Microjet-based Separation Control
Using a Virtual Sensor for Degree of Separation

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Abstract – Flow separation yields undesirable characteristics such as increased drag and energy consumption, and reduction in lift, factors that degrade the aerodynamic performance of a vehicle. This paper presents an approach to flow separation control that uses microjets for actuation and feeds back the output of a virtual sensor that measures the *degree of separation*, a flow separation property characterized by the extent of separated flow and the magnitude of the reverse velocity. In particular, the degree of separation was chosen to be the distance between the occurrence of the maximum turbulent shear stress and the surface of the airfoil. The virtual sensor described in this article operates by performing relatively simple signal analysis on an unsteady pressure measurement that serves as its input. The output from this virtual sensor is then used as a feedback signal for the microjet controller. The objective of this study is to demonstrate separation control using microjets and explore the feasibility of realtime feedback control using this virtual sensor.

Keywords: Separated flows, Microjets, unsteady surface pressure, active flow control, feedback control.

1 Introduction

Flow separation occurs over external surfaces such as aircraft wings, compressor and fan blades, and in internal flows such as engine inlets and ducts when the boundary layer moves away from the surface against an adverse pressure gradient. It is undesirable in most applications since it leads to energy loss. In addition, it increases drag and noise, reduces lift, and generally limits the performance and maneuverability of an aerodynamic vehicle. Flow separation can be regulated using both passive and active approaches. Passive approaches such as increasing the inlet length or using vortex generators (vgs) can help reduce/eliminate separation. However, passive approaches are effective only in a limited range of system operating conditions and lead to unwanted results such as increases in the overall length and weight of the vehicle and an increase in drag [1].

Active approaches are another class of solutions towards controlling flow separation. They involve using sensor feedback, actuators (e.g., microjets), along with robust or adaptive control algorithms to regulate flow separation. In contrast to passive approaches, active approaches are effective in large operating ranges, are not accompanied by parasitic drag, and lead to relatively small increases in vehicle size and weight [1]. Studies illustrating the effect of microjets for separation control [2, 5,6] have shown that microjets can successfully eliminate or reduce the flow separation over a generic backward facing ramp with very low mass flux [5,6], increase the airfoil lift by almost 40% [2], and increase the stall angle from 14° to 16°. A recent study [2] analyzed microjet-based separation control over an ONERA-D wing profile using Particle Image Velocimetry (PIV) measurements and Proper Orthogonal Decomposition. However, direct PIV measurements can be used only for analysis in laboratory experiments and not for realtime feedback control. Therefore, alternative methods must be developed to characterize separation for

practical feedback control. This paper uses PIV measurements in a laboratory setting to construct a virtual sensor that can potentially be used for realtime feedback control in real world settings.

An adaptive feedback disturbance rejection algorithm in conjunction with a synthetic jet actuator and an unsteady pressure transducer to control flow separation on an airfoil model has been demonstrated by Tian et al[3]. The goal of their study was to suppress pressure fluctuations on the upper surface of the airfoil model, thereby reducing flow separation. The study in [3] assumes that pressure fluctuations are larger when the flow is separated and uses recursive system identification to estimate the flow dynamics. The results show that the control algorithm is able to reattach the flow, thereby reducing or eliminating adverse effects originating from the flow separation. This study also shows the feasibility of closed-loop control of flow separation. Another implementation of active control is presented by Tian et al. in [4], where an adaptive closed-loop control mitigates the effect of flow separation. The adaptive closed-loop control is used to optimize the lift to drag ratio over an airfoil using multiple amplitude modulated or burst modulated, zero net mass flux actuators. An optimization program uses the lift and drag measurements from a strain gauge to search for optimal actuation parameters. This study attempts to minimize flow separation by maximizing the lift to drag ratio. Hence, the lift to drag ratio is used as an indirect measure of the degree of separation. The increase in performance using these kinds of implementations are usually developed as standalone applications and integration with the actual system may usually lead to a higher input cost to the system in form of a higher mass-flux and/or higher power requirements. However, if one has a finer control on the controller input and output, particularly in terms of size of the separation, one can weigh various options available and accordingly adjust the control parameters for an increase in *overall system performance*. The research reported in this paper presents such an approach where we use a more direct measure for the degree of separation and the controller output is adjusted based on this input.

