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Active Control of Supersonic Impinging Jets: Flowfield Properties and Closed-loop Strategies

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Supersonic impinging jets produce a highly unsteady flowfield leading to a very noisy environment with very high dynamic pressure loads on nearby surfaces. In prior work, we demonstrated that supersonic microjets can be used to disrupt the feedback loop inherent in high-speed impinging jet flows, thereby significantly reducing the adverse effects produced by this flow. In this paper, we explore two aspects of the microjet control scheme. First, detailed PIV measurements are used to examine the role of streamwise vorticity in the feedback interruption using microjets. Second, a novel closed-loop control strategy which uses on-line pressure measurements near the nozzle exit to achieve optimal flow control irrespective of flow conditions, is explored. The PIV measurements revealed that the activation of microjets produces substantial streamwise vorticity in the form of well organized, counter-rotating pairs of streamwise vortices. The production of significantly higher streamwise vorticity due to microjets comes at the expense of the azimuthal vorticity in the shear layer. This weakens the large-scale axisymmetric structures in the jet shear layer while also introducing more three-dimensionality into the flow. Both these factors, lead to a weakening of the feedback loop, which may account for the success of this control scheme. The closed-loop control strategy consisted of determining the dominant POD mode using pressure measurements at the nozzle exit and using a 'mode matched strategy' to determine the microjet pressure distribution along the nozzle. The results demonstrated a significant reduction in the unsteady pressure loads along with a consistent improvement compared to an open-loop control strategy where the microjet pressures were kept constant. It is proposed that this improved reduction may be due to the fact that the mode-matched strategy results in the intensity of the microjets to be proportional to the corresponding acoustic wave intensity near the nozzle. The stronger microjets then provide a stronger local disruption and perhaps generate more streamwise vorticity, both of which lead to more efficient local disruption of the feedback loop resulting in larger reductions in the flow unsteadiness.

1. Introduction

The impingement of high-speed jets, on a surface, generally results in an extremely unsteady flowfield accompanied by a host of undesirable aeroacoustic properties. These include, but are not limited to, very high ambient noise levels dominated by discrete frequency tones – referred to as impingement tones – and highly unsteady pressure loads on the ground plane and on nearby surfaces.

Unfortunately, high-speed impinging jets are ubiquitously present in Short Take-Off and Vertical Landing (STOVL) aircraft during hover. In this context, the flow induced effects such as the high noise levels and impingement tones can lead to structural fatigue of the aircraft surfaces in the vicinity of the nozzles, while the high dynamic loads on the impingement surface results in increased erosion of the landing surface. For STOVL aircraft these problems are collectively referred to as ground effect.

A host of studies on the aeroacoustics of impinging jets by Neuwarth (1974), Powell (1988), Tam and Ahuja (1990), and more recently Krothapalli *et al*. (1999) have clearly

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established that the self-sustained, highly unsteady behavior of the jet and the resulting impinging tones is governed by a feedback mechanism, between the instability waves in the jet that originate at the nozzle and grow as they propagate downstream towards the impingement surface, and the acoustic waves that are produced upon impingement which then travel upstream and excite the nascent shear layer near the nozzle exit. For further details of the feedback loop, the reader is directed to the above articles.

A few years ago, a study was initiated at the Fluid Mechanics Research Laboratory (FMRL), FSU, in Tallahassee, Florida, with the aim of understanding, and more importantly controlling, supersonic impinging jet flows in order to eliminate or at least substantially reduce the ground effect.

The logical approach to controlling the adverse ground effect is to disrupt the feedback mechanism responsible for this behavior. A number of researchers have attempted varied passive and active methods in order to accomplish this goal. A brief summary of some the past attempts can be found in Alvi *et al.* (2000) (also Shih *et al*., 2001) who describe a unique approach for controlling supersonic impinging jets. The results discussed in this paper are part of this ongoing study discussed by Alvi *et al*. (2000) and Shih *et al* (2001) where arrays of supersonic microjets are used to control much larger supersonic impinging jets.

The geometry used is very simple and consists of a single jet as shown in Fig. 1. The microjets are arranged around the primary nozzle as shown in Fig. 2. Further details of the hardware will be discussed in the Experimental section.

The reasoning behind this control approach was based on the fact that the array of supersonic microjets may disrupt the feedback loop in number of ways. The microjet streams may partially intercept the upstream propagating acoustic disturbances and this attenuates their influence on the shear layer. Second, these high momentum jets can provide spatial/temporal distortions to the coherent shear-layer instabilities thus disrupting their interactions with the acoustic field. Third, the microjet streams may generate streamwise vorticity, which could weaken the downstream traveling large-scale structures thus further weakening the feedback loop. A brief summary of earlier results of this control approach is provided in § 3. As this subsequent discussion will show, this control technique proved to be very effective overall. However, some questions remained, requiring further investigation.

First, the efficacy of this control was not uniform at all the operating conditions. Furthermore, the underlying physical mechanisms behind its effectiveness were not well-understood. However, the earlier work provided strong circumstantial evidence that the generation of streamwise vorticity might perhaps be one of the primary mechanisms responsible for the success of this approach.

