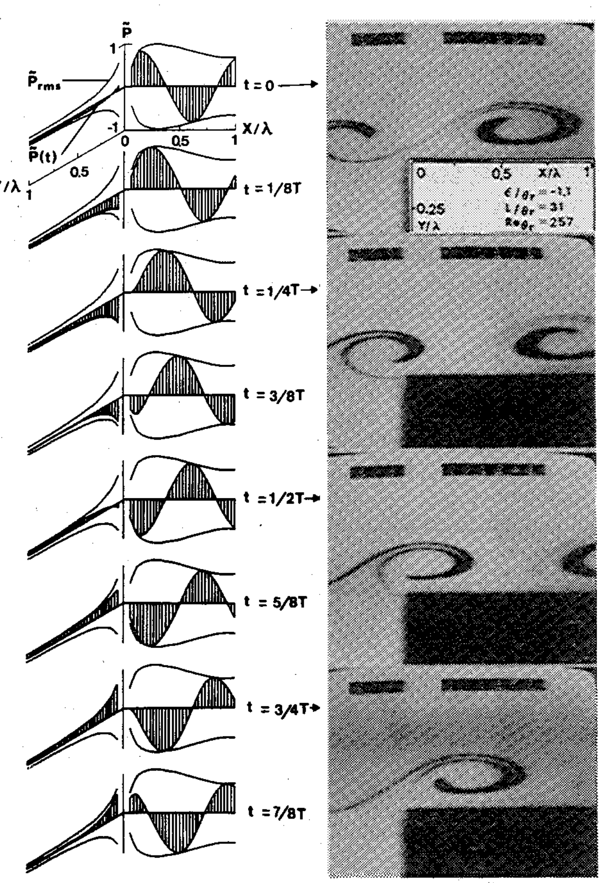


**Fig. 6 Vortex-corner interaction and instantaneous pressure fields for case where major share of incident vortex passes above corner. $Re_{\theta_R} = 257$; $\epsilon/\theta_R = -1.1$, $L/\theta_R = 31$ (Ref. 61).**

traveling downstream and encountering an impermeable surface can be employed. Such inviscid modeling of distributed vorticity-edge interaction has involved either assuming that the vortex structure is invariant as it passes by or impinges upon the surface, or accounting for detailed distortion of, for example, the instantaneous streamlines in the interaction region. Concerning the former, Widnall and Wolf[47] relate the upwash seen by the airfoil to the vorticity distribution, offset ($h$), and angle of obliqueness of the vortex (Fig. 3n); consequently, induced lift and radiated noise can be related to vortex structure by linear aerodynamic theory. With regard to the impingement of an incident vortex upon a leading edge, Ziada and Rockwell[39] have assumed that an inviscid, linearized distribution of vorticity[37] remains undistorted, the induced force being proportional to annhiliation of transverse momentum of the vortex by the edge (Fig. 3o); phase and relative amplitude of the force are reasonably well-modeled.

Concerning the category of flows where distortion of the incident vorticity field is accommodated, Goldstein and Attasi[48] have developed a second-order theory involving incidence of a periodic gust, having defined streamwise and transverse wavenumbers, upon an airfoil of finite thickness and camber accounting for gust distortion by the steady-state potential flow (Fig. 3p). For the special case of nonlinearized flow about a thin flat plate at nonzero incidence, the Kutta condition at the trailing edge is satisfied by appropriate choice of circulation, leaving a singularity at the leading edge. Rogler[49,50] takes a different approach to the distortion problem, concentrating on the effect of "impermeability" of a thin flat plate at zero incidence immersed in a rotational disturbance field; a variety of disturbance fields are examined, and detailed consideration is given to the leading-edge region. For example, for an array of square vortices (Fig. 3q) and a vortex street (Fig. 3r), severe distortion of the streamlines is readily apparent in both cases. Moreover, pressure isobars for the case of Fig. 3q clearly depict a singularity at the leading edge. With regard to distortion of the approach flow imposed by the edge, these elliptic formulations of Rogler typically show that disturbance streamlines are distorted, at most, about a quarter-wavelength upstream of the edge; however, the incident vorticity disturbances were uninfluenced. This extent of distortion of the upstream velocity field agrees with LDA measurements of Rockwell and Knisely[38] wherein the structure of the vortex was found to be distorted a distance less than about one-half wavelength upstream of the edge. Although these representations of the interaction formulated by Rogler may approximate certain aspects of large-scale activity near the leading edge, he correctly points out that, at least in the domain very near the edge, nonlinear and viscous effects must be accounted for. Vortex shedding resulting from viscous-inviscid interaction at the edge could well lead to a scale of the shed vortex commensurate with that of the incident vortex (e.g., see Figs. 4 and 5); consequently, caution is required in considering apparently "localized" viscous effects.

### Incident Disturbance-Instability Wave Conversion

Many of the aforementioned models involve a singularity at the leading edge; a possible means of relieving such a singularity involves generation of an instability wave at the edge, triggered by nonlinear and viscous effects. (For certain ranges of frequency, amplitude, and viscosity, separation may also be required to completely relieve the singularity.) Goldstein[51] and Howe[52] simulate this conversion between an incident disturbance and an instability wave, along with the resultant diffracted field, important for assessing the nature of the upstream influence of interest herein. In his formulation of this interaction, Goldstein considers a harmonic disturbance and a sheared mean flow incident upon a leading edge, triggering exponentially growing instability waves downstream of the edge (Fig. 3s). By considering the simplified case of a uniform (plug) mean flow upstream of the edge, and both causal (but singular leading-edge and unbounded at infinity) and nonsingular leading-edge (but noncausal and unbounded) solutions, he demonstrates that the normalized amplitude of the instability wave at the edge (at a given Helmholtz number) tends to a maximum as $\theta_G \to \pi/2$ (see Fig. 3s).

Goldstein[53,54] also examines the case where the incident acoustic wave of Fig. 3s is replaced by a propagating vortical disturbance in a mean shear flow, with the corresponding trailing-edge problem being examined as well. Both high- and low-frequency limiting cases were considered. In the high-frequency limit, the concept of the Kutta condition and causality become irrelevant because the shear-layer instability waves are "cut off." The low-frequency limit[53,54] does include the downstream instability wave triggered at the edge through a Kutta condition or causality; however, in this limit, the solutions corresponding to imposition of either a Kutta condition or causality are the same, both differing from the solution not associated with an instability wave but satisfying boundedness at infinity.[55] Experimental shapes of the leading-edge radiation patterns, taken for a long flat plate in turbulent flow,[56] show excellent agreement with Goldstein's[54] theory. Goldstein[55] points out that such agreement is possible only because the triggered instability waves are included in his analysis; the unresolved issue is whether causality or a Kutta condition is most appropriate. For the corresponding trailing-edge case, changes in experimental radiation patterns with variations in velocity[57] exhibit impressive agreement with Goldstein's[54] theory. It should be noted that, in essence, this appoach of Goldstein lies within the category of "rapid distortion" theories, whereby linear models can effectively simulate turbulent flows encountering "brutal" changes over short streamwise distances (see review of Moffatt[58]).

Howe considers the interaction of an incident sound field with a leading edge and the associated displacement thickness (or "velocity thickness" $\bar{v}$) of the boundary layer downstream of the edge (Fig. 3t). This analysis is based on a proposal of Liepmann[59] relating radiated sound to displacement velocity fluctuations immediately outside a boundary layer. By assuming a (not necessarily neutrally stable) vortex sheet model of the boundary layer and imposing the Kutta condition at the leading edge, it is shown that the augmentation of incident acoustic energy and the amplitude of induced velocity ($\bar{v}$) fluctuations is largest for incident acoustic waves from the downstream direction ($\theta_H = \pi$); this result, differing by $\pi/2$ from the prediction of Goldstein, physically means that acoustic waves traveling upstream to the edge yield maximum perturbations in the vicinity of the edge, resulting, in turn, in boundary-layer waves of "proportionate amplitude." Such acoustic waves can occur, for example, in a flue pipe organ pipe, where the leading edge is at the mount of the organ pipe. Howe[60] also applies a similar concept of displacement thickness fluctuations to the trailing-edge problem, accounting for the changes in properties of turbulence as it negotiates the edge and generates noise.

### Overview

Although each of the above models of simulating the leading-edge interaction has, in its own right, provided insight, much remains to be done in order to resolve the roles of nonlinear and viscous effects in the edge region, with a view toward clarifying the associated upstream influence; moreover, the phase between the incident unsteadiness and the upstream influence is desirable in arriving at an overall description of the oscillation process. Ziada and Rockwell[39] have characterized the amplitude and phasing of the force induced at the leading edge relative to the structure and offset of an incident vortex. As shown in Figs. 4 and 5, the leading-edge events are associated with shedding of vorticity having substantial scale relative to the incident concentration of vorticity. The amplitude and phase of the induced force, as well as the induced velocity at the upstream separation edge, were found to be very sensitive to variations of vortex offset ($\epsilon$) relative to the leading edge. Regarding the vortex shedding at the leading edge, it most likely relieves the pressure singularity there; extensive pressure correlations to resolve the degree to which this shedding mechanism dominates the force on the edge are currently underway.

As for the corner configuration, Tang and Rockwell[61] have examined the relationship between the induced pressure field and vortex-corner interaction, using simultaneous visualization and pressure correlation techniques, as a function of the transverse offset of the incident vortex. One case is shown in Fig. 6, where the major share of the incident concentration of vorticity passes above the corner. Along the top surface of the corner, the pressure amplitude decays slowly, compared to the rapid drop-off along the front face. Similar studies to those shown in Fig. 6 reveal that as a greater fraction of the incident vorticity is swept down along the front face of the corner, the instantaneous pressure (and force) fields on the top and front faces show an increased tendency toward dipole-like behavior. At longer impingement length ($L$) scales than those of Fig. 6, the interaction process exhibits rhythmic variations between vortex-corner patterns, as illustrated in Fig. 7, for the case where the incident vortex is "severed" at the corner (i.e., two complete cycles of the incident vortex correspond to one cycle of the rhythmic pattern). Such interactions yield substantial amplitude modulation of the upstream region of the shear layer.[62]

The aforementioned edge and corner interactions focus on the intermediate Reynolds number, incompressible regime. If the extreme case of shock-wave/corner interaction (in absence of vorticity of the incident flow) is examined (see Fig. 8), there is clear depiction of the diffracted and reflected waves, as well as the inducement of a concentration of vorticity through nonlinear and viscous effects. Moreover, the effect of sharpness of the edge on the interaction is shown for four cases: a small rounding of the edge drastically attenuates the shedding vorticity. These interactions, as well as a series of related wave-edge studies are summarized by Krause[64]; of course, they have importance for the case of incident disturbance—trailing-edge conversion as well—to be discussed subsequently.

