Implementing Rotating Stall Control in a Radial Diffuser Using Microjet Arrays

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Abstract This study is part of our effort to implement and refine microjet-based flow control in realistic and challenging applications. Our goal is to reduce/eliminate rotating stall in the radial diffuser of a production compressor used in commercial heating, ventilation, and air conditioning (HVAC) systems, using microjet arrays. We systematically characterize the flow using pressure and velocity field measurements. At low load conditions, the flow is clearly stalled over a range of RPM where the presence of two rotating stall cells was documented. Circular microjet arrays were integrated in the diffuser and the flow response to actuation was examined. The array closest to the initiation of stall cells was most effective in reattaching the flow. Control led to a very significant increase in the stall margin, reducing the minimum operational mass flow rate to 14% of the design flow rate, half of the original 28% flow rate before microjet control was implemented. The results will show that the parameters found be most effective in the simple configurations proved to be near-optimal for the present surge control application in a much more complex geometry. This provides us confidence that the lessons learned from prior studies can be extended to more complex configurations.

Keywords Active flow control · Microjets · Stall · Radial diffuser · PIV

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1 Introduction

Flow separation is ubiquitous in a wide range of internal and external flows, ranging from the simplest, e.g. on the leeward side of a cylinder or a backward facing ramp to the very complex such as in turbomachinery components of propulsion, power generation and other systems. Separating flows are nearly always undesirable as they lead to unsteadiness, increased aerodynamics loads (steady and unsteady), reduced pressure, reduced operational envelope (for aircraft, propulsion and power systems) resulting in a loss in performance and efficiency. As such, control of separated flows has been the focus of research for a number of decades where passive and active methods have been explored in the academic and applied fluid dynamics community.

Some of the more pervasive passive methods that have been explored for separation control, include vortex generators such as vanes, bumps, dimples and ramps among others [1, 2]. While passive methods have sometimes shown a favorable influence on separated flows, their impact is often limited to a narrow range of flow conditions as passive devices cannot be adjusted to changes in operational conditions. Active methods, ones that requires energy input, have shown more promise, in large part due to their potential ability to adapt to changing conditions. Hence a range of actuators for active flow control have been explored including acoustic excitation through speakers [3, 4]; synthetic jets (Zero Net Mass Flux, ZNMF actuators [5–7] that have been examined experimentally and computationally [8, 9]; dielectric barrier discharge plasma actuators [10], plasma arc actuators [11, 12], plasma driven jets [13–15], and many more. A recent review by Cattafesta and Sheplak [16] treats this topic in a comprehensive manner. One actuation technique that has shown considerable promise is the use of strategically located, very small-relative to the relevant length scale, high momentum, jets commonly referred to as ‘microjets’.

Microjet-Based Flow Control—This control approach has been implemented in a wide array of fundamental-canonical and application-driven flows, including by the present authors. The applications include the use of steady and unsteady microjet arrays for the control of flow oscillations in cavities [17–19], aeroacoustics of free jets [20–22] and the control of the highly unsteady supersonic impinging jets [23, 24]. In almost all these applications significant improvements were achieved through this active flow/noise control approach. As discussed in these references, the primary mechanism for their effectiveness is the ability of the microjets arrays, often injected in a wall-normal direction, to generate coherent streamwise vortices which increase longitudinal momentum near the wall and streamwise vorticity through the jets in crossflow (JICF) mechanism. The enhanced mixing so achieved can be leveraged for the control of different flow—applications through a careful choice of the location and operational conditions of actuation in the context of the base flow. An abbreviated discussion regarding the physical mechanisms is provided in Sect. 2.2. More details can be found in Refs. [24–26].

AFC of Separated Flows—Control of flow separation is an flow application where microjet-based control has been particularly effective. The primary reason for this is the JICF induced, enhanced mixing which energizes the near-wall, low momentum

fluid by efficiently mixing it with the higher momentum fluid in the upper region of the boundary layer [25–27]. Separation control has been examined extensively, starting with very fundamental flows and advancing to more complex, realistic, application-driven configurations—a very brief review of a selected number of these efforts follows next. The initial studies examining the use of microjet arrays for the control of boundary layer separation were conducted on a modified Stratford ramp that was nominally two-dimensional, although the separated flowfield was highly three-dimensional. The ramp was equipped with multiple linear arrays of steady microjets that allowed for individual arrays to be activated as needed. The angle of attack of the ramp was also variable allowing the adverse pressure gradient and hence the size of separation to be controlled. The effect of steady microjets in controlling increasingly larger separated flowfields was systemically examined where microjets were able to completely eliminate the strongest separation generated in this study. Further, the cost of this control in terms of the requisite mass flow through the actuator array was very low, fraction of a percent, once the optimal actuation conditions were identified. Details of this study may be found in Kumar and Alvi [25].

