BIFURCATING AND BLOOMING JETS

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Abstract It is classically assumed that the far field of a round turbulent jet discharging into quiescent fluid has a unique behavior characterized only by its momentum flux. However, there is now considerable evidence that different discharge conditions at the jet nozzle exit can give rise to very different far-field flows. Perhaps the most striking examples of these are the bifurcating and blooming jets produced by appropriate combinations of controlled axial and circumferential excitations at the nozzle exit. With the right excitations, a jet can be made to divide into two separate jets (bifurcating jet), each of which carries half the axial momentum and spreads in a manner similar to a single jet. Trifurcating jets can also be produced. Other excitations can produce blooming jets, in which the jet explodes into a shower of vortex rings, producing a far-field flow that is quite unlike a normal unexcited jet. Bifurcating and blooming jets exhibit much greater mixing than normal jets, suggesting possible applications in flow control. This article summarizes our work on bifurcating and blooming jets, which began with our discovery of them in the early 1980s and continued through the mid-1990s. One of us (D.E.P.) continued exploration of flow control using excited jets, first at the McDonnell Douglas Corporation, and more recently at the Georgia Institute of Technology. The key to flow control is the manipulation of the large vortical structures in the near field of the jet. Ultimately this work, and that of others, led to full-scale testing of jet engine exhaust mixing control. There it was shown that the jet temperature downstream of the engine can be very significantly reduced by application of well-designed and easily implemented excitation at the engine discharge, thereby solving problems encountered during ground operations. Related jet control work by other investigators is included in this review.

1. OVERVIEW

When a round jet discharges into quiescent fluid, the boundary layer on the jet nozzle forms a free shear layer originating at the nozzle lip and extending downstream. This shear layer exhibits rapidly growing Kelvin-Helmholtz (KH) instability. For a comprehensive review of the instability physics see Ho & Huerre (1984). If the
layer is laminar, axisymmetric ring vortices are formed in the jet shear layer. These are advected downstream, interact and merge in complex dances, and eventually themselves become unstable and break down to form turbulence, leading to a classical fully turbulent jet in the far field. Similar behavior is observed at higher Reynolds number where the nozzle boundary layer is turbulent, although the orderly vortex region is less prominent because of the turbulence in the free shear layer. Crow & Champagne (1971) were among the first to recognize the importance of orderly structures in turbulent jets. For a comprehensive discussion of structure in natural turbulent jets see Dimotakis et al. (1983).

The spacing of the vortex rings is controlled by disturbances (natural or imposed) at the nozzle lip. Therefore, if an axial velocity perturbation is imposed (by axial acoustic forcing upstream of the nozzle or by axisymmetric mechanical forcing at the nozzle lip), the ring spacing can be controlled. The cleanest control with small amplitude (1% axial velocity fluctuations) is obtained when the forcing frequency is in the range of rapidly amplified KH disturbances in the shear layer. Stability analysis shows that the most amplified frequency varies inversely with shear-layer thickness and has a relatively weak dependence on the shear-layer velocity profile. Figure 1 (left panel) shows the instantaneous ring vortex structure on an axial plane in the near field of an air jet. The vortical fluid is

![Figure 1](image_url)  
**Figure 1** Ring vortex structure on bisecting plane in an air jet at $Re = 10,000$: (left) axial forcing; (right) combined axial and helical forcing. From Parekh et al. (1988).
made visible by short-duration (30 µs) laser-sheet illumination of smoke injected into the nozzle boundary layer midway along the contraction. The axial excitation is at $S_{a} = f_{axial}D/U_{0} = 0.55$, where $f_{axial}$ is the axial forcing frequency, $D$ the nozzle exit diameter, and $U_{0}$ the jet velocity (centerline) at the nozzle exit, and the Reynolds number is $Re = U_{0}D/ν = 10,000$.