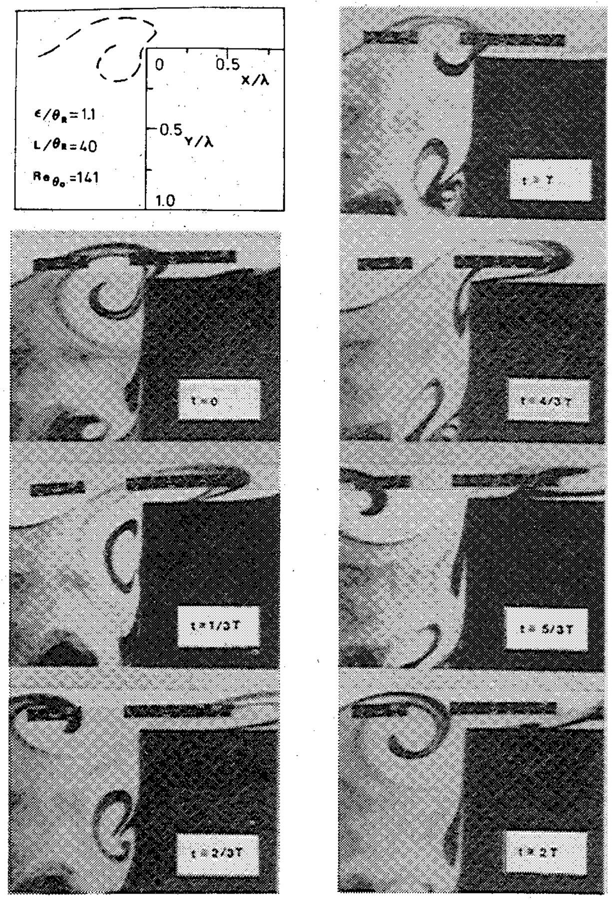


Fig. 7 Vortex-corner interaction at longer length scale showing variance of interaction mechanisms. $\epsilon/\theta_R = 1.1$; $L/\theta_R = 40$ (Ref. 61).

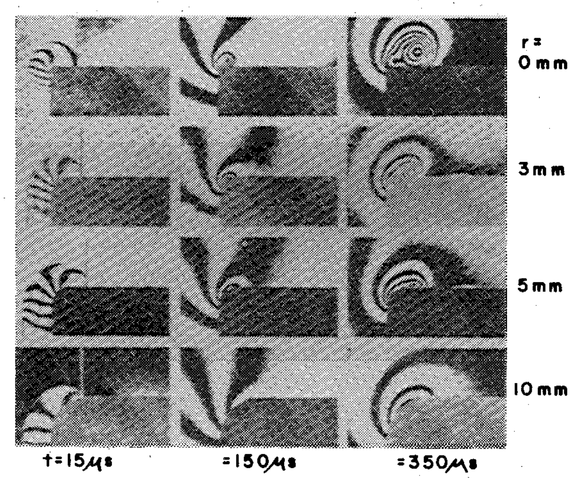


Fig. 8 Effect of roundness of edge on shock-corner interaction (Ref. 63).

## Upstream Influence

Since the upstream influence originating from the unsteady flow-surface interaction (at $x \approx L$) has its greatest consequence in the sensitive region near shear-layer separation ($x \sim 0$), the appropriate scale is impingement length $L$, normalized with respect to acoustic wavelength ($\lambda_a$). Often this sensitive region does not lie in the far field of the impingement region (i.e., $L/\lambda_a \gg 2\pi$ not satisfied), and near field or even "proximal field"[65] effects must be accounted for. Furthermore, if $L$ is not a significant fraction of $\lambda_a$, the upstream influence takes the aforementioned form of "pseudo-sound,"[15] the sensitive region lying on the nonpropagating pressure field of the impingement region; or, the effects of Biot-Savart induction are (essentially) instantaneously felt in the upstream sensitive regions.

Interpretation of the character of the upstream influence is depicted in Fig. 9 for three quite different configurations and values of $L/\lambda_a$. The nature of this influence is deduced from pressure measurements and/or visualization (distance between wave fronts not drawn to scale). Powell[22] has quantified the dipole nature of the pressure field resulting from planar jet-edge interaction shown in Fig. 9a; its influence on the sensitive region of the shear layer near the nozzle is interpreted in terms of the velocity induced by the dipole. Ho and Nosseir[16] show that the wave fronts due to axisymmetric jet (i.e., large-scale vortex rings) plate interaction (Fig. 9b) are at an angle of about 30 deg with respect to the jet axis, this angle being attributed to refraction effects associated with the wall jet on the plate. In the presence of an adjacent reflector or resonator (i.e., cavity), the wave front pattern takes on the sort of complexity shown in Fig. 4c, constructed by Tam and Block[24] with the aid of the visual study of Heller and Bliss,[26] and neglecting relatively weak secondary reflections. As shown, parts of waves above the shear layer propagate outward without reflections; within the cavity, wave front E′E″ experiences reflection at the trailing (end) and bottom walls of the cavity, producing wave fronts B′B″ and A′A″. In general, all three of these fronts should be considered in modeling the excitation of the shear layer; according to Tam and Block, reflected waves A′A″ have the greatest consequence. In fact, the high-speed visualization of Keller and

Escudier[28] shows a strong correlation between a wave front having the same orientations as A′A″ (not resulting from bottom wall reflection) and the formation of a large-scale structure in the separating shear layer.

Figures 9a-9c show that the orientation of and phasing between upstream traveling wave fronts and induced velocity fields are strongly dependent upon the nature of the flow-surface interaction, as well as adjacent reflectors; as will be shown, these aspects play a key role in determining the effectiveness of the conversion process in the sensitive upstream (trailing-edge) region. Concerning amplitude of the upstream influence (upstream pressure/velocity) in the region $x \approx 0$, little attention has been given to characterizing it experimentally. It is complicated by distortion of the induced velocity field, as well as diffraction of the arriving pressure waves, at the separation edge. Moreover, a major difficulty in determining, for example, the induced velocity field is sorting out the upstream-induced fluctuations from these associated with the amplifying disturbance in the separating shear layer. However, the relative strength of the upstream influence as functions of interaction mechanisms at impingement and impingement length scale can be deduced from measurements at the edge of the separating shear layer.[62,66] In the event that the sensitive region ($x \approx 0$) of the shear layer lies in the propagating pressure field of the source at the impingement region, the pressure amplitude can be sufficiently large ($p \sim \rho c_0 u$) to nonlinearly excite the separating shear layer,[16] drastically influencing its downstream evolution. In the following, the conversion between the upstream influence and fluctuations within the separating shear layer are discussed.

## Disturbance Conversion at Trailing Edge

Effective conversion of disturbances incident upon the sensitive region of the shear layer near separation (i.e., near the trailing edge) to downstream traveling instability waves is essential if an oscillation is to be self-sustaining. Moreover, it sets the initial fluctuation level of the shear-layer velocity fluctuations, thereby determining the streamwise extent of the exponential growth region of the fluctuations. This conversion process has received considerable attention for externally excited, nonimpinging flows, primarily from an analytical perspective. Inviscid simulation typically involves imposition of a Kutta condition to remove the trailing-edge singularity, the level of the singularity being relative to the magnitude of the shed vorticity. However, Crighton and Leppington[67] stress causality rather than the Kutta condition in their simulation of the case of discontinous mean velocity across the trailing edge; indeed, Goldstein[51] asserts that for some trailing-edge problems, uniqueness of the solution cannot be attained by employing the Kutta condition, in contrast to the causality condition, which he interprets as a "sort of radiation condition for instability waves," requiring all such waves to propagate outward from their sources. Howe[68] considers the Kutta condition within the framework of trailing-edge noise, and considers the validity of its application as unresolved. Concerning the physical nature of the Kutta condition, Bechert and Pfizenmaier[69] discuss the ramifications of assuming "full" and "rectified" conditions and related analytical studies. As for calculations of the trailing-edge region directly involving viscous effects, Rienstra[70] summarizes his own and previous "triple deck" studies (e.g., most recently Brown and Daniels,[71] and Daniels[72]); in essence, the existence of the Kutta condition appears to be confirmed at low frequencies and amplitudes. To maximize the "receptivity" or effectiveness of the conversion at the edge, Morkovin and Paranjape[73] stress the role of edge sharpness and transverse pressure gradient of the applied disturbance. Concerning the inherent receptivity of a shear layer to incident acoustical disturbances in the absence of trailing-edge effects, Tam[74,75] has analyzed obliquely excited planar, as well as axially excited axisymmetric, shear layers. For a planar shear layer at moderate subsonic Mach number, an incident acoustic beam at an angle between 50 and 80 deg to the mean flow direction is most effective, narrower beams enhancing the effectiveness of the excitation.

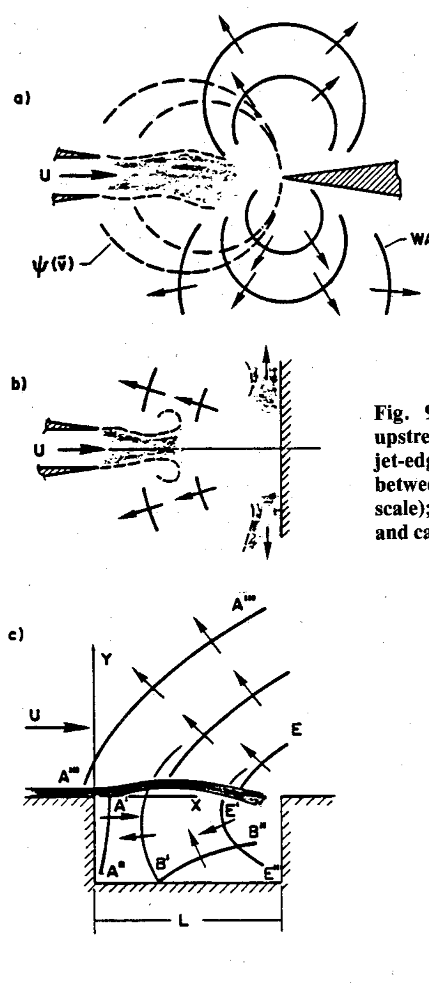


**Fig. 9 Interpretations of upstream influence for a) jet-edge (Ref. 22) (distance between wave fronts not to scale); b) jet-plate (Ref. 16); and cavity (Ref. 24).**

