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Active Control of Supersonic Impinging Jets

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Experimental studies of supersonic impinging jet flows suggest that they are greatly influenced by the flow-acoustic interactions through a feedback mechanism. The self-sustained oscillations of the jet column observed in these flows result in high velocities in the ambient medium induced by the large-scale coherent vortical structures in the jet shear layers. As a consequence, the suck down force on the surface from which the jet is issuing can reach as high as 60% of the primary jet thrust. In addition, the overall sound pressure levels (OASPL) increase significantly relative to a free jet. To alleviate these undesirable flow and acoustic characteristics, a novel control technique using supersonic microjets is demonstrated. Sixteen supersonic microjets are placed around the circumference of the main jet at the nozzle exit to disrupt the feedback mechanism. As a result, significant lift loss recovery (~ 50%) and reduced near field OASPL (~ 7dB) are observed.

1. INTRODUCTION

Short Take-off and Vertical Landing (STOVL) aircraft experience a number of performance-diminishing effects while hovering in close proximity to the ground. Some of the problems created by the impingement of high-speed hot lift jets on the landing surface are as follows. The lift loss associated with the jet entrainment results in low surface pressures on the airframe, creating a force opposite to lift. The loss in lift can be as much as 60% of the primary jet thrust and increases in magnitude as the aircraft approaches ground[1]. The impinging jet flow field generates significantly higher noise levels (8-10 dB) compared to that of a corresponding free jet. Increased Over All Sound Pressure Levels (OASPL) associated with high speed impinging jets affect the integrity of structural elements in the vicinity of the nozzle exhaust due to acoustic loading. In addition, the noise and the unsteady pressure spectra are dominated by high-amplitude discrete tones, which, in some cases, match the aircraft panel frequencies making the sonic fatigue problem more critical. Finally, the impingement of lifting jets results in areas on the landing surface with extremely high heat transfer rates and high wall shear. This produces significant erosion and spalling of the landing surface material in the jet impingement region and the outwash or 'wall jet' flow. Most of these problems have been observed in the Harrier/AV-8 family of aircraft. They are expected to become more severe when the jets operate at supersonic speeds and at higher temperatures, which is the case in the proposed Joint Strike Fighter aircraft.

It is well known that the near field noise spectrum generated by the impingement of high speed jets on a surface is dominated by high amplitude, discrete tones, generally referred to as impingement tones[1]. Similar impinging tones have also been observed in the near field acoustic spectra of high temperature supersonic impinging jets. Krothapalli et al.[1] demonstrated that the impingement tones are governed by a feedback loop in the following manner. Instability waves of a particular wavelength (or frequency) are generated by the acoustic excitation of the shear layer very close to the nozzle exit; a region of high receptivity. As the waves travel downstream they evolve into large-scale, spatially coherent structures. Upon impinging the surface they give rise to high amplitude pressure fluctuations, which produce acoustic waves, these waves in turn excite the shear layer near the

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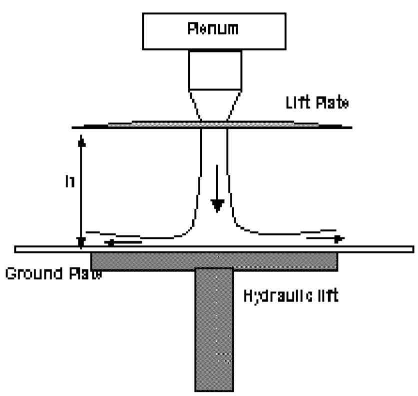
nozzle exit, thus completing the loop. The presence of the discrete tones is generally accompanied by a globally oscillatory behavior of the primary jet column.

To address some of these issues, a number of basic studies examining the aeroacoustic properties of single and dual supersonic impinging jets of various geometries have recently been undertaken at the Fluid Mechanics Research Laboratory. One of the goals of this work was to obtain detailed velocity field measurements in the entire flow, including the impingement zone and wall jet region, using unique Particle Image Velocimetry (PIV) technique. The velocity field data, combined with conventional shadowgraphy, near-field acoustic measurements and mean and *unsteady* pressure distributions has allowed us to study and understand the global as well as the detailed behavior of this flow. The salient results of some these experiments, in the context of the present study, are described as follows.

Detailed results of single jet studies can be found in Krothapalli et al.[1, 2] and Alvi & Iyer[3] while the dual jet results appear in Elavarasan et al.[4] The schematic shown in Fig. 1 depicts the simple geometry used for single and multiple jets. The test model consists of an axisymmetric nozzle mounted perpendicular to the ground plane. The jet flow issues through a circular hole in an instrumented 'lift plate' where the lift plate represents a generic aircraft planform. The model used for dual impinging jets is essentially the same with the exception that two supersonic Mach 1.5 C-D nozzles are used for these tests.