In this paper, we focus on two aspects of the impinging jet control problem. The first concerns direct measurements of the velocity and vorticity field using Particle Image Velocimetry (PIV), which provide further insights into the role of vorticity in this control scheme. The second concerns the use of closed-loop control to obtain a uniform reduction of the ground effect over the entire operating range. This is achieved through the use of a novel POD-based, on-line parametric control strategy. The motivation, design, development, and implementation of this control method are also presented in this paper.

2. Experimental Details

2.1 Test Configuration and Facility

The experiments were carried out at the STOVL supersonic jet facility of the Fluid Mechanics Research Laboratory (FMRL) located at the Florida State University. A schematic of the test geometry with a single impinging jet is shown in Fig.1. This facility is used primarily to study jet-induced phenomenon on STOVL aircraft hovering in and out of ground effect. Further facility details can be found in Krothapalli *et al*. (1999).

The measurements were conducted using an axisymmetric, convergent-divergent (**C-D**) nozzle with a design Mach number of 1.5. The throat and exit diameters (**d, $\mathbf{d_e}$**) of the nozzle are 2.54cm and 2.75cm (see Figs. 1 & 2). The divergent part of the nozzle is a straight-walled conic section with a 3^o divergence angle from the throat to the nozzle exit. Although tests were conducted over a range of Nozzle Pressure Ratios (NPR, where NPR = stagnation pressure/ambient pressure), the results discussed in the present paper are limited to NPR = 3.7 and 5. NPR = 3.7 corresponds to an ideally expanded Mach 1.5 jet, while NPR = 5 produces a moderately under-expanded jet. A circular plate of diameter D (25.4 cm ~10d) was flush mounted with the nozzle exit. The circular plate, henceforth referred to as the 'lift plate', represents a generic aircraft planform and has a central hole, equal to the nozzle exit diameter, through which the jet is issued. A 1m x 1m x 25 mm aluminum plate serves as the ground plane and is mounted directly under the nozzle on a hydraulic lift.

Active flow control was implemented using sixteen microjets, flush mounted circumferentially around the main jet as shown in Fig. 2a. The jets were fabricated using 400 µm diameter stainless tubes and are oriented at approximately 20^o with respect to the main jet axis. The supply for the microjets was provided from compressed Nitrogen cylinders through a main and four secondary plenum chambers. In this manner, the supply pressures to each bank of microjets could be independently controlled. The discussion in the controls portion of this paper (§ 5) will illustrate why independent control of the microjet banks is an important requirement. The microjets were operated over a range of NPR = 5 to 7 where the combined mass flow rate from all the microjets was less than 0.5% of the primary jet mass flux.

2.2 Pressure Measurements

The unsteady loads generated by the impinging jet flow were measured using Kulite™ transducers on the lift plate and the ground plate. In addition, near-field noise was measured using B&K ™ microphones placed approximately 25 cm away from the jet. As discussed in § 5, in order to implement closed loop control, the azimuthal distribution of the unsteady loads on the lift plate was needed. Six high frequency response miniature Kulite ™ pressure transducers, placed symmetrically around the nozzle periphery plate, at r/d =1.3 from the nozzle centerline, were used to obtain this distribution (Fig. 2). The transducer outputs were conditioned and simultaneously sampled using National Instruments digital data acquisition cards and LabView ™ software. Standard statistical analysis techniques were used to obtain the spectral content and the Overall Sound Pressure Level (OASPL) from these measurements.

2.3 Particle Image Velocimetry

Particle Image Velocimetry was used to obtain whole-field velocity data at various jet cross-sectional planes. The primary jet was seeded with small (~0.3µm) oil droplets generated using a modified Wright Nebulizer. The ambient air was seeded with smoke particles (~1-5µm) produced by a Rosco 1600 fog generator. A schematic of the experimental arrangement of the PIV system is shown in Fig. 3.

For PIV measurements, a double-pulsed Nd:YAG laser (Spectra-Physics, 400 mJ) was used for flow field illumination. A light sheet, about 1.5 mm thick, was created using a combination of spherical and cylindrical lenses. The images were recorded by a cross-correlation CCD camera (Kodak ES 1.0) with a 1k x 1k resolution. The PIV images were acquired at a rate of 15 image pairs per second. Although it was possible to cover a larger area, the present measurements were limited to approximately 60 x 60 mm square cross section. The time between pulses was optimized at 1.2 µs. The double-pulsed images were acquired through an Imaging Technologies ICPCI board, which resides on a single slot of the PCI bus of a personal computer.

An image matching approach was used for the digital processing of the image pairs to produce the displacement field. To achieve velocity data with high spatial resolution, a novel processing scheme was used. Details of this technique are described in Lourenco *et al.* (1998). We simply note that a principal advantage of this approach is that velocity field is obtained with second-order accuracy, hence the spatial derivatives are computed with a higher precision.

The main controlling parameter in the experiment was the ground plane height *h* with respect to the nozzle exit, which was varied from 2d to 5d. For the PIV tests, the laser sheet position, z (see coordinate frame in Figs. 1 & 3) with respect to the nozzle exit, was varied from 1d to 3d. Experiments were conducted at NPR=2.5, 3.7 and 5, which corresponds to an over-expanded, ideally expanded and under-expanded primary jet flow, respectively. However, PIV results presented here will be limited to NPR = 5 and 3.7. The jet stagnation temperature was nominally maintained at 320 ±5 K. The slight heating of jet was used to avoid condensation during PIV measurements.