Very complex behavior can be obtained by combining the axial disturbance with a nonaxisymmetric helical disturbance at a lower frequency (dual-mode excitation). Helical disturbances (called orbital in our early work) can be obtained by wobbling the nozzle slightly or using nonaxisymmetric acoustic or other forcing at the nozzle lip. Wobbling causes successive vortex rings to be placed slightly off the average axis, such that adjacent rings are eccentric with respect to one another. Figure 1 (right panel) shows the near field of the same jet as on the left with an added helical excitation at half the frequency. Note the opposite tilting of consecutive vortex rings. The physics is simple; eccentric rings tend to tilt one another by mutual induction, causing both to move away from the common axis, stretching the jet core fluid between them, as shown by the cartoon in Figure 2. If the disturbance frequency ratio $r_{f} = f_{axial}/f_{helical}$ is 2, the ring vortices will be tilted alternately to the left and right, and with sufficient forcing, the jet will bifurcate and appear to flap. Figure 3 shows the instantaneous structure in a bifurcating water jet at $Re = 4300$, visualized by laser-sheet illumination of fluorescent dye in the jet core fluid. Note the core fluid stretched between the two legs of the jet.

![Figure 2](image)

**Figure 2** cartoon showing vortex tilting in a row of nonconcentric ring vortices and stretching of core fluid between the vortices. From Lee & Reynolds (1985a).
and the rapid mixing with ambient fluid. The bisecting plane reveals secondary vortices caused by the turning and stretching of shear-layer vorticity between the two legs of the jet.

If \( r_f \) is very slightly different from 2, the jet will bifurcate and the bifurcation plane will precess slowly around the nozzle axis. If \( r_f = 3 \) or 4, the jet can be made to divide into three or four separate vortex streams. And if \( r_f \) is an irrational multiple of the orbital frequency, no vortex ring will exactly follow any other shed previously, and the jet can be made to “bloom” in an amazing shower of vortex rings that we dubbed the blooming jet. Blooming can occur for any small \( r_f \) not close to an integer. Figure 4 shows the instantaneous structure of blooming water jet at \( Re \approx 20,000, St_a = 0.5, r_f = 2.4 \), visualized by dye in the plenum fluid.

How did we discover this? Inspired by a presentation on flapping jets by Binder & Favre-Marinet (1981), W.C.R. & M.J.D.L. (initials without a date indicate a coauthor of this article) combined axial and orbital disturbances and observed bifurcating and blooming jets using a water flow rig with a piston system to produce a steady axial flow with periodic axisymmetric perturbations and a wobbled 1-inch-diameter nozzle (Lee & Reynolds 1982, 1985a,b). While on sabbatical leave at Caltech in 1984, W.C.R. built the smaller water flow rig with which Figure 4 was obtained. That nozzle was wobbled orbitally and jiggled axially to modulate a constant-head flow feed (Reynolds 1984).
Figure 4  Blooming water jet at $Re \approx 20,000$. From Reynolds (1984).

D.E.P. carried out an early vortex simulation that confirmed the vortex tilting mechanism (Parekh et al. 1983, 1988). The model predicted that as the vortex rings were brought closer and closer together by increasing the axial frequency while maintaining the orbital frequency as half the axial so as to form a bifurcating jet, the spreading angle of the two legs of the bifurcating jet would increase, up to a point where the vortices are so close that they become entangled before the bifurcation can occur. This was subsequently confirmed by M.J.D.L.’s water experiments.

Our initial experiments (by M.J.D.L.) were all done with jet Reynolds numbers in the range $Re \approx 10^3 – 10^4$, where the shear-layer instability frequency is such that the vortex spacing is only a bit smaller than the jet diameter and vortex interactions are strong. Subsequently D.E.P. showed that bifurcation and blooming could also be obtained in air at these relatively low $Re$ using only acoustic dual-mode excitations. Figure 1 is from these air experiments with weak acoustic forcing. At very high $Re$ the shear layer is very thin, and so the vortex formation frequency in the shear layer is much too high and the vortex spacing too close to allow the mutual induction that separates eccentric vortices. However, D.E.P. found that, with sufficient forcing, control could be effective at least up to $Re_D \approx 10^5$, and we believe it is possible at any $Re$. P.J.D.J. explored a number of means for thickening the shear layer, hoping to enhance control ability for jets at high $Re$. Interesting discoveries by P.J.D.J. were the Coanda jet and a self-excited cousin, discussed briefly in Section 4.