The fundamental problem of a realtime closed loop active flow separation control implementation is how to quantitatively measure or characterize flow separation such that measurements can be fed back to a controller to regulate the flow separation. In general, a flow separation sensor is needed. However, to our knowledge there is no technique or sensor that can quantitatively characterize flow separation. One solution to the problem can be to define an indirect approach where one identifies signals that can be measured in realtime and uses them to extract characteristic features of the separated flow. The research of [5,6] develops an approach to quantifying the degree of flow separation based on unsteady pressure measurements. The approach uses unsteady pressure spectra to extract the distance of the occurrence of the maximum turbulent shear stress from the airfoil surface, which was shown using PIV analysis to be correlated to the extent of separated flow and the magnitude of the reverse velocity. In this paper, the estimated distance of the occurrence of the maximum turbulent shear stress is viewed as the output of a virtual sensor. This distance measurement was used in [5,6] along with microjet trajectory analysis in an open loop fashion to determine the desired microjet pressure. In this article, we will use this output for realtime feedback control to develop a more robust separation control approach.

2 Experimental Setup

The experiments were performed in a subsonic closed return wind tunnel with a maximum free stream velocity of 65m/s with a test section of $0.61\text{m} \times 0.61\text{m}$. The geometry of the test model used in the experiments is a simple diverging 'Stratford' ramp, shown in Fig. 1 and is schematically illustrated in Fig. 2. The test model is instrumented with pressure taps along the centerline at selected locations. In addition, the test model setup is modular, allowing the control parameters as well as the base flow to be altered. As an example, the test model can be rotated about a pivot point, which provides the flexibility to change the adverse pressure gradients, and hence control the size and location of the separated flow. Seven arrays of modules containing microjets, labeled MJ1, MJ2,…, MJ7, are incorporated in the test model as shown in Fig. 1 and Fig. 2. Each module has microjets, which are 400μm in diameter, and the spacing between microjets is approximately 5mm.

Fig. 1 and 2 also shows the location of high frequency Endevco pressure sensors as TR1,… ,TR4 used in our experiments. These pressure sensors have a resonant frequency of 55 KHz and a pressure range of 0-1psi and were calibrated before each data acquisition. Data was acquired using a LabVIEW-based data acquisition (DAQ) system from National Instruments.

A block diagram illustrating the experimental setup, computational system, and data acquisition is shown in Fig. 3. A proportional/servo valve is used to control the microjet pressure and is interfaced with a National Instruments data acquisition board. The input pressure to the valve is maintained at approximately 80psig from commercially available compressed N_2 (Nitrogen) tanks. It should be noted that Nitrogen is used because of its availability in pure form and nitrogen has essentially the same gas dynamic properties as air. The valve accepts command currents from 4-20mA (which corresponds to an output pressure of 1.5-15psi) and was experimentally observed to have a first order linear response with a time constant of 0.6sec.
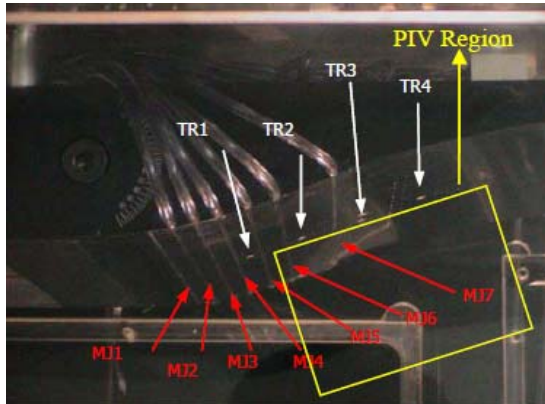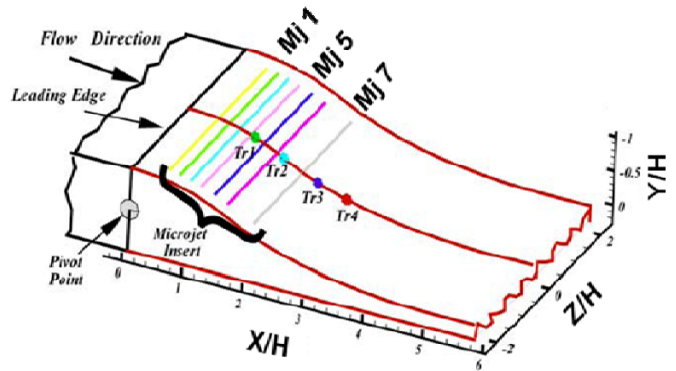