The rest of the paper is arranged as follows. In the next section we briefly summarize the results of our microjet control experiments (§ 3). This is followed by a discussion of the PIV results with an emphasis on the role of vorticity on this control scheme (§ 4). Finally, the development and implementation of the closed-loop control algorithm is presented in § 5.

3. Previous Microjet Control Studies

This section summarizes the results of prior experiments using supersonic microjets for flow control. Details of these prior studies can be found in Alvi *et al*. (2000) and Shih *et al*. (2001)

As mentioned in the introduction, supersonic impinging jets produce a very unsteady flowfield, with high noise levels and discrete frequency acoustic tones. The instantaneous shadowgraph in Fig. 4a shows a representative image for an uncontrolled – microjets off – impinging jet. The presence of multiple, strong acoustic waves, marked in the figure, clearly signify the presence of acoustic tones (Alvi *et al*., 2000). Also visible are large-scale structures in the shear layer, which are responsible for the generation of acoustic tones upon impingement on the ground plane. Furthermore, the enhanced entrainment associated with such structures is also thought to be responsible for the 'lift loss' suffered by STOVL aircraft during hover (Krothapalli, 1999). The instantaneous shadowgraph in Fig. 4b shows the visual effect of microjet control on this flow. The effect is visually dramatic: the ambient environment becomes 'quiet' since the strong acoustic waves have disappeared. Furthermore, the large-scale structures are no longer visible in the jet shear layer. Also visible in Fig. 4b are the 'streaks' generated by the supersonic microjets. It is worth noting that such streaks have been taken as an indicator of the presence of streamwise vorticity. Whether these streaks truly represent streamwise vorticity is discussed in the next section.

Fig. 5 shows the narrowband spectra of the unsteady pressure signal on the lift plate for NPR = 3.7, h/d = 4.0. The presence of multiple tone is apparent by the discrete peaks in the spectra. The effect of microjet control on the spectral content can be surmised through a comparison of the uncontrolled case (dashed line) to the control data (solid lines). The distinct tones present in the uncontrolled impinging jet are either significantly diminished or entirely eliminated by the activation of microjets. In addition, and perhaps more significantly, the attenuation in the discrete tones is accompanied by a broadband reduction in the spectral amplitudes. This broadband reduction indicates an overall decline of the unsteadiness in the flow under control. Although only data from the lift plate is shown here, the ground plane dynamic pressures and the near-field acoustic measurements show similar trends (Alvi *et al*., 2000).

The overall reduction in the unsteady pressure and acoustic levels (P_{rms}) on the lift plate, ground plane and the nearfield noise for NPR=3.7 and 5 are summarized in Figs. 6 and 7, respectively. First of all, the fluctuating loads are significantly reduced at all three measurement locations for almost all heights. Second, the reductions due to microjet control are generally larger for the under-expanded impinging jet, operating at NPR = 5 (Fig.7). Finally, for a given NPR, the magnitude of reduction is strongly dependent upon the ground plane distance (h/d). For example, as seen in Fig. 6, the maximum attenuations occur at h/d = 4, followed by a minimum at h/d = 4.5, where the microjets have almost no effect.

It is well-known that the unsteady properties of feedback loop of the uncontrolled jet, such as the amplitude and frequency of the impingement tones and the dominant instability modes in the flow, are highly sensitive to operating conditions. It is also worth noting that, due to the sensitivity of the feedback loop on the *exact* operating conditions, the effect of microjet control can vary even if all parameters are unchanged. As an example, as discussed in § 5, although the height at which the microjets are minimally effective is h/d = 4.5 for the conditions in Fig. 6, it can on occasion shift to h/d = 4 or 5 during a particular test. Hence, an efficient control scheme should be able to *adapt* to the changes in the local flow conditions, in real time, to provide optimal control over the entire operating range. Such a control strategy is explored in § 5 of this paper.

4. PIV Results

In a previous paper (Shih *et al* 2001) it was hypothesized that the streamwise vorticity generated by the microjets weakens the primary instability structures in shear layer. This suggestion was partially based on the presence of streamwise streaks observed in the shadowgraphs (Fig. 7) and their marked similarity to the streaks observed in other studies (Samimy *et al*., 1993 & Krothapalli, *et al*., 1999).

The role of vorticity was also suggested by Planar Laser Scattering (PLS) visualizations of this flowfield. Figs. 8 and 9 show representative PLS images where the laser sheet cuts diametrically (Cross-stream) across the jet. The shear layer is made visible due to the scattering of the laser light by the water droplets or ice crystals which condense as the cold jet flow entrains the relatively moist ambient air.