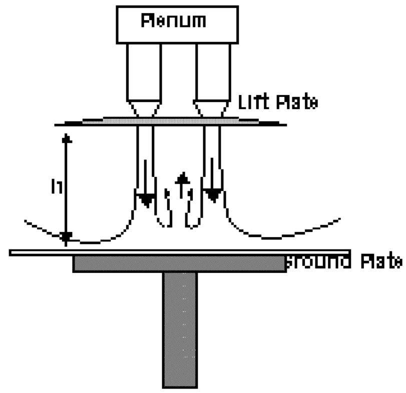


Figure 1. Schematic of single (a) and twin (b) impinging jet set up.

Two different nozzles, a converging (sonic) and a Mach 1.5 C-D nozzle, both with the same throat area, were used for the single jet studies. The combined areas of the two Mach 1.5 C-D nozzles used in the dual jet experiments are the same as the area of the nozzles used in the single jet studies.

The highly unsteady nature of the impinging jet flow-field and the presence of strong acoustic waves can be clearly seen in the instantaneous shadowgraph image of a single supersonic impinging jet shown in Fig. 2. The jet is issuing

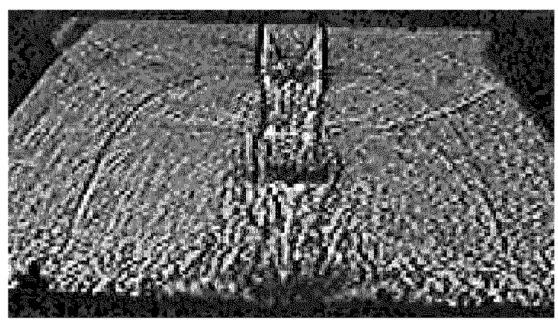


Figure 2. A schlieren picture of a supersonic axisymmetric impinging jet. NPR = 3.7, h/d = 4.

from the Mach 1.5 C-D nozzle operating under ideally expanded condition at a Nozzle Pressure Ratio (stagnation pressure/ambient pressure), NPR = 3.7 and impinging on the ground plane at a distance of h/d = 4 (h: the distance between the nozzle exit and the ground plane; d = the nozzle throat diameter). The strong acoustic waves, which appear as sharp lines in the image, are readily visible. The incident waves, traveling towards the nozzle lip, appear to emanate from the ground plane near the center of the jet impingement region. As the acoustic waves reach the nozzle lip they excite the instability waves traveling downstream in the jet shear layer. These instability waves rapidly develop into large-scale spatially coherent shear layer structures while traveling downstream. Upon impingement on the ground plane, these structures generate coherent, high amplitude pressure perturbations, which in turn generate acoustic waves, thus completing the feedback loop.

The presence of such large-scale structures, not normally present in such high-speed jets, can be confirmed from the shadowgraph image in Fig. 2. However, more dramatic and direct evidence of these structures is provided in Fig. 3 which shows instantaneous PIV (Particle Image Velocimetry) images for the single and dual impinging jets issuing from C-D nozzles operating at a Nozzle Pressure Ratio, NPR= 3.7 at h/d = 4. The large-scale structures visibly grow as they travel downstream and then propagate outward along the wall jet, while maintaining their coherence. These observations show the dominant nature of the flow-acoustic interactions in the flow, which leads to the oscillatory behavior of the jet column.

To gain a better physical understanding of the global flow field, PIV images such as those shown in Fig. 3 were used to obtain detailed velocity and vorticity field data in the entire plane. Instantaneous PIV velocity fields corresponding to the images in Fig. 3 are shown in Fig. 4a and Fig. 4b for the single and dual impinging jets, respectively. The velocity field data shows that the presence of large-scale structures in the shear layers significantly enhance the entrainment velocities (measured velocities up to 100m/sec) in their vicinity. The high entrainment velocities result in suction pressures on the bottom surface of the lift plate and a downward force (lift loss). An additional feature observed for dual jet flows, which can further complicate the flow-field, is the fountain flow formed by the collision and coalescence of the radial wall jets in the region between the two jets. The results reveal that, for selected cases, the fountain flow can provide additional thrust, compensating some of the lift loss[4]. On the other hand, the impingement of the hot fountain fluid on the undersurfaces of the aircraft can lead to additional thermal loading and possible hot gas ingestion. Furthermore, coupling between the two jets can also add to the global unsteadiness of the flow field.