Upon moving to the McDonnell Douglas Research Laboratories, D.E.P. became involved in applying flow-control ideas to high-speed jets and in transitioning these concepts to full-scale applications. Ultimately this led to the first large-scale
application of bifurcating (flapping) jets to the control of jet engine exhaust (Kibens et al. 1999).

D.E.P.’s vortex filament simulation was resurrected in 1998 for a study of genetic algorithms for optimization of flow control (Koumoutsakos et al. 1998). Surprisingly, they found a particular excitation combination that produced a slightly greater bifurcation angle, resulting from a secondary bifurcation in which the rings change path a short distance after the initial bifurcation and the bifurcation plane rotates by an angle of $\pi/4$ from the original plane of bifurcation. This has not yet been confirmed by experiments, but it stimulates further work. Danaila & Boersma (1998) conducted direct numerical simulation of bifurcating and blooming jets that provides nice insight into the vortex dynamics. Sbalzarini et al. (2000) used P.J.D.J.’s apparatus in an experiment in which the orbital and axial excitations were adjusted using an evolutionary algorithm to optimize entrainment.

In the first few sections below we provide more quantitative detail on our work mentioned above. This is followed by review of related work by others, including important engineering applications that have been made. The story provides an excellent example of how fundamental research in fluid mechanics, carried out simultaneously by researchers at several institutions for more than a decade, funded largely by the Air Force Office of Scientific Research and stimulated by frequent interactions at professional meetings and sponsor conferences, produced ingredients that enabled important new applications.

2. BIFURCATING JETS

M.J.D.L.’s experiments showed that range over which control can be obtained can be expressed nondimensionally in terms of the corresponding Strouhal numbers $St_a = f_{\text{axial}} D / U_0$ and $St_h = f_{\text{helical}} D / U_0$. M.J.D.L. found that bifurcation ($r_f = 2$) could be obtained in the range $0.4 \leq St_a \leq 0.6$, which is in the range of what some have called the preferred frequency of the jet. At lower frequencies the vortex rings are too far apart to undergo bifurcation before they break down by other instabilities, and at high frequency they are too close together to escape one another.

M.J.D.L. made detailed mean and fluctuating velocity measurements using a Bragg-shifted laser Doppler anemometer in a tracking mode. Figure 5 shows typical mean velocity profiles in the bifurcation and bisection plane at downstream locations. Note the two peaks in the bifurcation plane that separate as the jet flows downstream. The profiles in the bisection plane have only the one peak on the centerline, and jet does not broaden appreciably in the bisection plane. Figure 6 shows the peak axial velocities for the natural and bifurcating jet under identical conditions. Similarity analysis shows that these velocities should decrease inversely with distance, hence the normalized reciprocal velocity $U_0 / U(x)$ is plotted versus the normalized distance from the nozzle exit $x/D$. Note that the similarity behavior is confirmed for the natural jet and for the bifurcating jet once the bifurcation is established. Moreover, at a given $x/D$ the peak axial velocity on each leg of the
Figure 5  Mean velocity profiles in the bifurcating water jet at $Re = 4300$, $r_f = 2$. Axial rms velocity fluctuation amplitude $0.17U_0$, orbital nozzle displacement $0.04D$: (left) bifurcation plane; (right) bisection plane. From Lee & Reynolds (1985a).
bifurcating jet is approximately half the peak axial velocity for the natural jet. Because together they must carry the same axial momentum as the natural jet, and the momentum flux is proportional to $U^2$, the bifurcating jet must have entrained considerably more mass than the natural jet.

