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Objectives and Approach

The primary objective of this research is to investigate the usability of mechanical actuators, manufactured using MEMS technology, in the control of high-speed, compressible free shear flows. Appropriate development of MEMS-based actuators for flow control applications must address two issues: (1) the ability of the micron-size amplitude and forces of the MEMS devices to affect larger-scale flows with orders of magnitude higher energy, and (2) the survivability of the fairly fragile actuators when they are exposed to the flow in which they are embedded. Therefore, the current investigation is aimed at testing MEMS actuators for the purpose of controlling supersonic jet screech. For this application, the high-speed, highly-unsteady nature of the flow during screech provides a reasonably harsh environment for testing the survivability of the actuators. Furthermore, the shear layer surrounding the jet at its exit is known to be highly unstable to minute disturbances in the vicinity of the lip of the jet, and hence it is anticipated that the micron-size disturbances introduced by the MEMS actuators will be amplified through the shear layer instability mechanisms to produce large scale effects on the jet itself.

The approach followed utilizes an array of 16 MEMS actuators positioned around the perimeter at the exit of a sonic nozzle (the MEMS devices and the test facility have been described in last year's report[1]). To control screech, two strategies based on closed and open loop control methods will be tested. In the closed loop control approach, the MEMS actuators will be used to introduce disturbances that have mode shape and phase such that they counteract the natural shear layer instability modes existing during screech. Alternately, the open loop approach will make use of a few of the actuators (e.g., the top half of the array) to attempt to break the symmetry of the naturally existing flow structures. This is expected to have a similar effect on screech as that produced by intrusive tabs, while having a much smaller effect on the jet thrust due to the extremely small size of the MEMS devices.

Progress and Results

Positioning and Observation of MEMS Operation. As will become evident in the results to be presented later, the effectiveness of the MEMS actuators in exciting the flow is strongly dependent on precise positioning of the devices in the vicinity of the jet lip. Therefore it was necessary to determine with micron accuracy the position of the actuator at the two extreme ends of its motion with respect to the nozzle lip. This was achieved by adjusting the actuator position at the jet exit while viewing it under a microscope at a high magnification of about 50. A high-intensity fiber-optic strobe light was used to illuminate the actuator during observation under the microscope. This resulted in a clearly observable "slow-motion" view of the device while oscillating at frequencies as high as 14 kHz. Measurements of the relative actuator location and its oscillation amplitude were achieved by mounting a CCD camera on the microscope and displaying the video images on a Silicon Graphics Indy work station where measurements were done utilizing the screen pixels after appropriate calibration. The same optical observation system described above was also used to visualize the operation of the MEMS actuator while running the jet up to speeds corresponding to screech conditions. However, in this case the microscope was positioned at an angle of about 45 degrees with respect to the jet center line, as shown in Figure 1. This oblique angle, combined with the relatively large working distance of the microscope allowed observation of the device during flow conditions without protrusion into the flow. Inspection of a video tape of the actuator operation revealed that the MEMS actuator operated properly with no damage or stoppage due to the large flow speeds and highly unsteady conditions associated with screech.

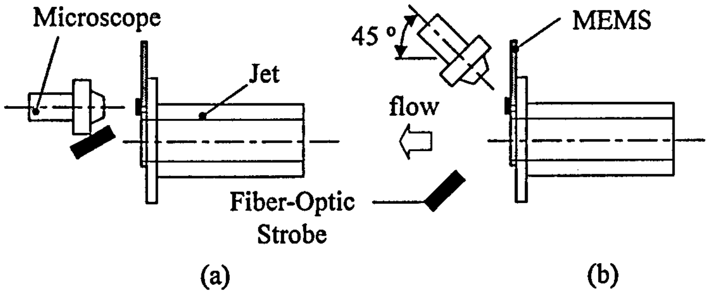
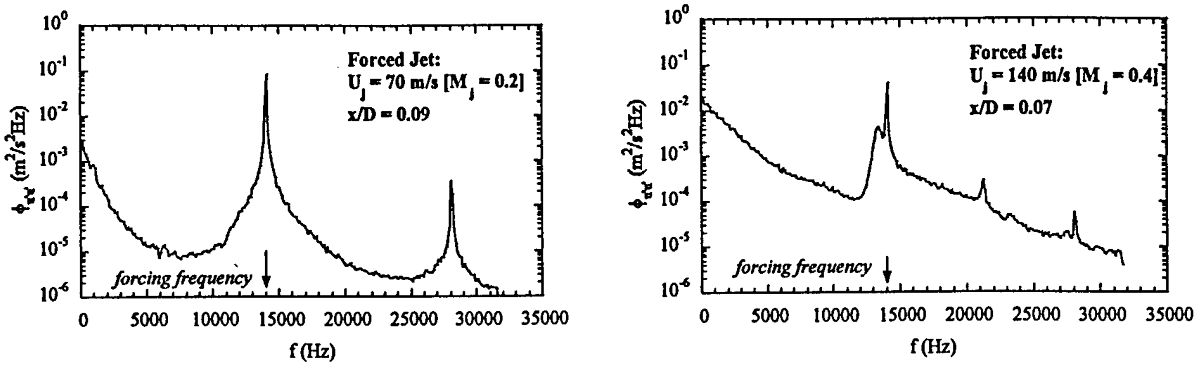


