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Active Control of Rotating Stall in a Low-Speed Centrifugal Compressor

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This paper addresses rotating stall control in centrifugal compressors, presenting the results of an experiment directed at the suppression of stall in the Purdue Low-Speed Centrifugal Research Compressor. The control technique uses a phase-controlled inlet distortion generated by an array of 12 air-injection ports located in the compressor inlet endwall. The active control of first-mode (one-cell) rotating stall was successfully demonstrated. In the cases investigated, the stall control system provided only slight increases in stall margin. However, the control system demonstrated an ability to restore system stability to the compressor when exhibiting a developed stall condition.

Introduction

GAS-turbine engines have made dramatic strides in performance and efficiency since their first appearance almost 40 years ago. Throughout this period, however, the persistent apparition of compression system instability has plagued gas-turbine designers. The region where these instabilities are encountered is demarcated on the compressor performance map by a boundary, referred to as the surge line, which separates the regions of stable and unstable operation. Current generation turbomachines must allow for a safety margin, known as the surge margin, which places the operating point in a region far enough removed from the surge line so as to prevent the onset of instability.

The term, surge line, is somewhat misleading because surge is only one of two possible phenomena that can occur when this boundary is reached. In turbomachinery compressors, the types of instabilities found can be categorized as rotating stall or surge. Surge refers to a global oscillation of the mass flow through the compression system, often with complete flow reversal occurring. Surge is regarded as a phenomenon of the entire compression system, consisting of the compressor and system into which it discharges. Rotating stall, in contrast, is an instability local to the compressor itself, and is characterized by a circumferentially nonuniform mass deficit that propagates around the compressor annulus at a fraction of wheel speed.

The disadvantages of bringing a compressor into a stall or surge condition are twofold. First, compressor performance falls drastically when instability is encountered. On flight-rated turbine engines, such a performance degradation in the compressor can lead to a loss of engine thrust and to component overheating through a reduction of engine cooling air and improper fuel scheduling. Second, rotating stall and surge can represent dangerous unsteady aerodynamic excitations to compressor blading. For these reasons, efforts to increase the stable operating range of compressors is an area of vigorous research activity.

The cost of producing an experimental build of a compressor before the stalling behavior can be accurately determined has been a strong motivational factor in the movement for the active control of compressor instabilities. As postulated by Epstein et al.,[1] a compressor equipped with a device that would suppress instabilities in their weak initial stages would allow operation on a previously unreachable region of the compressor performance map. With control models tailored to the behavior of an entire class of turbocompressors, such a system could conceivably relax the requirements imposed on the designer to supply adequate surge margin. In addition, such a system would allow the researcher the ability to explore compressor performance in the near-stall region while still safely operating the compressor.

Research on active suppression of compressor instabilities has focused on both surge and rotating stall. Significant progress was made on surge suppression in centrifugal compressors by researchers such as Pinsley et al.,[2] and Ffowcs Williams and Graham.[3] These control systems attacked the essentially one-dimensional phenomenon by developing actuators that provided additional system damping when the surge condition was encountered.

The control of rotating stall has also been of interest to researchers. The two-dimensional nature of the disturbance (circumferential and time variance) presents more challenges than that posed by surge. Recent investigations into rotating stall initiation in axial compressors revealed two apparent types of disturbances that precursor the stall condition. Short-length scale disturbances dominated the stalling behavior observed by Day[4] in a low-speed axial compressor. In this case, the stalling process appeared to be related to the growth of a finite separation zone that began on a small portion of the compressor annulus. In contrast, McDougall et al.[5] and Garnier et al.[6] provide evidence of the development of rotating stall as the culmination of a process that begins with selective amplification of initially weak spatial harmonic waves in the compression system.

Based on the information garnered from the stall initiation studies, active control systems for rotating stall suppression have been demonstrated for axial compressors. Day[7] implemented a control system that was successful in manipulating both short- and long-length scale disturbances, and was able to significantly extend the range of a low-speed compressor. Paduano et al.[8] reported success with a control system based on the detection and suppression of long-length scale spatial harmonic waves.

Rotating stall behavior is also encountered in centrifugal compressors, albeit with a much wider variety of stall cell numbers, speeds, and strengths than in axial machines.[9–11] It is commonly the dominant instability in low-pressure ratio centrifugal compressors and in high-pressure ratio compressors when operated at part speed. In addition, rotating stall may be

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an important mechanism in triggering surge in the full-speed operation of high-pressure ratio centrifugal compressors, as has been observed in axial compressors.