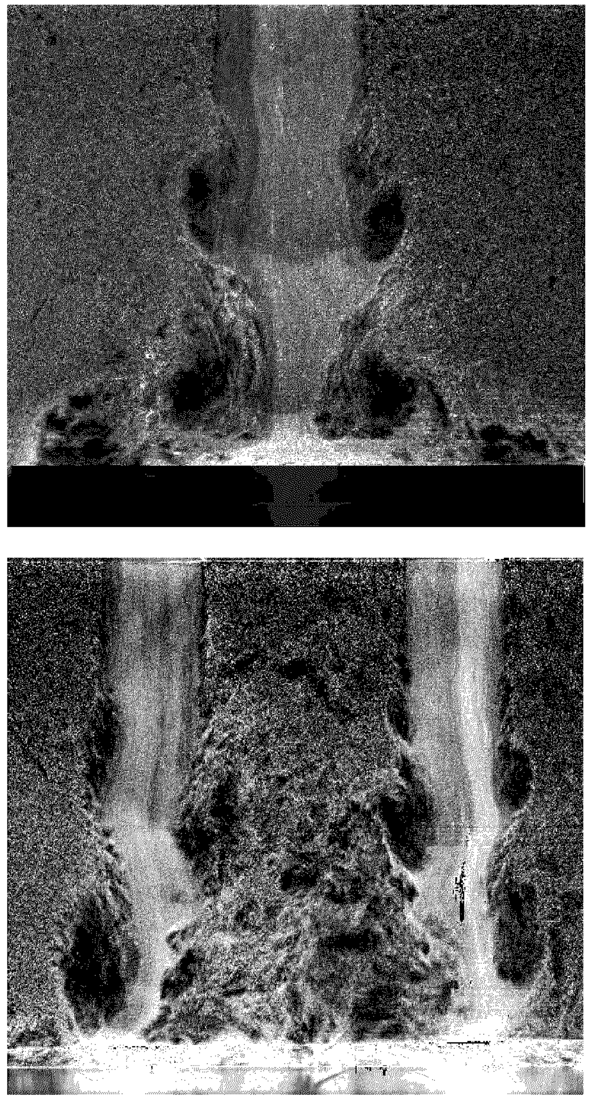


Figure 3. PIV Images of single and twin impinging jets. NPR = 3.7, h/d = 4.

It is evident from the previous discussion that the flow field for impinging jets is highly unsteady. It is manifested as a highly fluctuating pressure field on the nearby surfaces, specifically on the lift plane and ground surfaces. Similarly, in the acoustic field, the unsteadiness results in high Over All Sound Pressure Levels (OASPL).

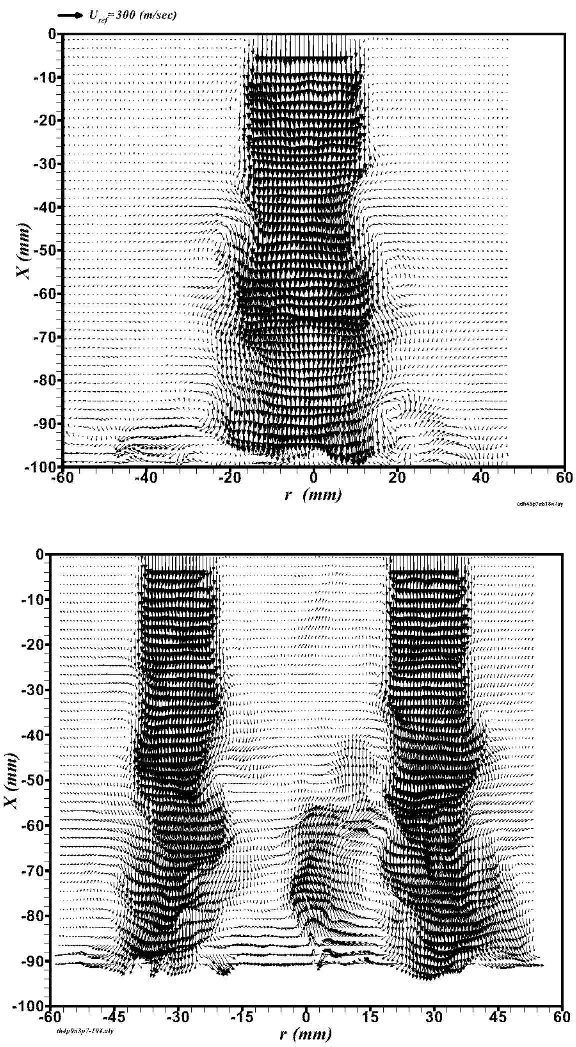


Figure 4. Instantaneous velocity fields corresponding to the images shown in figure 3.