Figure 1. Optical Observation System: (a) MEMS Mounting, (b) MEMS Operation

Detection of the Flow Disturbance Generated by a Single MEMS Device. Prior to implementation of the full MEMS actuator array it was decided to examine the dependence of the strength of the MEMS-produced flow disturbance on various flow and forcing parameters, such as the Mach number, actuator position and amplitude, forcing frequency, etc., for a single MEMS device. This was done in order to allow identification of the appropriate values of these parameters when implementing the full actuator array in the screech control problem.

To test if the MEMS actuator is able to generate a flow disturbance, the spectrum of the streamwise fluctuating velocity (u') was measured at different streamwise (x) locations on the center line of the jet shear layer (where $U/U_j = 0.5$: U is the local mean velocity and U_j is the jet velocity) for different Mach numbers. The measurements were repeated for two different actuators with resonant frequencies of 5 kHz and 14 kHz. Figure 2 provides a sample of the measured spectra for a single streamwise location and two different Mach numbers for the high-frequency actuators. A very strong peak is observed at the forcing frequency for a Mach number of 0.2 (Figure 2a). In addition to the peak at the forcing frequency, a second strong peak at 28 kHz is also observed. For a Mach number of 0.4, a clear peak is depicted in the spectrum at the forcing frequency, as seen from Figure 2b. The peak magnitude is about an order of magnitude larger than a broad spectrum peak which seems to exist at about 13 kHz, slightly to the left of the forced peak.



(a)

(b)

Figure 2. Streamwise Velocity Spectra When Forcing the Jet Using the 14 kHz Actuator

Magnitude of the MEMS-Induced Disturbances. To evaluate the level of the disturbance introduced into the shear layer by the MEMS actuator, the *rms* content of the spectral peak at the forcing frequency ($<u_{rms,f}>$) was calculated. The forced disturbance *rms* dependence on the streamwise location for Mach numbers of 0.2, 0.4 and 0.6 is shown in Figure 3. The disturbance *rms* is normalized by the jet velocity and the streamwise coordinate is normalized by the jet diameter. Inspection of Figure 3 shows that for both $M_j = 0.2$ and 0.4 no region of linear growth is detectable. For these two Mach numbers, $<u_{rms,f}>$ only increases slightly before reaching a peak followed by a gradual decrease in value: a process which is reminiscent of non-linear amplitude saturation.

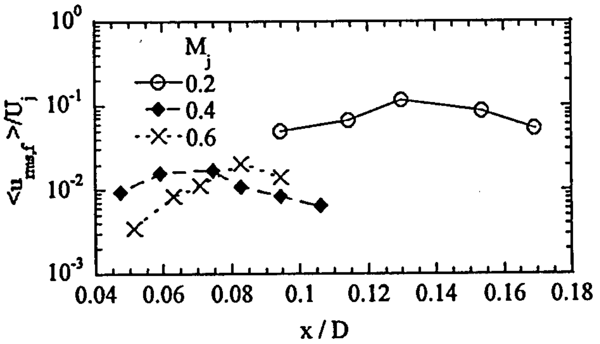


Figure 3. Streamwise Dependence of the MEMS-Induced Disturbance Energy for the 14 kHz Actuator

To "gauge" the magnitude of the MEMS forcing it is compared to other types of "macro-scale" forcing. To this end, the disturbance *rms* value produced by internal acoustic (Lepicovsky et al[2]) and glow discharge (Corke and Cavalieri[3]) forcing is compared to the corresponding rms values produced by MEMS forcing in Figure 4. The results for MEMS forcing contained in the figure are those obtained using the high- (14 kHz) and low-frequency (5kHz) MEMS actuators.