This control strategy was next explored for controlling separation induced stall on the wing of an RC aircraft during a high α maneuver. Using tuft based visualization and GPS data the ability to extend the stall angle was demonstrated [28]. Steady microjet actuation for separation control was also demonstrated on a *Low Pressure Turbine* (LPT) blade in a simplified linear cascade. The efficacy of control on an L1A blade (L1A is the arbitrarily designated model name), which is an Air Force Research Laboratory (AFRL) designed configuration with a higher loading than conventional low-pressure turbine profiles, was demonstrated over a range of conditions. Separation was completely eliminated on the blade with AFC resulting in a very significant reduction in the integrated wake loss coefficient [29].

Present Study—The study described in this paper is part of our continuing effort to implement, demonstrate and refine microjet-based active flow control in increasingly realistic and challenging applications. The results of the studies in canonical configurations were used to guide the design of the actuators for the present. Our goal is to reduce rotating stall in the radial diffuser of a production compressor used for commercial HVAC systems. These compressors use R-134a refrigerant where energy added to the fluid by the impeller is recovered as high pressure when the refrigerant is decelerated through a radial diffuser. For ‘low-load’ conditions, where the mass flow rate through the compressor is reduced, the reduced velocity and hence momentum of the fluid as it moves radially outwards through the diffuser makes it susceptible to separation which leads to rotating stall [30]. This is obviously problematic as it limits the compressor efficiency, increases vibration and noise and limits the viable operational range of the machine.

Passive methods such as vortex generators, vanes, and bumps, as well as active methods such as acoustic excitation have been utilized with limited success. They require high degrees of customization in order to remain effective, and even when optimally designed are only effective for specific flow ranges. Kurokawa et al. [31] have shown that customized radial grooves completely suppressed rotating stall in a

vaneless diffuser, however, the implementation resulted in an overall loss of pressure in the diffuser. Alternatively, low-speed blowing has been found to be effective in controlling flow separation in a vaneless diffuser, but resulted in a loss of impeller-diffuser combination performance [32].

The goal of this study was to attempt to eliminate or significantly reduce stall at the low load conditions, corresponding to low mass flow rate, thus improving efficiency and extending the operational range. Implementing AFC in a production turbomachinery system is non-trivial due to the system complexity, limited space and access, and limited measurement capability. Furthermore, limited information is available in open literature regarding the rotating stall flowfield, even for simple configurations and even less so for production systems- these are challenges that had to be addressed in this project.

2 Experimental Hardware and Methods

2.1 Model Details—Radial Diffuser and Compressor

The experiments were conducted at the Florida Center for Advanced Aero-Propulsion at the Florida State University. The TT300 compressor was supplied by Danfoss Turbocor Compressors Inc. The original design (Fig. 1a) features a diffuser built into a large shroud, creating a high degree of difficulty in reaching the diffuser. In order to improve access, while realistically modeling the problems faced by the production line of compressors, the compressor was modified in collaboration with the manufacturer to provide simplified access to the unbladed radial diffuser during testing. The multistage compressor was modified for testing with a single stage. The shroud was removed and the impeller shaft was elongated to bring the diffuser to the edge of the compressor body. The flow path was slightly modified, creating a diffuser that was purely radial, but retained the size (radius, $R_{Diffuser} = 127$ mm) and basic shape of the production model diffuser. Air replaced R-134a as the working fluid and the impeller was also modified for the alternative working fluid. Schematic of the modified diffuser-compressor configuration is shown in Fig. 1b and the general flow direction of the working fluid in the diffuser is indicated in Fig. 4.

2.2 Physical Mechanism and Implementation of Microjets in Diffuser

Steady microjets injected into the diffuser crossflow (see Fig. 2) alter the flowfield both locally and globally by promoting mixing in the boundary layer. This is due to the creation of counter rotating vortex pairs (CVP), which are streamwise oriented vortices, that transfer high momentum fluid from the freestream into the boundary

Fig. 1 **a** Three-dimensional cut-away of production configuration TT300 compressor, and **b** cross-section of modified diffuser configuration used for testing

