Research report 2011:10

Excited Jet and Its Applications

MOHSEN JAHANMIRI

Division of Fluid Dynamics
Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2011

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M O H S E N   J A H A N M I R I

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ISSN 1652-8549

Division of Fluid Dynamics
Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
SE-412 96 Göteborg
Sverige
Telephone +46 (0)31 772 1000

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Mohsen Jahanmiri

Dept. of Applied Mechanics, Chalmers University of Technology
Göteborg, Sweden
&
Dept. of Mech. and Aerospace Engineering, Shiraz University of Technology
Shiraz, Iran

Abstract

In recent years, a wide variety of applications have been found for the use of pulsed or excited jets in the area of flow control (Jahanmiri, 2010). Many researchers have worked on jet flow control to enhance mixing and/or reduce noise. The impetus for the present study was to throw some light on various types of excited jets used so far in engineering applications, and meanwhile explaining fundamental multifaceted research activities which has been accomplished to identify the flow field and mixing characteristics associated with such kind of jets.

Introduction

Excited jets are an excellent platform for the study of fluid dynamics and turbulence as they display numerous phenomena that are encountered throughout the field of fluid dynamics. Topics represented in an excited jet include instability, receptivity, vortex dynamics, transition, coherent structures and fully developed turbulence. As these features present themselves and develop with increasing distance from the jet nozzle, a jet flow field is convenient for the in-depth study of any of these topics by making measurements at the appropriate location downstream of the nozzle exit.

Jets have received considerable attention over the last several decades (see Crow and Champagne (1971), Yule (1978), Ho. and Huange (1982), Dimotakis et al. (1983), Husain and Hussain (1983), Gutmark and Ho (1983), Ho and Huerre (1988), Samet and Petersen (1988), Liepmann and Gharib, (1992), Corke and Kusek (1993), Verzicco and Orlandi (1994), Wicker and Eaton (1994), Cho et al. (1998), Oh and Shin (1998), Schram and Rietmuller (2002), Olsen et al. (2003), Reynolds et al. (2003), Tinney et al. (2005), Birbaud et al. (2007), Iqbal and Thomas (2007) for a small literature review available on the subject). Briefly, a jet's flow field can be summarized as follows. The flow at the exit of the nozzle is uniform at the jet centerline with a region of shear near the wall. Upon exiting the nozzle, the shear layer with thickness, θ, is susceptible to the Kelvin-Helmholtz, or shear-layer, instability where small disturbances, typically characterized by their Strouhal number ($St_\theta=f\theta/U$), are amplified and eventually roll-up into organized and quasi-periodic sets of vortices. Further shear layer growth is dominated by the dynamics of these vortices and described by events such as vortex pairing. As the vortices grow and move towards the end of the potential core, the dominant jet instability mode becomes that of the preferred mode, or jet column mode, which is characterized by the Strouhal number based on the nozzle diameter ($St_D=fD/U$). Near the end of the potential core and beyond, the interaction of vortices leads to complex non-linear motion that destroys the organized motion of vortices in the flow and results in the transition to turbulence. Many jet diameters further downstream the flow is well described as fully developed turbulent flow.

Jet excitation generally refers to the introduction of disturbances to the flow to excite either the shear layer instability or the jet column instability. The most common form of excitation is that of acoustic excitation where a loudspeaker(s) is used to excite the initial shear layer with acoustic pressure/velocity fluctuations. By adjusting the frequency, amplitude and phase of the acoustic signal, researchers have demonstrated the ability to manipulate the formation, size and spacing of vortices; their subsequent growth and dynamics; and eventually their transition to turbulence (Thurow and Lynch, 2008).

Over the last few decades, a significant amount of work has focused on establishing the relationship between the excitation signal and the vortex structure in the near field of the jet (e.g. Crow and Champagne (1971), Ho. and Huange (1982), Gutmark and Ho (1983), Ho and Huerre (1988), Samet and Petersen (1988), Corke and Kusek (1993), Wicker and Eaton (1994), Cho et al. (1998), Oh and Shin (1998), Schram and Rietmuller (2002), Olsen et al. (2003), Reynolds et al. (2003), Birbaud et al. (2007)). The ability to easily change the excitation frequency and amplitude of the excitation has allowed in-depth study of the instability mechanisms at play in both the initial shear layer and the jet column. In addition, although the flow is unsteady and three-dimensional, the ability to phase lock measurements to the excitation signal has allowed researchers to investigate these flows in great detail. Overall, this has led to an improved understanding of the instability mechanisms in jets and free shear layers. For example, it is fairly well known that the preferred mode of the jet is for $St_D \approx 0.3$–0.4. In addition, linear instability analyses are fairly accurate at predicting the shear layer and jet column's susceptibility to external disturbances.

The development of the flow beyond the potential core, however, has received considerably less attention. In this region, the well-organized structure present near the nozzle exit diminishes as the flow is governed by non-linear dynamics and eventually breaks down into fully developed turbulence. As the flow in this region of the jet is highly unsteady and three-dimensional, it is much more difficult to investigate. Classically, it has been assumed that the far field pattern of the jet is self-similar and independent of the initial disturbances provided. Experiments on bifurcating and blooming jets, however, show that the far field flow can be dramatically altered through the proper introduction of disturbances at the jet exit (Reynolds et al., 2003). These experiments suggest that different far-field turbulent states are possible for a given geometry. This alteration of the far field is directly connected the near-field vortex structures created by the disturbances and the dynamics of these vortices as they undergo the transition to turbulence (Thurow and Lynch, 2008).

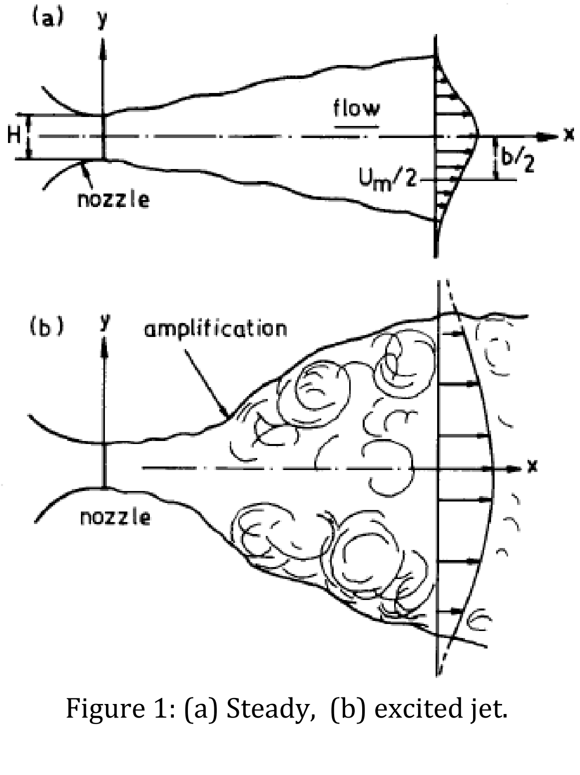

Figure 1: (a) Steady, (b) excited jet.

One of the significant characteristics of a turbulent jet is its ability to entrain more fluid from its surroundings due to the shear inherently present in the flow. The induced flow even in the case of a steady jet is not smooth and continuous but is indented with large turbulence structures (Figure 1) which exhibit a wavy motion along the outer edge of the flow (Townsend, 1976). Though these large eddies are formed in a random fashion, they do follow a well-defined statistical pattern which enables us to describe the overall characteristics of the flow using a minimum number of parameters such as a velocity and a length scale for a given nozzle flow.
Crow & Champagne (1971) observed that the large eddies in a round jet could be energized in a selective manner by imposing disturbances at some definite frequencies. Their pioneering work initiated further activity in jet excitation. Since the eddies play a major role in the production of noise, selective modification of the large-scale turbulence structures can be usefully employed for altering the radiating noise pattern. Recently, this subject has evoked further interest due to its application to V/STOL aircraft propulsion, which requires efficient thrust augmenting ejectors (Bevilaqua 1984; Braden et al., 1982). In this system, the induced flow plays a major role. An excited jet which has a higher mixing capability could satisfy the above requirement.
As mentioned by Badrinarayanan (1988), the oscillations for exciting the jet can be categorized as: (a) pulsating the flow which produces periodic fluctuations in mass flow, and (b) the flapping of the jet. It is not always necessary that the application of such disturbances should induce excitation. The criterion for excitation is still under exploration and the available information on this subject indicates that the configuration of the jet, the strength of the imposed disturbance, and the mode of applying it, influence the process in a selective manner. For instance, a plane jet and a round jet exhibit entirely different behaviour when subjected to the same disturbance. The former can be excited only by anti-symmetric oscillations whereas a round jet is sensitive to many modes (Rockwell & Niccolls 1975; Bernal & Sarohia 1984). A round jet gets excited through the dynamics of vortex rings, but the process involved in a plane jet is still under speculation.
Due to the importance of jet flow in engineering applications and wide use of excited jet in recent flow control techniques, in this paper an attempt is made to compile a major body of the available knowledge on this context in past decades.

Fundamental Research

Existence of coherent structures as centers of high concentration of vorticity has been well established in jets and mixing layers (Browand and Laufer (1975), Brown and Roshko (1974), Hussain (1983)). There are increasing evidences to support that it is the interaction between coherent structures, rather than the dynamics of coherent structures themselves, which plays the dominant role in the underlying mechanisms for turbulence phenomena such as mixing, momentum transfer and aerodynamic noise generation (Winant and Browand (1974), Petersen (1978), Hussain and Clark (1981), Browne et al. (1984)).
The most common mode of interaction is the pairing of successive coherent structures in the same shear or mixing layer forming larger coherent structures. In planar mixing layer, pairing in a number of cascades of successive initial vortex sheets rolled up from the instability of the shear layer, is believed to be the basic mechanism for the growth and spreading of the mixing layer (Brown and Roshko, 1974). In a round jet, similar shear-layer mode pairings occur when the jet exit shear layer is laminar, resulting in large-scale vortical structures further downstream (Hussain and Zaman, 1980). Regardless of whether the initial jet exit condition is laminar or turbulent, evolution of the structures is related to the jet-column mode interaction, which involves not only vortex pairing or coalescence but also tearing of coherent structures between adjacent successive structures (Hussain and Clark, 1981). Further, interaction of successive coherent structures in the round jet is suggested to be one of the dominant mechanisms in jet noise generation (Juve et al., 1983). Tang and Ko (1993) suggested the acceleration and deceleration of the structures during their pairing in the free shear layer are the basic mechanism for the far field noise generation. The recent detailed study suggests further the radial accelerations and the rate of change of the axial accelerations of the structures are important in the generation of sound at low Mach number (Tang and Ko, 1995).

In round jet, interaction of coherent structures in the azimuthal direction occurs from two diameters downstream, resulting in the development of azimuthal lobes (Crow and Champagne (1971), Saffman (1978)). Interaction of coherent structures had been reported as the mixing layers of the plane jet merge at the end of the potential core (Hussain and Clark (1981), Browne et al. (1984)). Dramatic re-distribution of turbulence quantities occurs with a rearrangement of coherent structures in an azimuthal pattern (Browne et al. 1984). While streamwise interaction of coherent structures in the form of pairing results primarily in the growth of the structures, azimuthal or lateral interactions may lead to the decay of the structures.
Coherent structures in two or more shear layers or mixing layers of different origins have attracted increasing attention (Kwan and Ko (1976), Ko and Au (1985), Ko and Lam (1985)). However, most investigations of coaxial and annular jets were limited to measurements of integral flow properties such as velocity profiles, entrainment rates, statistical turbulence quantities and spectra. The interaction dynamics of coherent structures, which provide the mechanisms for these flow characteristics have seldomly been investigated. Based on correlation measurements, interactions of the two trains of coherent structures with coaxial jets are found to depend on the mean velocity ratio and a number of interaction mechanisms are in action (Kwan and Ko (1976), Ko and Au (1985)). Recently, based on two-color planar laser-induced-fluorescence technique, at low velocity ratios the vortex structures in one mixing layer might excite the instability of the other shear layer and consequently modify the roll-up processes as well as the evolution of coherent structures [Dahm et al., 1992). With the shear-layer excitation of the outer mixing layer by the structures in the inner layer, delayed vortex pairings in the outer layer were observed. During coalescence more than two vortices were involved to form a large structure which subsequently interacted with the vortices in the inner layer.
In the special case of annular jet, that is the coaxial jet with a zero velocity ratio, based on pressure and velocity measurements, a train of wake vortices at the inner wake region is found to somewhat excite the outer mixing layer, leading to the formation of a train of new coherent structures near the end of the annular potential core (Chan and Ko (1978), Ko and Chan (1979)). Based on correlation and conditional sampling measurements of flow velocities, in an annular jet excitation of the outer jet shear layer appears to be caused by the lateral velocity fluctuations associated with the shedding of wake structures from the inner region (Lam et al. 1986). This affects the rolling process of the jet shear layer and towards the end of the potential core, a number of initial vortices somewhat merge together to form a train of large coherent structures with a passage frequency centered at that of the shedding of wake structures. The detailed mechanism of this vortex merging remained not understood, but it was observed that the train of wake-induced structures so formed exhibits a two-dimensional orderly pattern (Ko et al., 1998).
In the decade since the existence of large-scale coherent structures superimposed on a background of 'turbulence' in a plane mixing layer was demonstrated by Brown and Roshko (1974), considerable effort has been directed at identifying similar structures in other flow configurations and determining their roles in establishing the basic characteristics of the flow field. Crow and Champagne (1971) reported that in an axisymmetric jet, the most dominant and frequently occurring of all large-scale coherent structures, known as the 'preferred mode', corresponded to a Strouhal number, St, of about 0.3; these structures can be enhanced by introducing controlled acoustic excitation at St=0.3. Results of such controlled excitation experiments (Zaman and Hussain (1980), Zaman and Hussain (1981), Hussain and Thompson (1980)) provide improved understanding of fundamental phenomena such as the structure of turbulence, shear-layer instability, and the natural entrainment process. On the other hand, excitations introduced at any arbitrary frequency may produce non-naturally occurring structures which may alter the characteristics of the flow field and may have potential practical applications in areas such as noise reduction, fluidics and combustion systems (Lai, 1984). There is a need to enhance jet entrainment and mixing for developing compact, yet efficient, thrust augmenting ejectors for aerospace propulsion systems, particularly for VSTOL aircrafts. Different jet excitation techniques have been reported, such as acoustic excitation (Crow and