As seen from Figure 4, for all cases of MEMS forcing, except that for the low frequency actuator/$M_j = 0.42$, the MEMS-generated disturbance grows to a level which is similar to or larger than that produced by glow discharge and acoustic forcing. Furthermore, the power required to drive the MEMS actuator was measured to be 1 mW. This demonstrates one of the main advantages of MEMS-based systems in flow applications similar to the current one: the ability to provide efficient control with large effect-to-expenditure ratios. For $M_j = 0.42$, the 5 kHz MEMS actuator produces a small disturbance level. However, as will be demonstrated next, the level of the MEMS-generated disturbance is highly dependent on accurate positioning of the actuator at or very close to an optimal forcing location. For the results for $M_j = 0.42$, no special provisions were taken to ensure that the device was positioned as close as possible to its optimal position. This could affect the outcome by an order of magnitude.

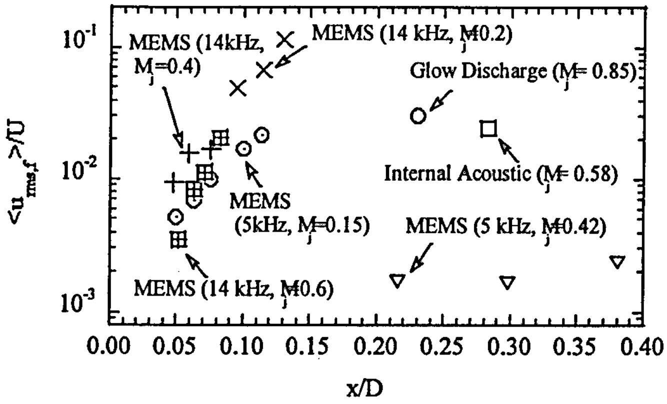


Figure 4. MEMS-Induced Disturbance Level Compared to Other Types of "Macro-Scale" Forcing

Significance of the Jet Lip. The ability of the MEMS devices to excite flow disturbances at a level comparable to that produced by other large-scale forcing, notwithstanding the MEMS micron-size amplitude and force, is believed to be due to the ability to position the MEMS extremely close to the point of high-receptivity at the nozzle lip where the flow is sensitive to minute disturbances. To investigate this matter further, the radial position of the MEMS actuator with respect to the nozzle lip (y_{off}) was varied systematically. The *rms* of the spectral peak at the forcing frequency was calculated for all actuators positions. The results are displayed in Figure 5 for a jet velocity of 70 m/s as a function of the actuator radial position. For reference, a dimension indicating the momentum thickness of the boundary layer emerging at the exit of the jet is included in Figure 5. As seen from the figure, the largest disturbance energy is produced when the actuator is closest to the nozzle lip ($y_{off} = 0$). If the actuator is placed a distance as small as 75 μm off the position corresponding to the maximum shear layer response, an order of magnitude reduction in disturbance rms value is observed. Figure 5 highlights the significance of the ability to force the shear layer in the immediate vicinity of the jet lip, as discussed earlier.

Design of the Third Generation Actuators. During the last year an additional modification into the design of the actuator was incorporated to make it more robust. In the original design, as shown in Figure 6a, the tip of the actuator was parallel to the glass edge. This created a problem when the actuator started to move toward the jet nozzle. Only part of the tip (AB) is exposed to the flow while the other part (BC) remains unaffected. The actuator, therefore, becomes unstable because of the imbalance of force acting upon it when there is a high flow. The problem may be solved by rotating the actuators ±11.25° to match the curvature of the nozzle lip, as shown in Figure 6b. The new actuators have been fabricated at CISC of the University of Michigan. A

SEM view of one of them can be seen in Figure 7. These actuators can generate an amplitude of about 88μm peak to peak at the resonant frequency of 5.466kHz using a 60V pulse signal. Further testing of the actuators on HSJF at IIT will be conducted.