The aforementioned variety of rotating stall conditions in centrifugal compressors is one reason why the initiation process is less well understood than that for axial compressors. An analysis by Moore[12] suggested that the weak spatial waves seen to precursor rotating stall in axial compressors may also play a role in the initiation of rotating stall in centrifugal machines. Experiments conducted by the authors on a low-speed centrifugal compressor[10,11] have shown that the stalling process in that facility is characterized by an initially weak, spatially coherent pattern that develops over a finite period of time into a rotating stall condition.

The feasibility of implementing a rotating stall control system on a low-speed centrifugal compressor was previously evaluated by the authors.[13,14] The models developed for this purpose were again based on the assumption that rotating stall in a centrifugal compressor can be modeled as a weak disturbance that grows in a region of preferential amplification on the performance map. The proposed control scheme involved the introduction of a weak inlet distortion that was phased to adjust system stability and damp out the stall condition before reaching significant amplitude. However, there have been no experimental studies of active control of rotating stall in centrifugal compressors and, thus, no validation of the conclusions drawn from the model.

This paper addresses rotating stall control in centrifugal compressors, presenting the results of an experiment directed at investigating and validating the centrifugal compressor rotating stall control modeling and, thus, the conclusions drawn from the mathematical model. This was done in the Purdue Low-Speed Centrifugal Research Compressor (PLCRC), with the experiments based on the information gained from the experimental investigation into the stalling behavior of this compressor, specifically the single-cell rotating stall condition. This choice of the one-cell stall condition not only enables the fundamental flow physics to be addressed, but also fulfills two basic concerns. First, the ability to effectively introduce a control wave is dependent on controller and actuator bandwidth. The one-cell stall is the lowest frequency condition encountered in the compressor, and therefore, provides the least risk for achieving acceptable controller bandwidth. Second, the one-cell stall condition plays a strong role in the stalling behavior of all compressor configurations tested and, therefore, is of interest in further investigations of stall initiation.

Experimental Facility and Instrumentation

PLCRC

The PLCRC features a shrouded, mixed-flow impeller with 23 backswept blades, and a diffuser that may be configured with up to 30 cambered vanes. The compressor is driven by a 29.8 kW (40 hp) induction motor. The nominal operating speed for the impeller is 1790 rpm, giving an impeller pass frequency of 29.8 Hz and a blade pass frequency of 686.2 Hz. As shown in Fig. 1, the compressor discharges into an exit plenum and the flow is then discharged through an exit duct and throttle valve.

The flow path through the compressor is presented in Fig. 2. Flow enters the compressor axially, passes through the impeller, enters into a curved vaneless space, and then exits into a parallel-walled vaned radial diffuser. These cambered diffuser vanes have a chord length of 16.5 cm (6.5 in.) and feature a NACA 4312 airfoil profile. The vanes can be adjusted for stagger angle. For these experiments, the vanes were set at 50 or 70 deg stagger. The vaned section of the diffuser discharges into a vaneless, parallel-walled section that in turn empties into the collection plenum.

Instrumentation

Two impeller blades were instrumented with PCB103A miniature microphones located on the pressure and suction sides of the blading. The transducers were located at midspan and 4.9, 58.2, and 95% meridional chord. These locations will henceforth be identified as leading edge, midchord, and trailing edge.

The PLCRC facility is also instrumented with an array of electret microphones connected to the flow by means of static pressure taps located on the o.d. endwall of the inlet section of the compressor. Eight microphones are distributed uni-

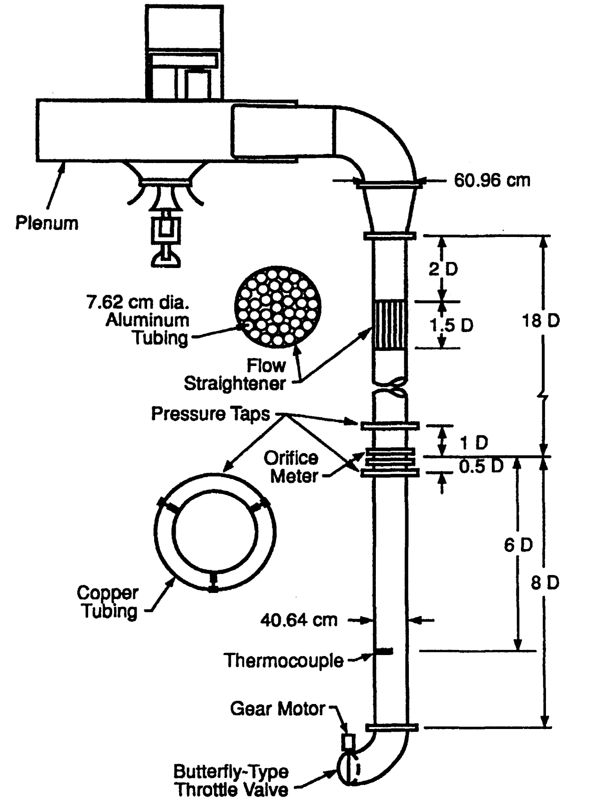

Fig. 1 Top view of compressor facility showing discharge ducting.