Fig. 5 shows typical near field narrowband frequency spectra of ideally expanded free and impinging jets. The near-field microphone spectra clearly reveal the presence of tones for the impinging jet case. The results of an earlier investigation[1] show that a relatively small change in the h/d, can lead to a significant change in the magnitude and frequency of these tones. Representative acoustic spectra for dual supersonic impinging jets reveals a behavior very similar to that of single jets. As in single jets, the frequencies of these tones is a strong function of the jet NPR, h/d and geometry.

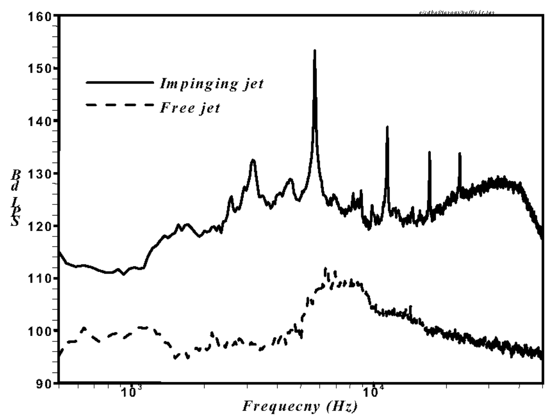


Figure 5. The near-field narrowband frequency spectra of an ideally expanded, single, free and impinging jet. NPR = 3.7, h/d =4.

Figure 6 shows a comparison of typical narrow band spectra of the lift plate unsteady surface pressure with that of the near field microphone signal. The unsteady surface pressures on the lift and ground planes were measured using high frequency response Kulite transducers. An inspection of these spectra provides further confirmation of the globally unsteady nature of the impinging jet flows. Whenever distinct impingement tones are present in the microphone measurements, spectral peaks also appear in the unsteady surface pressures, both on the lift and ground planes at nearly identical frequencies[3]. Furthermore, shifts in the spectral peaks in the noise measurements due to changes in the operating conditions, such as NPR or ground plane height, leads to a similar shift in the surface pressure spectral peaks, providing further evidence of the intimate relationship between acoustic and flow field properties. Fluctuating pressures as high as *170-180 dB were measured on the lift plane,* which can potentially compromise the structural integrity of nearby surfaces. Similarly, *unsteady pressures as high as 190 dB* were measured on *the ground plane* for some cases. Such an intensely fluctuating surface pressure field together with the fact that the flow in the radial wall jet is usually transonic/supersonic with the peak velocities occurring very close to the surface (Alvi & Iyer[3]), will result in significant thermal (for hot jets) and shear loading of the ground surface leading to a significant ground erosion problem.

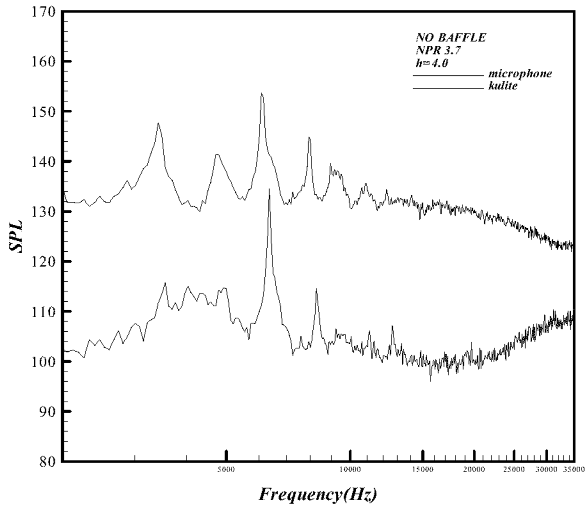


Figure 6. Narrowband frequency spectra for unsteady pressure on the *lift* plate and nearfiled micorphone measurements. Twin impinging jets, h/d = 4, NPR = 3.7.