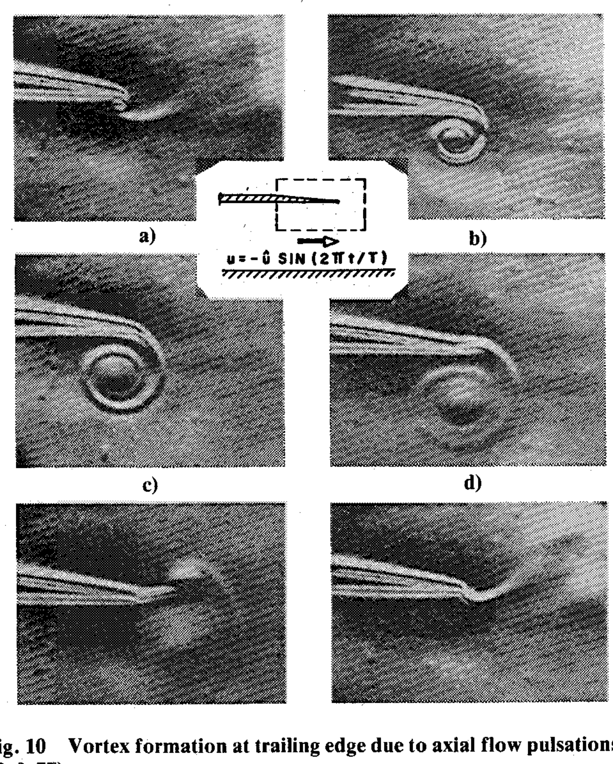


**Fig. 10 Vortex formation at trailing edge due to axial flow pulsations (Ref. 77).**

Experimental characterization of the very near field of an axisymmetric jet (excited by a loudspeaker upstream of its nozzle) in terms of the "jet order deflection" (i.e., deflection of smoke streakline emanating from nozzle lip) by Bechert and Pfizenmaier[69] reveals that the deflection envelope takes the form of a parabolic-shaped region, its size becoming smaller with decreasing Strouhal number. Interpretation of such measurements of the laboratory shear layer within the framework of the aforementioned studies involving inviscid, infinitesimally thin shear layers requires considerable caution: Bechert and Pfizenmaier note that if one focuses on the outer potential flow at the outer border of the shear layer, their measurements suggest transition from a full Kutta to a non-Kutta condition as frequency of excitation is increased. It is important to note that their investigation was limited to low Helmholtz numbers ($He = MS_D = D/\lambda_a$), allowing an assumption of incompressibility,[76] and to fully laminar conditions at boundary-layer separation. It is also insightful to examine the nonlinear nature of trailing-edge dynamics (in contrast to the linear study of Bechert and Pfizenmaier) due to axial flow pulsations, as shown in Fig. 10. During the suction part of the cycle (Figs. 10a-10c), there is well-defined vortex formation, followed by its ejection during discharge. Though it is not obvious in Fig. 10, Disselhorst and Van Wijngaarden[77] contend, from study of additional close-up photos, that the Kutta condition is satisfied at all instants of time in that streamlines leave tangent to the trailing edge.

In general, there will be diffraction of an incident pulse or harmonic plane waves at the trailing edge as illustrated conceptually by Rienstra[70] (Fig. 11) for the case of a wake flow. With regard to this diffracted wave, an interesting approach to examining the trailing-edge region involves visualization of incident, reflected, and diffracted waves via a schlieren technique[78,79] then with the aid of inviscid, thin shear-layer theories accounting for the nature of the diffracted wave at the edge[70,80] or even its cancellation,[80] attempt to link together the degree to which the Kutta condition is satisfied and the character of the diffracted wave. Though it is much to ask experimentally, combining such a visualization method with the quantitative optical compensation technique of Bechert and Pfizenmaier would allow direct assessment of these complex wave interactions and related shear-layer deflections in the trailing-edge region. In fact, if the extreme, highly nonlinear, case of a shock wave passing over a trailing edge is examined, the phase relations between transmitted and diffracted waves, as well as the associated vortex shedding, can be dramatically depicted (see Fig. 12).

In summary, among the unresolved aspects of the trailing-edge domain are the effects of the character of possible turbulence of the approach flow; the separation of the mean flow just upstream of the edge; the location of, and phasing between, sources in downstream regions of the flow; and higher frequencies and amplitudes of excitation—such amplitudes arising, for example, in the presence of adjacent acoustic resonators. In these situations, the initial fluctuation level induced in the shear layer at separation may be so high that the exponential growth region of the instability wave is bypassed entirely.

## Streamwise Amplification of Disturbances

Disturbance growth in the shear layer is usually characterized by initially exponential amplification (i.e., "linear growth" on semi-log coordinates), followed by nonlinear distortion involving energy transfer between the fundamental and its higher harmonics (see Fig. 1). Moreover, there exist mechanisms whereby frequency components lower than the fundamental can become substantial in downstream regions of the flow, their effect extending to upstream regions of the shear layer. If the impingement length scale is sufficiently long, onset of substantial three-dimensional effects can be expected. It is insightful to examine all these features for cases of both externally excited oscillations of nonimpinging shear layers and corresponding self-excited oscillations of impinging shear layers, bringing out equivalent or differentiating aspects.

### Linear Growth Region—Parallel Flow Approximations

Exponential growth of disturbances induced by external excitation (via loudspeaker) of nonimpinging shear layers for laminar (e.g., Freymuth[83]) as well as turbulent[84-86] boundary layers at separation can, in general, be remarkably well simulated via an inviscid stability theory assuming quasiparallel flow.[81] In comparing predicted and experimental disturbance growth rates ($-\alpha_i\theta$) and wavenumbers ($2\pi\theta\lambda$), assuming parallel flow, it is necessary to select an appropriate value of $\theta$, keeping in mind that, for transitional mixing layers, its value can increase severalfold over typical length scales $L$. Too often, the choice of $\theta$ is unclear, clouding the significance of comparison with parallel theory; a suitable approximation involves choosing $\theta$ at the middle of the linear growth region.[62,66] This dilemma might seem to be alleviated by considering the streamwise evolution of the flow to be a succession of locally parallel flows.[86,88,89] Indeed, the remarkable agreement of data of Fiedler et al. at low Strouhal number with Michalke's parallel flow theory, involving variation of $-\alpha_i\theta$ with streamwise dependent Strouhal numbers, $S = f\cdot(x - x_0)/U$ and $S_\theta = f\cdot\theta(x)/U$, is intriguing. However, recent jet studies of Crighton and Gaster[90] and Plaschko[91] using the technique of multiple scales, as well as the free- and boundary-layer studies of Haaland[92,93] and Saric and Nayfeh[94] involving the Orr-Sommerfeld equation, accounting for nonparallelism of the flow, emphasize that there are additional contributions, dependent upon streamwise and transverse coordinates, that

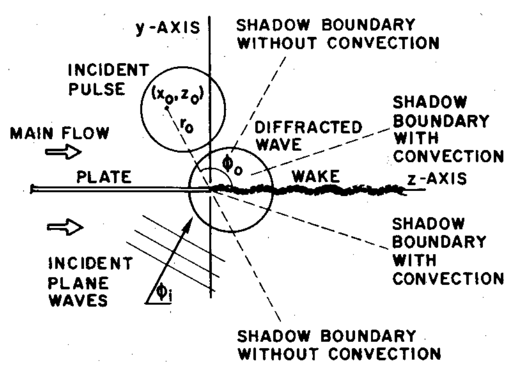


**Fig. 11 Diffracted wave and wake fields at trailing edge associated with incident pulse or incident harmonic waves (after Rienstra) (Ref. 70).**

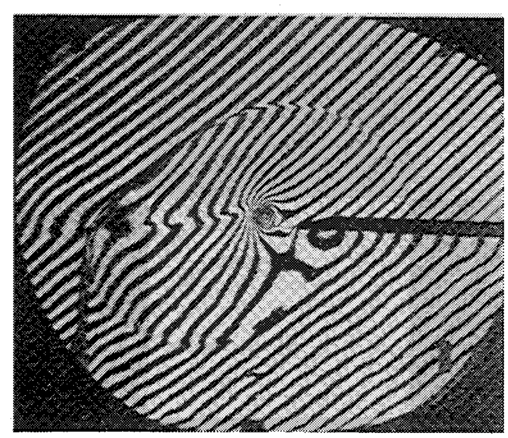

**Fig. 12 Formation of vortex in two-stream turbulent mixing layer and diffraction pattern at trailing edge due to passage of shock wave over a trailing edge. Flow from right to left; higher-speed stream on bottom; shock passes through high-speed stream (Ref. 82).**

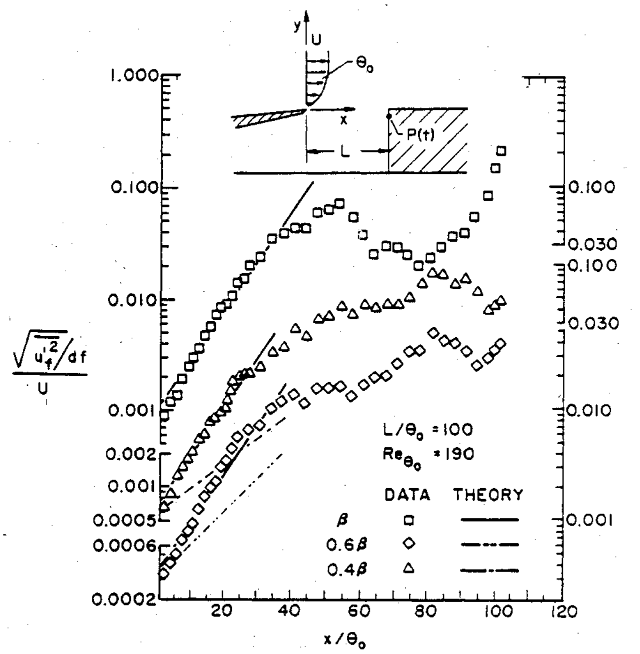


**Fig. 13 Growth rates of low-frequency components ($\sim 0.4\beta$, $\sim 0.6\beta$) and fundamental ($\beta$) with downstream distance. $Re_{\theta_0} = 190$; $L/\theta_0 = 100$ (Ref. 62).**

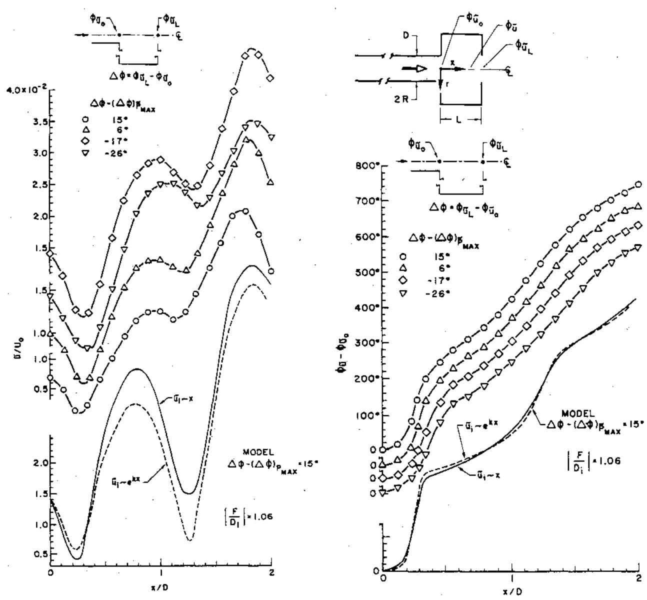


**Fig. 14 Distributions of organized wave amplitude and phase along centerline of cavity for case where acoustic wave and instability wave have nearly equal amplitudes at separation ($Re_{\theta_0} = 2.2 \times 10^3$; $L/D = 2$). Curve parameter is deviation of phase difference of centerline velocity $\Delta\phi = \phi_{\tilde{u}_L} - \phi_{\tilde{u}_0}$ from that value producing maximum organized pressure amplitude $[(\Delta\phi)\tilde{p}_{max} = (\phi_{\tilde{u}_L} - \phi_{\tilde{u}_0})\tilde{p}_{max}]$ (Ref. 102).**

must be accounted for in making meaningful comparisons. Physical consideration of the magnitude of the nonparallel correction terms for a range of shear-layer parameters, as well as comparison of the evolution of transverse amplitude and phase distributions, is called for.