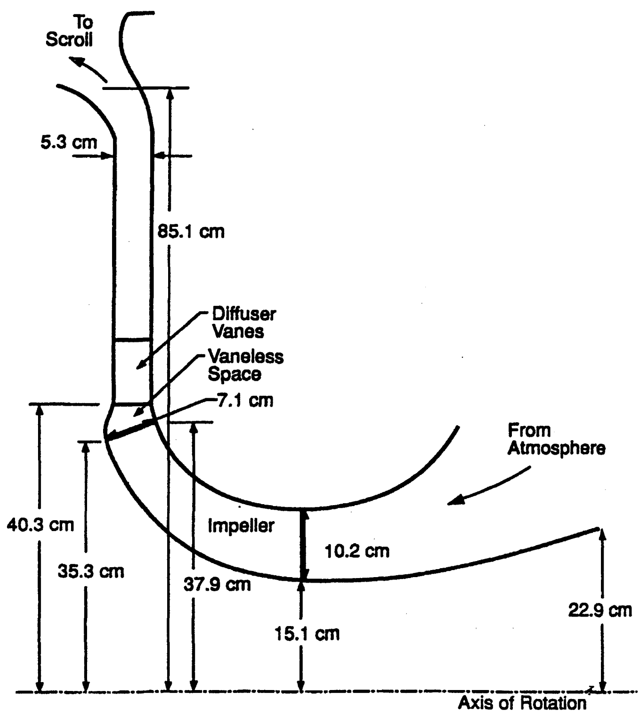

Fig. 2 Compressor flow path schematic.

formly around the inlet circumference 1.8 cm (0.7 in.) in front of the tip of the impeller leading edge. These microphones are used as detectors to characterize the eruption of stall disturbances in the compressor. To prevent the high-frequency signals from rotor blade passage and the flow noise from dominating the low-frequency signals of interest, a short attenuator tube is installed between the microphones and the static taps in the compressor endwall. The detailed characteristics of these microphones are given in Ref. 10.

The quasisteady performance of the machine is characterized by monitoring the compressor mass throughflow and scroll pressure. The scroll pressure is monitored with a Scanivalve pressure transducer. As characterization of the performance during rotating stall and surge is not intended, it is sufficient to guarantee that the throttle closure rate was kept to a value sufficiently low so that the frequency response of these transducers was not exceeded. The transient mass flow measurements were made with a hot-film sensor located in the exit pipe and calibrated against a sharp-edged orifice meter.

Controlled Distortion Generation

An array of 24 fast-acting solenoid control valves was employed to introduce a jet of air into the o.d. endwall of the compressor inlet. The valves were used in pairs to deliver air from a distribution plenum regulated to a nominal gauge pressure of 620 kPa (90 psig) to 12 air-injection ports of 4.8 mm (3/16 in.) diameter located around the compressor circumference. As shown in Fig. 3, the ports inject air at an angle of 30 deg from the horizontal. The solenoid valves are of the miniature type, with a significant total pressure loss between the supply plenum and the air-injection ports. During the control experiments, the microphone array was located just upstream of this inlet section, as shown in Fig. 3. For waveform interrogation experiments, the microphones were mounted just upstream of the injection section.

Two air valves are actuated at any given time in the inlet. Under steady air injection, the mass flow addition to the compressor was found to be less than four-tenths of 1% of the mass flow through the compressor just prior to stall. In the control application, the valves were operated in a pulsed manner and the net mass flow addition would be substantially less than this value.

The control system consisted of a Macintosh Quadra 950 microcomputer configured with two National Instruments NB-A2000 boards providing eight channels of simultaneous sampling A/D conversion. In addition, the computer was configured with a National Instruments NB-DMA2800 direct memory access board and a National Instruments NB-DIO-32F digital I/O board. The control valves were actuated with solid-state relays activated by the logic state of a 12-bit word output from the digital I/O board. The 12 air-injection jets were divided into six groups of two ports each, effectively dividing the compressor annulus into 60-deg sectors. This arrangement for propagating the control wave in 60-deg increments was chosen based on a favorable *phase window* predicted from the mathematical model[14] and the requirement to minimize cycle frequency for the control valves.