Fig. 8 is an instantaneous image while Fig. 9 is time averaged; the laser sheet is placed one diameter downstream of the nozzle exit for both cases. For flow without control, Fig. 8a, weak-to-moderate indentations are observed around the shear layer periphery. More clearly defined indentations emerge when the microjets are turned on and one can identify a total of 16 of these modulations inside the ring in Fig. 8b. The corresponding time-averaged images support these observations. Without control, there appears to be few identifiable indentations, indicating that the streamwise vortices are not stationary in an average sense. However, with microjet control, the shear layer displays a strongly modulated ring with a total of 16 indentations where the azimuthal locations of these indentations correspond to the microjet position around the nozzle periphery.

Prompted by the visual evidence, we quantitatively examined the role of microjets on the impinging jet flow by obtaining whole flowfield measurements using PIV. The measurements presented here are limited to NPR=3.7 and 5, with and without microjets control. For the PIV results discussed here all the microjets were operated at 100 psi for the control cases. All the measurements shown here were made in cross-sectional planes normal to the jet axis. The instantaneous and mean vorticity contours extracted from the velocity-field data are shown in Figs 10-13 for NPR= 5, h/d=4, with and without control. The plotted vorticity corresponds to the out-of-plane component and has been normalized by (Uj/d) where Uj is the jet velocity at the nozzle exit. Furthermore, the color of the vorticity contours in the middle of the vorticity range for each plot has been represented by white to allow one to visually emphasize the vorticity in the jet periphery, on the 'gray-scale' contour plots.

In Fig. 10a and 10b we show instantaneous vorticity distributions at the z/d=1 cross plane without and with microjet control, respectively. Only scattered, weak vortical structures are seen in the no control case (Fig. 10a.) In contrast, much stronger, and more organized pairs of counter-rotating vortical structures are seen in Fig. 10b, when the microjets are turned on. The difference in streamwise vorticity due to microjets is much more dramatically revealed in the corresponding *ensemble-averaged* vorticity contour plots shown in Fig. 11. These contour plots were obtained by averaging data from 100 instantaneous PIV samples. (Although it is difficult to appreciate the sign of vorticity on a gray-scale image, however, the counter-rotating vortex pairs can be clearly seen in color vorticity plots.) A comparison of the no-control case, Fig. 11a, to the microjet control data, Fig. 11b, leaves no doubt that the activation of microjets introduces significant streamwise vorticity at the jet shear layer.

In order to study the evolution of the streamwise vortices due to microjets, velocity (or vorticity) measurements were made at multiple z locations. Fig. 12 and 13 show vorticity plots corresponding to those in Figs. 10 and 11 but at a further downstream location of z/d =2. At least visually, the effect of microjets on the instantaneous vorticity field in Fig. 12b, does not appear to be significant relative to the no control case in Fig. 12a. However, a comparison of the mean vorticity plots in Fig. 13 shows that although somewhat diffused, the flowfield with control, Fig. 13b, still contains significantly more vorticity than the corresponding no control case.

Fig. 14, 15 show plots of the streamwise vorticity distribution as a function of the azimuthal angle at z/d = 1 and 2, respectively. The vorticity values, shown on the ordinate in these plots, were extracted from the corresponding mean vorticity contours (Figs. 11 and 13) along a radial position roughly in the middle of the shear layer at each z/d location. Taking advantage of the flow symmetry, data for only half of the jet periphery is shown. In each plot, the solid line corresponds to the microjet control case, while the dashed line corresponds to no control. The organized, counter-rotating vorticity pairs due to microjets observed in Fig. 11b are revealed as adjacent pairs of large-amplitude, vorticity peaks and valleys in Fig. 14. In contrast, the no control data, depicted in dashed lines, shows a much weaker and more disorganized streamwise vorticity distribution. At the next downstream location as shown in Fig. 15, the difference between the control and no control case is still significant, although the maximum vorticity values are somewhat lower.

In order to further quantify the effect of microjets on the streamwise vorticity, the overall circulation, Γ, was calculated at various z/d locations. A plot summarizing the non-dimensionalized circulation, $\Gamma/U_j{*}d$ as a function of z/d is shown in Fig. 16. Note that the circulation shown here is calculated by integrating the absolute values of the ensemble-averaged vorticity over a specified area in the cross-flow plane. In order to provide a reliable, consistent estimate, normalized vorticity levels below 0.3 were assigned a zero value. The magnitude of the circulation can be interpreted as a measure of the overall strength of the streamwise vorticity at the specific z/d location.

A comparison between the no control circulation values (open symbols) to the control data (filled symbols) reveals that the overall circulation is significantly higher when the microjets are turned on. Also, there is a substantial difference in the circulation with microjets between the underexpanded (NPR = 5) and the ideally expanded case (NPR=3.7). The significantly higher vorticity for the underexpanded case is not altogether unexpected. It is well known that the concave curvature and the presence of a strongly accelerated flow at the nozzle exit of an underexpanded jet makes it more susceptible to a Talyor-Goërtler type instability, which enhances the growth of streamwise vorticity (Samimy et al., 1992 and Krothapalli, 1998). Whether this is truly in the present situation is difficult to state conclusively.

Regardless of the reason for the emergence of higher streamwise vorticity for the under-expanded jet, it seems reasonable to suggest that there is a direct correlation between the presence of streamwise vorticity and the efficacy of microjet control. A review of Figs. 6 and 7 demonstrates that microjets are much more effective for the under-expanded jet, that is also the jet with much stronger streamwise vorticity.