### Linear Growth Region—Modulation Effects

Experimental study of the linear growth region of nonimpinging shear layers typically involves excitation at a discrete frequency (e.g., Freymuth[83]); however, self-excited impinging flows are driven by unsteady events at the impingement edge that may exhibit time-dependent variations in amplitude and phase, especially at larger values of impingement length $L$.[62] Such variations have been discussed in conjunction with Fig. 7. In general, the upstream consequence is an amplitude-modulated growth of the disturbance in the linear region. As shown in Fig. 13, the frequency components ($\sim 0.4\beta$, $0.6\beta$) associated with an amplitude modulation of the oscillation at the fundamental ($\beta$) follow the growth rate of the fundamental, rather than independently growing at their own rate[83,87]; as will be discussed, all of this is associated with a process of nonlinear wave interaction.[62] On the basis of these observations, it is evident that spectral analysis can tell what frequencies are present (e.g., $\sim 0.4\beta$, $\sim 0.6\beta$), but reveals little of the mechanisms involved. Since a number of oscillations exhibit multiple frequency behavior (e.g., Rossiter,[95] Tam and Block,[24] and Rockwell and Naudascher[96]), it would be of interest to characterize the linear growth rates of such oscillations to determine the extent to which each of the components grows independently. A different experimental approach to this moduluation concept is to excite the impingement edge of an oscillating mixing layer that otherwise exhibits well-defined growth of a single frequency component $\beta$. Not only do multiple peaks appear in velocity spectra taken in the linear growth region, but at certain excitation frequencies there is remarkably well-ordered modulation (in position and vorticity concentration) of vortices incident upon the edge.[97]

### Linear Growth Region—Acoustic Wave Contamination

Streamwise variations of amplitude[98-103] and phase[102] may be significantly influenced by background acoustic waves arising from loudspeaker excitation or self-excitation of an acoustic mode of the system (see Fig. 14). Consequently, measured growth rates (top of Fig. 14) and streamwise phase variations (bottom of Fig. 14) cannot be modeled using hydrodynamic stability concepts if the ratio of acoustic to instability wave amplitude is sufficiently high, even though the acoustic wavelength is much larger than the instability wavelength.[102] Rather, it is necessary to superpose hydrodynamic and acoustic wave contributions (see models of Fig. 14). Moreover, from examining a case where the relative acoustic wave amplitude is smaller than that of Fig. 14 (see Ref. 102), it is evident that apparent spatial nonhomogeneity associated with the nozzle exit region, and apparent occurrence of nonlinear saturation of disturbance amplitude, may be due, at least in part, to simple superposition of acoustic and instability waves. The dilemma in estimating these effects is that the degree of acoustic wave contamination can, in general, be determined accurately only by combinations of velocity and pressure measurements, since the acoustic $Q$ factor of a system is a function of flow-dependent impedances.

### Onset of Nonlinear Distortion and Saturation

Departure from the experimental (i.e., "linear") growth of disturbances occurs when the disturbance amplitude becomes sufficiently large, from about 0.02 to 0.30 of the freestream velocity, lower values occurring at higher frequencies.[83] For most impinging flows of practical interest, the nonlinear region extends over a substantial portion of the impingement length scale,[62,66,104] unless it is very short. In fact, in systems where there is acoustic resonance leading to high initial amplitudes, the linear growth region extends over the entire impingement length. The implication is that wavenumber values ($2\pi\theta/\lambda$) determined from linear theory are assumed to be valid in the nonlinear region as well; the essentially linear streamwise phase variations of fluctuation velocity taken along the edge of a mixing layer[66] and cavity[62] extending through the nonlinear region suggest that this is the case. Clearly, this aspect deserves critical evaluation; it should be noted that most models also embody the linear amplification factor ($-\alpha_i\theta$), obviously invalid in the nonlinear region.

### Vortex Coalescence

Continued evolution of the unstable shear layer downstream of the onset of nonlinear effects in a *nonimpinging* flow leads to vortex formation and successive vortex pairing, provided the initial conditions are laminar or quasilaminar (e.g., Winant and Browand,[106] Brown and Roshko,[107] Hussain,[108] and Rockwell and Niccolls[109]). The nature of this vortex coalescence is, at least at frequencies lower than the fundamental instability frequency, a strong function of the amplitude of the applied disturbance, simultaneous coalescence of several vortices occurring at sufficiently high amplitude[17] (see Fig. 15). At even lower excitation frequencies, as many as ten vortices can collectively coalesce (Ho and Nosseir[16]). For turbulent initial conditions, the acoustically excited (one-stream) shear layer exhibits large-scale coherent vortices that subsequently experience only occasional pairing[86] (Fig. 16). However, at high amplitudes of excitation, early and consistent pairing can be induced.

For corresponding impinging flows at low Mach number, where the oscillation is clearly "locked-on" and self-sustaining, there is no evidence that vortex coalescence occurs,[3,62,66,110] posing the intriguing question of to what extent the finite length scale $L$ inhibits the vortex interaction leading to coalescence. However, in certain cases, coalescence can be induced in impinging flows if, for example, free-surface effects interact with the unstable shear layer[111]; higher Mach number ($M \gtrsim 0.8$) results in large amplitude perturbations at separation[16]; or a long impingement length and a three-dimensional impingement process (narrow edge) minimize the "lock-on.[104]"

Whether or not such coalescence occurs has important consequences for the frequency, scale, and vorticity concentration of the vortical structure(s) incident upon the impingement edge, as well as the magnitude of the force induced at the edge. The Stuart[37] vortex model, which accommodates variable concentration of vorticity, has successfully simulated a single incident vortex in a mixing layer system,[39] though it may not be applicable for different upstream histories. It would be desirable to apply similar inviscid (and linearized) concepts, in the spirit of Stuart, as well as Knight and Murray[112] and Pierrehumbert and Widnall,[113] allowing simulation of the phase-averaged contours of constant vorticity[86,108] of incident vortical structures in turbulent shear layers, thereby defining the structure of the coherent unsteadiness incident upon the edge.

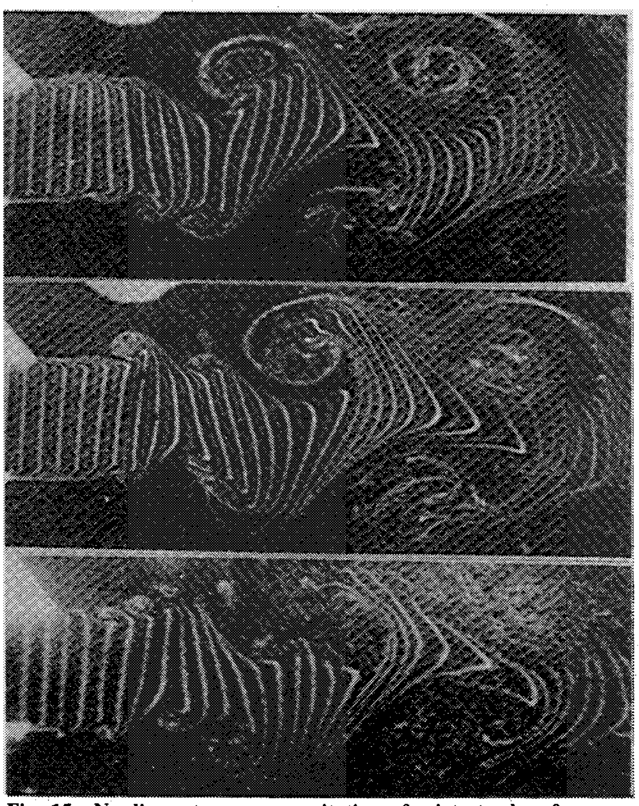

**Fig. 15 Nonlinear transverse excitation of a jet at a low frequency producing simultaneous coalescence of three vortices (top and middle photos: $Re_w = 5220$; $S_w = 0.32$) and a number of vortices (bottom photo; $Re_w = 10{,}500$: $S_w = 0.16$) (Ref. 17).**

### Multiple Frequency Content

Velocity and pressure spectra of excited nonimpinging[114] and nonexcited impinging[3,62,104] shear layers and impingement corners typically exhibit a number of organized peaks, representing frequencies higher and lower than the fundamental instability frequency of the shear layer. It is necessary to distinguish between the mechanisms giving rise to these various components, involving nonlinear distortion of the fundamental; vortex coalescence; and wave selection associated with the finite length scale (with and without adjacent resonators).

#### *Nonlinear Distortion of the Fundamental*

The onset of nonlinearity discussed earlier can also be viewed as the amplitude of the fundamental at which higher harmonics are detectable.[18,114-117] For purely hydrodynamic oscillations ($M \ll 1$), there appears to be equivalence between the (externally excited) nonimpinging and self-excited impinging shear layers,[18] both cases promoting formation of highly coherent (therefore strongly nonlinear) waves at the fundamental frequency $\beta$ leading to vortex formation. At least $2\beta$, $3\beta$, and $4\beta$ components are usually detectable, the higher harmonics having lower amplitudes (see Fig. 17). A comparison of the Stuart[118] and Robinson[119] nonlinear theories with growth rates of an impinging mixing layer where all higher harmonics grow 1.6 times as fast as the fundamental[18] shows that the strong nonlinear theory of Robinson is most appropriate. The nature of the nonlinear interaction sustaining the higher harmonics is addressed in the bicoherence analysis of Knisely and Rockwell.[62] It should be noted that even an excited shear layer having turbulent initial conditions[86] exhibits $2\beta$ and $3\beta$ components, their streamwise evolution being similar to the initially laminar mixing layer of Miksad,[114] thereby suggesting the predominance of inviscid mechanisms in the initially turbulent layer.