The control variable for the system was the first spatial mode of the endwall static pressure detected by the inlet microphone array. To improve the signal-to-noise ratio, the microphones' signals were processed with analog biquad active amplifying filters. The filters were designed with a bandwidth of 10 Hz (based on a 3 dB cutoff) centered around the 24 Hz frequency expected for one-cell rotating stall. Because real-time scaling of the microphone signals would needlessly tax the control system, the filter gain was adjusted to match each microphones' response to a 24-Hz test pressure wave.

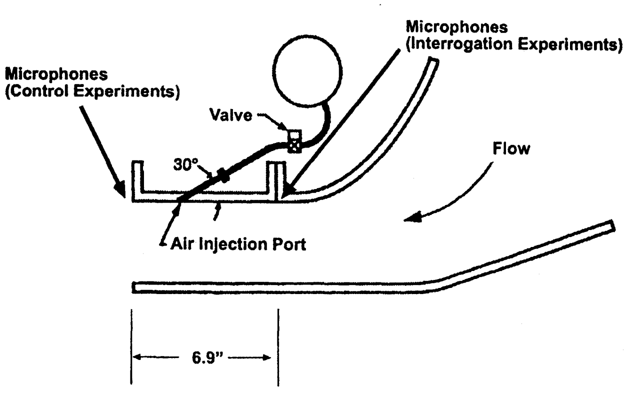

Fig. 3 Extended compressor inlet showing air-injection ports and microphone locations.

Control Implementation

The control algorithm was based on a spatial Fourier transform of the signals from the filtered inlet microphone arrays in conjunction with the analog filters for each microphone channel. Continuous data acquisition of the inlet microphones at a sampling frequency of 5000 Hz was accomplished in the background. The most recent samples were fetched by the main processor of the Quadra 950 as required. The phase information from the spatial Fourier transform of the signal from the inlet microphones, with a specified control phase shift, was then employed to actuate the appropriate inlet control valves. The control phase shift that achieved optimum stability improvement was determined by trial and error.

To properly address the eruption of a stall event in the compressor, the controller must have sufficient bandwidth to identify the precursor wave and introduce the correcting waveform before the condition in the compressor inlet has changed substantially. The computer code that performs the aforementioned control routine cycles at approximately 180 Hz, which is sufficient to deal with the first-mode disturbances encountered in this compressor at 23–26 Hz.

Data Acquisition and Analysis

Data acquisition was accomplished by employing a separate Macintosh Quadra 950 computer equipped with three National Instruments NB-A2000 boards, providing 12 channels of simultaneous sampling A/D conversion. This allowed raw microphone signals as well as performance data to be acquired independently of the computer implementing the control.

Analysis techniques employed on the signals from the inlet microphone array were identical to that described for the stall initiation characterization described by Lawless and Fleeter.[10] Data from the microphones were numerically bandpass filtered using Butterworth filtering algorithms. After filtering, the signals for each microphone were scaled by the appropriate gain value and then processed with the spatial Fourier transform.

Results

Control Waveform Characterization

To evaluate the nature of the waveform created by the air-injection jets, a series of experiments were performed to determine the effect of the air injection on the compressor running at a stable operating point. The first experiments employed the inlet microphone array and the compressor configured with 30 diffuser vanes at 70-deg stagger. This build was chosen because multiple spatial modes play a role in stall initiation and, thus, allowed interrogation of several system resonances with the control jets. These experiments consisted of using the air-injection jets to propagate a circumferential distortion around the compressor annulus while monitoring the inlet microphone array. The waveform was propagated at frequencies from impeller speed (30 Hz) to a frequency below the expected stall pattern propagation speed. At a given frequency, the waveform was allowed to propagate for period of

10–20 revolutions before stepping to the next frequency value. Spatial modes of one to three were investigated. For these experiments, the inlet microphone array was located upstream of the inlet extension that housed the air-injection system. The microphones were therefore situated to monitor static pressure perturbations propagating upstream of the jets. Because of the low level of the signal produced prior to reaching the stall point of the compressor, the signals were ensemble-averaged over 200 revolutions, with the averaging phase locked to the disturbance waveform.