Based on the above observations that a feed back loop is responsible for self-sustaining oscillations of the jet, an attempt was made to weaken it using a passive control technique by Elavarasan et al.[5]. The feedback loop was interrupted by preventing the acoustic waves from reaching the nozzle lip by placing a small plate near the nozzle lip. This technique was successful for some cases, wherein the disruption of the feed back loop led to a significant reduction in the appearance of large structures in the jet shear layers as shown in Fig. 7 (compare to Fig. 3). PIV results revealed that this led to a significant reduction in the entrainment velocities and a reduction in lift loss by as much as 20% for some cases. These results clearly suggest that the suppression of the feed back mechanism is the key to minimizing the thrust loss associated with the impinging jets. Although, the passive control technique has shown promising results in one particular configuration, its effect is strongly dependent upon operating parameters, such as NPR, temperature ratio and ground plate height and is therefore not well suited for implementation in an aircraft.

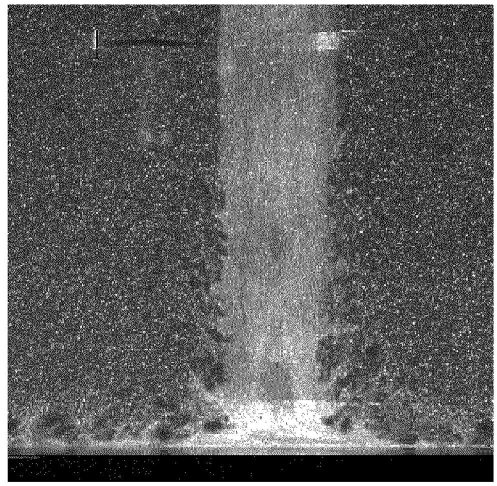


Figure 7. PIV image of an impinging jet with feedback loop suppression by passive control. NPR = 3.7, h/d = 4.

Although only selected results are presented here, all the undesirable features related to jet impingement discussed here, namely discrete tones, globally unsteady flow field, large scale structures, lift loss have been observed for single and dual nozzles of various geometries, including round (sonic and C-D nozzles) and elliptic. This behavior has been observed over a wide, JSF relevant, parametric space in terms of NPR and h/d for hot and cold jets. Given the many adverse effects of this flow, in this paper we propose an active flow control technique to suppress the feedback loop thereby enhancing the performance of STOVL aircraft in ground effect operating with lift jets.

The control strategy we aim to explore in this study is distinctive in that it takes advantage of the strong coupling between the fluid and acoustic fields near the jet exit to control the large-scale global unsteadiness of the flow. This is accomplished through the use of *actively controlled supersonic microjets*, which provide *on-demand-control* and disruption of the feedback loop. Initial results of this approach are presented in the following.

2. EXPERIMENTAL SET UP

Experiments were carried out in STOVL research facility of the Fluid Mechanics Research Laboratory at the Florida State University. The facility has been used to study jet-induced forces on STOVL configured aircraft models hovering in and out of ground. Positioning the ground plane at various heights relative to the model through a traversing mechanism simulated the hovering effect. An aluminum plate of size 1m x 1m x 25mm served as a ground plane. The height between the ground plane and nozzle exit (***h***) was varied from 0.04m to 1.5m. The schematic of the experimental setup is shown in Figure 1. A shock free nearly ideally expanded jet was obtained from a converging diverging (C-D) axisymmetric nozzle operating at design conditions. The throat (d) and exit diameters are 2.54cm and 2.75cm respectively. The nozzle was designed for an exit Mach number of 1.5. The divergent portion of the nozzle was a straight conic section with a 3-degree divergence angle. In order to simulate the airframe, a circular plate of diameter ***D*** (25.4 cm) was flush mounted with the nozzle. The circular lift plate contained 17 pressure taps arranged along a radial line and the pressure was measured with a Validyne strain gauge transducer mounted in a Scanivalve unit. At each port, several seconds of digitized data were taken. The lift force was calculated from the jet-induced mean pressures on the lift plate. The near field acoustic measurements were made using a 0.635cm diameter B&K microphone placed at 25 cm away from the nozzle exit and at 90^0 to the jet axis. The microphone signal and the lift plate surface pressures were acquired through a National Instruments data acquisition system with associated "Lab View" software. For the acoustic measurements, the nearby exposed metal surfaces were covered with 10 cm thick acoustic foam to minimize sound reflections.

All the experiments described here were conducted at a nozzle exit Mach number of 1.5 and at several **h/d**. The choice of the operating pressure and ground plane height was based on earlier experiments (Krothapalli et al.[1]) conducted in the same facility.

A top hat velocity profile with laminar boundary layers was maintained at the nozzle exit. The jet stagnation temperature was maintained with in ± 2^o of 20^oC. The nominal exit Reynolds number, based on the nozzle exit diameter and the exit velocity was $7x10^5$. A cylindrical coordinate system is used with its x – axis aligned with the centerline of the jet and r represents the radial direction. The corresponding velocity components are u and v respectively.