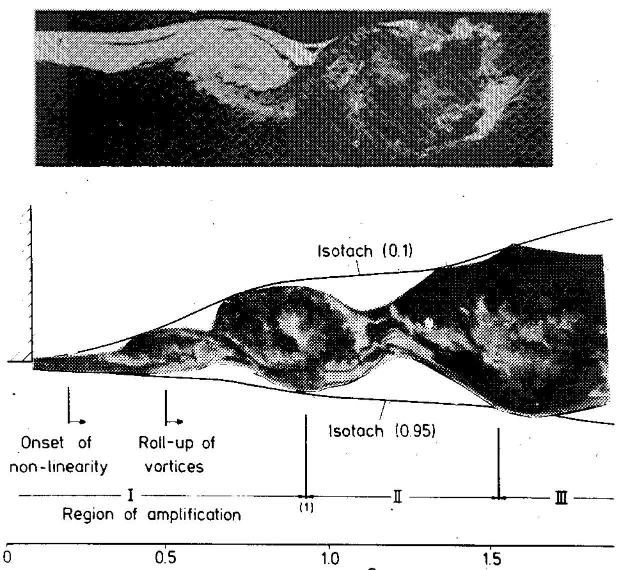


**Fig. 16 Development of externally excited shear layer having turbulent initial conditions (top photo); and regimes of development of the layer (bottom photo) (Ref. 86).**

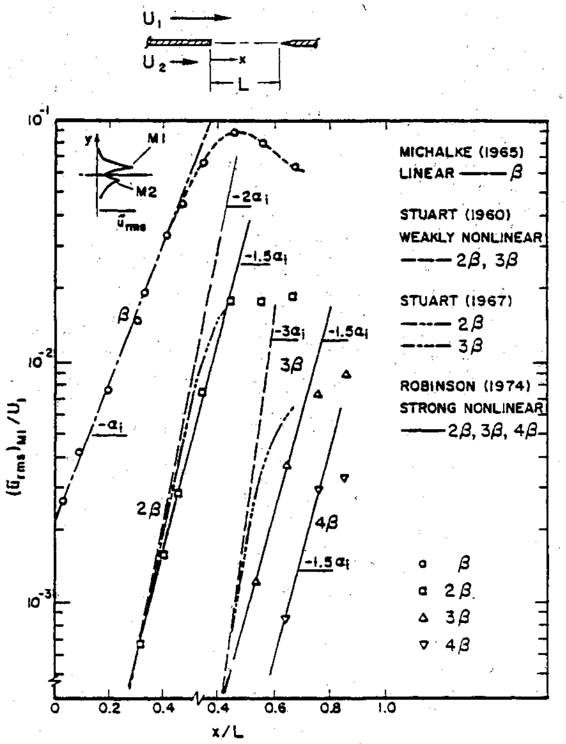

Fig. 17 Comparison of experimental and theoretical streamwise evolution of maximum fluctuation velocity components $\tilde{u}(\beta)_{MI}$, $\tilde{u}(2\beta)_{MI}$, $\tilde{u}(3\beta)_{MI}$ and $\tilde{u}(4\beta)_{MI}$. $L/\theta_0=37$, $Re_{\theta_0}=239$ (Ref. 18).

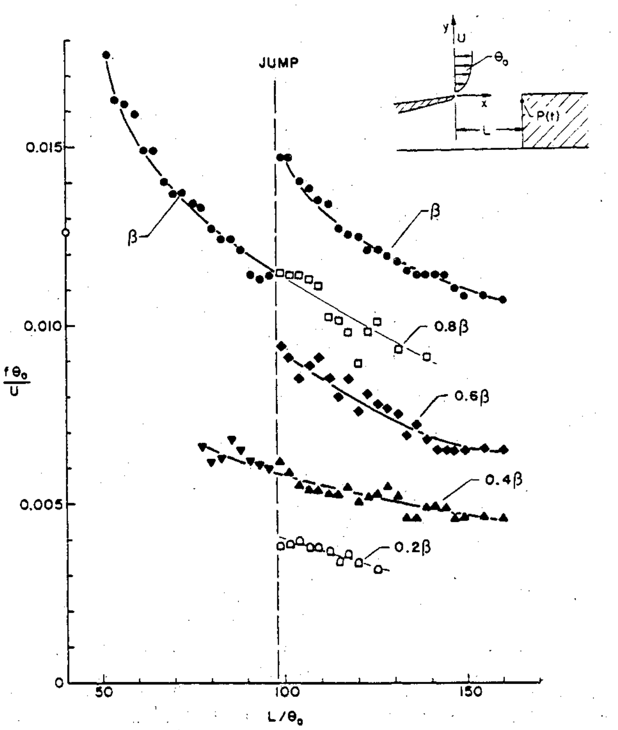

Fig. 18 Peak frequencies of pressure fluctuations spectra as a function of impingement length showing multiple low-frequency components after frequency jump, $Re_{\theta_0}=190$. Solid symbols indicate predominant and persistent components (Ref. 62).

*Vortex Coalescence*

In the simplest case of a nonimpinging shear layer, interaction of two adjacent vortices (initially formed at frequency $\beta$) yields a strong ($\beta/2$) subharmonic component, with its (nonlinear) harmonic $3\beta/2$, or harmonics, sometimes being detectable. Of course, simultaneous, or collective, coalescence of a number of vortices[16,17] or successive coalescence[120] produces a corresponding reduction in predominant frequency. In accordance with the aforementioned upstream influence, the lower frequency resulting from coalescence is clearly detectable in the region of flow well upstream of coalescence.[12,16,114] However, for impinging flows, coalescence tends not to occur for typical conditions noted previously; therefore an alternative mechanism must be responsible for the strong subharmonics observed in certain configurations of impinging flows,[62] addressed in the following.

*Wave Selection Associated with Finite Length Scale*

Existence of well-defined subharmonics ($0.5\beta$ or $\sim 0.4$, $0.6\beta$) of the fundamental ($\beta$) in a cavity shear layer can be traced to a self-selection process, whereby the fundamental and each subharmonic velocity fluctuation satisfy an overall phase difference of $\sim 2k\pi(k=1,2,...)$ over the impingement length $L$, in conjunction with nonlinear interaction between a subharmonic and the fundamental instability frequency. (The fact that these subharmonics $0.5\beta$ or $\sim 0.4$, $0.6\beta$ persist over a range of length scales $L$ is evidenced in Fig. 18; components $\sim 0.2$, $0.8\beta$ do not satisfy the overall phase $2k\pi$ and are nonpersistent.) Such nonliner interaction means that there must be a phase coherence between the waves, which can be quantified using bicoherence analysis. So, in general, for these subharmonics to be sustained, each must satisfy a certain phase difference ($2k$) over length $L$, determined by simple two-point (at $x=0$ and $x=L$) coherence measurements; and, simultaneously, there must be a phase coherence *between* them, determined by one-point bicoherence measurements.

Since each of the fundamental and subharmonic components satisfies a given phase difference over length $L$, their existence can most likely be predicted using one of the models summarized by Tam and Block[24] and Rockwell and Naudascher,[96] not accounting for possible phase coherence between the corresponding waves. Agreement of these models with various high- and low-speed data is indeed remarkable. However, the *origin* of certain of these waves, corresponding to simultaneously existing frequencies (as many as four in the study of Tam and Block[24]; see Fig. 19) may be due to nonlinear wave interaction, keeping in mind that when there is such nonlinear interaction (i.e., phase coherence) between any two waves, both sum and difference frequency waves can be generated.[62] This unresolved issue presents a fascinating prospect for further study.

*Effects of Intermittency*

Quite apart from all of these considerations, possible intermittency of the oscillating shear layer may produce multiple modes that apparently exist for all time. That is, an oscillation may have the potential to exist in more than one metastable state, erratically jumping between them[62]; classical time-averaged spectra of pressure and velocity fluctuations will show corresponding multiple peaks. To determine the degree of such intermittency, discrete event characterization, involving use of zero crossing statistics in conjunction with digital filtering, can provide self- and cross-probability densities of the discrete event history of the oscillation.[121]

**Three-Dimensional Effects**

Although oscillations of impinging flows are typically viewed as two-dimensional, a loss in spanwise (or azimuthal) coherence in downstream regions of the flow, and therefore at the impingement edge, can decrease the strength of the upstream influence, and consequently the amplitude of the oscillation. In fact, appropriate management of such three-dimensionality can provide effective attenuation of the coherent oscillation. This aspect will be addressed in a forthcoming work; herein only naturally occurring degradation of the two-dimensional structure of the flow is addressed.

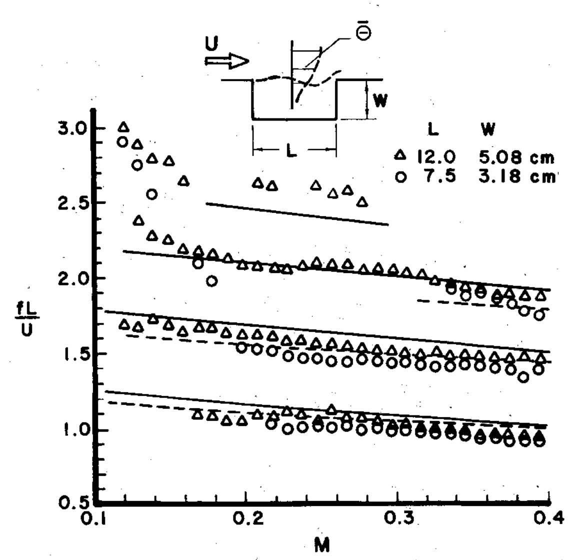


Fig. 19 Frequencies of coherent tones as a function of impingement length (Ref. 24).

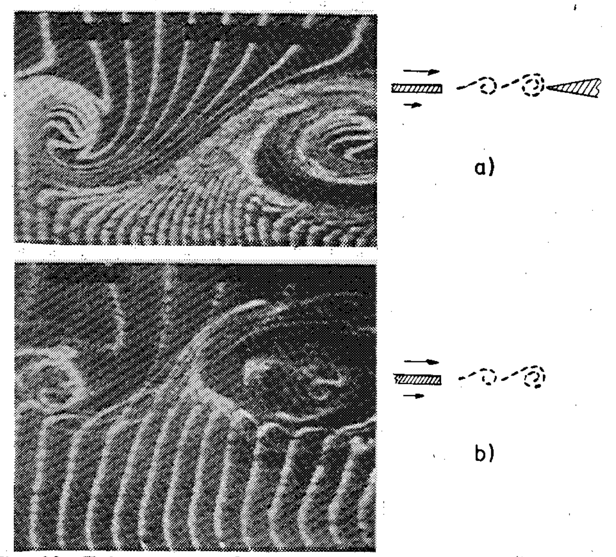


Fig. 20 Enhancement of coherence of vortex formation due to presence of impingement edge; $Re_{\theta_0} = 239$ (Ref. 18).

