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Piezoelectric Controlled Pulsed Microjet Actuation

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ABSTRACT

A piezohydraulic actuator has been designed and tested for broadband flow control of a microjet actuator. This actuator is under development to understand fundamental flow characteristics near a pulsed flow microjet for active flow control on a number of aircraft structures including impinging jets, cavities, and jet inlets. Recent research has shown substantial reductions in flow separation and noise reduction using steady blowing microjets. This approach often leads to inefficiencies due to excessive mass flux that is typically bled off of an aircraft compressor. Reductions in mass flux without performance losses are desired by actively pulsing the microjet. A piezohydraulic actuator design is presented to investigate this concept. The actuator includes a piezoelectric stack actuator and hydraulic circuit to achieve sufficient displacement amplification to throttle a 400 μm diameter microjet. This system is shown to provide broadband pulsed flow actuation up to 900 Hz. Key parameters contributing to dynamic actuation are shown to include hydraulic fluid behavior, biased microjet air pressure, and voltage inputs to the stack actuator.

INTRODUCTION

Flow control actuators have provided important contributions to aircraft structures including fixed wings, cavity flow, impinging jets, and rotor blades, in terms of reducing undesirable flow characteristics, improving energy efficiency, suppressing noise, etc. Actuation techniques can be classified as passive and active control designs. Passive systems such as micro vortex generators [1] create undesirable drag and a lack of robustness over a broad range of flow conditions. Active systems can be divided into open-loop control and closed-loop control systems. Active open-loop control is often limited in bandwidth and requires large power. Closed-loop control designs can reduce the amount of power required [2], but the lack of broadband actuation has limited its implementation in many applications.

Current active control systems typically utilize actuators that provide steady mass flow, pulsed mass flow, or zero-net mass flow (synthetic jets). Steady mass actuation increases the shear boundary and reduces undesirable vortices. Pulsed mass actuation includes a steady flow component and a zero mean oscillation component which is believed to enhance flow control and reduce acoustic emissions [3], although the underlying mechanim(s) are still unclear. Synthetic jets produce not net mass flow and control flow through second order effects [4].

The primary drawbacks of pulsed flow actuators are the lack of actuation forces and bandwidth limitation. Pulsed mass flow actuators such as oscillating fluidic actuators [5] can operate at high frequency (low kHz regime) but only operate over a narrow operating regime. Similarly, plasma or spark jet actuators [6] can operate at high frequency, but the pulsed flow is limited to the combustion process and heat transfer rate. These narrow bandwidth controllers often lead to splitting the resonant peaks (spillover) [3].

In comparison to pulsed flow, steady flow microjets have demonstrated significant improvement in reducing undesirable flow characteristics on a broad range of aircraft structures including cavities, inlet designs, and impinging jets [7,9]. In these systems, an array of orifices (each with diameter of ~400 μm) is strategically placed on an aircraft surface and steady blowing from the orifices reduces flow separation and acoustic emissions. Implementation of steady flow microjets have demonstrated up to 11 dB of reduction in the overall sound pressure level in a supersonic cavity flow application [7]. However, different cavity geometries required different microjet mass flow rates to obtain similar reductions in the sound pressure level. This has motivated the need for active microjet actuators that can be applied to aircraft structures operating under different external flow conditions. The implementation of pulsed flow over a broad frequency range is expected to enhance efficiency by reducing mass flux without sacrificing flow separation control or acoustic emission reduction; however, many questions remain about the complex flow behavior between a high frequency pulsed microjet and interactions with the surrounding flow field.

A new piezohydraulic actuator was designed, modeled, and characterized recently [8] to address some of these challenges. This system has achieved displacement amplification sufficient enough to throttle a microjet with a typical diameter of 400 μm. In this paper, the device is coupled with a microjet interface to pulse the ambient air flow. The microjet actuator is characterized at different ambient air pressures, voltage amplitudes, and frequencies. Pulsed flow actuation is achieved up to approximately 900Hz. The microjet actuator design is first summarized. The experimental setup and testing results are then presented. Discussion and concluding remarks are given in the final sections.