Figure 4 presents results from a frequency sweep of a first spatial mode wave in the compressor inlet at two flow coefficients approaching the stall point of the compressor. At f = 0.40, in the top frame of the figure, only slight excitation (less than 1 Pa) of the compressor modes is evident, with little change in the mode magnitude as the wave propagation frequency is changed. In the bottom frame of Fig. 4 the flow coefficient is reduced to f = 0.37, and a dramatic change in the mode magnitude can be seen. The first-mode magnitude peaks at a frequency of 24 Hz, which corresponds to the propagation frequency of the eventual one-cell stall pattern. This indicates that the control wave is beginning to excite the natural frequency of the compression system. Similar behavior was observed for spatial modes of two and three, with the peak excitation occurring at a value of 28 and 29 Hz, respectively. Again, these propagation frequencies are identical to those observed during the stall initiation studies performed on the PLCRC.

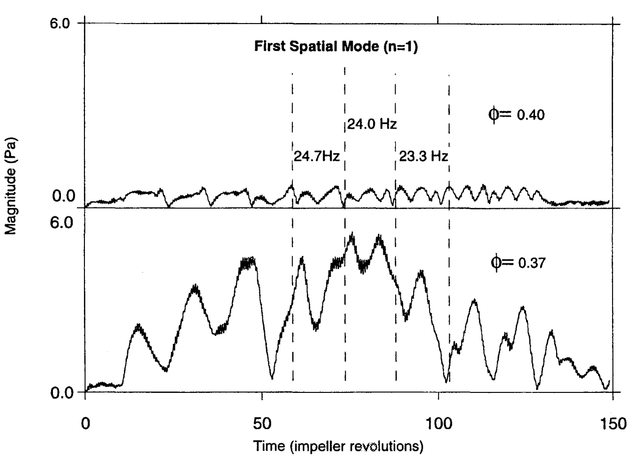

Fig. 4 Compressor response to the introduction of a first spatial mode wave.

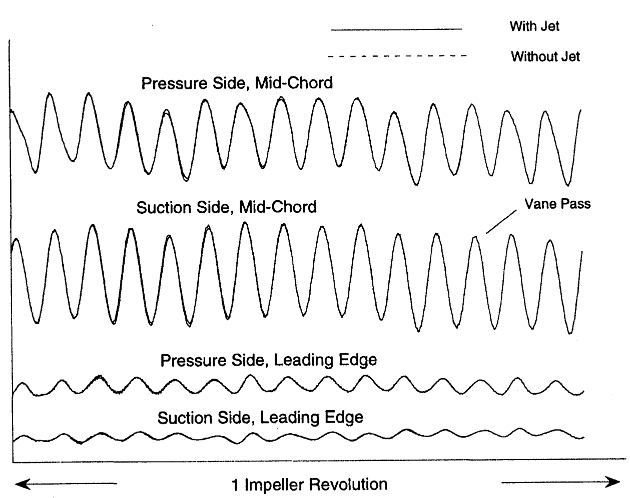

Fig. 5 Two-hundred revolution ensemble-average on-impeller pressure signals at a stable flow coefficient.

A second set of experiments was performed when the compressor was running at an open throttle condition using the on-impeller microphones. The goal was to determine what effect steady blowing from a single pair of air jets would have on the impeller unsteady loading when the compressor was operating at a point well-removed from the surge line. Figure 5 presents an overlay of the signal traces of a 200-revolution ensemble-average of the impeller microphones with and without a single pair of air jets activated in the inlet. The oscillations in the trace represent the potential effects resulting from the downstream diffuser vanes. There is no discernible effect of the jets on the blade unsteady surface pressures, as both traces appear as one.

The weak response indicated by the endwall and on-impeller microphones when the compressor is operated away from the stalling point, or at frequencies different from those near resonance, indicates that the potential effects of the control jets are minimal. Of particular interest is the fact that the air jets were able to excite the spatial modes of the compressor prior to stall at the same propagation velocities as those seen in the developed stall conditions.

Compressor Stalling Behavior

The inlet microphone array was employed to characterize the stalling behavior of the PLCRC. The analysis techniques employed on the signals from the inlet microphone array were identical to that described for the stall initiation characterization described in detail by Lawless and Fleeter.[10] Data from the microphones were numerically bandpass filtered using Butterworth filtering algorithms. After filtering, the signals for each microphone were scaled by the appropriate gain value and then processed with a spatial Fourier transform. The results of this transform separates the signal into spatial Fourier components, known as spatial modes. These spatial modes are the spatial-domain equivalent of the harmonics obtained from a temporal-domain transform, the mode number representing the number of disturbance wavelengths around the machine circumference. Hence, the fundamental mode for a one-cell stall condition will be the first mode, and that for a two-cell stall condition is the second mode.