Fig. 2 Schematic of microjet injection into diffuser cross-flow

Fig. 3 Flowfield induced by microjets injected into a crossflow, with inter-microjet spacing of $25d_{jet}$, for different microjet blowing ratios. Streamwise vorticity contours along flow normal planes obtained from stereo-PIV measurements at two different streamwise locations ($x/D = 16$ —top row, $x/D = 64$ —bottom row). Figure has been redrawn to improve print quality and is similar to the original figure from Fernandez and Alvi [27]

layer. A representative example from Fernandez et al. [27] showing the growth and evolution of multiple CVPs at different blowing ratios can be seen in Fig. 3, which indicates the flowfield in planes normal to the flow and downstream of steady microjet injection. The vorticity contours clearly indicate the presence of streamwise vortices created by multiple microjets. The microjet spacing, location and blowing ratio for the present surge control application were informed by prior studies in canonical configurations that were aimed at exploring the fundamental physical mechanism behind microjet-based control. Studies by Fernandez [33] and Fernandez et al. [27] discovered that the most effective blowing ratio, BR, ranged between 1.5 and 3, as this is where the CVP remain within the boundary layer and efficiently mix the low momentum and high momentum fluid within the boundary layer. Similarly, these studies also demonstrated that while inter-jet spacing of $12.5d_{jet}$ and $25d_{jet}$ were both effective, in terms of benefit versus cost, $25d_{jet}$ was the most efficient. This spacing maximized the interactions between neighboring CVPs in enhancing inter-boundary layer mixing. A more detailed analysis of the fundamental physical mechanism underpinning microjet actuation can be found in the work of Fernandez [33].

Microjet assemblies, consisting of multiple microjets, were designed to inject nitrogen gas into the boundary layer and reattach the flow to the diffuser wall, extending the operating range of the compressor. The position of the microjets relative to the working fluid is shown in Fig. 4a, where the nitrogen is injected normal to the plane of the drawing. The system design involved microjet-containing caps attached to four individual pressurized stagnation chambers. The microjet caps were aluminum plates with four rows of 0.4 mm diameter (d_{jet}) microjets, spaced 5 mm ($12.5d_{jet}$) apart, located 63.5, 76.2, 88.9 and 99.7 mm from the diffuser center. The modular design allows for simplified variation of microjet arrangement between tests. By varying the selected microjet row, injection could occur before, on, or after the approximate boundary of stall cells. Blocking alternate microjet openings allowed for tests with $25d_{jet}$ inter-microjet spacing. The stagnation chambers were individually filled with nitrogen. Two inlets were used to ensure even distribution throughout the chamber, and the inlets were angled for the nitrogen to impinge upon the opposing chamber walls. This allowed the fluid to be evenly distributed before it reached the microjet openings.

2.3 Measurement Techniques

Steady Pressure Measurements Sixteen static pressure taps were placed at incremental distances from the center of the diffuser, as shown in Fig. 5. Surface pressures were scanned by a ScanivalveTM pressure transducer. The steady pressure data were used to determine the approximate radial location of stall, shown by rapid rise in the static pressure to atmospheric conditions (As seen in Fig. 7, to be discussed later).

Fig. 4 **a** Diffuser back plate schematic. Microjets injected normal to the plane of the drawing, and **b** diffuser upper plate showing airflow inlet, tapered to accommodate smooth flow from the impeller

Fig. 5 Steady pressure taps are shown placed at incremental distances from the diffuser center, with tubing attached

Unsteady Pressure Measurements Using the radial location of stall determined by the steady pressure measurements, Endevco[®] piezoresistive pressure transducers with a 1 psig range were installed at various intervals along the stall radius. Two transducers were located 77 mm from the center of the diffuser, and five were located at a radial distance of 111 mm. These radial distances were chosen both to encompass stalled flow region, as well as to accommodate the geometric constraints of the diffuser. The two located 77 mm from the center were spaced 12.7 mm apart, and the other five were located with 12.7, 25.4, 38.1, and 50.8 mm spacing between each tap. The machined holes for Endevco transducers may be seen in Fig. 6. Transducer

Fig. 6 Diffuser top plate shown with holes for unsteady pressure transducers and an acrylic window added for optical access

signals were low-pass filtered using a Stanford Research Systems filter and sampled at a rate of 5120 Hz. Power spectral density (PSD) estimates were calculated through Welch's method using a Hanning window and 75% overlap. This data was used to determine frequency and velocity of stall motion.