PIEZOHYDRAULIC ACTUATOR DESIGN

The piezohydraulic actuator consists of a piezoelectric stack actuator, piston, two rubber diaphragms, hydraulic fluid, and aluminum structural housing. Hydraulic amplification of this device is achieved using a converging nozzle design as shown in Figure 1(a). When an electric field is applied to the piezoelectric stack actuator, fluid is forced through an orifice at the top of the cylinder head and subsequently deforms the external diaphragm that seals the fluid and controls air flow to a microjet. A detailed description of this actuator is given in [8].

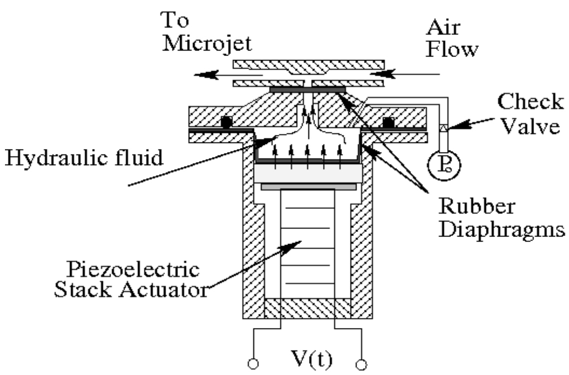
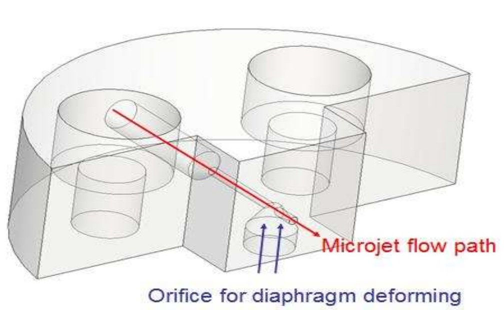


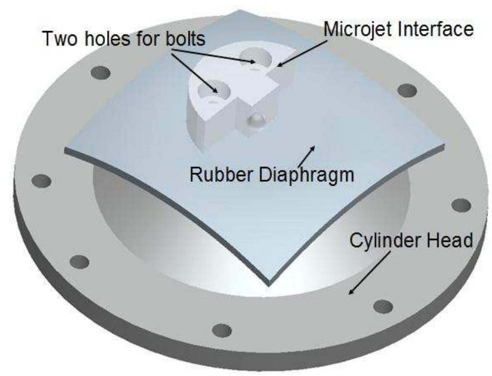
Figure 1. A cross section of the piezohydraulic actuator

The prior design focused on quasi-static performance attributes and model comparisons to illustrate the underlying system dynamic performance and displacement amplification behavior. Here, a microjet interface is integrated into the system to couple the actuation mechanism with pulsed microjet flow. The interface structure was designed such that the top diaphragm deforms into the microjet flow path as the hydraulic pressure in the cylinder head increases. This requires careful tuning of the external bias pressure to achieve high actuation performance and subsequently, pulsed flow actuation.

The microjet interface design is illustrated in Figure 2. Bias pressure is applied to the input side of the microjet and subsonic flow occurs at the exit on the opposing end. The diaphragm deforms into the path of the microjet to throttle flow during piezohydraulic actuation.



(a)



(b)

Figure 2. (a) The schematic of the microjet interface rendering; (b) The assembly of microjet interface with rubber diaphragm and cylinder head. The corresponding hardware is shown in Figure 5.

EXPERIMENTAL SETUP

The experimental set-up consists of a hydraulic circuit and data acquisition system used for characterizing the pressure change of the microjet outlet flow. A schematic of the hydraulic circuit is shown in Figure 3 followed by a schematic of the drive electronics and data acquisition system in Figure 4. The hydraulic system was set up to charge the piezohydraulic actuator with fluid, control the bias pressure, and purge air from the device. A hydraulic accumulator was used to control bias pressure in the piezohydraulic actuator and a fluid reservoir was connected to a vacuum pump to purge air from the system. Shut-off valves were used to pressurize the system and evacuate entrained air using a vacuum pump. During operation, the shut-off valve between the fluid reservoir and the piezohydraulic actuator was closed and the shut-off valve to the accumulator was left open. Hydraulic fluid was prevented from flowing back into the accumulator by including a check valve in the hydraulic circuit.