Fig. 1. Experimental test model

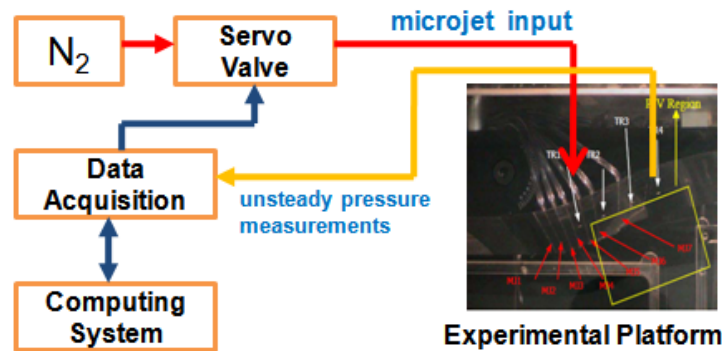**Fig. 2.** Schematic of the test model

Fig. 3. Block diagram of the experimental setup

3   Experiment Descriptions, Results and Discussion

As mentioned earlier in section 1, the fundamental problem in development of a real-time closed loop active flow separation control is the need for a sensor which can quantitatively and reliably measure flow separation characteristics. Research by Kumar [5, 6] suggests that the unsteady surface pressure is very closely related to the flow above the surface and the resulting pressure spectra can be used to extract the distance of the occurrence of the maximum turbulent shear stress from the airfoil surface. The location of the maximum turbulent shear stress was also shown to be correlated to the extent of separated flow and the magnitude of the reverse velocity, obtained using PIV analysis, for a wide range of conditions examined. This distance of maximum disturbance obtained using the unsteady surface pressure can then be developed as a sensor for degree of separation. Additionally, this approach narrows the analysis of the separated flow to a limited range of frequencies and thus has a relatively higher sensitivity compared to the unsteady pressure.

In the following sections, we will examine the results of feedback control using unsteady surface pressure measurements, presented primarily for a freestream velocity of 40m/s. The signal analysis in [5,6] is used to estimate the distance from the airfoil surface to the location of the occurrence of the maximum shear stress, which is used here as the measure of the degree of separation. This analysis requires computation of the power spectrum of the unsteady pressure signal. The horizontal and vertical scales of the corresponding frequency response are transformed linearly into appropriate non-dimensional coordinates. A nonlinear relationship is then developed between the slope to the right of the maximum peak in the frequency response and the degree of separation, which is measured using PIV analysis. Note that the development of the relationship between the unsteady pressure spectra and the degree of separation is necessary because PIV cannot be used in realtime control.

3. 1 Feedback Approach to Separation Control

Fig. 4 shows the block diagram for feedback control approach. In this figure, Y_d is the desired degree of separation and Y_m is the "measured" degree of separation determined by the virtual sensor. Surface pressure is obtained using high frequency transducers at a sampling rate of 10 KHz and processed to measure the degree of separation (Y_m). A PI controller using Y_m is implemented to control the microjet pressure and thereby obtain the desired degree of separation (Y_d). Although not shown in the figure, an integral anti-windup is also implemented to prevent unwanted responses such as large overshoots that can occur due to actuator saturation. This is accomplished by automatically switching the integral gain to zero when the actuator is saturated. Hence, during this time the controller becomes a proportional controller.
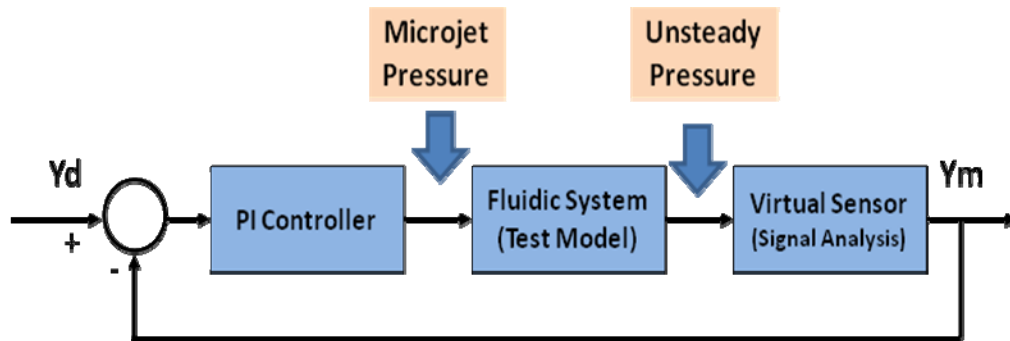