Having shown that the microjets introduce measurable and substantial vorticity, we come back to the physical mechanism responsible behind microjet control. Using an order of magnitude analysis, it is easily shown that total streamwise vorticity due to all sixteen microjets is less than 10% of the streamwise vorticity measured in the main jet when microjets are turned on. This suggests that a significant portion of the streamwise vorticity has to come from the primary shear layer. As suggested by an earlier study (Shih *et a*l. 2001), vorticity tilting and stretching mechanisms for the spanwise or azimuthal vorticity in the primary jet shear layer are the most plausible candidates responsible for this vorticity redirection. This drainage of azimuthal vorticity into streamwise direction can also be thought of as a weakening of the large-scale axisymmetric structures in the jet shear layer, a result clearly revealed in the shadowgraph images. Consequently, the weakening vortical structure produce weaker acoustic waves when they impinge on the ground plane, thus further attenuate the feedback loop. In addition, the introduction of strong counter-rotating pairs of vortices in the shear layer near the nozzle exit due to microjets further weakens the spatial coherence of the coupling between the acoustic waves and shear layer instability, an important characteristic for efficient feedback loop lock-in.

5. Active Closed-loop Control of Impingement Tones

The motivation for considering active control comes from the behavior of the flow-field in the presence of the supersonic microjets. As can be seen in Fig. 6 and 18, the microjets disrupt the feedback loop thereby reducing the OASPL. This reduction, however, is non-uniform with respect to the height (see Fig. 6) and is unpredictable (as seen in Fig. 6 and 18). In order to obtain a uniform and guaranteed reduction over a range of operating conditions in a reliable manner, closed-loop control that uses on-line measurements and active-adaptive algorithms is an appropriate methodology that can be employed.

Much of feedback control consists of designing suitable external actuators that introduce a control input so as to alter, typically, the dynamic characteristics of the process being controlled. In many of these problems, the control method begins with a description of the process in the form of a differential equation

$$\dot{x} = f(x,u)$$

where x denotes the process state, and u denotes the control input-source. The control strategy then consists of determining a feedback signal according to the rule

$$u = g(x)$$

where $g(.)$ is to be determined so as to realize the desired objective in the process. When f and g are linear, which corresponds to the most ubiquitous case in dynamic systems, the control design and implementation is considerably simplified.

In the above scenario, it is clear that the control input is typically required to be modulated at the natural frequencies of the system. It is therefore necessary that the external actuator have the necessary bandwidth for operating at the natural frequencies (see for example, Cattafesta *et al.,* 1999, Williams *et al.,* 2000). In the problem under consideration, the edge tones associated with the flow-field are typically a few kilohertz. Given the current valve technology, the above control methodology of modulating the control input at the system frequencies is a near impossibility.

The approach adopted in this paper is distinctly different from the standard control framework, and consists of modulating a control input at a slow time-scale, so that it behaves like a parameter. If this control input is chosen judiciously, then even small and slow changes in this "parameter" can lead to large changes in the process dynamics, as will be shown below.

5.1 Active Closed-loop Control of Impingement Tones

With the goal of identifying a control input that has a maximum impact on the impingement tones even with a small and slow change, we take a closer look at the feedback mechanism that produces the self-sustained oscillations of the impinging shear layer. Instability waves are generated by the acoustic excitation of the shear layer near the nozzle exit, which then convect down and evolve into spatially coherent structures. These waves in turn excite the shear layer at the nozzle exit, thereby providing the feedback (see Fig. 17 for a schematic). As indicated by the active control results in Fig. 5, the introduction of the microjets at the nozzle has a large impact on the flowfield even for a mass-flux addition of 0.5% of the main flow. Given the strong sensitivity of the flow-field as well as the tendencies of specific shear-layer modes to be driven into resonance to the boundary conditions at the nozzle, we chose the microjet pressure distribution at the nozzle exit as the control input. Based on the pressure data both without and with microjets at the nozzle, a reduced-order model of the impingement tones can be derived as

$$\begin{aligned} \dot{x} &= A(u)x \\ p &= Cx \end{aligned} \qquad (1)$$

where x corresponds to the amplitudes of the impingement tones, p corresponds to the pressure measurements at the nozzle and u corresponds to the microjet pressure distribution along the nozzle.

5.2 The POD-based Closed-loop Control Strategy

The aim here is to choose u, the microjet pressure distribution such that x is reduced in magnitude by making use of the measurements p. In order to extract as much information possible about the state of the system, x, we adopt the Principal Decomposition Method (POD), which is briefly described below.

The Proper Orthogonal Decomposition (POD) is used to systematically extract the most energetic modes from a set of realizations from the underlying system. These modes can be used as basis functions for Galerkin projections of the model in order to reduce the solution space being considered to the smallest linear subspace that is sufficient to describe the system. The decomposition is 'optimal' in that the energy contained in an N-ordered POD base is greater than any other N-ordered base in a mean-squared sense. Over the years, it has been applied in several disciplines including turbulence in fluid mechanics, stochastic processes, image processing, signal analysis, data compression, process identification and control in chemical engineering, and oceanography, and has been referred to by various names including Karhunen-Loeve decomposition, principal component analysis, and singular value decomposition.