For nonimpinging flows, the spanwise[122,123] and azimuthal[108] structure of transitional shear layers has received a great deal of attention, involving well-defined streamwise vortices interacting with the major, primary vortices. Such three-dimensional patterns can be expected to exist, to a degree, in impinging flows,[124] but if one compares nonimpinging and impinging cases of a mixing layer (see Fig. 20), there is evidence that the two-dimensionality is enhanced, most likely due to the fact that the upstream influence from the edge is equivalent to externally exciting the nonimpinging mixing layer. Indeed, Miksad[114] has demonstrated that external excitation dramatically increases the concentration of energy in one-dimensional spectra in a nonimpinging mixing layer in a manner very similar to that observed in the corresponding, nonexcited, impinging flow.[18] Clearly, corresponding spanwise correlations are required for the sort of impinging vs nonimpinging comparison carried out in conjunction with Fig. 20.

However, it appears that if the length scale is sufficiently long, the oscillation ceases to lock-on, and there are no evident peaks in velocity spectra taken in the shear layer, as well as in pressure spectra taken at impingement. For mixing layer and cavity flows at moderate Reynolds numbers (and low Mach numbers) having laminar initial conditions at separation ($100 \lesssim Re_{\theta_0} \lesssim 300$), this loss of coherence in the oscillation has been observed to occur at length scales of the order of from 100 to 200 momentum thicknesses in a variety of configurations[62,66,104,110]; the implication is that the shear layer is sufficiently three-dimensional at impingement so as to attenuate the effectiveness of the upstream influence. At higher Reynolds and Mach numbers, a series of axisymmetric jet flow experiments indicates that there are no coherent oscillations for jet-plate[16,125,126] length scales ($L$) greater than the order of from 6 to 7 jet nozzle diameters.

Moreover, an issue not completely resolved is whether a fully turbulent shear layer at separation can give rise to self-sustained organized waves, even at short and moderate impingement length scales. Although the presence of an adjacent acoustic resonator unquestionably allows such oscillations,[102,105] there is no evidence that an increase in coherence is attainable without them at low Mach numbers where acoustic effects are not significant.

Finally, in addition to these issues associated with generation of coherent component(s) of oscillation, the background turbulence structure of the approach shear layer as well as the emitted noise may be affected, even in cases where coherent oscillations do not arise; this aspect seems to have received very little attention. For example, it is known

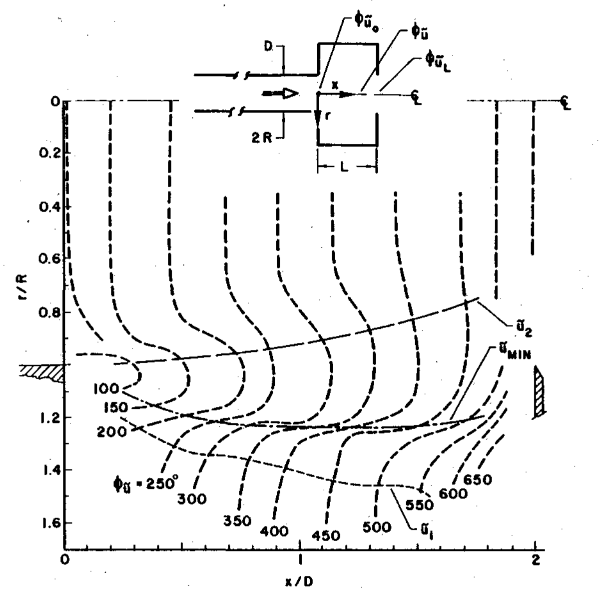


Fig. 21 Composite phase map showing contours of constant phase of $\tilde{u}$ (i.e., $\phi_{\tilde{u}}$); locus of peak $\tilde{u}_1$; locus of peak $\tilde{u}_2$; and locus of $\tilde{u}$ minimum. $Re_{\theta_0} = 2.2 \times 10^3$; $L/D = 2$ (Ref. 102).

that the acoustic power emanating from turbulent jet-plate impingement ($\sim M^8$) as determined by Olsen et al.[127] can substantially exceed that associated with the jet itself ($\sim M^6$), attributed to dominance of the volume quadrupoles over the surface dipoles[20]; possible alterations in structure of the upstream jet have not been addressed.

### Overall Phase Difference Between Separation and Impingement

For oscillations that are clearly coherent, much attention has been devoted to defining a favorable, overall phase difference between fluctuations at separation ($x=0$) and impingement ($x=L$) that allows the oscillations to be self-sustaining. Of course, the severe gradients of disturbance amplitude and phase *across* the shear layer are well known for unstable laminar[66,83,104,128] and turbulent[102,105,108] (Fig. 21) shear layers, being reasonably well approximated by simple inviscid theory[87] except for regions of spatial nonhomogeneity near separation ($x=0$) or impingement ($x=L$). Consequently, it should be clear that, in characterizing *streamwise* variations of amplitude and phase, it is not meaningful to do so along paths determined by geometry of the system [e.g., mouth of a planar ($y=0$) or axisymmetric ($r=R$) cavity]. Other criteria involve following one of the disturbance amplitude maxima[66,104] and/or phase maximum or minimum[104] within the shear layer; each of these criteria yields different streamwise variations in amplitude and phase[105] and it is difficult to ascertain which is most physically significant. With regard to streamwise variations of amplitude, the most meaningful criterion of all is to consider the streamwise evolution of integrated disturbance energy, approximated by $\tilde{u}^2$ (Ref. 114). As for streamwise phase variation, a different approach involves tracking values of phase along the edge of the mean shear layer,[62,66,102] on the assumption that there should be some sort of favorable *streamwise* phasing in the core or freestream flow where *transverse* phase gradients are very small. In fact, for quite different configurations of the axisymmetric jet cavity, two-stream mixing layer, and planar cavity, an overall phase difference between separation ($x=0$) and impingement ($x=L$) of $\sim 2n\pi$ is satisfied at maximum amplitude of oscillation. To be sure, overall phase differences measured within the shear layer [e.g., $\sim(n+½)2\pi$ of Hussain and Zaman[104] and Sarohia[110]] are important as well, deserving further attention with a view toward relating them to corresponding differences measured along the edge of the shear layer; accounting for spatial nonhomogeneity of separation and impingement regions would be highly desirable.

However, in general, the notation of a universal and sacred phase difference between separation ($x=0$) and impingement ($x=L$ in Fig. 1) must be treated with great caution: the center of the source(s) at impingement may not be exactly at $x=L$, as assumed in all the above! Indeed Powell's[9] high-speed study, as well as the low-speed study of Coltman,[23] shows that this is not the case for certain jet-edge configurations.

## Models for Predicting Frequency of Overall Oscillations in the Absence of Resonators/Reflectors

The historical development of shear-layer-edge models in absence of resonators is given in reviews of Karamcheti et al.,[129] Hussain and Zaman,[104] and Rockwell and Naudascher.[14] In essence, Powell's[22] conceptual framework has continued to provide the basis for recent advances that have quantitatively clarified details of the unstable wave evolution and the upstream influence. Wooley and Karamcheti[89] and Sarohia[130] emphasize the concept of maximum (streamwise) integrated amplification of a disturbance in determining the frequency of oscillation. It is generally recognized that some sort of "feedback condition" must be employed as well; Sarohia[130] has simulated it by imposing an empirically determined phase difference between separation and impingement. King et al.,[131] Martin et al.,[132] and Rockwell[133] assume different descriptions of the amplified disturbance, but all models represent the feedback as the perturbations at separation being out of phase with cavity volume fluctuations.

A new approach by Crighton and Innes[31] involves simulating the shear layer by a vortex sheet, and representing the feedback through application of the Kutta condition at the separation edge; that is, the strength of the downstream source (naturally appearing in the analysis) is adjusted to remove the inverse square-root singularity at the separation edge. For incompressible flow, only a single frequency corresponding to $L=0.449\lambda$ of the freely developing wave is predicted, whereas for low Mach number ($M \ll 1$) compressible flow that satisfies the condition $\lambda_a \ll L$ ($\lambda_a$ is the acoustic wavelength), the condition $L/\lambda = n+7/8$ ($n=1,2,3,\ldots$) results. A particularly attractive feature of this analysis is that the phase delay and attenuation of the feedback appear explicitly. As yet, there has been no comparison with experiments of streamwise phase variation associated with the downstream traveling instability wave; in comparing with the finite thickness shear layer, an appropriate criterion for determining the phase at each streamwise station must be carefully chosen.

## Effects of Resonators/Reflectors—Mechanisms and Models

In general, the effect of an adjacent resonator can enhance or dominate the character of the aforementioned oscillations. In this section, features of various shear-layer-resonator configurations (see Fig. 22) are addressed, followed by some overall observations.

Resonant oscillations in shallow and deep cavities have been reviewed by Rockwell and Naudascher[96]; here, only the most recent studies are highlighted. In the case of shallow cavities, where the wave motion is primarily in the streamwise direction, considerable insight is provided by the visualization study of Heller and Bliss[26] (see Fig. 22) and the model of Tam and Block,[24] which incorporates (finite thickness) shear-layer stability parameters, as well as expressions for acoustic waves inside and outside the cavity. Using the condition that the maximum downward deflection of the shear layer at $x=L$ yields the maximum positive pressure, good agreement was obtained with measured frequencies over the range $0.2 \lesssim M \lesssim 1.2$. As noted by Heller and Bliss, the frequencies of shallow cavity oscillations do not necessarily correspond to those calculated assuming an idealized "closed-box" resonator, except perhaps at high Mach numbers, where the shear layer exhibits a "stiff" behavior. Numerical simulation of the shallow cavity oscillations, involving solutions of the Navier-Stokes equations, has been carried out by Hankey and Shang.[134] Although long-time spectral analysis of their unsteady pressure signals could not be performed, indications

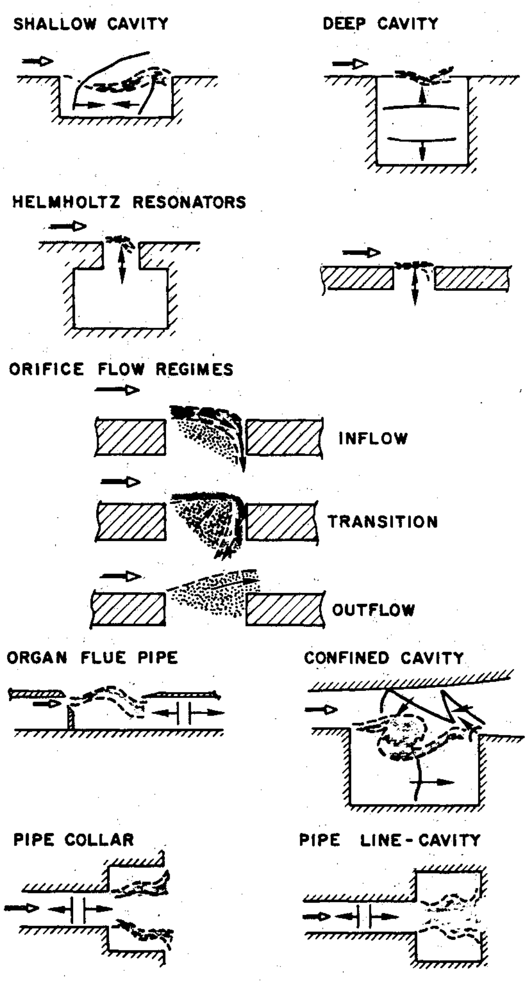


**Fig. 22 Oscillations influenced/controlled by resonant acoustic modes of system.**

are that the frequencies and amplitudes are qualitatively approximated by this nonlinear simulation.