Champagne (1971), Zaman and Hussain (1980), Hussain and Thompson (1980), Chambers and Goldschmidt (1982)) fluidic excitation (Piatt, M. and Viets, H. (1979), Binder and Favre-Marinet (1981)) and mechanical excitation (Binder and Favre-Marinet (1973), Simmons et al. (1978), Lai and Simmons (1980), Galen and Simmons (1983), Badri Narayanan and Platzer (1986)).
Many previous studies have focused on the existence of preferred modes and the link between these and coherent periodic structures within a free jet flow (see, for example, Becker and Massaro (1968), Wygnanski and Feilder (1969), Yule (1978) and Hussain and Zaman (1981)). Later studies showed that the development of a turbulent free jet is altered dramatically by the injection of energy into these preferred modes in a process known as excitation (Zhang and Turner, 2010).
A variety of methods of excitation have been investigated by Zaman and Hussain (1980), Gutmark and Ho (1983), Szajner and Turner (1986) and Reeder and Samimy (1996). These studies confirm that the excitation energy (from an acoustic or other source) can amplify the coherent structures naturally present in any turbulent jet and produce significant changes in its axial development.
In addition, vorticity is generated in the shear layers, and complex vortical structures arise that are conveniently studied using flow visualization (Szajner and Turner (1986), Koch et al. *(*1989), Nixon and Turner (1997), Romano (2002)). Then, the toroidal vortices centred on the jet axis, and the secondary mushroom-shaped vortices that emerge in cross-sectional planes embracing the jet axis, create circumferential and streamwise vorticity components, respectively.
Since the formation processes for both the toroidal and the mushroom-shaped vortices are periodic, each component of the vorticity will be oscillatory and these vorticity components strongly influence the entrainment and mixing processes. Consequently, the axial rate of development of the free jet can be increased or decreased (Szajner and Turner (1986) Liepmann and Gharib (1992)).

Jet Mixing

Mixing is an important feature of jets in practical applications. Since the mixing is affected by the vortices evolving in jets, it is crucial to clarify the vortical structures related to the mixing mechanism. In circular jets, axisymmetric and streamwise vortices evolve, interact and break down. The vortex motions are three-dimensionally complicated and very difficult to detect experimentally.
Although a few works have been reported on the vortical structure (Lasheras et al. (1991), Liepmann and Gharib, (1992), Samimy et al. (1993), Reeder and Samimy (1996), Grinstein et al. (1996)), they do not give us enough information to understand the three-dimensional structure related to the mixing mechanism.
Toyoda and Mori (2001) investigated the three-dimensional vortical structure and the mixing mechanism of a circular water jet by a flow visualization technique. The jet was excited by axial and azimuthal perturbations to stabilize and enhance axisymmetric and streamwise vortices. A laser fluorescent dye and a laser light sheet were used to visualize the jet. The three-dimensional views of vortical structure were constructed by applying the Taylor hypothesis to the jet cross-sectional images.
Their results reveal that the simultaneous enhancement of axisymmetric and streamwise vortices is very effective to increase the jet-boundary surface and to decrease the unmixed region. The variations of A/A_o (A_o: the area of jet exit) in the streamwise direction are shown in Figure 2. In the figure, the decrease of the area corresponds to high mixing. The figure reveals that the excited jet with vortex generators (VG) is very effective to increase mixing, while the excited jet without vortex generators increases the unmixed region. It is noticed that the enhancement of only large-scale axisymmetric vortices increases both of the jet-boundary surface and the unmixed region.

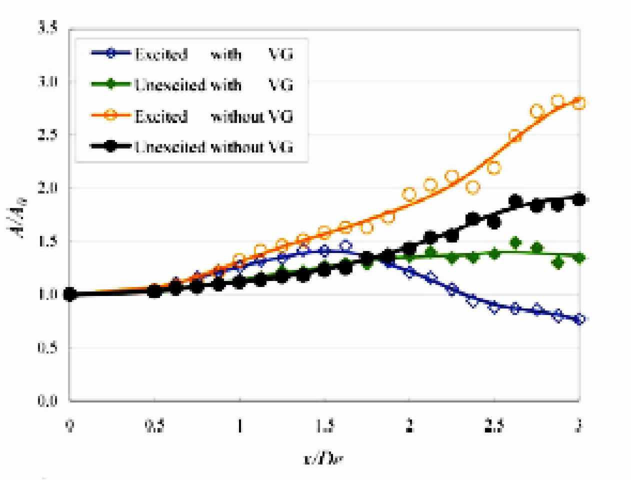

Figure 2: Areas of unmixed region

Yuan et al. (2004), presented a control law to improve jet flow mixing. The control law employs a pair of actuators at the jet nozzle exit that act on the shear layers near the corners by blowing and subtracting fluid in an anti-symmetric fashion and a sensor downstream or at the nozzle exit with a time delay that measures the pressure difference across the nozzle diameter. A 2-D jet flow is numerically simulated along with massless/mass particles and a passive scalar. The mixing enhancement produced by these controllers is demonstrated visually by snapshots of the vorticity (Figure 3), streaklines, particle distribution and scalar field.

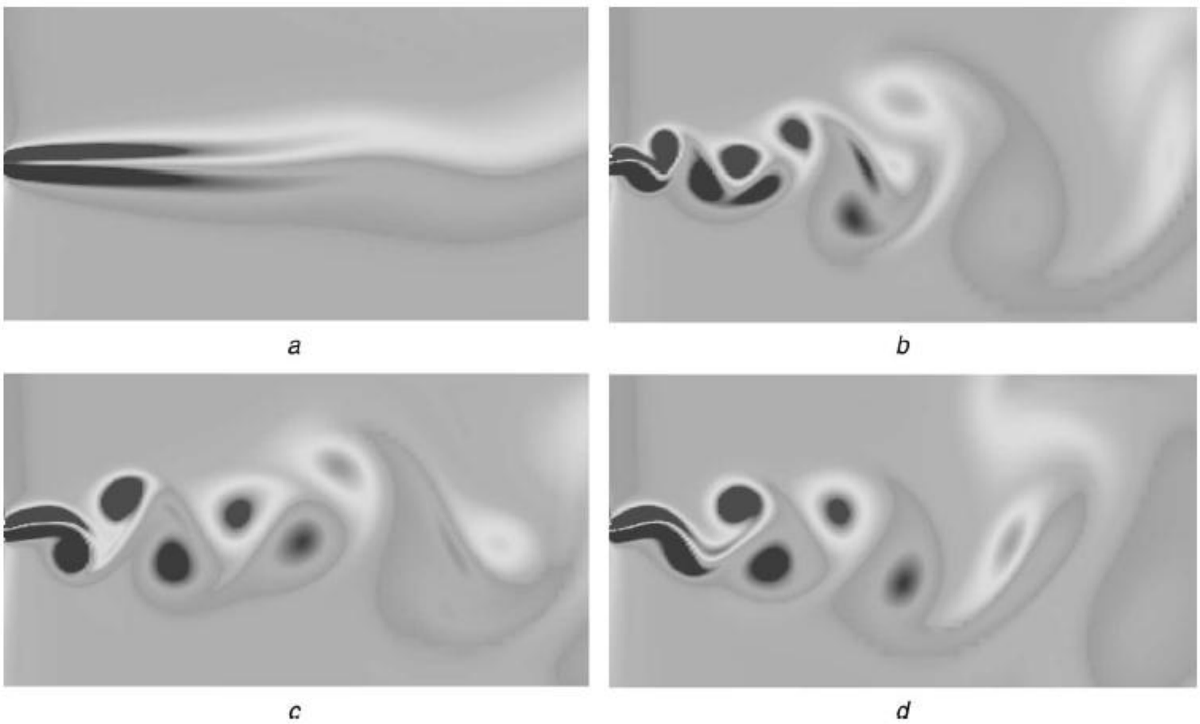

Figure 3: Vorticity fields at t=500: (a) Uncontrolled jet, (b) x_1 =5, (c) τ=15, (d) Open-loop forcing.

Later, the influence of modifying a jet's exit flow pattern on both the near and far-field turbulent mixing processes and on the resulting combustion performance, is explored by Nathan et al. (2006). This reveals that, in contradiction to some common assumptions, increasing the coherence of large-scale motions can decrease molecular mixing rates, and yet can still be beneficial in some applications. Also, precessing and flapping jets are found to cause an increase in flame volume relative to an equivalent simple jet (SJ), implying lower molecular mixing rates (Figure 4).

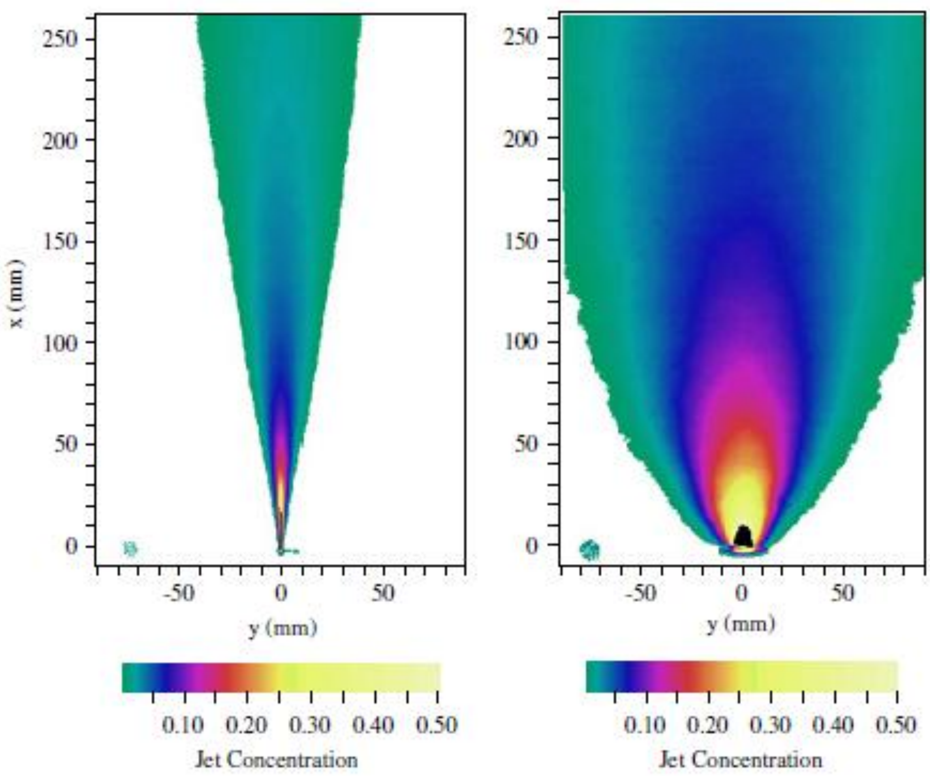

Figure 4: Mean non-reacting mixture fraction of the emerging simple jet (left) and a fluidic precessing jet (right). The diameter of the simple jet nozzle and of the precessing jet chamber inlet is 3mm and Re =37,000 there [88].