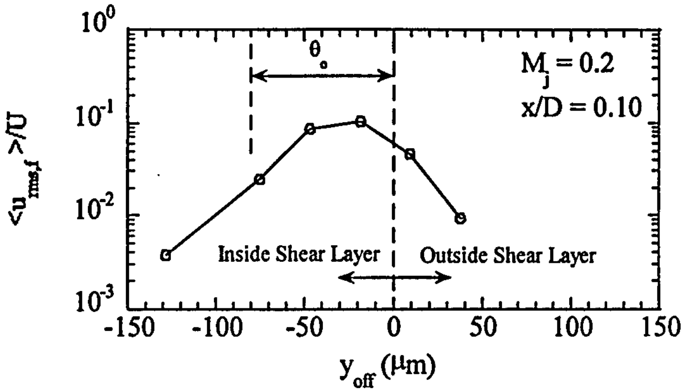
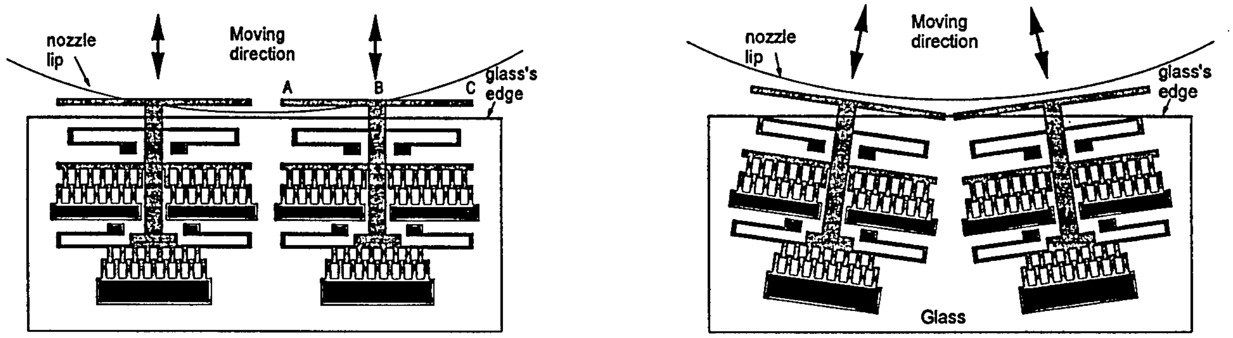


Figure 5. Effect of MEMS Actuator Radial Position on the Generated Shear Layer Disturbance Level



(a)

(b)

Figure 6. Second and Third Generation Actuator Design

Finally, in addition to this new actuator design, we have also designed an array of sound detectors. These detectors have just been fabricated and will be used to measure the phase of the feedback acoustic waves associated with screech. This will allow determination of the appropriate phase of the control input in the closed-loop control scheme discussed in the approach section of this report. A detailed description of these detectors and their operation will be provided in the final report.

Future Work

We are currently in the process of installing an array of 16 MEMS devices (32 actuators) on the jet for the purpose of testing the full array ability to introduce helical and axi-symmetric disturbances as well as to implement the screech open-loop control method. As outlined in the body of the report, installation of the MEMS on the jet lip must be done with extreme precision. We are working on developing an automated optical and hot-wire traversing systems to allow for precise positioning and detection of the operation of the full array of 32 actuators in an efficient and convenient manner. Furthermore, testing of the third generation devices will follow and they will be used towards implementation of the screech closed-loop control method, after characterization of the on-board microphones.

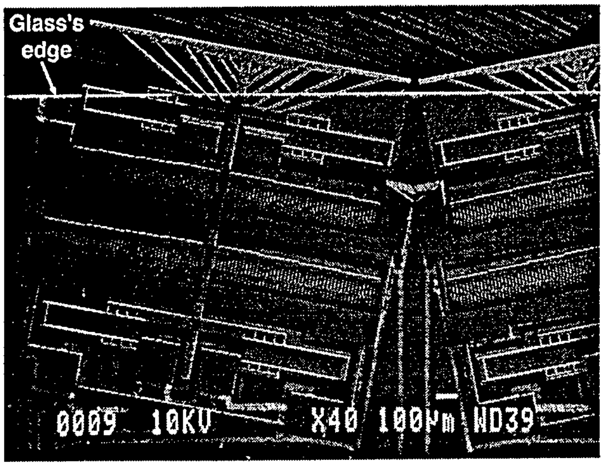


Figure 7. SEM View of Two Actuators in the New Design

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1. Alnajjar, E., Naguib, A. M., Nagib, H. M. and Christophorou, C. 1997. "Receptivity of High-Speed Jets to Excitation Using An Array of MEMS-Based Mechanical Actuators. Proceedings, 1997 *ASME Fluids Engineering Division Summer Meeting*. Paper FEDSM97-3224.
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3. Corke, T. C. and Cavalieri, D. 1996. "Mode Excitation in a Jet at Mach 0.85". *49th American Physical Society Meeting, DFD,* Syracuse, NY.

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