Particle Image Velocimetry and High Speed Imaging Particle Image Velocimetry (PIV) studies were conducted to further characterize the flow inside the diffuser. Optical access was obtained through an acrylic window on the top surface of the diffuser, as shown in Fig. 6. A LaVision Imager sCMOS double frame camera with 2560×2160 pixels spatial resolution was used to capture images at 15 Hz. The flow was seeded with micro sized oil droplets and illuminated by a 200 mJ/pulse Nd:YAG laser (Quantel Evergreen) with the illumination plane coincident to the plane of radial flow within the diffuser. Dual frame images were cross-correlated using LaVision DaVis software through a multi-pass algorithm using interrogation windows of size 48×48 pixels for the first two passes and 24×24 pixels for the last four passes and with 75% overlap. Due to the periodic nature of the stalled flow, phase conditioned measurements were required to characterize the flow field. An Endevco pressure sensor was used, where its band-passed signal was fed into a phase-locking delay generator. The LaVision system was triggered using the signal from the delay generator and images were captured at 8 different phases of the stall cycle. Three hundred dual frame images were captured for each phase and processed to obtain velocity fields, where the instantaneous velocity fields were ensemble averaged to obtain each phase-averaged velocity field. Due to the periodicity of the flow, the phases were stitched together, in order to obtain the complete velocity field of the stalled flow. Once stall was eliminated, phase locking was no longer possible since no discrete signal (stall frequency) existed for locking. Conventional non-phase condi-

tioned PIV was also attempted, however the attached/unstalled flow field was found to be unremarkable with the flow exiting radially in a uniform manner.

Flow fields with particle seeding were also imaged using a high-speed Photron FASTCAM SA5 camera at a resolution of 1024×1024 pixels and sampling rate of 1280 Hz, with illumination provided using a 10 mJ/pulse Nd:YLF dual head laser (New Wave Research Pegasus-PIV). The high-speed images are used for visualization of stall cells.

3 Results

3.1 Baseline (Uncontrolled) Flow

3.1.1 Radial Pressure Distributions

Steady Pressure Distribution Steady pressure data was collected from the 16 radial taps during compressor operation. Impeller speeds of 10000, 15000, 20000, 24000, and 32000 RPM were tested. For each impeller speed, the mass flow rate was slowly decreased while the pressure was closely monitored. Rotating stall cells were assumed to form at the mass flow rate associated with a sudden onset of strong fluctuations in the unsteady pressure. The mass flow rate was held at the initial position of induced stall, and pressure data were again acquired. Figure 7 shows the normalized pressure distribution in both the unstalled and stalled cases as a function of non-dimensional radial location. For the unstalled case, an initial rapid increase in pressure as the flow exits the impeller ($r/R_{Diffuser} = 0$) was followed by a gradual increase to the diffuser exit pressure (ambient pressure conditions). The deviation from a smooth curve between $0.15 < r/R_{Diffuser} < 0.4$ can be explained by con-

Fig. 7 Pressure distribution in the presence (dashed) and absence (solid lines) of stall

Fig. 8 Unsteady pressure during stalled flow at 20000 RPM. **a** Time series showing periodic oscillations, and **b** PSD with dominant peak at 78 Hz

sidering the diffuser profile contraction, shown in Fig. 4b, which contributes to a change in rate of pressure increase. The stalled pressure distribution shows the same rapid rise as seen in the unstalled case immediately after the impeller exit. Deviation from the unstalled condition occurs at approximately $0.15 r/R_{Diffuser}$, with rapid pressure rise in the diffuser during stalled flow persisting until approximately $0.6 r/R_{Diffuser}$. At this point, the non-dimensional pressure approaches $\sim 95\%$ of the exit atmospheric pressure. The region from $0.6 < r/R_{Diffuser} < 1.0$ in the stalled pressure distribution corresponds to the location of the stall cells, where airflow at atmospheric pressure was pulled back into the diffuser.

Unsteady Pressure Distribution Unsteady pressure data along the determined stall radius was recorded during stalled and unstalled conditions. Time series of the pressure from all unsteady pressure sensors during constricted mass flow (stalled) show distinct oscillations associated with rotating stall. This can be seen in Fig. 8a for an impeller speed of 20000 RPM at a mass flow rate of 26.6% unstalled mass flow, along with its associated power spectrum (Fig. 8b). The dominant frequency identified in the spectrum, 78 Hz, is the frequency of the rotating stall cells. Based on the stall frequency, the lag between simultaneous measurements from sequential sensors, the inverse of the sampling rate, and the angular separation of the pressure sensors, the speed and number of stall cells present in the diffuser were calculated. These results show that an increase in impeller speed corresponds to increases in stall cell velocity and percent of baseline mass flow rate at which stall begins. The impeller speeds with the highest mass flow rates at which stall is initiated should have the greatest potential for improvement.