Georgiadis and DeBonis (2006) in their article present the current status of computational fluid dynamics (CFD) methods as applied to the simulation of turbulent jet flowfields issuing from aircraft engine exhaust nozzles. Besides the conventional methods like Reynolds-averaged Navier–Stokes (RANS), direct numerical simulation (DNS), and Large-Eddy simulation (LES), a related approach is the group of hybrid RANS/LES methods, where RANS is used to model the small-scale turbulence in wall boundary layers and LES is utilized in regions dominated by the large-scale jet mixing. These computational methods used to analyze the jet flow field behind an exhaust of aircraft engine, which could be excited (actively or passively) for enhancing the mixing characteristics resulting in better jet aeroacoustics.

A new self-excitation method (Figure 5) was conceived and tested to enhance the mixing of jet fluid with its surrounding fluid (Vandsburger and Yuan, 2007). The concentration and velocity fields of jets emanating from square and rectangular shaped nozzles were studied in order to clarify the mixing performance and the flow mechanisms responsible for the performance of the excited jet.

The quantitative examination of the concentration field indicated that the mixing rate increased substantially in the excited jet. The square nozzle exhibited a higher mixing rate than the rectangular nozzles. The near field of the flow exhibited a high degree of complexity with strong three-dimensional characteristics. Moreover, the excited jet gained as much as six times the turbulent kinetic energy at the nozzle exit over the unexcited jet. Most of the turbulent kinetic energy is concentrated within five diameters from the nozzle exit, distributed across the entire jet width, explaining the increased mixing in the near field.

The proposed and tested active, self-excited nozzle has been shown to offer significant enhancement of nozzle fluid mixing with co-flowing fluid streams.

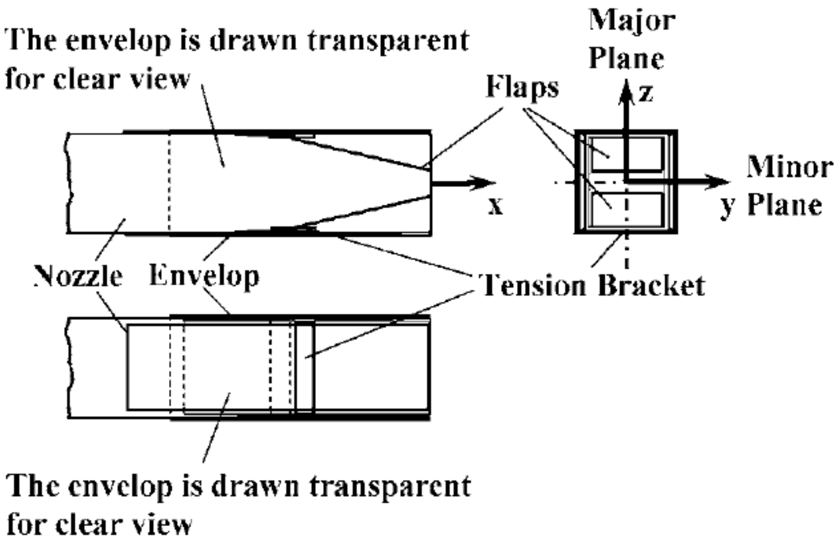

Figure 5: Schematic of the self-excited nozzle.

Flow control techniques for increasing the rate of jet mixing in axisymmetric nozzle flows have been investigated (Behrouzi et al., 2008). A combination of water tunnel and high-speed airflow facilities is used to assess the near-field jet behaviour. Solid tabs (Figure 6), steady fluid tabs (i.e. discrete radially discharged control jets located close to the core jet exit), and pulsed fluid tabs are compared. The effect of fluid tab velocity amplitude, pulse rate, and pulse phase are studied using openloop control. The measurements indicate that fluid tabs generate a similar streamwise vortex formation process (and hence display increased mixing) as previously observed in solid-tabbed nozzle flows. In incompressible testing the mixing effectiveness with a pair of pulsed fluid tabs 180u out-of-phase was as good as a twin solid tab nozzle for a control jet flow rate of only 0.5 per cent of the primary (core) jet flow. In preliminary high-speed testing similar benefits of fluid tabs over solid tabs were observed. Pulsed fluid tabs have the attractive performance benefit that they can be easily switched off when not needed and offer increased flexibility as the basis of an optimized active control jet mixing device.

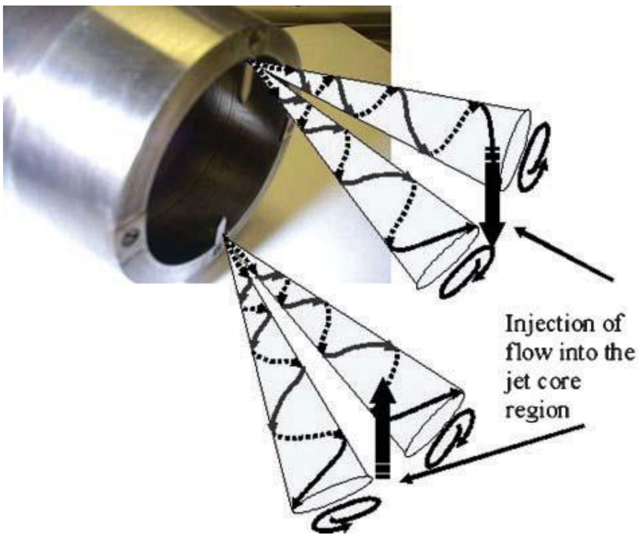

Figure 6: Streamwise vortices created by a solid tab.

Knowles and Saddington (2006) in their review paper explain techniques applicable to enhancing the mixing of jets, with particular emphasis on infrared (IR) signature reduction of high-speed jets. They discuss rapid mixing technologies under the categories of: geometric modifications (to the nozzle); high shear stress mixing; normal stress mixing; self-acoustic excitation; external acoustic excitation; mechanically oscillated; self-oscillated. It is shown that mixing enhancements of the order of 100 per cent are possible with some techniques and that by combining techniques this can be increased by at least as much again. Simple geometric calculations demonstrate that with rectangular nozzles such high levels of mixing enhancement may be necessary in order to reduce IR signature. Some apparent rapid mixing technologies, however, have been shown to increase jet spreading without increasing entrainment, whereas other techniques can reduce entrainment as easily as they can increase it.

Impinging Jets

Impinging jet flow is of great interest in industrial applications because it is often utilized to heat, cool or dry materials. The reason of such utilization in the processing of materials is that the flow results in high heat and mass conductivity in the stagnation region. This feature has led many researchers to study impinging jets from the standpoint of heat and mass transfer (rather than the fluid dynamics), and to propose empirical equations which relate heat or mass transfer rates, Reynolds number, distance between the nozzle and the impinging plate and so on.

Tsubokura et al. (2003) investigated three-dimensional eddy structures arising in plane and round impinging jets (see Figure 7) excited at the nozzle inlet numerically by direct numerical simulation and large eddy simulation. It was found that the round jet showed definite instability at spatial wavelength $\lambda/\pi D=1/6$ while the plane jet showed almost equivalent sensitivity to all modes tested. As regards the eddy structures in the stagnation region, elongated twin vortices along the impinging plate of the plane jet were reproduced and the number of pairs was found to agree exactly with the spanwise wave number imposed at the inlet. In contrast to the plane jet, no organized structures were observed in the stagnation region of the round jet.

Hsiao et al. (2004) studied experimentally the dynamics of coherent structures and their instability evolution of the small cylinder impinging plane jet using hot-wire measurements. The jet shear layer act as a wave amplifier, which can absorb the applied or the induced instability waves (such as the pressure wave of the cylinder or the acoustic excitation wave) and then evolve in the rule of subharmonic evolution model with downstream direction. The augmentation effect of acoustics excited at the resonant frequency on the impinging flow with the small cylinder is also explored in detail to substantiate the feedback mechanism used in these experiments.

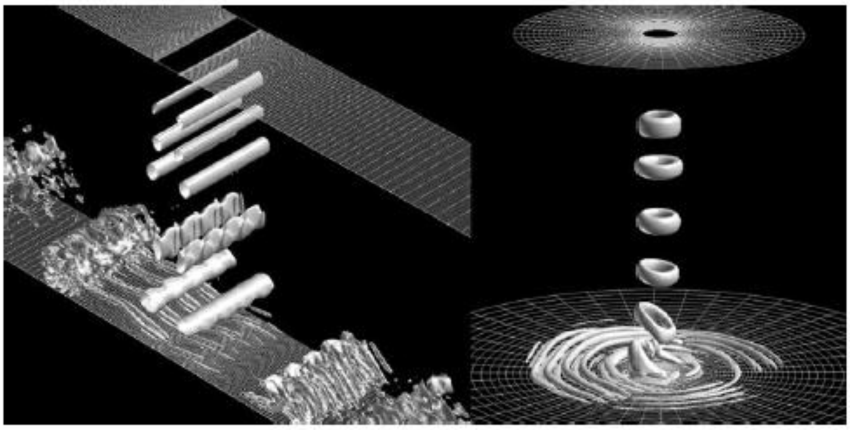

Figure 7: Instantaneous eddy structures of plane (left) and round (right) impinging jets, indicated by iso-surfaces of the Laplacian of pressure excited by the fundamental frequency.

The effect of an external excitation on circular impinging jet flow is studied experimentally by Vejrazka and Tihon (2005). The basic flow is excited by a small sinusoidal modulation of the nozzle exit velocity. The phase-averaging technique is used to study the behavior of vortex structures in the jet, specifically rolling-up, pairing, and interaction with the wall.

The flow was found to be sensitive to excitations in a wide frequency range characterized by a Strouhal number, $St_e = f_e D/U$, from 0.3 to 3. Different flow regimes were identified in the near-wall region (see Figure 8) depending on the excitation frequency: a periodic regime exhibiting flow fluctuations locked on the excitation frequency f_e, a regime irregularly alternating between the fundamental frequency f_e and the subharmonic frequency $f_e/2$, a subharmonic periodic regime with regular vortex pairing and finally border regimes with complicated nonperiodic flow response. The phase-averaging technique provided some insight into the behavior of vortex structures inside the impinging jet. The processes taking place during the vortex impact on the wall and the subsequent unsteady flow separation were demonstrated. However, the question of how the changes in the near-wall velocity field, which are caused by the jet excitation, affect heat and mass transfer processes at the wall remains unanswered.

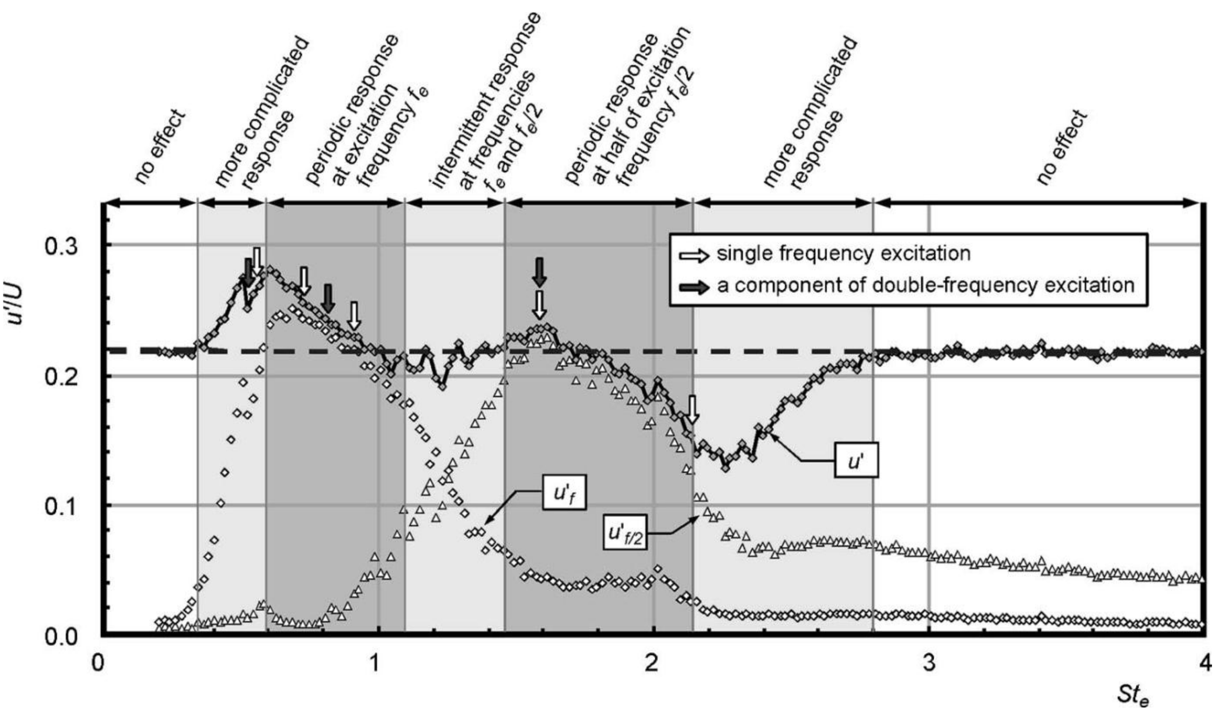

Figure 8: The different flow regimes identified with respect to the excitation frequency from the near-wall velocity data.