Figure 7 shows the experimental bifurcation angle as a function of $St_a$. D.E.P.’s interacting vortex filament analysis gave a curve of similar shape but with a maximum bifurcation angle of $58^\circ$ at $St_a = 0.43$. The quantitative differences are no doubt due to differences between the experimental and analytical disturbances and vortex cores, hence D.E.P.’s analysis confirms the basic explanation of the bifurcation.

M.J.D.L. also conducted some water “flame” experiments following a suggestion by Dimotakis (Dahm et al. 1984, Dahm & Dimotakis 1990). Acid and dye were introduced into the jet fluid and a base into the ambient fluid. When mixed molecularly with the acid, the fluorescence was quenched. The resulting laser-sheet visualization produced a flame brush. Figure 8 compares time exposures of the water flame for a natural jet and a bifurcating jet under the same conditions (except for the forcing). Note that the bifurcating flame was shorter, indicating that molecular mixing was achieved in a shorter distance than in the natural jet (for more detail, see Lee & Reynolds 1985a).
Our data and visualizations suggest that once the jet has bifurcated it will never again return downstream to a normal jet. Figure 9 shows W.C.R.’s visualization of the bifurcation in a water facility (Reynolds 1984), visualized by dye in the plenum fluid. The two legs of the bifurcating jet continued to separate at least to $x/D \approx 80$. This supports the conjecture that the far field of a jet is not unique as is classically assumed, but instead depends on the disturbance field imposed on the initial jet.

D.E.P. constructed an air rig to study these phenomena at higher Reynolds numbers. The axisymmetric excitation was provided by a loudspeaker on the axis at one end of the upstream plenum chamber. The orbital excitation was provided to four segments 90° apart around the nozzle exit plane by four loudspeakers feeding waveguides to the exit plane. The phase of these circumferential speakers could be controlled to form a precessing (orbital or helical) excitation as in the water rig. A bifurcating jet could also be obtained using two opposite circumferential speakers out of phase, forming a flapping jet. Because the axisymmetric and nonaxisymmetric frequencies were independently controllable, other modes, including blooming, could be obtained. Visualization was done by injecting smoke onto the nozzle wall midway along the contraction, illuminating the smoke with a sheet of copper vapor laser light having a 30-$\mu$s pulse duration triggerable at up to 6 KHz.
Figure 1 is an example of the fine detail of the vortex structure observable with this apparatus (see also Parekh et al. 1987).

Some of the visualizations by D.E.P. were instantaneous, others were phase averaged on the axial forcing. Axial and helical forcing amplitudes were expressed in terms of the rms pressure fluctuations measured at a point one diameter downstream of the nozzle exit and a half-diameter off the jet centerline when the speakers were operated at a given voltage without flow. The axial and helical rms pressure fluctuations were then expressed as fractions of the dynamic pressure $\rho U_0^2/2$ at the jet exit, $P_a' = p_a'/\left(\rho U_0^2/2\right)$ and $P_h' = p_h'/\left(\rho U_0^2/2\right)$. Detailed velocity measurements were also made using constant-temperature hot-wire anemometry (for details, see Parekh et al. 1988).

D.E.P.’s air experiments confirmed the general conclusions from M.J.D.L.’s water experiments, and then D.E.P. went on to see if these effects could be managed at much higher $Re$. Figure 10 (left) shows a natural jet at $Re = 10^5$ in the air rig. Note the very thin shear layer, the thickness of which is comparable to the spacing of the axisymmetric vortices barely discernable in the first half-diameter of the near field. In order to control the jet, one needs sufficient amplitude to force a “collective interaction” (Ho & Huang 1982) of the very small-scale ring vortices to roll them into large vortices spaced roughly by one jet diameter. Figure 10 (center) shows
Figure 9  Bifurcating water jet at $Re \approx 20,000$ showing flow to $x/D \approx 80$: (left) bifurcation; (right) side view of the bifurcation. From Reynolds 1984.

a collective interaction produced by axial excitation. Figure 10 (right) shows the effect of a solo helical excitation. The superposition of axial and helical excitation causes bifurcation, which has the same large-scale behavior as at low $Re$ (Figure 3). Figure 11 shows the bifurcating air jet at $Re = 10^5$, $St_a = 0.55$, $P'_a = 0.018$, $P'_h = 0.014$. Each picture is a superposition of eight sequential 30-$\mu$s laser sheet pulses phase-locked on the axial excitation (for more detail, see Parekh et al. 1988).