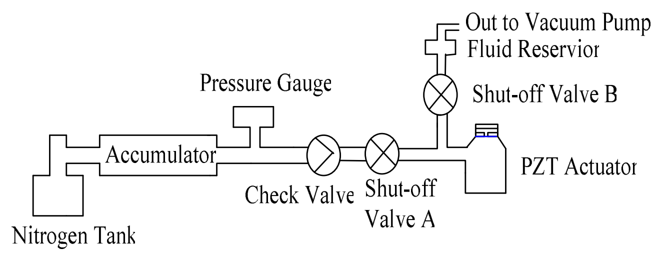


Figure 3. The schematic of the hydraulic system used to charge the piezohydraulic actuator with fluid and remove entrained air.

The microjet actuator was characterized at different voltage amplitudes, frequencies and ambient air pressures using the drive electronics and data acquisition set-up illustrated in Figure 4. A 1000V/7A switching power supply (PEIZOMechanik) amplified the voltage applied to the piezoelectric stack actuator. A Labview data acquisition system (NI PCI-6110) was used to collect pressure change data of pulsed flow. A Kulite pressure transducer with a sensitivity of 192.3 mV/psi was used to detect the ambient air from the microjet outlet. The top view of the assembled hardware and pressure transducer are shown in Figure 5. The signal of the pressure transducer was then amplified by an amplifier for the terminal collection of Labview.

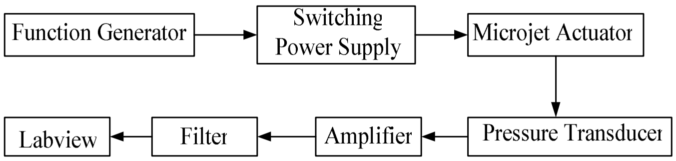


Figure 4. The schematic of the drive electronics and data acquisition system used to characterize the microjet actuator.

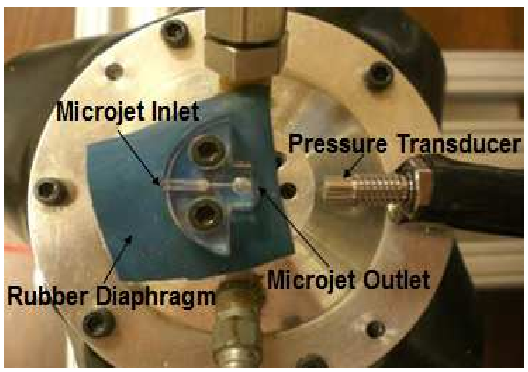


Figure 5. The experimental set-up for the pressure measurement of the microjet outlet air using Kulite pressure transducer.

EXPERIMENTAL RESULTS

The piezohydraulic actuator coupled with a microjet was characterized to assess the pulsed actuation characteristics. External biased air pressures of both 20 psi and 30 psi were used for the microjet flow testing. The outlet air flow was detected using the pressure transducer (Kulite) for different input voltage amplitudes and frequencies using a sinusoidal wave form. The optimal biased hydraulic pressure derived from the previous experiments [8] was utilized to optimize the diaphragm deformation. The response of the microjet actuated by the piezohydraulic actuator is illustrated in Figures 6 and 7 for a select number of frequencies and external air pressures. Additional data is given in Tables 1 and 2 and the corresponding Bode plot is given in Figure 8. The biased hydraulic pressure was read from pressure gauge at the end of each test. Minor changes in the hydraulic pressure were recorded during testing.