Cvetinovic et al. (2006) carried out experimental investigation of the velocity field of the turbulent air jet acoustically modified by the self-sustained oscillations in the whistler nozzle operation together with it's visualization with a high-speed digital camera. Main aim was to describe vortical structures of turbulent air jet issuing from the nozzle of special configuration, modified by the controlled oscillations in free jet setup.

Excitation frequency with Strouhal number $St_e=0.3$, close to the preferred mode, could be effective in shortening the length of the potential core and increasing turbulent fluctuations in a shorter axial distance from the nozzle lip.

Visualization of the excited and non-excited air jets showed very high sensitivity of jet flow patterns to the excitation frequency (see Figure 9). This fact can lead to the conclusion that the local heat transfer characteristics of jet impingement are also remarkably dependent on the jet excitation.

Also, significant decrease of the jet time-averaged velocity and the corresponding increase of turbulence intensity at smaller axial distances from the nozzle can lead to the conclusion that the maximum heat transfer in impinging jet configuration can be obtained at shorter nozzle-to-plate distances compared to non-excited turbulent jet case.

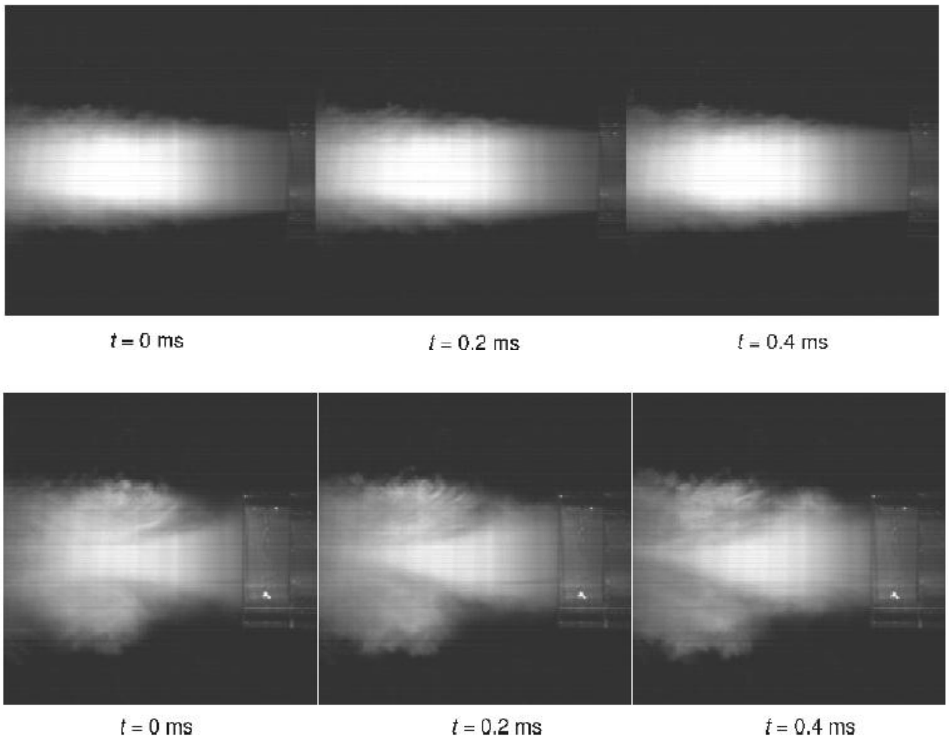

Figure 9: (Top) High-speed video images of non-excited jet, Lp = 6D; Re = 91,000, (Bottom) High-speed video images of excited jet, Ste = 0.29; Lp = 6D; Re = 91,000.

Earlier, the near wall behavior of an impinging jet was studied by Guerra et al. (2005). They investigated the applicability of scaling log-laws to the turbulent impinging jet. The results found at this investigation indicate that the level of the logarithmic portion of the velocity and the temperature laws of the wall increases with increasing maximum jet velocity and decreasing minimum temperature. This research is particularly relevant due to its application for the development of methods that can be used for the determination of the local skin-friction and of the local heat transfer coefficient.

More recently, Bilgin (2009) performed experimental investigation of heat and fluid flow in an actuated impinging jet flow. His results show that, acoustic excitation decreases the local heat transfer of the jet at the stagnation region because the excitation increases turbulence intensity and therefore spreads the jet. Minimum local Nusselt numbers are observed to be occurring at Strouhal number St=0.5 where the maximum jet spread is seen by the visualizations.

Due to the importance of applications of impingement jets in industry for heating and cooling purposes which requires a high convective heat transfer coefficient, a pulsating jet has a very high potential in replacing steady jet after it been found able to increase the heat transfer coefficients at certain pulsating frequencies. So, Zulkifli et al. (2009) made an experimental study to determine the velocity profile of a circular pulsating air jet at different pulse frequencies and Reynolds Number using a rotating valve pulse jet system and compared the normalized steady and pulsed jet velocity at highest Reynolds number of 32000 and highest pulsating frequency of 80Hz. Pulsation of the air jet was produced by a rotating cylinder valve mechanism at frequencies between 10-80 Hz (see Figure 10). Their results indicate that, stagnation point velocities are the same for steady and pulsating jet for all pulse frequencies. As the radial distance from the stagnation point increases, pulsating velocity increases between 20-30% from radial distance of 2-22 mm. Also, the flow structures plot show a distinctive exit air jet profile which can affect the impingement heat transfer characteristics. They speculated that, it was the result of enhanced turbulence intensity due to pulsating jet produced by the rotating cylinder. From the jet exit velocity profile obtained, it is found that mass flow rate for different test frequencies are slightly different due to the difference in the local velocity measurement affected by the pulses.

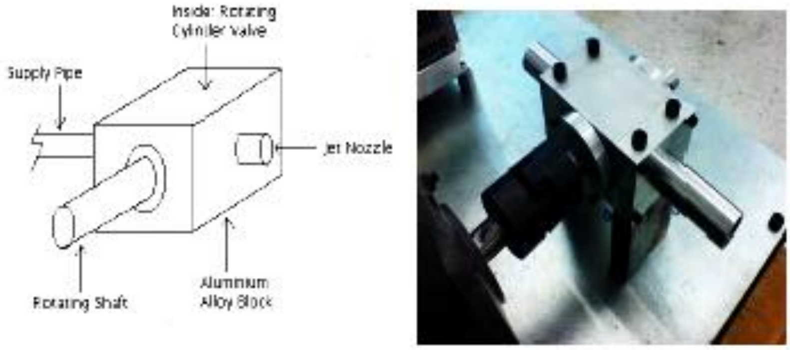

Figure 10: Schematic diagram and photo of the rotating cylinder valve pulse jet system.

Supersonic Jets

Supersonic jets, in addition to possessing very rich flow physics, have many engineering applications. Therefore, they have been the subject of numerous research activities over several decades. A supersonic jet, similar to a subsonic jet, has two instabilities: free shear layer instability and a jet column (or jet preferred mode) instability. It has been known that a free shear layer is unstable and acts like an amplifier of disturbances in the flow over a range of frequencies. This instability is referred to as Kelvin-Helmholtz instability. In sufficiently high Reynolds numbers, the effect of viscosity in the amplification of disturbances is relatively small, and thus the instability is also called inviscid instability.

The second instability arises from the inward growth of the free shear layer of the jet towards the jet centerline and its eventual interaction/merging on the centerline, which ends the jet potential core. Many researchers have shown experimentally that the passage frequency of large-scale structures at the end of the potential core, called preferred mode or jet column mode frequency, is scaled with the nozzle exit diameter ($St_D=f_pD/U_j \sim$ constant, where f_p is the jet column frequency and U_j is the jet exit velocity).

In an axisymmetric jet, a third instability in the shear layer of the jet is called azimuthal instability. The azimuthal modes due to this instability compete for energy and growth among themselves. The principal factor deciding the growth rate and amplitude of azimuthal modes seems to be the ratio of the nozzle exit diameter to the boundary layer momentum thickness at the nozzle exit (D/θ_0).

More details on the three instabilities in jets, which are similar in both subsonic and supersonic jets, along with many references can be found in Samimy et al. (2007 a & b). While a subsonic incompressible jet can operate only in the ideally expanded flow regime, where the nozzle exit pressure is the same as the ambient pressure, a subsonic compressible jet can also operate in an underexpanded flow regime, where the nozzle exit pressure is higher than the ambient pressure. In such a jet, a cycle of expansion and compression waves form and interact with the instability waves and the ensuing large-scale structures. A supersonic jet, in addition to an underexpanded flow regime, could also operate in an overexpanded flow regime where the nozzle exit pressure is lower than the ambient pressure. In such a jet, a cycle of expansion and compression waves from. Another complication could arise from separation of the boundary layer at the nozzle exit, if the nozzle exit pressure is significantly lower than the ambient pressure and the adverse pressure gradient is strong. Controlling supersonic jets operating in various flow regimes is the subject of many research activities.

Recently a class of plasma actuators developed, called localized arc filament plasma actuators (LAFPAs) that can provide excitation signals of high amplitude and high bandwidth for high-speed and high Reynolds number flow control (Samimy et al. 2004 & 2007a & b, Utkin et al. 2007). The actuators frequency, phase, and duty cycle can be controlled independently.

Therefore, several of these actuators can be used to excite jet column modes, shear layer instability modes, and their various azimuthal modes.
Samimy et al. (2008) used LAFPAs (Figure 11) to control a supersonic jet from an axisymmetric nozzle of design Mach number of 1.3 operating from overexpanded to underexpanded flow regimes with the fully expanded jet Mach number (M_J) from 1.1 to 1.5. Laser based planar flow visualizations, schlieren imaging, and particle imaging velocimetry measurements were used to evaluate the effects of control. The preliminary results in the underexpanded jets (M_J=1.4 and 1.5) were quite similar to previous results in the ideally expanded jet (M_J=1.3). The jet responded to the forcing over the entire range of frequencies, but the response was optimum (in terms of development of large coherent structures and mixing enhancement) around the jet preferred Strouhal number of 0.33 (f=5 kHz). On the other side, the overexpanded jets (M_J=1.1 and 1.2) did not respond at all or the response was relatively small.

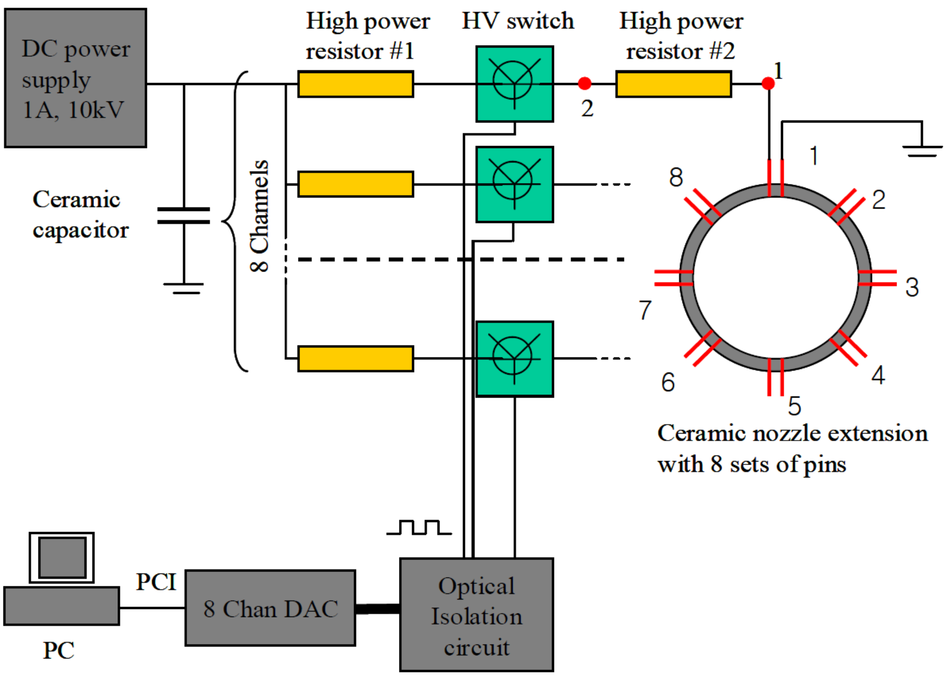

Figure 11: Schematic of the plasma generator and the arrangement of 8 actuators used.