With regard to deep cavities (Fig. 22), where the primary wave motion is transverse to the direction of mean flow, Elder[105] has employed a root locus technique to examine the overall resonant behavior. His model also incorporates shear-layer concepts, yielding the frequencies of oscillation; absolute amplitudes can be determined if the nonlinear orifice characteristic is known. Tam and Block[24] demonstrate that the frequencies of deep cavity oscillation can be well approximated at low $M$ using the calculated depth mode of the cavity at no flow. Important in their experiments is an apparent transition from shallow to deep cavity resonance (at $M \simeq 0.2$) as $M$ is decreased for constant cavity geometry. Taking a different approach, Howe[135] considers displacement thickness fluctuations downstream of the impingement to drive the resonator cavity, eliminating the leading-edge singularity of Howe,[30] and modeling reasonably well the experimental profiles of shear-layer displacement.[136] Moreover, Howe's[30] analysis of mean shear flow past an aperature bounded by a deep cavity predicts remarkably well the excited resonance frequencies of Demetz and Farabee.[137]

Investigations of wall-mounted Helmholtz resonators (see Fig. 22 and the summaries/investigations of Ronneberger,[136] Hersh et al.,[138] Anderson,[139] and Howe[140]) have focused primarily on characterizing their acoustic impedance and the associated flow patterns in the neck region. Baumeister and Rice[141] and Ronneberger[136] have simulated the interaction between the incident (grazing) flow and transverse pulsations through the neck of the orifice using a low-speed water apparatus (the orifice flow regimes in Fig. 22). According to the visualization of Baumeister and Rice,[141] involving high amplitude, low Strouhal number excitation, there can be simultaneous inward and outward flow through the resonator neck during part of the cycle; moreover, the flow patterns indicate that the acoustic resistance of the neck is a function of its length ($L$) to depth ratio. These observations would seem to be dependent, to some degree, on the Strouhal number ($fL/U$) as well. Indeed, Ronneberger's experiment involved a higher Strouhal number (at low amplitudes), such that the interface at the mouth of the resonator exhibited growth in accordance with linear stability theory. Nelson et al.[142] have recently examined the detailed structure of pressure in the cavity; when vortices were clipped at the impingement edge ($x=L$), the pressure was maximum negative. In addition, they point out that interpretation of the contours of constant amplitude and phase is complicated by interference patterns; perhaps they are analogous to those characterized by Rockwell and Schachenmann.[102]

Concerning oscillations of a jet-drive (i.e., flue) organ pipe, the predominant mechanism for provoking the acoustic motion has been attributed to the transverse undulations of the jet (see review of Fletcher[143]), whereby the jet both adds to the acoustic velocity and builds up pressure that drives the acoustic flow in the pipe.[144,146,147] Howe[52] questions this classical interpretation and formulates a model whereby displacement thickness fluctuations downstream of the lip of the mouth (see Fig. 3t) play the central role in transfer of mean flow to acoustic energy; consequently, he contends that the motion of the jet is not significant in sustaining oscillations in the pipe, though its nonlinearity must certainly be accounted for in amplitude considerations. In an earlier work, Howe[148] relates the nonlinear features of vorticity shed from the leading edge to the acoustic amplitude. The severe transverse undulations of the jet at resonance have been visualized by Cremer and Ising[144] (see Fig. 23); the dashed lines represent their model, involving up- and downstream waves that are spatially amplified, and a wave of defined amplitude associated with forcing of the jet.

Keller and Escudier[28] have investigated a variety of confined cavity configurations operating at low pressure ratio (i.e., high Mach number) and producing large pressure fluctuation amplitudes (on the order of one bar), one of which, the (confined) wall jet cavity, is shown in Fig. 22. Using a Schlieren-like technique, the resonant wave motion within the cavity, as well as large-scale structures of the shear layer, were visualized. They assert that the larger, eddy-like structures are created by the resonant wave field rather than by the unstable shear layer, though at low Mach numbers this may not be the case. Keller[149] has developed a second-order theory showing that a given mode of the cavity is strongly excited only if the shear-layer deflection at $x=L$ is sufficiently large, having important consequences for attenuation.

A pipe collar mounted at the end of a pipe [i.e., whistler nozzle (see Fig. 22)][150] can produce discrete frequency oscillations, apparently due to the coupling between unstable reattachment at the exit of the whistler and organ pipe modes; these modes calculated by Hasan and Hussain.[151] A pipeline-axisymmetric cavity system (see Fig. 22) with fully turbulent approach flow[102] yields well-defined tones over a range of velocity ($U$) and impingement length scale ($L$) due to interaction between organ pipe modes of the approach pipe cavity and the inherent hydrodynamic instability of the shear layer between separation ($x=0$) and impingement ($x=L$), whereby a $2n\pi$ phase difference is satisfied between fluctuations at these locations when maximum amplitude is reached; this phase difference is substantially influenced by the acoustic wave contributions if the corresponding acoustic mode is strongly excited. Finally, in such cases of through flow, the Helmholtz resonance mode of the cavity can be induced, as revealed by Wilson et al.[152] and Morel,[153] the latter demonstrating amplitudes as high as 5.6 times the jet dynamic pressure.

For the variety of aforementioned oscillations in the presence of resonators, it is desirable to seek some general features of their behavior; in doing so, differentiating aspects of oscillations with and without resonators should be brought forth:

1) The limiting amplitude in the absence of a resonator is imposed by nonlinear saturation of the disturbance growth; with a resonator, the amplitude is higher, being determined by the nonlinear character of the jet resonator interaction.[105,143,154] To what extent can the amplitude be determined solely on the basis of nonlinear theory without empiricism?

2) The effects of the shear-layer-edge interaction involving the induced lift on the edge and the associated upstream influence[22] are overshadowed by the acoustic resonator and its upstream influence when oscillations occur at the frequency of an acoustic mode, though at higher speeds the effect of the shear-layer-edge interaction may start to become significant.[146] Thus an oversimplified interpretation of "coupling" between, for example, jet-edge and organ pipe modes is misleading.[103,155] It is, however, intriguing that such oscillations appear to occur (at least at low Mach number) only if the shear layer is hydrodynamically unstable at that

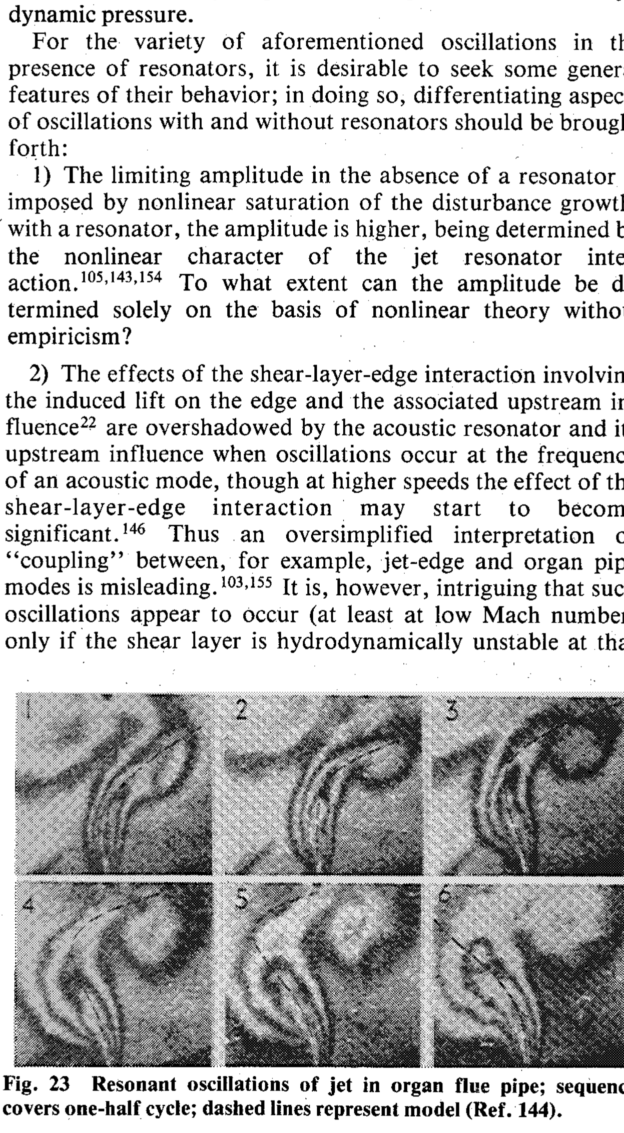


**Fig. 23 Resonant oscillations of jet in organ flue pipe; sequence covers one-half cycle; dashed lines represent model (Ref. 144).**

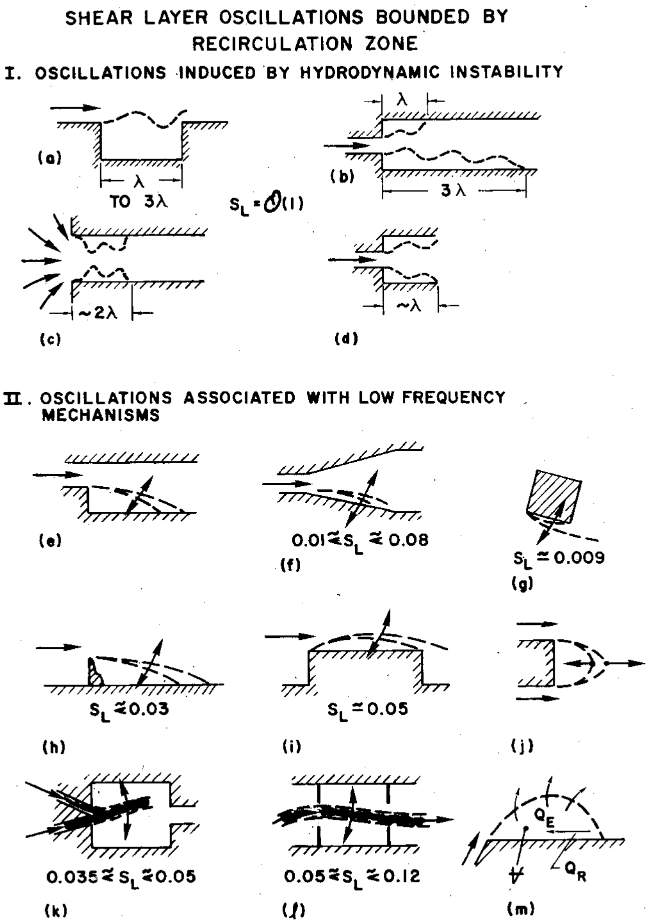


**Fig. 24 Comparison between oscillations arising from hydrodynamic instability and those associated with imbalance of entrained ($Q_e$) and return ($Q_R$) flows.**

frequency; the transient development from a small amplitude linear oscillation, where there may be "coupling," to the large amplitude, resonator-dominated oscillation is basically unexplored.