Fig. 4 Block diagram of the closed loop system

The current implementation of the control algorithm has a sampling rate or update rate of 15Hz. This low value of the update rate is due to the computational time needed for the signal analysis used in the virtual sensor. Updates are currently underway to simplify the analysis to yield an increase to the update rate. Nevertheless, even in the present configuration and as described in the next section, the technique is relatively simple and computationally feasible for separation control applications.

3.2 System Response with Open Loop and Closed Loop Control

To illustrate the effectiveness of the microjet, open loop experiments were conducted at an incidence angle of 5° and a free stream velocity of 40m/s. Realtime DAQ and analysis based on unsteady pressure was incorporated to evaluate Y_m. Fig. 5 shows an open loop response of the system as the microjet array MJ5 is actuated at 10psi. Fig. 5 also indicates the time signal for the microjet control as a red dotted line. One can notice the response time of the system is close to 6 seconds. This includes both the response time of the microjet valve to the control signal and that of the separated flow to the effect of microjet control. Considering that the control valve has a time constant of ~ 0.6seconds, it indicates that the flow itself takes ~ 5seconds to respond to the microjet control. It can also be noted that with microjets actuated, the measured degree of separation, Y_m, is drastically reduced albeit not zero. It is

expected because for any given real flow, shear stress will exist and as such, Y_m cannot be made equal to zero. Based on experimental observations from [5,6], as the microjet pressure is increased, Y_m reduces until it plateaus; any continual increase in microjet pressure after this point results in an increase to Y_m. One should also note that this trend also holds true for the unsteady surface pressure. However, the frequency range used for the estimation of Y_m is substantially smaller than the root mean squared (RMS) value used for the unsteady pressure measurements and as such has a much higher resolution for developing control for the separated flows.

There is no robust way to use open loop control to accurately yield a variety of output (degree of separation) responses. However, being able to set the degree of separation provides the ability to fine tune the performance of the vehicle based on the availability of bleed air and desired inlet flow conditions to the compressor. This ability of the closed loop system response, Y_m, to track a reference input signal, Y_d, is illustrated in Fig. 6. Fig. 6 shows essentially a series of step inputs of various magnitudes and finite length. It can be noticed in Fig. 6 that the noisy measurement Y_m tracks the desired value fairly well. The closed loop response time is tuned to be relatively slow due to the sensor noise. Based on experimental observations, high gains in the PI controller led to faster rise times. However, high gains also tended to saturate the controller due to the effects of amplifying the sensor noise and also led to transient oscillations.
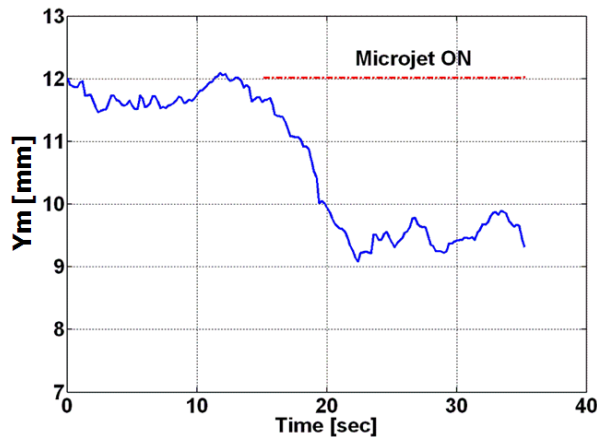