Fig. 9 Instantaneous high-speed image showing stall cell. Dashed line indicates stall boundary

3.1.2 Velocity Field

The velocity field in the radial diffuser was obtained through phase-locked PIV. Stall cells are clearly visible even in instantaneous images (Fig. 9), where the dark regions (marked in Fig. 9) correspond to reverse flow into the diffuser from the unseeded ambient environment. A complete flow field was constructed by shifting the measured quadrant by the proper phase offset. Figure 10 shows a complete stall cycle at 20000 RPM, using the eight phases measured. This was possible due to the rotational nature of the flow. The stall regimes are visible by areas of radially inward flow, as seen in the streamlines shown in Fig. 10. This locally reverse region can also be seen as blue colored contours and are marked in the figure. The velocity field results shown here confirm the radial location of stall cells, beginning approximately 76 mm from the center of the diffuser. This information was used to choose the appropriate radii for microjet injection, as detailed in the following section.

3.2 *Effect of Microjet Control*

After identifying the onset of stall at different RPMs using mean and unsteady pressure measurements (Figs. 7 and 8) and subsequently characterizing the velocity field, see Fig. 10, we systemically implement steady microjet control. These experiments were conducted over a range of operating and actuation conditions, only a summary is provided here along with some representative results for the sake of brevity. Hence,

Fig. 10 Contours of radial velocity at impeller speed of 20000 RPM. Spatial dimensions are in units of meter and solid black line represents the edge of the diffuser

although actuator arrays at four radial locations in the diffuser were tested, we only present results for the most effective case, corresponding to a radius of 63.5 mm (see Sect. 2.2). Prior studies on the use of this control strategy identified that the most effective range of blowing ratio (BR) for control of separated flows ranges between 0.5 and 3 [27, 33]. This is the range of blowing ratios examined here, where it is defined as the ratio of the velocity of the jets issuing from the actuator to that of the crossflow. The microjet velocity was estimated by measuring the mass flow rate as well as the stagnation pressure and temperature in the microjet supply chamber. The latter measured properties then provide an estimate of the microjet velocity through the actuator orifices and the total mass flow rate. By comparing the two mass flow rates, a loss coefficient was estimated to account for head losses through the orifices. Following this procedure, the requisite microjet stagnation chamber pressures corresponding to each blowing ratio were determined for all combination of array configurations.

3.2.1 Unsteady Pressures and Flowfield

The innermost circular array of microjets, located 63.5 mm from the diffuser center and ~ 31.8 mm inward of the stall boundary (based on pressure and velocity field results) proved to be the most effective for elimination of stall cells. The effect of this control is readily evident in the unsteady pressure signals as shown in Fig. 11a.

As seen here, the large-scale fluctuations characteristic of stall cells (in the green trace) were dramatically reduced, essentially to a pressure signature corresponding to unstalled flow (blue trace) through the application of microjets. Figure 11b shows

Fig. 11 Unsteady pressures at impeller speed of 28000 RPM with and without control. **a** Time series, and **b** Corresponding spectral content

the same impact of flow control in the spectral domain—the high-amplitude spectral peaks corresponding to stall, in the dashed green line spectrum, have been eliminated in the blue spectrum. The remaining lower amplitude peaks in the controlled case correspond to impeller passage frequency. The results shown here correspond to an inter-microjet spacing of $25d_{jet}$ with the compressor operating at 28000 RPM. This impeller speed is of particular interest, since this speed is most similar to normal compressor operating conditions.

Flow control tests were also conducted at two other RPMs, using two different inter-microjet spacing: $25d_{jet}$, discussed above, and $12.5d_{jet}$. Results of these tests are summarized in Table 1. As seen here, microjets arrays with a $25d_{jet}$ spacing achieved an 11.5% extension of the compressor operating range, while microjets spaced 12.5 diameters apart improved the operating range by 13.9%. Compared to the original stall limit, the $25d_{jet}$ and $12.5d_{jet}$ spacing microjets showed improvements of 40.4% and 49.1%, respectively. Although a higher improvement was achieved using the closer jet spacing this does not necessarily translate to higher efficiency, when accounting for the cost of control. This is discussed in a subsequent section.

Finally, in Fig. 12 we depict the effect of microjet control on the surge limit at the three RPMs corresponding to Table 1. The cases shown here correspond to $25d_{jet}$ spacing only. The surge limit has now been moved to significantly lower mass flow rates with a concomitant increase in the pressure recovery through the diffuser. The pressure ratio between the diffuser inlet and exit is a pivotal measure of compressor performance and microjet control has significantly reduced the adverse impact due to rotating stall. As seen here, the improvement in the operating range and pressure ratio are more significant at higher impeller speeds, translating to greater improvements at normal operating conditions.