3) At resonance, the transverse oscillation of, for example, a jet in a jet-organ pipe system may be highly nonsinusoidal, with the jet having long residence times at its extreme positions; this contrasts with the nearly sinusoidal (excepting nonlinear hydrodynamic distortions) oscillations of a free jet-edge system.[146]

4) Away from the immediate vicinity of an acoustic mode, the shear-layer/edge interaction and the standing-wave resonance appear to enhance each other through mutual assistance.[146]

5) The gross phase relations between, for example, transverse jet deflection and induced pressure on each side of the jet are substantially (~90 deg) different for a simple jet edge, and a jet-edge bounded by an organ pipe.[23]

6) In many cases, the consequence of an acoustic resonator is to focus the energy of oscillation at a single frequency, corresponding to the most readily excited normal mode at the respective length scale $L$ and velocity $U$ (see Refs. 24, 102, 154, 156, 157); however, certain jet-edge oscillations in the presence of a resonant pipe can give rise to a large number of harmonics (~20) of the resonator.[141] The associated nonlinearities (see 1 and 3) deserve further attention.[143]

7) As previously noted, nonlinear interactions between frequency components in purely hydrodynamic oscillations of an impinging shear layer give rise to multiple frequencies.[62] Is there any relation between this mechanism and the often-discussed nonlinear interaction between modes associated with the presence of a resonator?[146]

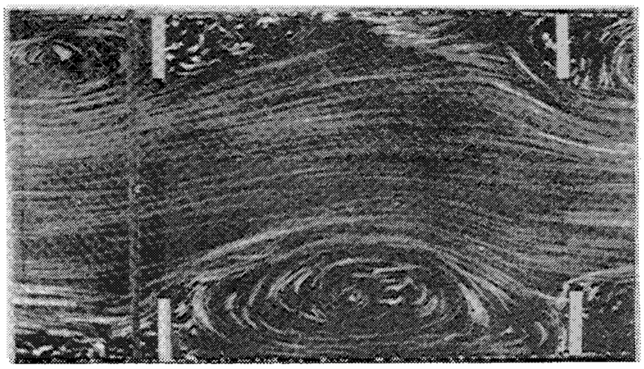

**Fig. 25 Transverse oscillations of a channel flow with (white) wall protrusions associated with growth and decay of large-scale vortices on either side of flow (Ref. 170).**

8) Oscillations in the presence of a resonator typically yield velocity fluctuations ($\tilde{u}_0$) at separation, relative to freestream velocity ($U$), of magnitude $\tilde{u}_0/U = (10^{-1})$ (see Refs. 101, 150, 158) compared with $\tilde{u}_0/U = (10^{-3})$ in the absence of a resonator. How do the phase speeds and wavenumbers of these large amplitude oscillations compared with linear theory?[66]

All of these aspects challenge us; particularly important in gaining further insight will be rigorous experimental characterization involving appropriate pressure-velocity correlations at the mouth of and within the resonator, as a function of the degree of coupling between the inherent hydrodynamic instability of the shear layer and the acoustic mode of the resonator, providing the framework for more detailed analysis.

## Shear-Layer Oscillations Bounded by a Recirculation Zone

In presence of a recirculation zone, a shear layer may exhibit well-defined oscillations due to classical hydrodynamic instability as described previously, or, in some cases (generally less coherent), oscillations associated with a completely different mechanism. A comparison of these two categories is given in the following.

#### Oscillations Induced by Hydrodynamic Instability

The oscillations of primary interest herein are triggered/driven by the inherent instability of the shear layer, and have Strouhal numbers ($S_L = fL/U$) in the range ~0.5-2.5 (Ref. 14). If the convective velocity ($U_c$) of the instability is crudely taken as $U_c \simeq 0.5$, then the ratio of impingement length ($L$) to wavelength of the instability ($\lambda$) takes values $1 \lesssim L/\lambda \lesssim 5$. Such oscillations are represented in Figs. 24a-d. They encompass the unstable separated shear layer due to flow 1) past a rectangular cavity[62] (Fig. 24a); 2) through a sudden expansion[159] (Fig. 24b); 3) through a pipe inlet[160] (Fig. 24c); and 4) through a truncated sudden expansion[150] (Fig. 24d).

#### Oscillations Associated with Low-Frequency Mechanisms

However, for certain initial conditions and configurations, as shown in Figs. 24e to 24m, there seems to be indication of persistent (but, in general, less coherent) oscillations at Strouhal numbers $S_L \ll 1$. The backward facing step[161,162] (Fig. 24e); wide-angle diffuser with transitory stall[163] (Fig. 24f); rectangular cross-section cylinder[164] (Fig. 24g); leaf gate[165] (Fig. 24h); protruding wall[152] (Fig. 24i); bluff body[167,168] (Fig. 24j); and mixing chamber[169] (Fig. 24k) have all exhibited low-frequency components having varying degrees of coherence; in those cases where resonance effects are present[120] (Figs. 24l and Fig. 25), the oscillation can be expected to exhibit a high degree of organization. In fact, examination of an entire series of photos for the sequence corresponding to Fig. 25 reveals a remarkably consistent growth and decay in size of the large-scale recirculation vortex on upper and lower (alternately) sides of the stream.

Although the mechanism for these oscillations has not been conclusively demonstrated, it has been hypothesized to be due to an imbalance between flow entrained by the separated shear layer ($Q_E$) and that returned to the separation zone ($Q_R$) at reattachment.[161,171] A schematic of a model[171] is given in Fig. 24m. The conservation of mass applied to the separation zone gives

$$\frac{dV}{dt} = Q_R - Q_E$$

Using this expression in conjunction with the momentum equations, it should be possible to determine characteristic response times of various separation zones, leading to the prediction of the most probable oscillation frequency. Of course, this interpretation may be intertwined with, or even overshadowed by, the complexities of coherent structure/surface interactions at impingement, as well as three-dimensional effects that could alone be a source of low-frequency contributions!

Clearly, further experimental study is called for, including characterization of the reattachment point fluctuations,[162] streamwise evolution of the large-scale unsteadiness, and correlation between events at separation and reattachment. Moreover, the role of the aforementioned entrained-return flow mechanism, relative to the nonlinear interaction mechanism giving rise to low-frequency components in unstable reattaching flows,[62] as well as the successive or simultaneous coalescence of vortical structures[16,17,106,107] needs to be resolved. Finally, great care is required in ensuring that observed low-frequency components do not arise from mechanisms peculiar to a given flow system: pump/compressor unsteadiness in other regions of flow separation upstream of the test section, and overall resonance of water tunnels and wind tunnel flow loops. Indeed, in some of the configurations shown in Fig. 24, this may have been the case (e.g., Ref. 165, Fig. 24h); the spectral nature of the approach flow has not been adequately characterized.

## Supersonic Flow Oscillations

Unstable oscillations of shock patterns, associated with complex interactions between supersonic and subsonic flow regions, and impinging/reattaching shear layers can occur in a variety of configurations including spiked bodies, airfoils, free jets impinging on obstacles and sudden expansions in ducts (see review of Jungowski[172]). Although detailed consideration of such oscillations is beyond the scope of this review, it is insightful to consider the case of the sudden expansion[173] (Fig. 26), for which extensive experimental information is available. The top interferogram shows that the shock is further to the right and weaker than in the bottom interferogram, both taken during a typical cycle of oscillation for a pressure ratio $p_e/p_a = 0.364$. Anderson et al.[173] model the oscillation as generated by the supersonic flow region terminating in the shock, involving interaction between pressure fluctuations immediately up- and downstream of the shock and in the subsonic base region. Its frequency is controlled by the resonant organ pipe modes of the downstream ducting. Measurements of phase of the streamwise velocity fluctuations show that a source-like region is located immediately downstream of the shock, from which waves travel in up- and downstream directions.[174] Similar experimental insight is needed for the range of supersonic oscillations reviewed by Jungowski,[172] some of which involve ingredients characteristic of aforementioned categories of oscillation: imbalance of entrained and return flow; hydrodynamic instability of the shear layer; and acoustic-resonant coupling.

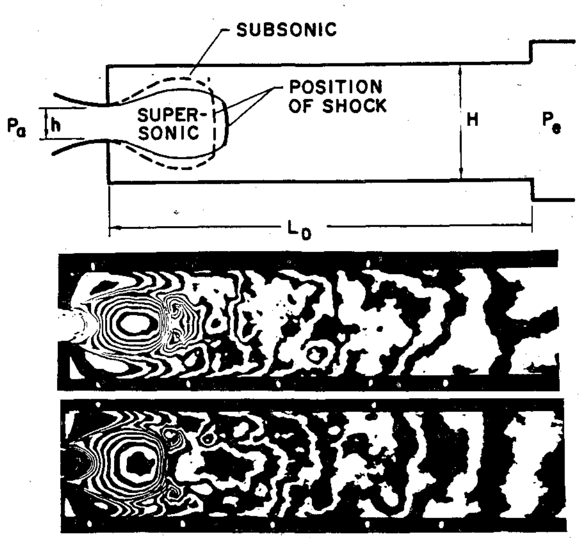


**Fig. 26 Oscillations of a shock wave and associated supersonic flow pocket in a sudden expansion (Ref. 173).**

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