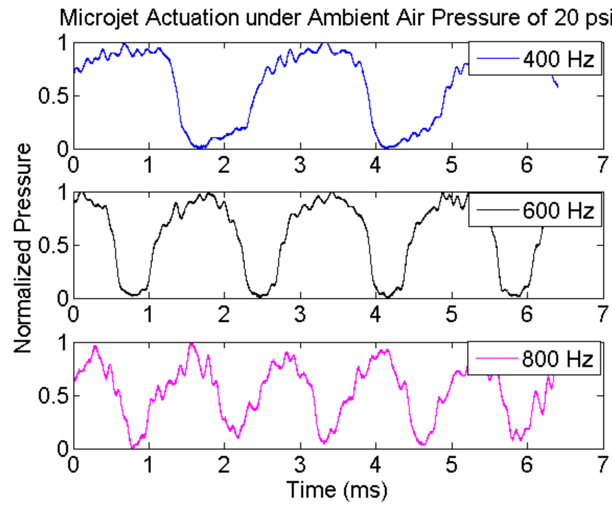


Figure 6. The response of the microjet pulsed by the piezohydraulic actuator at different frequencies and optimal biased hydraulic pressures. The external air pressure of 20 psi was applied and the electrical field was 0.8 MV/m.

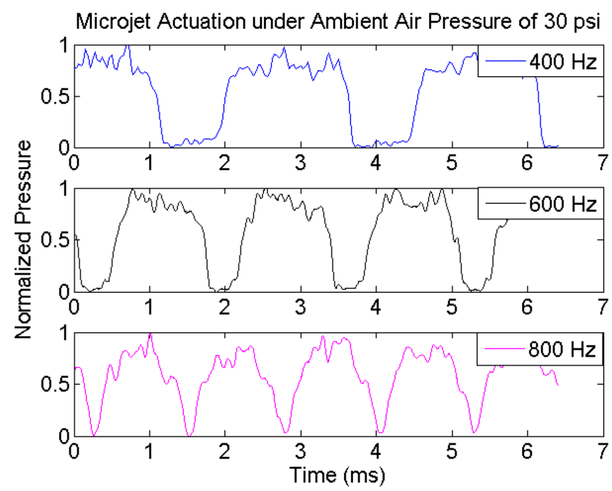


Figure 7. The response of the microjet pulsed by the piezohydraulic actuator at different frequencies for an external air pressure of 30 psi. The electrical field was 2 MV/m.

Table 1. The pressure change of pulsed microjet flow detected by pressure transducer (Kunite) under ambient air pressure of 20 psi at 0.8 MV/m and different frequencies.

Frequency (Hz)	Maximum pressure (psi)	Minimum pressure (psi)	Peak to peak (psi)
400	6.76	3.64	3.12
500	6.76	3.64	3.12
600	6.76	3.64	3.12
700	6.76	4.16	2.60
800	6.76	4.68	2.08
900	6.76	5.20	1.56

Table 2. The pressure change of pulsed microjet flow detected by pressure transducer (Kunite) under ambient air pressure of 30 psi at 2 MV/m and different frequencies.

Frequency (Hz)	Maximum pressure (psi)	Minimum pressure (psi)	Peak to peak (psi)
100	6.76	3.64	3.12
200	7.28	3.64	3.64
300	7.28	3.64	3.64
400	7.28	3.64	3.64
500	7.28	3.64	3.64
600	7.28	3.64	3.64
700	7.28	3.64	3.64
800	7.28	4.16	3.12
900	7.28	5.72	1.56

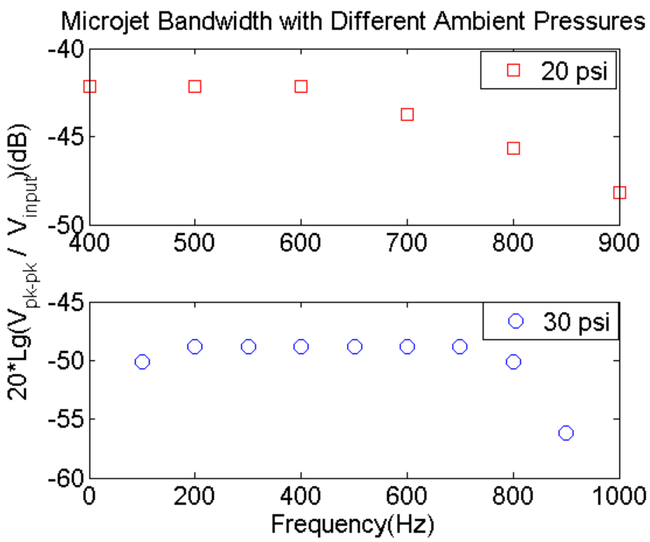


Figure 8. The bode plots of the microjet flow control system for different ambient air pressures, 20psi for (a) and 30psi for (b) respectively.