For cases where rotating stall is completely eliminated and the radial flow is completely attached due to microjet control, the velocity field contains no unusual features as noted in the discussion of the PIV results in Sect. 2.3. However, the

Table 1 Improvement in stall limit with microjets located 63.5 mm from diffuser center

Microjet spacing	Impeller RPM	Design flow rate (kg/min)	Original stall limit (kg/min)	Percent design flow rate (%)	New stall limit (kg/min)	Percent design flow rate (%)	Extension of operating range (%)	Improvement from original stall limit (%)
12.5 d_{jet}	20000	7.90	2.10	26.6	1.10	14.0	12.6	47.5
	25000	9.85	2.76	28.0	1.35	13.7	14.3	51.0
	28000	10.84	3.07	28.3	1.56	14.4	13.9	49.1
25 d_{jet}	20000	7.90	2.10	26.6	1.35	17.1	9.5	35.7
	25000	9.85	2.76	28.0	1.70	17.3	10.7	38.4
	28000	10.84	3.07	28.3	1.83	16.9	11.5	40.4

Fig. 12 Effects of control on surge limit and pressure ratio. Shown for impeller speeds of 20000, 25000 and 28000 RPM

Fig. 13 Time history showing reduction of large-scale pressure fluctuations with control. Impeller speed is 28000 RPM

Fig. 14 Elimination of stall cell under microjet control. **a** Stall cell before microjet initiation (same as Fig. 9), **b** stall cell moving outward in the diffuser as microjets take effect, **c** complete flow reattachment. Dashed line indicates stall boundary

progressive reduction in stall as the actuator control authority is gradually increased provides interesting insight. This is seen in the images shown in Fig. 14, which show a succession of high speed, instantaneous images acquired at 1280 Hz. The flow was seeded to enable visualization as microjet actuator flow was progressively increased. Starting from the leftmost image, the presence of stall cells very close to impeller exit is clearly seen—this corresponds to the stalled condition. Moving to the right, one can see the transient effect of actuation where the stall cells—visible as dark, unseeded regions, are progressively ‘pushed’ radially outward towards the diffuser exit. This culminates in the completely attached flowfield, seen in the last image on the right (Fig. 14c).

3.2.2 Parametric Effects

While the innermost actuator array proved to be most effective, the impact of the other three actuator arrays, located at 76.2, 88.9 and 99.7 mm (from the diffuser center), was also systematically examined. The second, 76.2 mm, row of microjets was significantly less effective in stall control. While the first array led to a significant improvement in the stall limit, stall occurred at the same mass flow rate with and without microjets for the second row. However, there was some beneficial impact at certain conditions in that pressure fluctuations were somewhat attenuated with microjet actuation. This can be seen in the pressure time history shown in Fig. 13. These results are shown for the $25d_{jet}$ spacing at 28000 RPM and 28.3% baseline mass flow rate, the original stall limit. Similar results were found at all blowing ratios and microjet spacings for this radial actuator. Furthermore, control effectiveness is reduced as impeller speed are increased. Finally, the last two microjet arrays located at 88.9 and 99.7 mm were completely ineffective in eliminating or reducing rotating stall cells. This is expected as the most effective control schemes require actuation

Table 2 Effective blowing ratios and microjet flow rates for microjets located 63.5 mm from diffuser center

Microjet spacing	Impeller RPM	Minimum blowing ratio for control	Microjet flow rate (kg/min)	Percent diffuser flow to supply microjets (%)
12.5 <i>d_{jet}</i>	20000	2.5	0.15	14.0
	25000	2	0.16	12.1
	28000	2	0.22	14.1
25 <i>d_{jet}</i>	20000	3	0.13	9.6
	25000	2.4	0.14	8.5
	28000	2	0.16	8.6

in the near vicinity of separation whereas these arrays are significantly downstream of where separation is first initiated in the diffuser.

When evaluating the effectiveness of a control strategy one must also consider the cost of control. In the present case, one of the most easily measured and commonly used ‘cost’ is the mass flow required through the microjet arrays. Similarly, in the context of the present application the relative extension of the stall limit is an appropriate measure of the benefit. The cost-benefit of this control scheme was characterized through parametric studies for the most effective actuator array. Here the blowing ratio was varied at each RPM and for two inter-microjet actuator spacings, the corresponding results are summarized in Table 2.