In fluid mechanical systems, the POD technique has been applied in the analysis of coherent structures in turbulent flows and in obtaining reduced order models to describe the dominant characteristics of the phenomena. One of the earliest works was on a fully developed pipe flow, studied by Bakewell and Lumley (1967). Since then, POD models have been used to model the one-dimensional Ginzburg-Landau equation (Sirovich and Rodriguez 1987), the laminar-turbulent transitional flow in a flat plate boundary layer (Rempfer 1994), pressure fluctuations surrounding a turbulent jet (Arndt *et al.* 1997), turbulent plane mixing layer (Delville *et al.* 1999), velocity field for an axisymmetric jet (Citriniti and George 2000), low-dimensionality of a turbulent flow near wake (Ma *et al.* 2000), low-dimensional leading-edge vortices in the unsteady flow past a delta wing (Cipolla *et al.* 1998), and flow over a rectangular cavity (Rowley *et al.* 2000). The eigenfunctions were developed using both experimental and numerical database.

Although POD has been used extensively in determining reduced order models of flow systems, relatively few attempts have been made to design active control strategies based on these models (Ravindran, 2000; Graham *et al.,* 1999a,b; Atwell and King, 2001; Arian *et al.,* 2000). In this paper, our goal is to use the POD method to extract information about the mode shapes using the pressure measurements p in order to determine the control input *u*. For easy reference, the POD method is briefly described below.

Using the Karhunen-Loeve expansion (Loève 1945; Karhunen, 1946), the pressure variable at the nozzle exit can be expressed as

$$p(\theta,t)=\sum_{n=1}^{N}\sqrt{\lambda_n}\,\psi_n(t)\phi_n(\theta)=\sum_{n=1}^{N}a_n(t)\phi_n(\theta) \qquad (2)$$

where $E[\psi_n(t)\psi_m(t)]=\delta_n^m$, $\int_D\phi_n(\theta)\phi_m(\theta)d\theta=\delta_n^m$, θ is the angular position along the nozzle circumference, $\phi_n(\theta)$ is the nth mode-shape, $a_n(t)$ is the amplitude of the nth mode, and N is the number of dominant modes. The spatial pressure distribution $\phi_n(\theta)$ can be calculated using the "method of snapshots" as follows (Tang *et al.* 2001). Let the $p^n(j)$ be the pressure variable at a spatial point *n* at some time *j* where $n = 1,....,N$ and $j = 1,....,J$, with *n* much smaller than *J*. Now the matrix *Q* can be expressed from singular value decomposition as

$$Q=\begin{bmatrix} p^1(1) & p^1(2) & \cdots & p^1(J) \\ p^2(1) & p^2(2) & \cdots & p^2(J) \\ \vdots & \vdots & \cdots & \vdots \\ p^N(1) & p^N(2) & \cdots & p^N(J) \end{bmatrix}=U\Sigma V^T$$

where U $(\mathrm{N}\times\mathrm{n})$ and V $(\mathrm{J}\times\mathrm{n})$ are unitary matrices, and

$$\Sigma=\begin{bmatrix} \sigma_1 & & & \\ & \sigma_2 & & \\ & & \ddots & \\ & & & \sigma_n \end{bmatrix},$$

$$\sigma_1\geq\sigma_2\geq\cdots\geq\sigma_n$$

The matrices *V* and *Σ* are the eigenvector and the square-root of the eigenvalue of the correlation matrix Q^TQ. The mode-shapes can then be computed as

$$\Phi\equiv QV=[\phi_1 \quad \phi_2 \quad \cdots \quad \phi_n].$$

Once the mode shape is determined, we simply choose the control strategy as

$$u=k\phi_1(\theta) \qquad (3)$$

where ϕ_1 is the most energetic mode and *k* is a calibration gain. The complete closed-loop procedure therefore consists of collecting pressure measurements $p(\theta)$, expanding them using POD modes as in (2), determining the dominant mode ϕ_1, and matching the control input, which is the microjet pressure distribution along the nozzle to this dominant mode as in (3). The results obtained using such a mode-matched control strategy are discussed in the next section.

5.3 The application of closed-loop control to impinging jets

The mode-matched control strategy described above was implemented in the experimental apparatus described earlier, for a range of heights. At each height, in addition to the mode-matched control, the active control strategy as in Shih *et al.* (2001) was also implemented. Since in the latter case, the spatial distribution of microjet pressure around the nozzle exit was kept uniform, it is referred to as "symmetric control." Since the latter does not use any system measurements and is determined *a priori,* the symmetric control can also be viewed as an open-loop control procedure. In order to ensure a fair comparison between the two control methods, the main nozzle was forced to operate under the constant condition throughout whole process. The calibration constant *k* in (3) was chosen such that the minimum and maximum values of the POD mode over θ corresponds to 70psi and 120psi, respectively. These values were chosen since they ensured maximum effectiveness. Since the actuator configuration was such that it consisted of four microjet-banks that can be controlled independently and each bank in turn controlled four microjets, the bank input pressure was chosen as the average pressure values of the position where the four microjets are located. Fig. 19 shows the shape of the first mode and the suggested microjet bank pressure distribution for several heights.