3. BLOOMING JETS

M.J.D.L. observed blooming jets in our mechanically excited water flow with noninteger $r_f$ in the range 1.5–3.2 and $St_a$ in the range 0.3–0.8, at $Re$ from 2800 to 10,000. Figure 12 shows one of M.J.D.L.’s first visualizations that gave rise to the name “blooming jet,” and Figure 13 shows the mean velocity profiles for this flow. The peak velocities for this case are included in Figure 6. Note that they vary as $1/x$ as suggested by similarity analysis (for more detail, see Lee & Reynolds 1985a).

Following D.E.P, P.J.D.J. used the air rig for further quantitative study of blooming air jets at $Re \approx 10^5$. Strong acoustic forcing was needed to obtain a collective interaction that would lead to strong vortex structures spaced by approximately one diameter. He characterized the excitation by the nondimensional axial and helical
pressure fluctuations defined in Section 2 and by $U'_a = u'_a / U_0$, where $u'_a$ is the rms axial forced velocity fluctuation $0.05 \, \text{D}$, where $D$ is the nozzle exit diameter, downstream from the nozzle lip on the jet centerline.

In order to make a quantitative measurement of the entrainment in natural and blooming jets, P.J.D.J. placed a shroud around the jet. The shroud diameter was $4.5 \, \text{D}$ and the shroud extended from $2.6 \, \text{D}$ to $8.3 \, \text{D}$. The mean velocity and temperature profiles were measured just inside the shroud exit plane at $x = 8D$ using a constant-temperature hot-wire anemometer. Axial or helical forcing by themselves broadened the jet only slightly. Figure 14 shows the substantial effect of dual-mode forcing (blooming) on the velocity and temperature profiles at the shroud exit. Note that the difference between the jet peak temperature and ambient temperature was reduced by more than 50% by the blooming. The entrainment of ambient fluid was calculated by performing the integration $\int U(r) r \, dr$. The entrainment plot in Figure 14 includes earlier experiments with weak axial forcing (Crow & Champagne 1971) and natural jets from elliptic nozzles (Ho & Gutmark 1987). Note that the entrainments of our natural jet and Crow and Champagne’s natural jet are commensurate at their common $x/D$ and that our strong blooming jet entrains approximately 2.5 times as much flow as a natural jet and twice as much as an elliptic jet.
Figure 11  Bifurcating air jet at $Re = 10^5$, $St_a = 0.55$, $P'_a = 0.018$, $P'_h = 0.014$: (left) bifurcation plane; (right) bisection plane. From Parekh et al. (1988).

Figure 12  Side and axial views of a blooming water jet at $Re = 4300$, $r_f = 2.4$. Disturbances as in Figure 5. From Lee & Reynolds (1985a).
Jets bloom easily at $Re \approx 10^4$, but require much stronger forcing at much higher $Re$, where the blooming range $St_a \approx 0.5$ is at a much lower frequency than the most amplified shear-layer disturbances. Thickening the boundary layer at the jet lip should lower the shear-layer amplification frequencies, allowing more control with less forcing. P.J.D.J. modified the air rig to explore this possibility. Around the original nozzle was placed a blowing channel, through which air could be added to thicken the boundary layer. This could be followed by a straight section or by an 8° conical diffuser. With the diffuser extension, there was indeed some increase in the entrainment, most noticeable for the modest blooming excitation, but the increase was not sufficient to generate much excitement; hence, this line of attack was abandoned. However, when the extensions were removed and the blowing device was used by itself, a remarkable Coanda jet was observed.