Later Samimy et al. (2010) used the LAFPAs actuators to study far-field acoustic, flow velocity and irrotational near-field pressure of an excited high Reynolds number axisymmetric supersonic jet with a three-fold objective: (i) to investigate the broadband far-field noise amplification reported in the literature at lower speeds and Re_D (Reynolds number based on the nozzle exit diameter) using excitation of azimuthal mode m=0 at low St_{DF} (forcing Strouhal numbers) ; (ii) to explore broadband far-field noise suppression using excitation of m=3 at higher St_{DF} ; and (iii) to shed some light on the connection between the flow field and the far-field noise.
Some of the noteworthy observations and inferences are (a) there is a strong correlation between the far-field broadband noise amplification and the turbulence amplification; (b) far-field noise suppression is achieved when the jet is forced with the maximum jet initial growth rate frequency thus limiting significant dynamics of structures to a shorter region close to the nozzle exit; (c) structure breakdown and dynamic interaction seem to be the dominant source of noise; and (d) coherent structures dominate the forced jet over a wide range of St_{DF} (up to~1.31) with the largest and most organized structures observed around the jet preferred mode St_{DF} (see Figure 12).

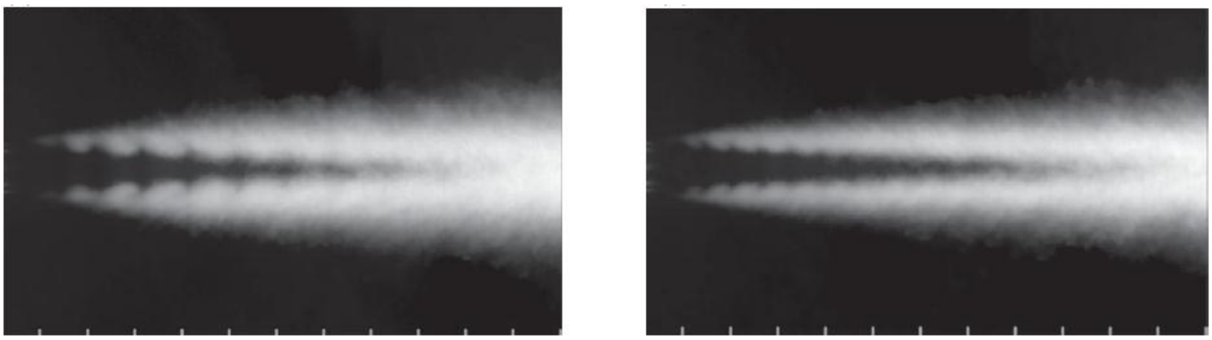

Figure 12: Phase-averaged flow images of the excited jet with m=0 for different St_{DF} (0.79 (left), 1.31 (right)). Mixing intensity decreases from white to black.

Recently, heating capabilities have been added to the free jet facility at the Gas Dynamics and Turbulence Laboratory (GDTL) of the Ohio State University using a storage-based off-line electric heater (Fischer and Samimy, 2010). This addition makes it possible to test the effectiveness of the localized arc filament plasma actuators for the purposes of noise mitigation and mixing enhancement over a wide range of temperatures. These actuators have been used successfully at GDTL in high Reynolds number, high-speed unheated jets. The facility consists of an axisymmetric jet of exit diameter 2.54 cm with different nozzle blocks and variable jet temperature in an anechoic chamber (Figure 13). The preliminary results show that the previously observed trends from both the unheated supersonic work and the heated subsonic experiments do extend to the heated supersonic case.

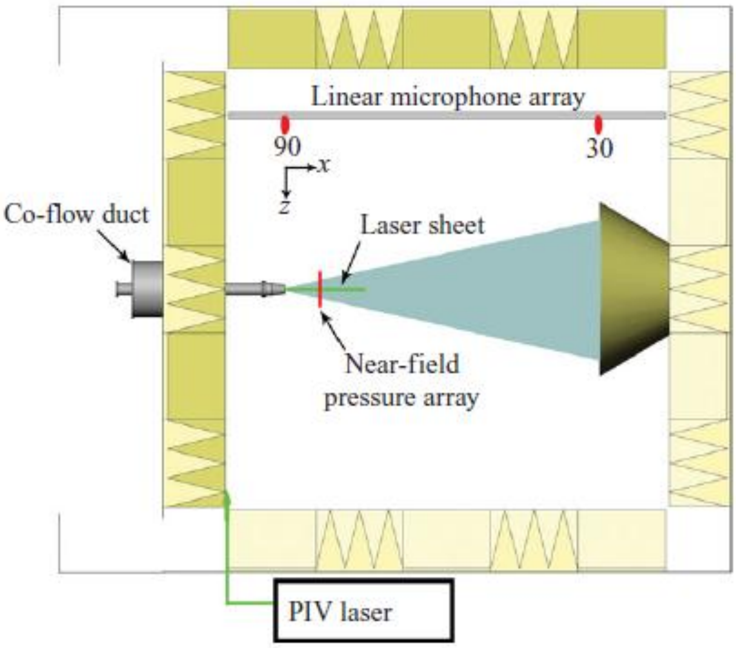

Figure 13: Layout of the jet facility and anechoic chamber.

Flip-Flop Jet

Unsteady excitation has been widely used as a tool to study shear-layer dynamics as well as to control transition, separation, and shear-layer mixing. Discrete-tone acoustic excitation can increase the spreading rate of a jet under certain conditions (Crow and Champagne (1971), Ahuja et al. (1982)). Further increases in the spreading rate can be obtained by multi-frequency plane-wave excitation (Ho and Huang (1982), Raman and Rice (1991)). By combining the right type of plane wave and azimuthal mode excitation, a higher spreading rate, and a distortion of the jet cross section, can be obtained over an extended region (Strange, and Crighton (1983), Cohen and Wygnanski (1987), Raman et al. (1991)). For laboratory research at low speeds, these techniques could be easily implemented using the electromagnetic acoustic driver as a source of unsteady excitation. However, for jets operating at a high Mach number, very high levels of excitation would be required to alter the spreading rate of the jet. In addition, higher turbulence levels representative of full-scale jet exhaust require higher levels of excitation (Raman et al. (1989)). Therefore, for high-speed jets operating under full-scale conditions, it appears that acoustic drivers cannot generate levels that are sufficient to excite the jet. It is also clear that the use of acoustic drivers is not practical due to their weight and volume, as well as their power and maintenance requirements. Some of the limitations of acoustic drivers have been overcome by excitation techniques such as rotating valves, (Binder and Favre-Marinet (1973)) oscillating vanes, (Rockwell, 1972) and self-excitation using counter flow (Strykowski and Wilcoxon, 1992). However, for practical applications, the excitation technique needs to be simple, yet effective. Several types of practical devices have been developed for jet mixing enhancement, such as the self-exciting "whistler nozzle" (Hill and Greene (1977), Hussain and Hasan, (1983)) and the screech-excited jet (Glass (1968), Krothapalli et al. (1986)). The whistler nozzle works well for subsonic flows, but ceases to work beyond sonic conditions (Hill and Greene, 1977). The ability to enhance mixing of a supersonic jet by using its own screech tones has recently received renewed attention due to interest in high speed jet mixing (Krothapalli et al. (1986), Rice and Taghavi (1992)).

Raman and co-workers (1993) focused on the fluidically oscillated nozzle, (Viets (1975), Viets et al. (1975), Viets (1981), Viets et al. (1981)) which seems promising as an excitation device for practical flows. The operation of the fluidically oscillated nozzle (Figure 14) is based on that of a bi-stable fluidic amplifier. The concept is easily understood by considering a rectangular jet issuing into the region between two plates. Despite the symmetry, the jet may attach to one of the walls (Coanda effect), and a small pressure gradient could cause the jet to detach from one wall and attach to the other. If this process could be controlled and repeated periodically, the result is an oscillating jet flow. Details of the operation of such nozzles can be found in a paper by Viets (1975). The fluidic nozzle can be used to produce a time-dependent flow with a substantial change in the time-averaged jet half-width spreading rate (Viets (1981), Viets et al. (1981)). There are several advantages to using the fluidic nozzle as an excitation device. It has no moving parts, and in addition to producing very high levels of streamwise velocity perturbation, the oscillating flow is self-sustaining (Viets, 1975).

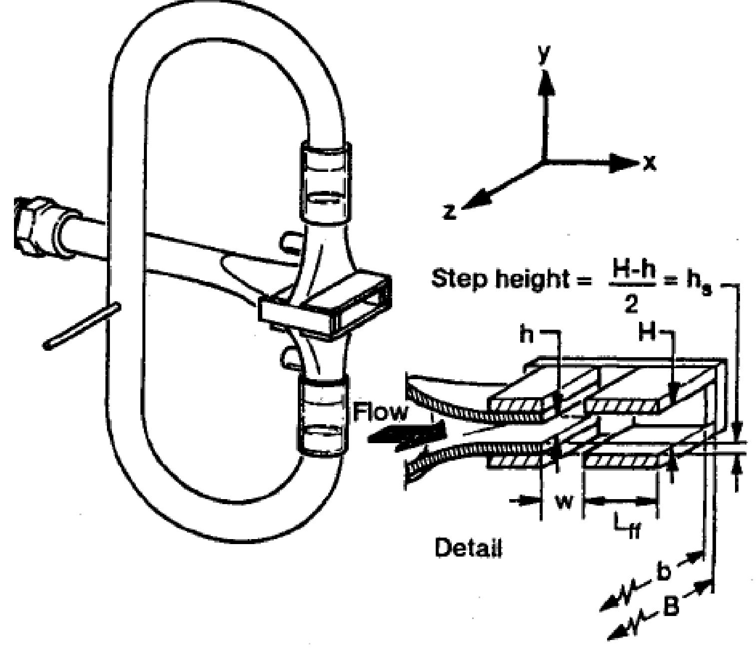

Figure 14: Schematic of the flip-flop nozzle.

Raman et al. (1993) conducted an experiment study on a fluidically oscillated rectangular jet flow using flip-flop nozzle. For the subsonic flip-flop jet, it was found that the apparent time-mean widening of the jet was not accompanied by an increase in the mass flux. It was found that it is possible to extend the operation of these devices to supersonic flows. The streamwise velocity perturbation levels produced by this device were much higher than the perturbation levels that could be produced using conventional excitation sources such as acoustic drivers. In view of this ability to produce high amplitudes, the potential for using a small-scale fluidically oscillated jet as an unsteady excitation source for the control of shear flows in full-scale practical applications seems promising.
Mi and Nathan (2001) investigated a self-excited flapping jet nozzle (flip-flop nozzle, Figure 15) which contains no external feedback loop and triggers to find scalar mixing characteristics . It is found that the mean scalar decays significantly faster in the flapping jet than in the non-flapping jet, indicating enhanced large scale mixing and increased jet spreading due to the flapping motion. Concurrently, however, the flapping motion suppresses fine-scale scalar mixing. Moreover, the their study suggests that the flapping Strouhal number has a significant impact on the jet mixing. Higher mixing rates appear to occur at higher Strouhal numbers.

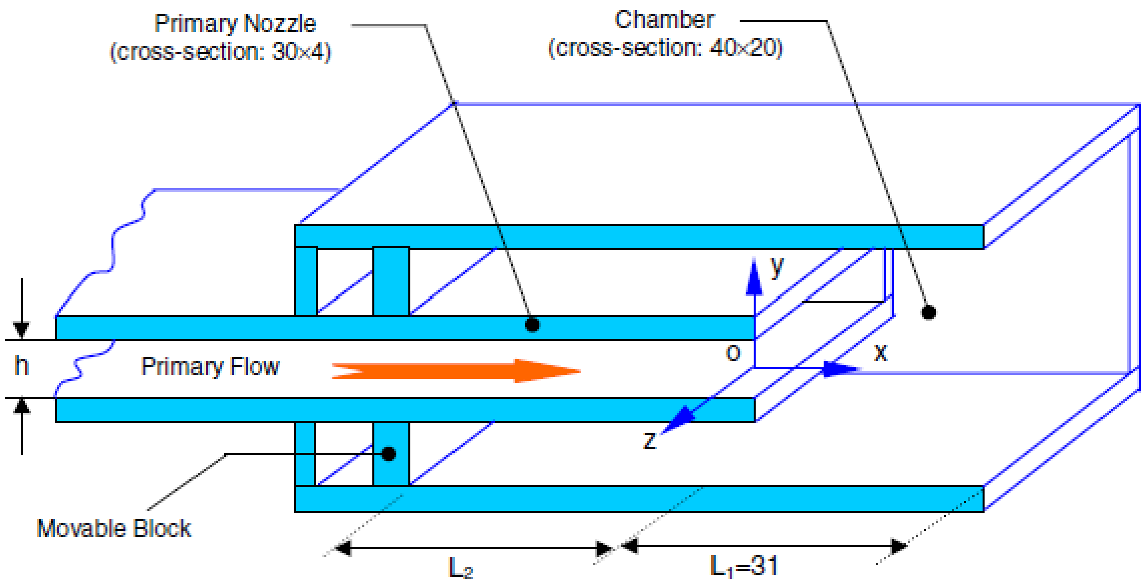

Figure 15: Schematic diagram of Mi and Nathan flip-flop jet nozzle. Dimensions are in mm.