The jet control configuration used in the present study is shown in Fig. 8, where 16 axisymmetric convergent micro-nozzles (exit diameter = 400 μm) are placed around the circumference of the main nozzle. The microjet Nozzle Pressure Ratio was about 6. The total mass flow rate of these microjets is less than 0.3 % of the primary jet mass flow rate. The microjets are oriented about 20^o to the main jet axis. Injection of high-speed microjet streams into the primary jet can effectively thicken the shear layer and, consequently, reduce its receptivity to the external disturbances. In addition, the supersonic jet flow exhausting out from the micronozzles will locally prevent the upstream propagation of the acoustic disturbances back to the primary nozzle exit. It is hoped that a spatially

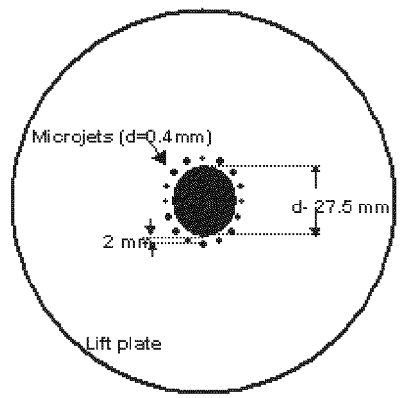


Figure 8. A schematic of the flow control arrangement using microjets.

incoherent microjet system could produce enough interference to disrupt the feedback mechanism. A typical schlieren picture of the microjet operating at NPR = 6, issuing from a 400 μm diameter convergent axisymmetric nozzle is shown in Fig. 9. Clearly seen in the picture is the shock cell structure that is commonly observed in underexpanded jet. The first shock cell contains the Mach disc, and its distance from the nozzle exit is in agreement with the macro nozzle studies at the corresponding pressure ratio. The picture clearly depicts that shock cells extend over a distance of about 10 mm, indicating the extent of the supersonic flow.

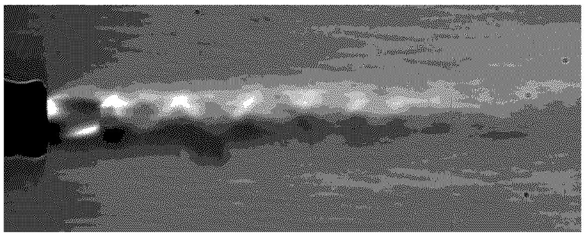


Figure 9. Schlieren picture of a supersonic microjet. NPR = 6, Exit diameter = 400 μm.

Much smaller microjets have also been fabricated on a 500-μm thick silicon wafer using the Deep Silicon Reactive Ion Etching (Deep Si RIE) processing. All nozzles and their corresponding settling chambers were patterned using photoresist as an etch mask and the unwanted

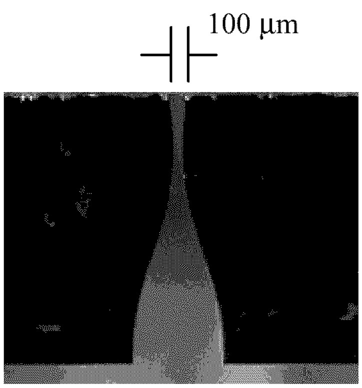


Figure 10. Converging-diverging micro supesonic nozzle.

parts were etched out using reactive ion beams with almost vertical (90°-95°) sidewalls. The C-D profiles of the microjet nozzles were computed based on a two-dimensional method of characteristics calculation without using boundary layer correction. A typical converging-diverging nozzle made with this technology is shown in Fig. 10. One of the most obvious advantages of using a micro-scale device for flow control is its small physical size, which produces minimal interference to the primary flow. Another advantage of the micro-devices is that they can be massively produced and patterned so that it is possible to fabricate an assembly of a very large number of microjets with desirable spatial distribution for multiple point control. Finally, micro fabricated sensors and actuators can be packaged with the control unit for multiple-point signal detection and control activation. This makes the in-situ active flow control possible. Such microjets/sensors will be used in future studies to achieve more precise, active control of the present flowfield.