4. COANDA JET

Figure 15 shows the nozzle geometry and flow structure for the Coanda jet. The idea was to use tangential blowing at the throat to help the boundary layer partway around the turn, thereby rendering the resulting jet more susceptible to blooming
Figure 14  Shrouded blooming jet at $Re = 95,000$, showing temperature and velocity profiles near the shroud exit and entrainment to that point, compared with previous experiments. From Juvet & Reynolds (1993).
Figure 15  Coanda jet with annular blowing flow at approximately twice the main jet velocity. The two smoke wire pictures established the basic flow structure shown in the cartoon. Velocity measurements confirmed the presence of a self-similar radial wall jet on the horizontal surface. From Juvet & Reynolds (1993).
by weak acoustic disturbances. With a blowing velocity of approximately twice the nozzle-throat velocity, the flow is diverted completely and becomes a radial wall jet that entrains all of the primary jet flow and produces a strong external flow toward the nozzle, as shown by the cartoon in Figure 15. It is clear from these data that relatively small amounts of blowing can have a profound effect on a jet. This phenomenon should have many practical applications.

P.J.D.J.’s last effort in our program explored a jet with self-excited axial oscillations produced using the Coanda jet apparatus without blowing. The blowing slot and plenum provided a cavity that could absorb and release fluid, producing an absolutely unstable system (see below). A self-excited flow with strong axial oscillations and collective interaction was observed. The oscillation frequency varied linearly with the throat velocity $U_0$ and hence occurred at a fixed $St = f D_0 / U_0$, indicating that the oscillation was driven by fluid mechanics and not by acoustics. $St$ ranged from 0.2 for a Coanda radius of 0.95D to 0.35 for a Coanda radius of 0.32D. The cavity volume did not seem to matter much, except that when the cavity was eliminated by filling it with wax the jet was no longer self-excited, so it is clear that the cavity was important dynamically. We tried unsuccessfully to devise a cavity to support self-excited helical oscillations, which might then produce a self-blooming jet. We leave this as a challenge for young researchers and inventors in the new century (for more detail, see Juvet & Reynolds 1993).

5. RELATED FUNDAMENTAL RESEARCH

There were several indications of bifurcation and blooming phenomena in the literature before we started, not all of which were known to us at the time. Leconte’s (1858) studies of the sensitivity of flames to sound, Tyndall’s (1867) bifurcating smokestack plumes, and Brown’s (1935) experiments on control of jet spreading by acoustic interaction, are among the oldest related literature. Research in the modern era was stimulated greatly by the work on large-scale structures in turbulent mixing layers by Brown & Roshko (1974), after which the Caltech group continued to make important contributions. Glezer’s (1981) work on trains of vortices produced by a pulsed actuator was in essence work on a synthetic jet (Glezer & Amitay 2002). Hence, Saffman’s (1981) photograph and description of Glezer’s pulsed vortex train as “blooming,” unknown to us until embarrassingly too long after it was published, probably is the earliest revelation of a blooming jet, although it was not recognized as such at that time.

There was a great deal of other flow control research ongoing during the 1980s and 1990s and considerable interaction between groups. Glezer and his students and colleagues developed and exploited piezoelectric springboard actuators for flow control (Wiltze & Glezer 1993). For low-speed flow these are operated at a high resonant frequency of the springboard (first or second mode), with amplitude modulation at a much lower frequency to which the flow is receptive. The flow then responds to the amplitude modulation of the actuators, which can be operated at different phases. For high-speed flow the actuators are designed so that the flow is
receptive to disturbance at the springboard resonant frequency. These were applied to active control of a supersonic jet at Mach number 1.1 by Parekh et al. (1996). They positioned an array of eight actuators around the outside of the nozzle lip, perpendicular to the jet axis so that the actuators would impose amplitude-modulated periodic axial velocity oscillations at the free edge of the nozzle-lip shear layer. They also experimented with eight pulsed fluid actuators, with which they imposed periodic radial velocity perturbations on the shear layer. They studied the mixing enhancement obtained by operating all actuators in phase, exciting the axial mode, and the flapping mode, obtained by operating four actuators on one side 180° out of phase with four actuators on the other side. Although aware of our work that showed the advantage of combining these two modes they were not able to explore this combination with their actuators. However, they found that the flapping excitation by itself gave a great enhancement of the downstream mixing. Corke & Kusek (1993) studied forcing with only the helical mode, which by itself does not significantly increase mixing.