Vane excited Jet

A plane subsonic jet can be excited to entrain more fluid from its surroundings by subjecting it to antisymmetric periodic disturbances. The essential feature in this phenomenon is the rolling-up motion of an initially flapping jet to form large vortices which are responsible for greater entrainment. Several methods developed to impart oscillations to the flow at the nozzle, such as the acoustic pressure oscillator, the vibration of a single vane in the potential core region, the reciprocating lip system and the twin vane exciter, are described in this article. A minimum threshold in amplitude is necessary for exciting the flow. However, the frequency of oscillation is much less than that predicted by stability considerations.
The investigations on excited plane jet have been mainly confined towards the development of various mechanisms to impart periodic oscillations to the flow (Fiedler and Korschelt (1979), Collins et al. (1981), Collins et al. (1984), Lai (1984), Badri Narayanan and Platzer (1987)). A twin vane oscillator has been developed which seems to have an edge over other techniques on account of its high efficiency (Badri Narayanan and Platzer, 1989). When the twin vanes oscillate with a rotary motion around a pivot as illustrated in Figure 16 (a), which is termed as

pitching mode, the vortex formation is different from that of the push-pull mode (Figure, 16 (b)), but similar to that of the reciprocating lip oscillator described by Badri Narayanan & Platzer (1987). The jet initially exhibit a flapping motion which rolls up as the frequency is increased. As in the case of other techniques, the movement of the amplification region varies with the imposed frequency and exit velocity. Mixing in this case is more predominant than in the push-pull mode. For low exit velocity and frequency operations, a critical Strouhal number around 0.05 could be identified for this system.

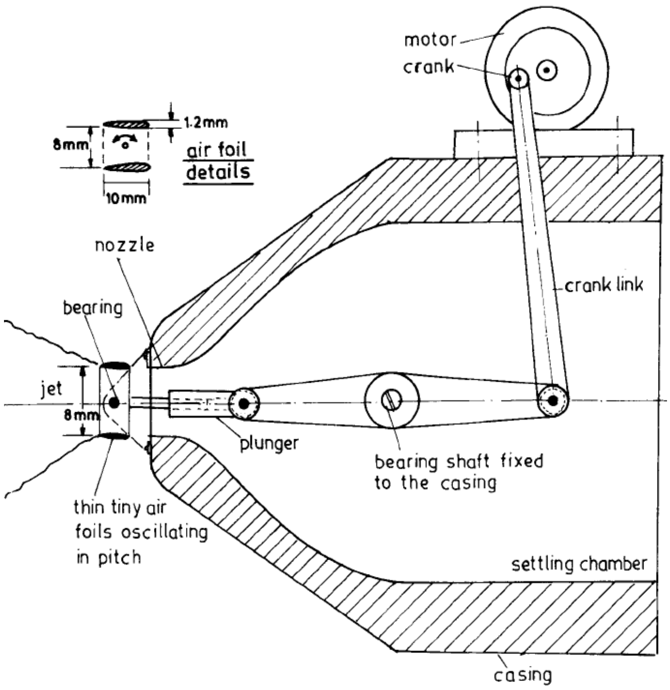

Figure 16 (a): Twin vane oscillator in pitching mode.

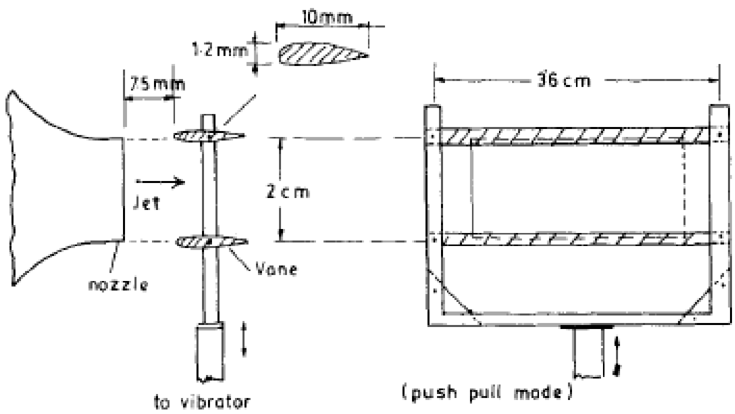

Figure 16 (b): Twin vane exciter in the push-pull mode.

Jahanmiri (2000) used a similar twin vane system to study a plane subsonic jet which was subjected to periodic oscillations in the near nozzle region. During excitation, the jet was found to spread significantly and entrain mass much more than its steady counterpart (Figure 17). Time averaged static pressure measured in the flow field with a disc probe exhibited prominent well defined suction regions different from that of a steady jet. As compared to steady jet, the increase in integral value of momentum downstream of excited jet is easily observed (Figure 18).

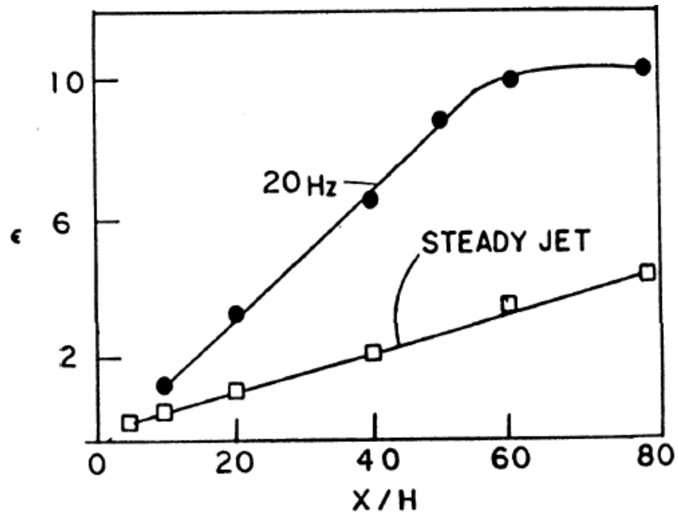

Figure 17: Entrainment in the jet.

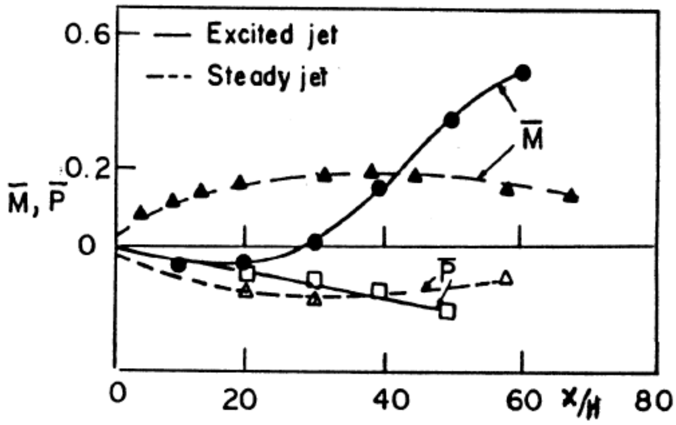

Figure 18: Momentum and integrated pressure.

It is resulted that, a plane turbulent jet can be excited only by subjecting it to antisymmetric oscillations. The jet which is initially in the flapping mode rolls up forming vortices, initiating amplification. During excitation, the entrainment increases appreciably from that of the steady counterpart, due to enhanced mixing. A critical Strouhal number seems to be associated with amplification. The conversion of flapping motion into a vortex mode seems to be a fundamental phenomenon of unsteady flows and further investigations are necessary to understand this process. Similarly, the mechanism involved in the ingestion of fluid into the jet is not clear. The role played by the large pressure fluctuations during excitation needs further study.

Synthetic Jet

A synthetic jet in fact is a sort of excited jet which is produced by the interactions of a train of vortices that are typically formed by alternating momentary ejection and suction of fluid across an orifice such that the net mass flux is zero (Figure 19). A unique feature of these jets is that they are formed entirely from the working fluid of the flow system in which they are deployed and thus can transfer linear momentum to the flow system without net mass injection across the flow boundary. Synthetic jets can be produced over a broad range of length and time-scale and their unique attributes make them attractive fluidic actuators for a broad range of flow control applications. Below are few research activities carried out on this context.

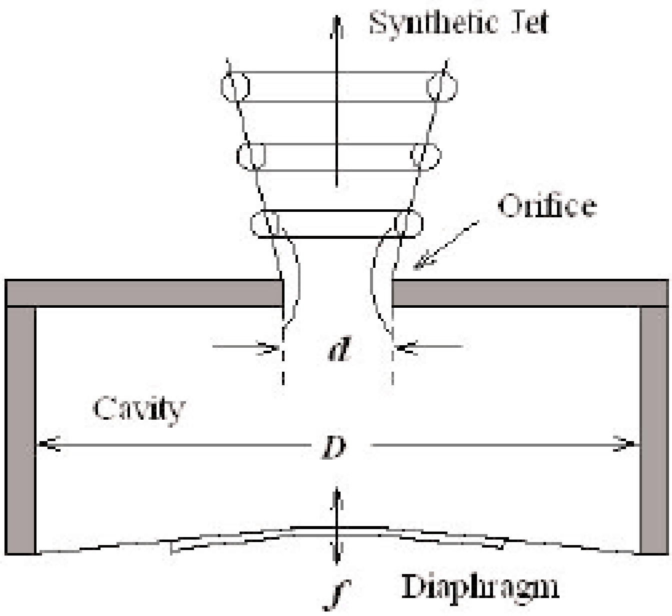

Figure 19: Schematic diagram of a synthetic jet produced with an oscillating diaphragm.

A nominally plane turbulent jet is synthesized by the interactions of a train of counter-rotating vortex pairs that are formed at the edge of an orifice by the time-periodic motion of a flexible diaphragm in a sealed cavity (Smith and Glezer, 1998).
Even though the jet is formed without net mass injection, the hydrodynamic impulse of the ejected fluid and thus the momentum of the ensuing jet are nonzero. Successive vortex pairs are not subjected to pairing or other subharmonic interactions. Each vortex of the pair develops a spanwise instability and ultimately undergoes transition to turbulence, slows down, loses its coherence and becomes indistinguishable from the mean jet flow.
The trajectories of vortex pairs at a given formation frequency scale with the length of the ejected fluid slug regardless of the magnitude of the formation impulse and, near the jet exit plane, their celerity decreases monotonically with streamwise distance while the local mean velocity of the ensuing jet increases.
In the far field, the synthetic jet is similar to conventional 2D jets in that cross-stream distributions of the time-averaged velocity and the corresponding rms fluctuations appear to collapse when plotted in the usual similarity coordinates. However, compared to conventional 2D jets, the streamwise decrease of the mean centerline velocity of the synthetic jet is somewhat higher and the streamwise increase of its width and volume flow rate is lower. This departure from conventional self-similarity is consistent with the streamwise decrease in the jet's momentum flux as a result of an adverse streamwise pressure gradient near its orifice.
The interaction of a modeled synthetic jet with a flat plate boundary layer is investigated numerically using an incompressible Navier–Stokes solver by Mittal and co-workers (2001). The diaphragm is modeled in a realistic manner as a moving boundary in an effort to accurately compute the flow inside the jet cavity.
The primary focus of this study was on describing the dynamics of the synthetic jet in the presence of external cross-flow (see Figure 20 which shows the plot of vorticity contour at four different stages for boundary layer thickness Reynolds number Re_δ=1200). A systematic parametric study has been carried out where the diaphragm amplitude, external flow Reynolds number and slot dimensions are varied. The simulations allowed to extract some interesting flow physics associated with the vortex dynamics of the jet and also provide insight into the scaling of the performance characteristics of the jet with these parameters.

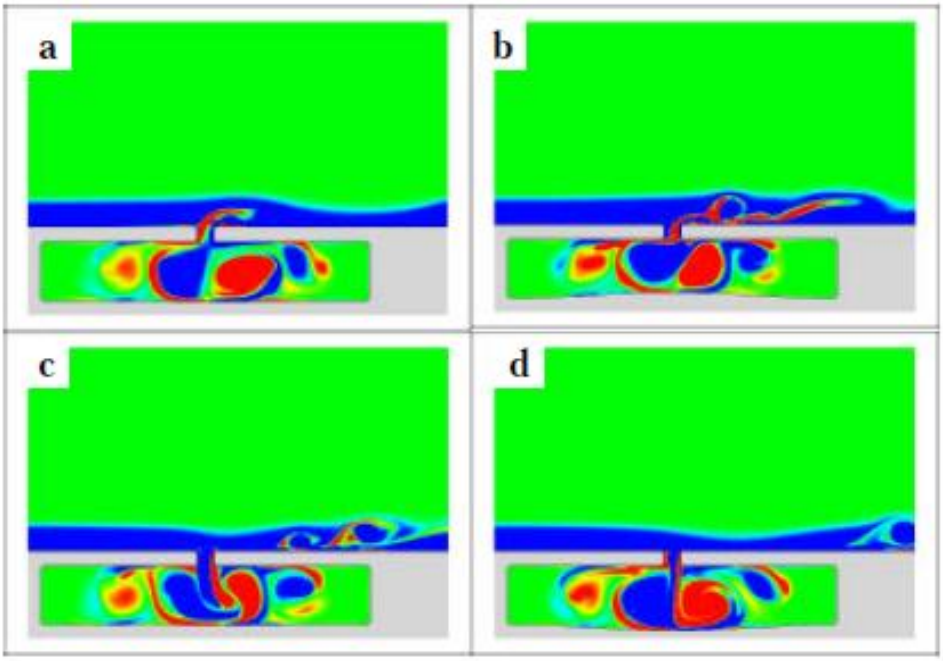

Figure 20: Plot of vorticity contour at four different stages for boundary layer thickness Reynolds number Re_δ=1200, h/d=1 (orifice width to height ratio) and A/H=0.1 (diaphragm amplitude to cavity height ratio). (a) Maximum expulsion (b) Minimum volume. (c) Maximum ingestion and (d) Maximum volume. External cross-flow from left to right.