4. RESULTS AND DISCUSSION

In this initial study, flow control was applied by simply activating the supersonic microjets placed at the nozzle exit. It was anticipated that

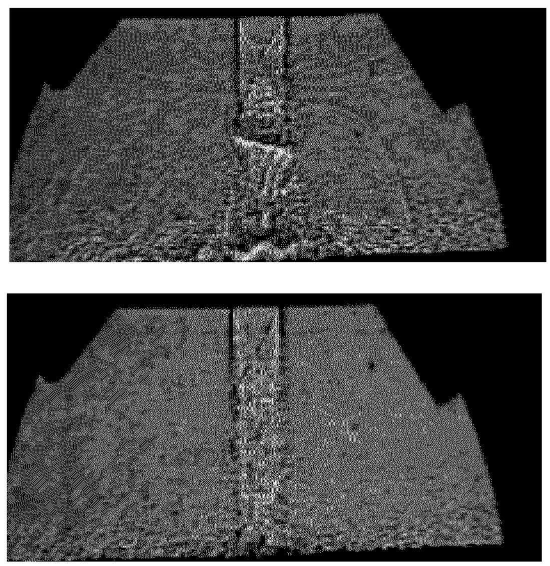


Figure 11. Instantaneous shadowgraph images of supersonic impinging jets without (top) and with (bottom) control at NPR = 3.7 and h/d = 4.5.

the penetration of the microjets into the primary lift jet shear layer at the nozzle exit will sufficiently modify the shear layer stability characteristics to disrupt the feedback loop and alleviate the associated adverse effects. It must be noted that in these tests no attempt was made to actively modulate and control the microjets based on the local flow conditions. The results shown here only compare the relevant properties with and without the microjets operating. A comparison of the instantaneous shadowgraph shown in Fig. 11 visibly reveals that the strong acoustic waves, corresponding to impinging tones, have been eliminated when the microjets are activated. Furthermore, the large-scale shear-layer structures have also been significantly reduced. The near field narrow band frequency spectra corresponding to the conditions of Fig. 11 are shown in Fig. 12. The distinct tones corresponding to the uncontrolled impinging jet are almost entirely eliminated by the activation of microjets. In addition, a reduction in noise level is observed in the entire spectrum.

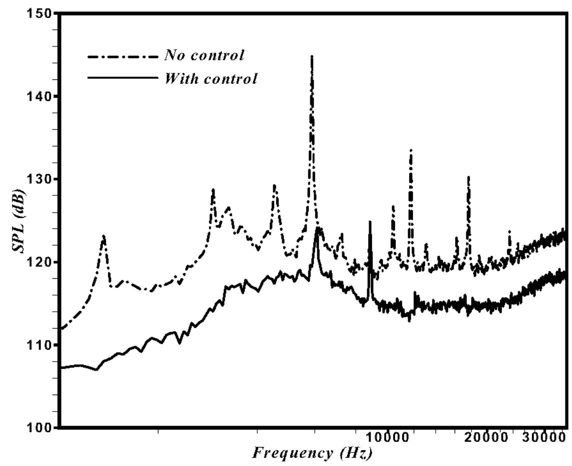


Figure 12. The effect of control on the nearfield noise spectra corresponding to the conditions of Fig. 11.

A comparison of the Overall Sound Pressure Level (OASPL) at different h/d, as shown in Fig.13, suggests the general trend of the overall noise reduction with the control. However, the noise reduction magnitude is dependent upon the h/d (e.g. a reduction of ~ 7 dB at ground plane h/d = 4.5 compared to 2-3 dB reduction at h/d = 3.5 and 4); an indication that the control technique does not track the flow changes brought about by the varying h/d.

The effect of microjet control on the lift plate surface pressure distribution is shown in Fig. 14 at jet operating conditions corresponding to those in Fig.11. A significant increase in the surface pressure is observed with the activation of microjets. It is suggested that the surface pressure increase observed is due to the reduction in the magnitude of the entrainment velocities.

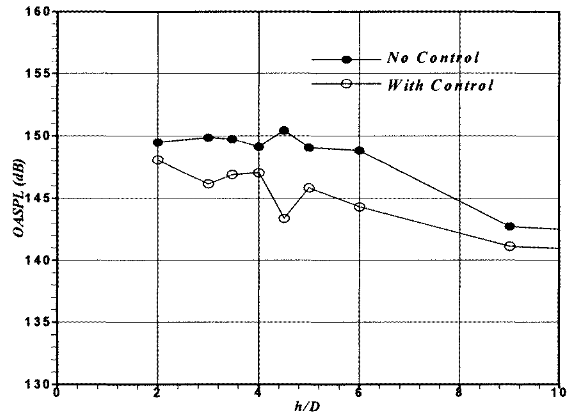


Figure 13. The variation of OASPL with h/d with and without control.