Fig. 5. Illustration of the effectiveness of a microjet in reducing degree of separation in open loop control
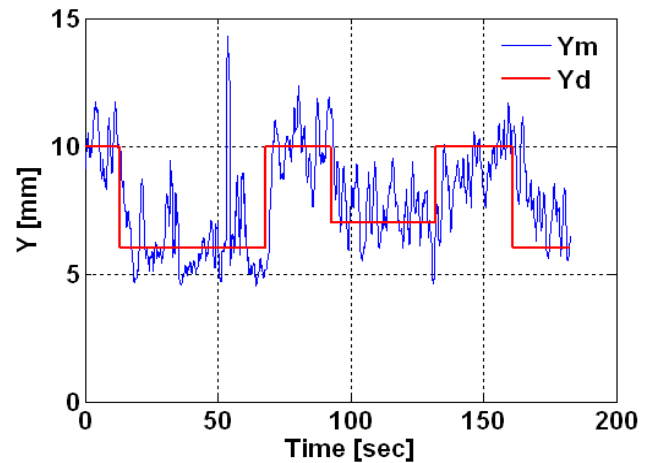
Fig. 6. Closed loop tracking of degree of separation

Corresponding microjet pressures from the PI controller for the commanded degrees of separation (Y_d) of Fig. 6 is shown in Fig. 7. One can clearly notice that as the commanded degree of separation is reduced i.e. smaller size of separation or move towards attached flow, the microjet pressure requirement increases. It can also be observed that for a given Y_d, the microjet pressure output varies substantially. For example, for a Y_d of 10mm, microjet pressure can vary from 5-12 psig. Ideally, as long as the free steam velocity and ramp incidence angle are invariant, the microjet pressures corresponding to identical value of Y_d should be roughly equal after the system reaches a steady state condition. The above observations are indicative of hysteresis and/or non-linear behavior present in the flow and possibly in the actuator. Coupled with the fact that the turbulent flows yield time-varying systems [3], a lot more research needs to be further conducted to explain this behavior. Nevertheless, a simple approach towards feedback control of the separated flows using a simple PI controller capable of yielding reasonable tracking performance can easily be ascertained from the results presented above. This can be further developed towards Distributed Matrix Control (DMC) approach, where multiple microjets at various pressures can be used to optimize the overall system performance and thereby increase the overall system efficiency.
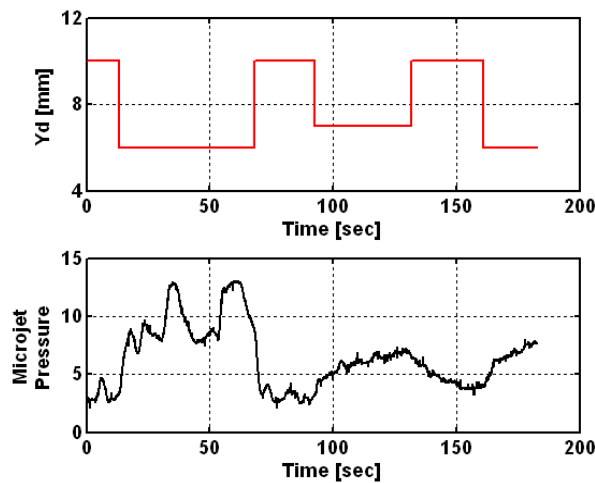
Fig. 7. Desired degree of separation (Y_d) and
microjet pressure as controller output

4. Summary and Future Work

This study presented a microjet-based separation control using a virtual sensor for degree of separation based on signal analysis of the unsteady pressure spectra. A simple PI controller was designed to implement this feedback control. Experimental result shows that the controller can track the desired input fairly well, demonstrating the feasibility of this approach to separation control.

Future research will focus on several areas. An effort will be made to speed up the signal analysis associated with the virtual sensor in order to yield a faster control update rate. Several open loop experiments will be performed to better characterize the system nonlinearities and the time-varying nature of the system. Also, more complex control strategies will be considered, for example, fuzzy PI control and adaptive control. In addition, the current study only considered a single-input, single-output system while future research will consider multi-input, multi-output systems, i.e., systems involving several arrays of microjets (multiple actuators) and several pressure measurements (multiple sensors).

5. Acknowledgments

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