A comparison between synthetic jets and continuous jets were made by Smith and Swift (2003). Their results show that, in the far field synthetic jets bear much resemblance to continuous jets in that the self-similar velocity profiles are identical. However, in the near field, synthetic jets are dominated by vortex pairs that entrain more fluid than do continuous jet columns. Therefore, synthetic jets grow more rapidly, both in terms of jet width and volume flux, than do continuous jets.

Zhong et al. (2005) carried out dye flow visualisation of circular synthetic jets in laminar boundary layers developing over a flat plate at a range of actuator operating conditions and freestream velocities of 0·05 and 0·1ms^{-1} (Figure 21) . The purpose of this work was to study the interaction of synthetic jets with the boundary layer and the nature of vertical structures produced as a result of this interaction.

The effects of Reynolds number (Re), velocity ratio (V_R the ratio of time-averaged and free stream velocity) and Strouhal number (St) on the behaviour of synthetic jets were studied. At low Re and V_R, the vortical structures produced by synthetic jets appear as highly stretched hairpin vortices attached to the wall. At intermediate Re and V_R, these structures roll up into vortex rings which experience a considerable amount of tilting and stretching as they enter the boundary layer. These vortex rings will eventually propagate outside the boundary layer hence the influence of the synthetic jets on the near wall flow will be confined in the near field of the jet exit. At high Re and V_R, the vortex rings appear to experience a certain amount of tilting but no obvious stretching. They penetrate the edge of the boundary layer quickly, producing very limited impact on the near wall flow. Hence it is believed that the hairpin vortices produced at low Re and V_R are likely to be the desirable structures for effective flow separation control. At high Re and V_R, the vortex rings appear to experience a certain amount of tilting but no obvious stretching. They penetrate the edge of the boundary layer quickly, producing very limited impact on the near wall flow. Hence it is believed that the hairpin vortices produced at low Re and V_R are likely to be the desirable structures for effective flow separation control.

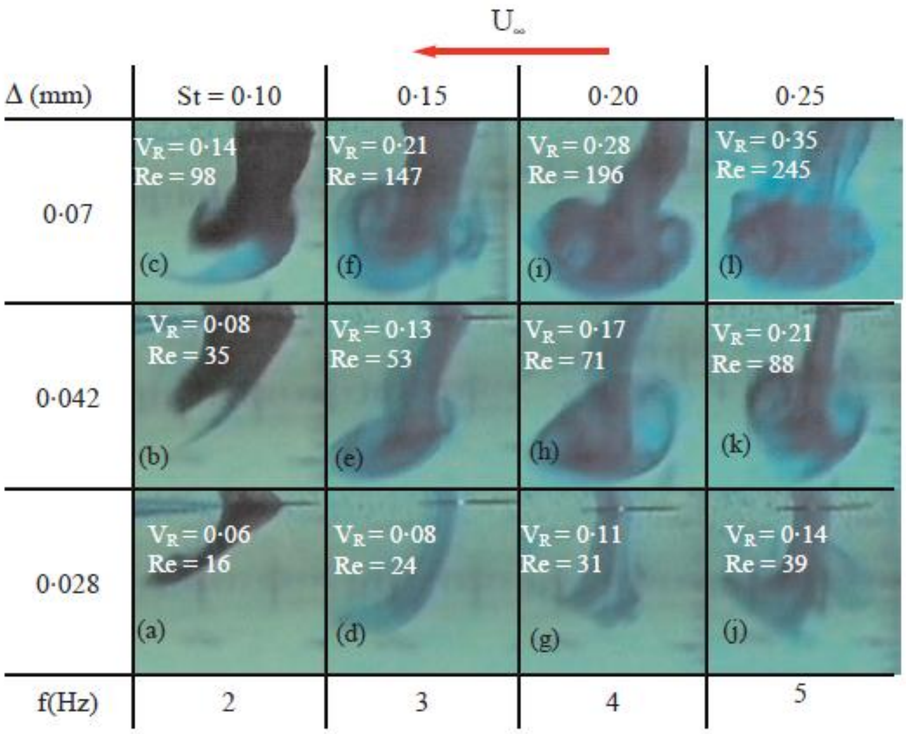

Figure 21: Close-up view of synthetic jets produced with different diaphragm displacements and frequencies in a laminar boundary layer at $U_\infty = 0{\cdot}1\text{ms}^{-1}$.

Li-shu and Zhi-de (2006) performed an experimental and analytical investigation of aerodynamic flow control using synthetic jet technology. The results show that stalling characteristic is improved, and maximum lift coefficient is improved on a certain extent.
Flow control with plasma synthetic jet actuators (PSJA, Figure 22) were tried by Santhanakrishnan and Jacob (2007). Pulsed operation of the actuator results in the formation of a starting vortex ring that advects ahead of the jet and secondary vortex rings near the actuator surface due to the additional plasma-induced fluid entrainment in the boundary layer. By varying the actuator pulsing frequency, multiple vortex rings were created in the flowfield and the resulting vortex ring interactions were found to increase both the peak velocity and streamwise extent of the jet.

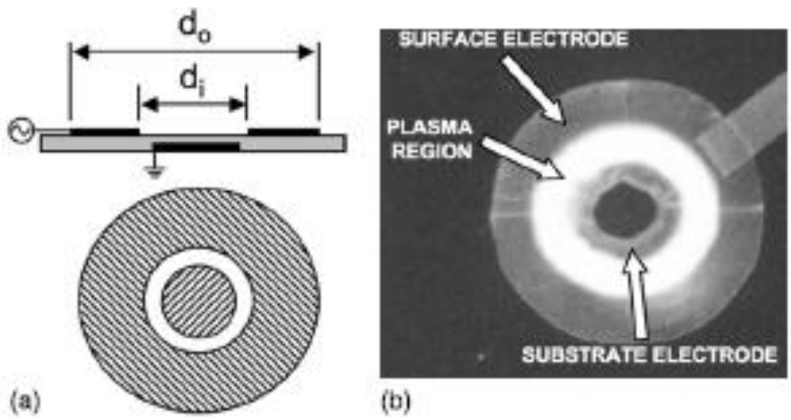

Figure 22: (a) Schematic of PSJA: top view and cross section. (b) Plasma ring created on actuation.

Active control of flow separation over an airfoil using synthetic jets is studied by You and Moin (2008). They performed large-eddy simulation of turbulent flow separation over an airfoil and evaluated the effectiveness of synthetic jets as a separation control technique. As in the experiment, large-eddy simulation confirms that synthetic-jet actuation effectively delays the onset of flow separation and causes a significant increase in the lift coefficient, this can easily be seen in Figure 23.

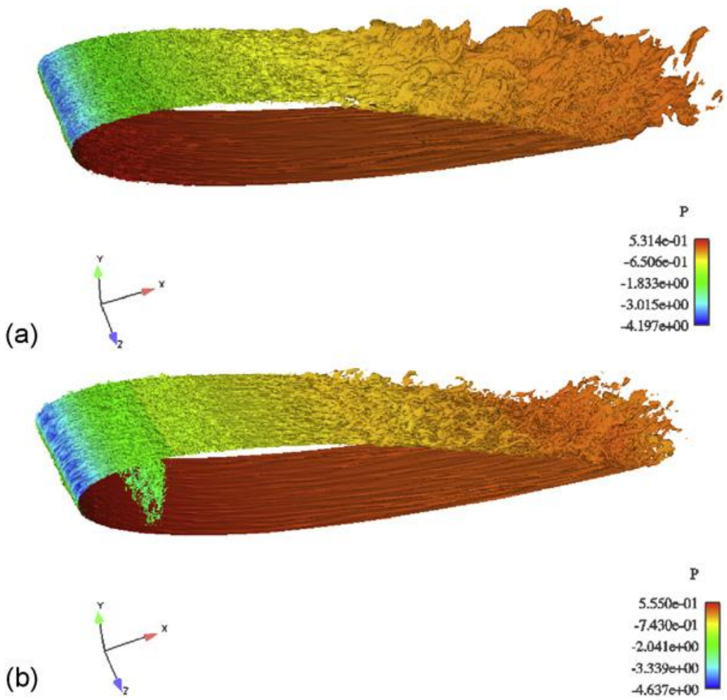

Figure 23: Iso-surfaces of the instantaneous vorticity magnitude of 40 overlapped with the pressure contours:(a)uncontrolled case; (b)controlled case.

Data on synthetic jets suggest that planar and axisymmetric turbulent synthetic jets exhibit self-similarity in the far field. Agrawal and Verma (2008) conducted a similarity analysis of planar and axisymmetric turbulent synthetic jets. Important differences between synthetic and continuous jets arise because of a larger spread rate in the case of synthetic jets. The analysis predicts the same streamwise variation of velocity and spread rate with synthetic jets as the corresponding continuous jets. It is argued that to first order, the momentum flux with contribution from both mean and fluctuating velocity should be conserved in the self-similar region, but with a value less than that supplied at the source.

Microjets for Noise Reduction

Considering the growth of airplane traffic during the last few years, jet noise reduction remains a crucial stake. Such a reduction has already been obtained by passive systems, like tabs or chevrons (Simonich et al. (2001), Zaman (1994), and Zaman, (1999)), to the detriment of a thrust reduction affecting airplane performances. As an alternative, a micro-injection system impacting the main jet has been suggested, and resulted in a turbulence level reduction in part or full jet mixing layer (Arakeri et al. (2003), Alkislar et al. (2005)), leading to jet noise reduction. Comparisons between the different microjets system implied in the above studies reveal that characteristic parameters of the control system, such as the flow at the microjet exit, the number of microjets and their diameters, could be quite different from one study to another. Few studies in this regard are reviewed here.

The effects of microjets on the aerodynamic characteristics of a Mach 0.9 high-Reynolds axisymmetric jet (Figure 24) are investigated (Castelain et al., 2007). Three parameters of the microjets system are varied: the outgoing mass flux per microjet, the number of microjets and their layout in the azimuth of the main jet. The aerodynamic results indicate a strong correlation between the maximum level of turbulence just behind the nozzle exit (characterized here one nozzle diameter downstream the nozzle exit) and the high-frequency noise, previously shown to potentially balance the acoustic benefits obtained for lower frequencies. The maximum level of turbulence measured downstream (here three nozzle diameters downstream the nozzle exit) is also highly correlated to the jet noise reduction, which is highlighted by the similar evolution of these two quantities regarding the mass flux per microjet and the number of microjets. For low values of the number of microjets, the microjets are shown to act independently, and their contributions to the turbulence reduction are retrieved far downstream the impinging point without any noticeable azimuthal diffusion.

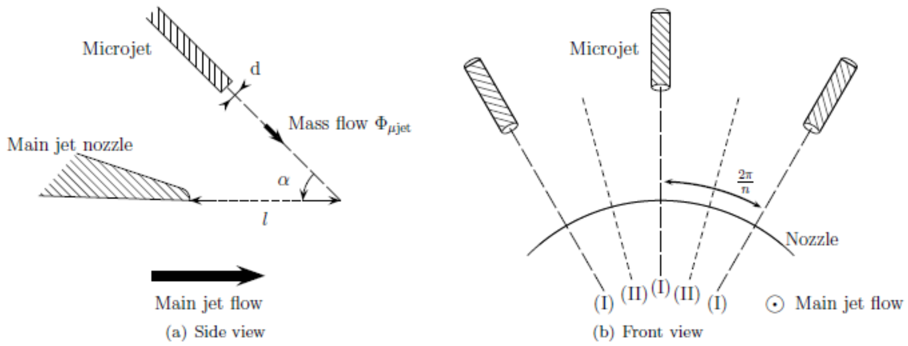

Figure 24: Schematic of the microjets impinging the jet mixing layer.

Pulsed microjet control of supersonic impinging jets via low-frequency excitation is studied by Annaswamy et al. (2008). The actuator used for active control consists of a pulsed microjet, by which it is shown that in a scaled supersonic experimental facility acoustic resonances can be reduced, utilizing a fraction of the mass flow-rate needed with a steady microjet (Figure 25). Several parameters related to pulsed injection are varied to evaluate their impact on the resonances, and it is found that duty cycle and pulsing frequency have the most dominant effect on the jet noise as well as on the overall flow field.