DISCUSSION

The piezohydraulic microjet actuator has provided sufficient actuation to pulse ambient air of 20-30 psi through a microjet with a diameter of 400 µm. Relatively large bandwidth was achieved for both ambient bias air pressures. The size of the microjet and ambient applied pressure are similar to previous steady flow microjet experiments [7,8]. This will therefore provide a reasonable correlation with future pulsed microflow visualization studies which are currently under investigation.

The microjet actuator was characterized under typical ambient air pressures of 20 psi and 30 psi at different voltage inputs and frequencies. For the ambient air pressure of 20 psi, the actuator exhibited sufficient actuation capability to pulse the microjet at frequencies up to approximately 900Hz with an electrical field of 0.8MV/m. Attenuation began to occur between 600 Hz and 700 Hz. As the ambient air pressure was increased to 30 psi, an electrical field of 2MV/m was necessary to generate detectable pulse flow at various frequencies. At this biased pressure, improvements in bandwidth up to 800-900 Hz were achieved. The additional dynamic response is likely to be related to faster restoring forces from ambient air during the reverse stroke of the piezoelectric actuator. The analysis from the recent system dynamic modeling indentified that the hyperelastic behavior of the rubber diaphragm is the key underlying contribution to the piezohydraulic actuation. In addition, fluid inertia may be the factor that limits the system bandwidth to less than 1kHz. This is supported by similar piezohydraulic systems [10] which illustrate bandwidth on the order of 700 Hz. The bandwidth of our system is currently under investigation using theory and numerical techniques.

CONCLUDING REMARKS

A piezohydraulic actuator coupled with a microjet interface was designed and characterized. The microjet flow pulsing experiments illustrated significant actuation capability with broad bandwidth performance. This device is expected to provide an important testing device for integration into bench top and wind tunnel microjet experiments to elucidate how micropulsed actuation interacts with different aircraft control surfaces. Current work is focused on microflow visualization of this system.

REFERENCES

1. W. Lord, D. MacMartin, T. Tillman. (2000). "Flow control opportunities in gas turbine engines." *AIAA paper 2000-2234*.
2. L. Cattafesta, S. Garg, M. Chourdhari, F. Li. (1997). "Active control of flow-induced cavity resonance." *AIAA paper 1997-1804*.
3. C. Rowley, D. Williams. (2006). "Dynamics and control of high-Reynolds-number flow over open cavities." *Annu. Rev. Fluid Mech.*, 38, 251-276.
4. A. Glezer, M. Amitay. (2002). "Synthetic jets." *Annu. Rev. Fluid Mech.*, 34, 503-529.
5. G. Raman, S. Khanafseh, A. Cain, E. Kerschen. (2003). "Development of high bandwidth powered resonance tube actuators with feedback control." *J. Sound Vib.*, 269, 1031-1062.
6. B. Cybyk, D. Simon, H. Land, J. Chen, J. Katz. (2006). "Experimental characterization of a supersonic flow control actuator." *AIAA paper 2006-0478*.
7. N. Zhuang, F. Alvi, M. Alkislar, C. Shih, D. Sahoo, A. Annaswamy. (2003). "Aeroacoustic properties of supersonic cavity flows and their control." *AIAA paper 2003-3101*.
8. W. Oates, F. Liu. (2009). "Piezohydraulic Actuator Development for Microjet Flow Control", J. Mech. Design. (accepted)
9. H. Lou, F. Alvi, C. Shih, J. Choi, A. Annaswamy. (2002). "Active control of supersonic impinging jets: Flowfield properties and closed-loop strategies." *1st AIAA Flow Control Conference and Exhibit, St. Louis, MI*.
10. A. Chaudhuri, N. Wereley. (2008). "Design and Testing of a PMN-PT Based Compact Hybrid Actuator." *ASME Conference on Smart Materials, Adaptive Structures, and Intelligent Systems, Oct. 28-30, Ellicott City, MD. (SMASIS08-495).*