As can be seen in Fig. 20, the mode-matched control strategy showed better performance at the experiment throughout all operational conditions, with a large improvement at heights h/D = 4, 4.5 and 5. The reason for this increased pressure reduction can be attributed to the percentage of energy contained in the dominant mode, which is used in the control strategy. As shown in Table 1, at heights 4 to 5, the energy content of ϕ_1 is above 86% where as at heights 2 and 3, the energy level drops to 55% and below. As a result, the corresponding improvement in the mode-matched strategy also drops to about half the db-value at heights 2 and 3 compared to at heights 4.0, 4.5, and 5.

6. Concluding Remarks

In this paper, two aspects of impinging jets were presented, (i) detailed PIV measurements that led to further insights concerning streamwise vorticity being a dominant mechanism in the feedback interruption using microjets, and (ii) a new closed-loop control strategy that uses on-line pressure measurements near the nozzle exit to result in an improved and uniform reduction, irrespective of the operating and flow conditions.

The PIV measurements revealed that substantially more well organized and paired streamwise vortices were present in the jet shear layer when microjets were turned on compared to when they were turned off. The ensemble-averaged vorticity field data revealed that the streamwise vortices, present as counter-rotating pairs, were highly organized within one diameter downstream of the nozzle exit. Further downstream, the vortices became more diffused but are still more organized relative to the no control case. The strength of the streamwise vorticity was found to be much higher with control than without control. This relatively stronger streamwise vorticity may be responsible for breaking up the large-scale structures, making them weaker and more three-dimensional. Thus, the feedback loop is attenuated due to two factors. First, by a weakening of the source of the acoustic waves which are generated by the impingement of the large scale structures and second, by reducing the spatial coherence of the coupling between the acoustic waves and shear layer instability due to three-dimensionality introduced by the microjets. The disruption of the feedback loop leads to a marked reduction in the unsteadiness of the supersonic impinging jet flow.

The closed-loop control strategy consisted of determining the dominant POD mode using pressure measurements at the nozzle exit and using a 'mode matched strategy' to determine the microjet pressure distribution along the nozzle. The results demonstrated a significant reduction in the unsteady pressure loads along with a consistent improvement compared to an open-loop control strategy where the microjet pressure was kept at a constant. This improved reduction may be attributed to the following: The mode-matched strategy results in the microjet pressure intensity to be proportional to the corresponding acoustic wave intensity near the nozzle. High microjet pressure in turn provides a stronger local disruption and perhaps generates more streamwise vorticity, both of which lead to more efficient local disruption of the feedback loop resulting in more efficient reduction in the flow unsteadiness. Experiments are underway to obtain more direct evidence of this hypothesis.

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8. References

1. Alvi, F.S., Elavarsan R., Shih, C., Garg G., and Krothapalli, A., 2000 " Control of supersonic impinging jet flows using Microjets," *AIAA Paper* 2000-2236.
2. Alvi, F.S., Shih, C. and Krothapalli, A., 2001 "Active control of the feedback loop in high-speed Jet," *AIAA Paper* 2001-0373.
3. Arian, E., Fahl, M. and Sachs, E.W., 2000 "Trust-region proper orthogonal decomposition for flow control," *NASA/CR-2000-210124, ICASE Report*, No. 2000-25.
4. Arndt, R.E.A., Long D.F. and Glauser, M.N., 1997 "The proper orthogonal decomposition of pressure fluctuations surrounding a turbulent jet," *J. Fluid Mech.,* Vol. 340, pp. 1-33.
5. Arnette, S.A., Samimy, M. and Elliott.G.S., 1993 " On streamwise vortices in high Reynolds number supersonic axisymmetric jets," *Phys. Fluids A* 5(1), January .
6. Atwell, J.A. and King, B.B., 2001 "Proper orthogonal decomposition for reduced basis feedback controllers for parabolic equations," *Mathematical and Computer Modeling,* Vol 33, pp.1-19.
7. Bakewell, P. and Lumley, J.L., 1967 "Viscous sublayer and adjacent wall region in turbulent channel pipe flow," *Physics of Fluids,* Vol.10, pp. 1880-1889.
8. Cattafesta III, L.N., Shukla, D., Garg, S. and Ross, J.A., May 1999 "Development of an adaptive weapons-bay suppression system," *AIAA Paper* 99-1901.
9. Citriniti, J.H. and George, W.K., 2000 "Reconstruction of the global velocity field in the axisymmetric mixing layer utilizing the proper orthogonal decomposition," *J. Fluid Mech*., Vol. 418, pp.137-166.