The work described above all uses some means of active excitation to control the vortex structure in the jet near field. Some control can be obtained passively simply by using a noncircular jet. Husain & Hussain (1983) and Ho & Gutmark (1987) showed that an unforced elliptical jet can have several times the entrainment rate of a round or two-dimensional jet. Hussain & Husain (1989) reported detailed measurements on the unforced and forced bifurcating elliptical jet, for which they provided an insightful discussion of the vortex dynamics. Gutmark & Grinstein (1999) provide a nice review of this research and the extensions to supersonic jets, where significant mixing enhancement can also be obtained using noncircular jets. Lee et al. (2002) used a triangular nozzle, discharging into a short axisymmetric cavity, to produce self-excited precessing flapping (trifurcating) jets with spreading angles as high as 160° and velocity decay rates more than five times that of a normal round jet. This is the most impressive use of passive jet control that we have seen to date.

The foundation for self-excited jet flow control was laid when Huerre & Monkewitz (1985) identified the important theoretical difference between convective instabilities, which wash downstream and die if not sustained upstream, and absolute instabilities, which persist without continual reinforcement. Strykowski and his students and colleagues (Strykowski & Niccum 1991; Strykowski & Wilcoxon 1992; Jendoubi & Strykowski 1994; Strykowski et al. 1996a,b; Strykowski et al. 1996; Washington et al. 1996; Alvi et al. 2000) have exploited the absolute instabilities of counterflow jets to control subsonic and supersonic jets, including the use of active control of Coanda flows (Van der Veer & Strykowski 1997). Monkewitz and his students and colleagues have explored forced and unforced heated jets, finding that heating an upward-flowing jet greatly enhances its receptivity to natural and applied disturbances (Monkewitz et al. 1990). In heated vertical jets, they observed vortices shooting out from the side, very reminiscent of our blooming jet (Monkewitz & Bechert 1988). Monkewitz & Pfizenmaier (1991) provided quantitative detail on the enhanced mixing of forced and self-excited
heated jets. Pfizenmaier et al. (1993) produced a picture of a bifurcated flame using only helical (flapping) excitation.

6. FULL-SCALE APPLICATION

The fundamental work described above ultimately transitioned to a demonstration of active flow control on an aircraft engine. Comprehensive numerical simulations of the controlled turbulent jet flow (Smith et al. 2001) made prior to the experiment showed that 3% of the compressor flow could be bled to pulsed tangential jet actuators placed around the nozzle exit to excite the subsonic jet in the flapping mode, thereby increasing the exhaust jet spreading rate and greatly accelerating the mixing with ambient fluid. The reader will find many similarities between their simulation visualizations and the bifurcating jet visualizations presented here. Based on these simulations, a full-scale engine test was made using off-the-shelf parts to construct the actuators (Glauser & Walker 1998, Kibens et al. 1999). Temperature measurements downstream of the engine showed dramatic reductions in the difference between the maximum jet temperature and ambient, comparable to what P.J.D.J. found with the shrouded blooming jet. When fully developed for operational systems, this technology will allow lower-cost wing-flap construction and a simpler approach to protection of aircraft ground crews. The saving is likely to be many times the investment made in the enabling fundamental research over a 20-year period.

There are many possibilities for practical application of these flow-control phenomena. We encourage creative inventors among the readers to exploit the large body of fundamental research that now exists in this area.

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