As the 28000 RPM condition is most relevant for this compressor in the context of its desired operating conditions, this case is highlighted in gray in Table 2. According to Table 1, the closer spacing of microjets improves the stall limit by 49% relative to the 25*d_{jet}* inter-microjet spacing which lead to a 40% improvement. However, the mass flow required for the 12.5*d_{jet}* spacing is considerably higher—14.1% than that for the larger spacing which require a mass flow of 8.6%. Unless the additional increase in the stall limit is critical, the array with the larger spacing is much more effective. The interaction of the CVPs generated by the JICF account for the difference in efficacy due to microjet spacing as discussed in Refs. [27, 33]. These results reaffirm the fact that efficient control requires an understanding of the underlying physical mechanisms and simply ‘more control’ or ill—conceived control is rarely effective.

4 Conclusion

In this paper we describe our study where we implement microjet-based active flow control to reduce, ideally eliminate, stall in the radial diffuser of a production compressor used for commercial HVAC systems. This research is part of the continuing

effort to translate microjet based control out of the laboratory to increasingly realistic and challenging applications. The results of the studies in canonical configurations were used to guide the design of the actuators for the present. In the present application, radial stall occurs in the diffuser at low load conditions where the reduced mass flow rate through the system leads to lower radial momentum which makes it susceptible to separation, i.e. stall, at certain RPMs. This can significantly limit the operational regime of such machines and delaying separation would result in efficiency gains.

Using a systematic approach, we first characterized the baseline, uncontrolled flowfield at unstalled and stalled conditions. Through steady and unsteady pressure as well as velocity field measurements the presence of two rotating stall cells was clearly identified, along with the extent of the separated flowfield and the conditions (RPM, mass flow rate) at which these occur. This was used to design and integrate a number of circular microjet arrays at various radial locations in the diffuser. The flow response to microjet actuation was examined over a range of compressors RPMs and diffuser mass flow rates where different actuator arrays were systematically activated over various blowing ratios. The array closest to the initiation of stall cells was found to be most effective in reattaching the flow, as somewhat anticipated based on our prior studies of separation control. Control of the modified compressor led to a very significant increase in the stall margin, reducing the minimum operational mass flow rate to 14% of the design flow rate. This is nearly half of the original 28% flow rate at which stall occurs before microjet control is implemented. This study clearly demonstrates the potential efficacy of this relatively simple and robust control strategy in a real-world application. The results showed that the parameters found be most effective in the simple configurations proved to be near-optimal for the present surge control application in a much more complex geometry. This provides us confidence that the lessons learned from prior studies can be extended to other applications. The next step in further evaluating this control strategy is to implement it in a closed compressor system using the actual working fluid used therein, R-134a.

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References

1. Storms, B.L., Ross, J.C.: Experimental study of lift-enhancing tabs on a two-element airfoil. *J. Aircr.* **32**(5), 1072–1078 (1995)
2. Lin, J.C.: Review of research on low-profile vortex generators to control boundary-layer separation. *Prog. Aerosp. Sci.* **38**(4–5), 389–420 (2002)
3. Zaman, K.B.M.Q., Bar-Sever, A., Mangalam, S.M.: Effect of acoustic excitation on the flow over a low-Re airfoil. *J. Fluid Mech.* **182**, 127–148 (1987). <https://doi.org/10.1017/S0022112087002271>