10. Cipolla, K.M., Liakopoulos, A. and Rockwell, D.O., 1998 “Quantitative imaging in proper orthogonal decomposition of flow past a delta wing,” *AIAA Journal*, Vol. 36, pp.1247-1255.
11. Delville, J., Ukeiley, L., Cordier, L., Bonnet, J.P. and Glauser, M., 1999 “Examination of large-scale structures in a turbulent plane mixing layer. part. 1. proper orthogonal decomposition,” *J. Fluid Mech.,* Vol. 391, pp. 91-122.
12. Graham, W.R., Peraire,J.P. and Tang, K.Y., 1999a “Optimal control of shedding using low-order models, Part I-Open-loop model development,” *International Journal for Numerical Methods in Engineering*, Vol.44, pp.945-972.
13. Graham, W.R., Peraire,J.P. and Tang, K.Y., 1999b “Optimal control of shedding using low-order models, Part II-Model-based control,” International Journal for Numerical Methods in Engineering, Vol. 44, pp.973-990.
14. Ibrahim, M.K. and Nakamura, Y., 2001 “Effect of Rotating Tabs on Flow and Acoustic Fields of Supersonic Jet.” *AIAA Journal*, Vol. 39, No. 4, pp. 745-748.
15. Karhunen, K., 1946 “Zur spektraltheorie stochastischer prozesse,” *Ann. Acad. Sci.,* 34.
16. Krothapalli, A., Strykowski P.J. and King, C. J., 1998 “Origin of Streamwise Vortices in Supersonic Jets,” *AIAA Journal,* Vol. 36, No. 5, pp. 869-872.
17. Krothapalli, A., Rajakuperan, E., Alvi, F.S. and Lourenco, L., 1999 “Flow field and Noise Characteristics of a Supersonic Impinging Jet,” *J. Fluid. Mech.,* Vol. 392, pp. 155-181.
18. Liepmann, D. and Gharib, M., 1992 “The Role of Streamwise Vorticity in the Near-Field Entrainment of Round Jets,” *J. Fluid Mech.* Vol. 245, pp. 643-668.
19. Loève, M., 1945 “Functions aléatoire de second ordre,” *Comptes Rendus Acad. Sci*., 220.
20. Lourenco., L., and Krothapalli, A., 1998 “Mesh-free, Second Order Accurate Algorithm for PIV processing,” *Proceedings of the International Conference on Optical Technology and Image Processing in Fluid, Thermal and Combustion Flow.* Yokohama, Japan.
21. Ma, M., Karamanos, G.S. and Karniadakis, G.E., 2000 “Dynamics and low-dimensionality of a turbulent near wake,” *J. Fluid Mech.,* Vol. 410, pp.29-65.
22. Neuwerth, G., 1974 “Acoustic Feedback of a Subsonic and Supersonic Free Jet Which Impinges on an Obstacle,” *NASA TTF-15719.*
23. Paterson, R.W., 1984 “Turbofan Forced Mixer Nozzle Flowfield-A Benchmark Experimental Study,” *ASME J. Eng. Gas Turbines Power* Vol. 106, 692.
24. Plesniak, M. W., Mehta, R.D. and Johnston, J. P., 1974 “Curved Two-stream Turbulent Mixing Layers: Three-dimensional Structure and Streamwise evolution,” *J. Fluid Mech.* Vol. 270, pp.1-50.
25. Powell, A., 1988 “The sound –producing oscillations of round underexpanded jets impinging on normal plates,” *J. Acoust. Soc.* Am 83(2), pp. 515-533.
26. Ravindran, S., 2000 “A reduced order approach to optimal control of fluids using proper orthogonal decomposition,” *International Journal for Numerical Methods in Fluids,* Vol. 34, pp.425-448.
27. Rempfe, D., 1994 “On the structure of dynamical systems describing the evolution of coherent structures in a convective boundary layer,” *Physics of Fluids,* Vol. 6, pp. 1402-1404.
28. Rowley, C.W., Colonius, T. and Murray, R.M., 2000 “POD based models of self-sustained oscillations in the flow past an open cavity," *AIAA Paper* 2000-1969.
29. Samimy, M., Zaman, K.B.M.Q. and Reeder, M.F., 1993 “ Effect of Tabs on the Flow and Noise Field of an Axisymmetric Jets,” *AIAA Journal,* Vol. 31, No. 4, pp.609-619.
30. Shih, C. Alvi, F.S., Lou. H, Garg. G and Krothapalli, A., 2001 “Adaptive Flow Control of Supersonic impinging jets,” *AIAA Paper* 2001-3027.
31. Sirovich, L. and Rodriguez, J.D., 1987 “Coherent structures and chaos: A model problem,” *Phys. Lett. A,* Vol. 120, pp. 211-214.
32. Tam, C.K.W and Ahuja K.K., 1990 “ Theoretical model of discrete tone generation by impinging jet,” *J. Fluid Mech.,* Vol. 214 1990 pp. 67-87.
33. Tang, D., Kholodar, D., Juang, J.N. and Dowell, E.H., 2001 ”System identification and proper orthogonal decomposition method applied to unsteady aerodynamics,” *AIAA Journal,* Vol. 39.
34. Williams, D.R., Fabris, D. and Morrow, J., June 2000 “Experiments on controlling

multiple acoustic modes in cavities," *AIAA Paper* 2000-1903.

35. Zaman, K.B.M.Q., Reeder. M.F. and Samimy, M., 1994 " Control of an axisymmetric jet using vortex generators," *Phys. Fluids. 6 (2) Feb.*

36. Zaman, K.B.M.Q., 1996 "Axis switching and spreading of an asymmetric jet: The role of coherent structure dynamics," *J. Fluid Mech.* Vol. 316. pp.1-27.