Typical variation of the negative lift force with h/d is shown in Fig. 15, where the lift force is normalized with the jet thrust calculated using one-dimensional isentropic equations. As the

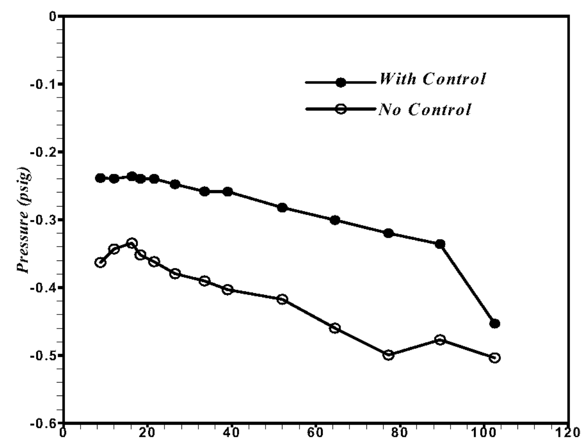


Figure 14. The distribution of the mean surface pressure on the lift plate with and without control. NPR = 3.7, h/d = 2.

ground plane approached the lift plate, a large downward force is generated. For example, at h/d = 2, the magnitude of the lift loss is greater than 60% of the primary jet thrust. This force decreases rapidly in magnitude with increasing h/d and approaches an asymptotic value of the free jet. A significant lift loss recovery is observed with the control at h/d=2. With increasing h/d, the magnitude of the recovery is much less and shows a non-monotonic behavior. Figure 16 summarizes the lift loss recovery variation with h/d. It is observed that control effectiveness varies with h/d, suggesting that the active control strategies are necessary to achieve optimal performance at all operating conditions.

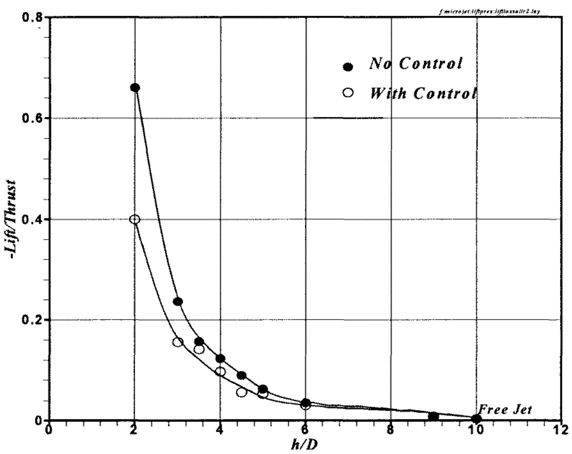


Figure 15. The effect of the control on the variation of lift loss with h/d.

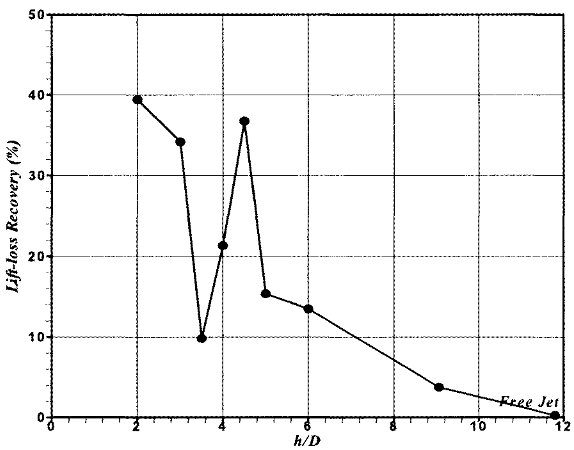


Figure 16. The variation of lift loss recovery with h/d.

4. CONCLUSIONS

The objective of this research program is to develop practical control strategies to enhance the STOVL aircraft performance under realistic operating conditions. In this paper we explored a novel control technique utilizing supersonic microjets to disrupt the feedback mechanism in supersonic impinging jet flows. The disruption of this feedback mechanism resulted in significant gains in lift and reductions in OASPL as well as elimination of discrete high amplitude tones in the noise spectra. However, the performance enhancements due to the control strategy are not uniform over the entire parametric space. We believe, that this is due to the fact that the microjets are used in a 'passive' mode. Due to the dynamic nature changes in the flow-acoustic interactions with operating conditions, an optimal control technique must be able to adapt to these changes.

Having demonstrated the efficacy and the potential for substantial gains in performance using this control technique in this initial, proof-of concept study, we are presently developing on-demand control methods using integrated sensor and supersonic microjet actuators. These control techniques will be implemented in more realistic planform geometries utilizing single and dual impinging jets.

5. ACKNOWLEDGEMENTS

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