4. Ahuja, K.K., Whipkey, R.R., Jones, G.S.: Control of turbulent boundary layer flows by sound. In: AIAA Paper 1983, p. 726 (1983)
5. Amitay, M., Pitt, D., Glezer, A.: Separation control in duct flows. *J. Aircr.* **39**(4), 616–620 (2002). <https://doi.org/10.2514/2.2973>
6. Glezer, A., Amitay, M.: Synthetic jets. *Annu. Rev. Fluid Mech.* **34**, 503–29 (2002)
7. Smith, B.L., Swift, G.W.: A comparison between synthetic jets and continuous jets. *Exp. Fluids* **34**(4), 467–472 (2003)
8. Raju, R., Mittal, R., Cattafesta, L.: Towards physics based strategies for separation control over an airfoil using synthetic jets. In: AIAA Paper 2007, p. 1421 (2007)
9. Raju, R., Aram, E., Mittal, R., Cattafesta, L.: Simple models of zero-net mass-flux jets for flow control simulations. *Int. J. Flow Control* **1**, 179–97 (2009)
10. Corke, T.C., Enloe, C.L., Wilkinson, S.P.: Dielectric barrier discharge plasma actuators for flow control. *Annu. Rev. Fluid Mech.* **42**, 505–29 (2010)
11. Samimy, M., Adamovich, L., Webb, B., Kastner, J., Hileman, J., et al.: Development and characterization of plasma actuators for high-speed jet control. *Exp. Fluids* **37**, 577–88 (2004)
12. Samimy, M., Kim, J.H., Kastner, J., Adamovich, I., Utkin, Y.: Active control of high-speed and high-Reynolds number jets using plasma actuators. *J. Fluid Mech.* **578**, 305–30 (2007)
13. Popkin, S.H., Cybyk, B.Z., Foster, C.H., Alvi, F.S.: Experimental estimation of SparkJet efficiency. *AIAA J.*, 1831–1845 (2016)
14. Narayanaswamy, V., Raja, L.L., Clemens, N.T.: Characterization of a high-frequency pulsed-plasma jet actuator for supersonic flow control. *AIAA J.* **48**, 297–305 (2010)
15. Cybyk, B., Grossman, K., Wilkerson, J.: Performance characteristics of the Sparkjet flow control actuator. In: 2nd Conference AIAA Flow Control, AIAA paper 2004, p. 2131, Portland (2004)
16. Cattafesta, L.N., Sheplak, M.: Actuators for active flow control. *Annu. Rev. Fluid Mech.* **43**, 247–72 (2011)
17. Zhuang, N., Alvi, F.S., Alkislar, B., Shih, C.: Supersonic cavity flows and their control. *AIAA J.* **44**(9), 2118–2128 (2006)
18. Zhuang, N., Alvi, F.S., Shih, C.: Another look at supersonic cavity flows and their control. In: AIAA 2005, p. 2803 (2005)
19. Bower, W.W., Kibens, V., Cary, A.W., Alvi, F.S., Raman, G., Annaswamy, A., Malmuth, N.: High-frequency excitation active flow control for high-speed weapon release (HIFEX). In: AIAA Paper 2004, p. 2513 (2004)
20. Alvi, F.S., Shih, C., Elavarasan, R., Garg, G., Krothapalli, K.: Control of supersonic impinging jet flows using supersonic microjets. *AIAA J.* **41**(7) (2003)
21. Alkislar, M.B., Krothapalli, A., Butler, G.W.: The effect of streamwise vortices on the aeroacoustics of a Mach 0.9 jet. *J. Fluid Mech.* **578**, 139–169 (2007)
22. Upadhyay, P., Gustavsson, J.P., Alvi, F.S.: Development and characterization of high frequency resonance enhanced microjet actuators for control of high speed jets. *Exp. Fluids* **57**(5), 1–16 (2016)
23. Lou, H., Alvi, F.S., Shih, C.: Active and passive control of supersonic impinging jets. *AIAA J.* **44**(1), 58–66 (2006)
24. Alvi, F.S., Lou, H., Shih, C., Kumar, R.: Experimental study of physical mechanisms in the control of supersonic impinging jets using microjets. *J. Fluid Mech.* **613**, 55–83 (2008)
25. Kumar, V., Alvi, F.S.: Towards understanding and optimizing separation control using micro-jets. *AIAA J.* **47**(11), 2544–2557 (2009)
26. Ali, M.Y., Alvi, F.S.: Jet arrays in supersonic crossflow—an experimental study. *Phys. Fluids* **27**(12) (2015). <https://doi.org/10.1063/1.4937349>
27. Fernandez, E., Alvi, F.S.: Vorticity Dynamics of Microjet Arrays for Active Control. AIAA Science and Technology Forum and Exposition, Maryland (2014)
28. Kreth, P., Alvi, F.S.: Microjet-based active flow control on a fixed wing UAV. *J. Flow Control Meas. Vis.* **2**(2) (2014)
29. Fernandez, E., Kumar, R., Alvi, F.S.: Separation control on a low-pressure turbine blade using microjets. *J. Propul. Power* **29**(4), 867–881 (2013)

30. Ljevar, S., De Lange, H.C., Van Steenhoven, A.A.: Two-dimensional rotating stall analysis in a wide vaneless diffuser. *Int. J. Rotating Mach.* **2006**, 1–11 (2006)
31. Kurokawa, J., Saha, S.L., Matsui, J., Kitahora, T.: Passive control of rotating stall in a parallel-wall vaneless diffuser by radial grooves. *J. Fluids Eng.* **122**(1), 90–96 (2000)
32. Tsurusaki, H., Kinoshita, T.: Flow control of rotating stall in a radial vaneless diffuser. *J. Fluids Eng.* **123**(2), 281–286 (2001)
33. Fernandez, E.: On the properties and mechanisms of microjet arrays in crossflow for the control of flow separation. Ph.D. Dissertation, Florida State University (2014)