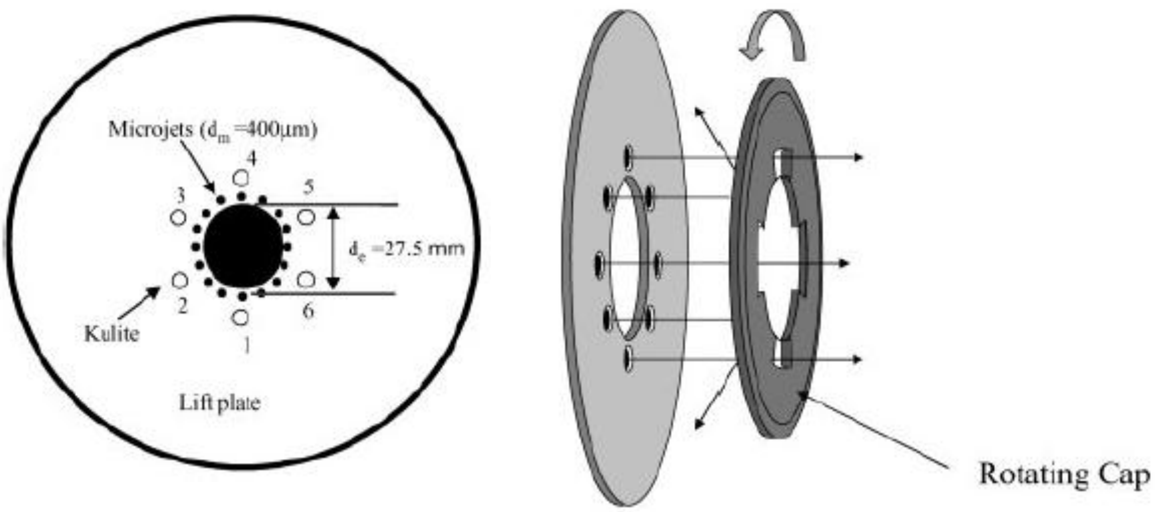

Figure 25: (left) Lift plate/microjet layout, (right) A schematic of the pulsing actuator. In the indicated position, the microjets are unblocked. With a clockwise turn, the cap geometry is such that the microjets are blocked, which simulates a pulsing action.

A parametric study is carried out (Zaman, 2010) to investigate experimentally the effect of injecting tiny secondary jets ('μjets') on the radiated noise from a subsonic primary jet. The μjets

are injected on to the primary jet near the nozzle exit with variable port geometry, working fluid and driving pressure. A clear noise reduction is observed that improves with increasing μjet pressure. It is found that smaller diameter ports with higher driving pressure, but involving less thrust and mass fraction, can produce better noise reduction. Centerline velocity data show that larger noise reduction is accompanied by faster jet decay as well as significant reduction in turbulence intensities.
LES-based evaluation is carried out of the efficiency of microjet injection for jet-noise suppression in both static and flight conditions (Shur et al., 2010). A major outcome of the microjet simulations is that this noise-reduction concept, considered competitive with chevrons nozzles in static conditions turns out to be virtually "passive" in flight conditions which were never studied experimentally. Specifically, according to CFD, at a typical take-off value of the flight Mach number, the microjet injection does not cause any noticeable reduction of the peak low-frequency noise and still results in the same level of high-frequency noise increase as in static conditions. Figure 26 visibly displays an intensification of fine-grained turbulence in the immediate vicinity of the MJ injection into the main jet stream and further downstream. This effect is clearly pronounced both in static and flight conditions in this figure. Note that exactly this behavior is probably the reason of the high-frequency noise penalty caused by MJ.

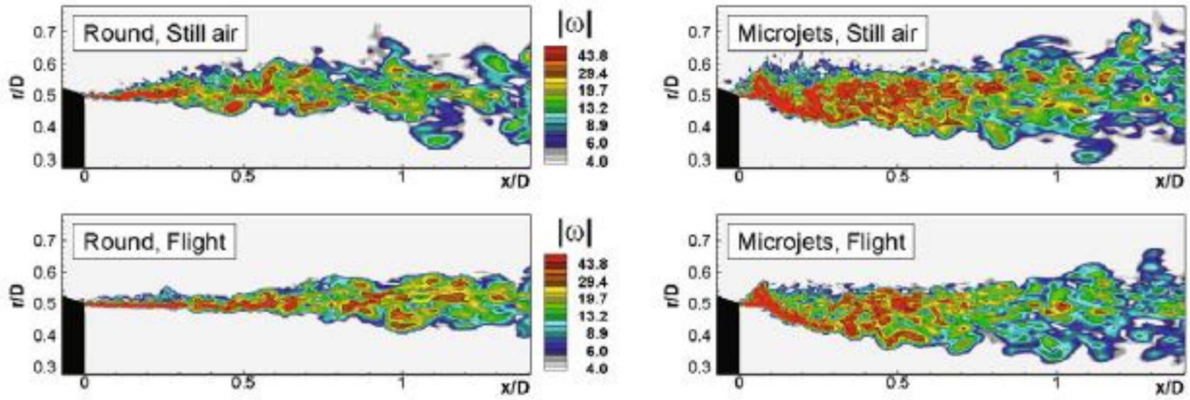

Figure 26: Instantaneous fields of vorticity magnitude in a meridian section passing through microjet center.

Munday et al., (2010) presents an overview of a joint Experimental/Numerical project sponsored by the Swedish Defense Materiel Administration (FMV) to apply flow control techniques to reduce the noise from high-performance military aircraft such as the Saab Gripen. At University of Cincinnati chevrons and trailing-edge fluidic injection were tested and compared with secondary flow simulating forward flight. At Chalmers University the same conditions were simulated with Large Eddy Simulation and Kirchhoff integral method. Both flow control approaches produced significant reductions in community noise. The area for a given peak perceived noise level was reduced by 20-27% by chevrons and by 23-38% by microjets. LES shows that microjets shorten the potential core of the jet. See Figure 27. This is an indirect indication of increased mixing and thus increased rate of thickening of the shear layer around the jet.
Finally, Henderson (2010) reviews 50 years of research investigating jet noise reduction through fluidic injection in his paper. Both aqueous and gaseous injection concepts for supersonic and subsonic jet exhausts are discussed. Aqueous injection reduces jet noise by reducing main jet temperature through evaporation and main jet velocity through momentum transfer between water droplets and the main jet. In the launch vehicle environment where large quantities of fluid do not have to be carried with the vehicle, water injection is very effective at reducing excess overpressures. For in-flight use, aqueous injection is problematic as most studies show that either large quantities of water or high injection pressures are required to achieve noise reduction. The most effective noise reduction injection systems require water pressures above 2000 kPa (290 psi) and water-to-mainjet mass flow rates above 10% to achieve

overall sound pressure level reductions of roughly 6 dB in the peak jet noise direction. Injection at lower pressure (roughly 1034 kPa or 150 psi) has resulted in a 1.6 EPNdb reduction in effective perceived noise level. Gaseous injection reduces noise through jet plume modifications resulting from the introduction of streamwise vorticity in the main jet. In subsonic single-stream jets, air injection usually produces the largest overall sound pressure level reductions (roughly 2 dB) in the peak jet noise direction. In dual-stream jets, properly designed injection systems can reduce overall sound pressure levels and effective perceived noise levels but care must be taken to choose injector designs that limit sound pressure level increases at high frequencies. The counter-rotating vortex pair resulting from the interaction of an injecting jet and main jet is bent by the mean flow and forms a longitudinal vortex pair as shown in Figure 28(a) (see Ref. 41). However, air injection into dual-stream subsonic jets has received little attention and the potential for noise reduction is uncertain at this time. For dual-stream supersonic jets, additional research needs to be conducted to determine if reductions can be achieved with injection pressures available from current aircraft engines. Additionally, the noise benefits of any reduction technology must be weighed against thrust degradation and system implementation limitations.

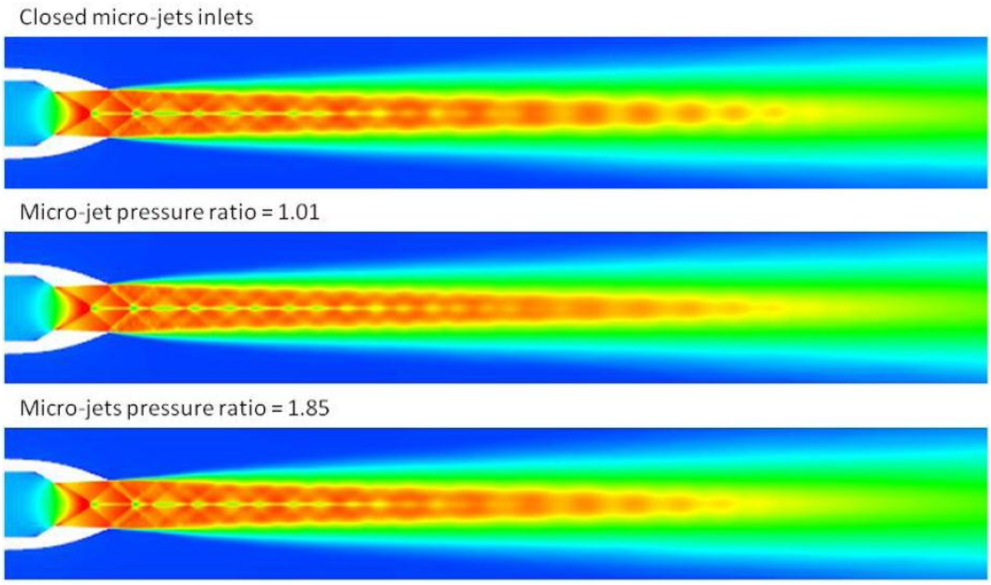

Figure 27: Axial velocity in axial planes from LES

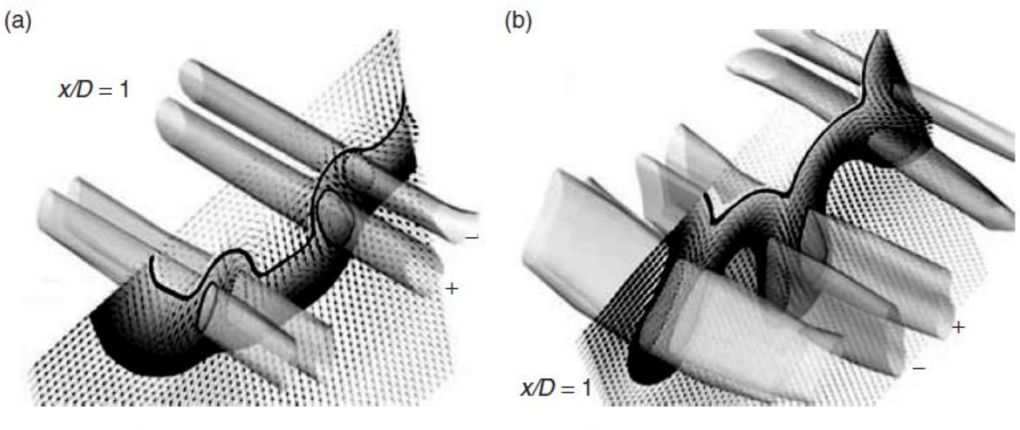

Figure 28: Iso-surfaces and velocity vectors obtained for (a) a main jet with microject injection and (b) a main jet produced by a mechanical chevron nozzle. The data were taken at one diameter downstream of the nozzle trailing edge.

Concluding Remarks

In the last 60 years or so, artificial excitation has been widely used as an experimental tool to advance our understanding of shear flow dynamics. The purpose of the excitation has been to introduce a disturbance (acoustic, fluidic or mechanical) to be followed in space or time for the instability study, or to organize the coherent structures so that they could be "educted" with relative ease from the background randomnesses of a turbulent flow. Experience from these studies has also led to the possibility of utilizing excitation to achieve control of certain types of flow phenomena, e . g., boundary layer transition and separation, and shear layer mixing (Rice and Zaman, 1987). In this paper we explained the research works carried out so far on different types of excited jets, with emphasis on experimental studies and on aspects of flow control. These studies showed there is a tremendous demand for application of various types of these jets in engineering and industrial fields. They could be categorized as: supersonic, synthetic, impinging, flip-flop, or micro jets. They are used for numerous flow control purposes like: boundary layer transition and separation control, improving heat transfer capability, enhancing flow mixing, augmenting thrust of nozzles, suppressing jet noise level. An important aspect of success in these practical applications will be the development of usable excitation devices.

Acknowledgements

This work is supported by Dept. of Fluid Dynamics of Chalmers University and Shiraz University of Technology. Many thanks to all who helped me in compiling this manuscript including those researchers whose papers are quoted here.

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