Effect of Active Control

The control system was evaluated on the compressor with 15 diffuser vanes at 70-deg stagger. For these studies, the microphone array was placed upstream of the air-injection jets. Without control, this case exhibited a strong one-cell rotating stall excitation. To observe the effect of suppressing the first spatial mode event, the control system was employed while the compressor was throttled down to a stall condition.

The results presented in Figs. 6 and 7 show the rise of the first and third spatial modes, representing the eruption of one-

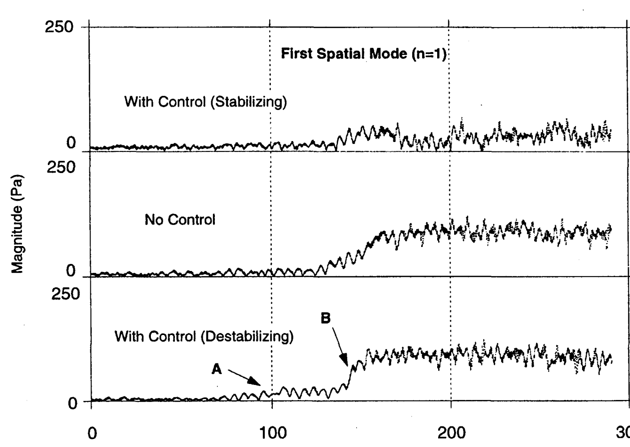

Fig. 6 Effect of control wave on the rise of the first spatial mode.

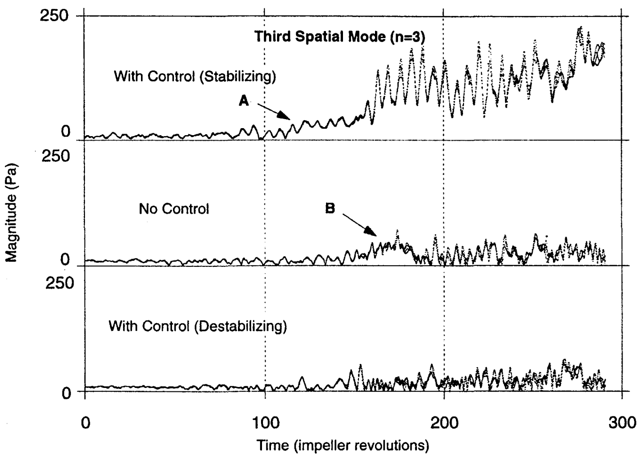

Fig. 7 Effect of control wave on the rise of the third spatial mode.

and three-cell stall patterns, as the compressor is throttled down. A second mode, or two-cell stall pattern, was not observed to play a significant role in this study. In these figures, data acquisition was accomplished by triggering the filtered signal from an inlet microphone. The trigger level was set to detect the onset of the stall condition and 150 revolutions of data were recorded before and after the trigger occurred. The results compare control waves introduced at stabilizing and destabilizing phase angles for the first spatial mode with the case when the control system is not activated.

The rise of the first spatial mode magnitude is shown in Fig. 6. The top frame shows the results of implementing the control wave at a phase difference that was experimentally determined to be optimum for the controller. As seen by comparison with the case where no control is used (shown in the middle frame), the control system suppressed the eruption of the first spatial mode and holds this mode to a level substantially reduced from that occurring with the natural stall process. The bottom frame presents data for the case when the control wave phase was changed by 180 deg, resulting in destabilization of the compressor. Premature rise of the first spatial mode magnitude is apparent as early as Point A in the figure, with a much sharper rise in the mode magnitude shown at Point B.

Figure 7 presents dramatic results for the rise of the third spatial mode magnitude. As shown in the top frame, the suppression of the first spatial mode results in a third-mode (three-cell) eruption at Point A, which grows rapidly and achieves a level exceeding that of the first-mode stall when no control is implemented. With no control, the third spatial mode shows only limited excitation (Point B) that occurs after the compressor has entered a finite one-cell stall condition. With destabilizing control, the third-mode activity is further suppressed as the rise of the first spatial mode is reinforced by the control wave.

The quasisteady pressure rise of the compressor for the three cases discussed in the previous text is presented in Fig. 8. The bottom three traces represent the data as recorded during the throttle down. Smooth-curve fits to these data are shown at the top of this figure, and demonstrate that the performance characteristics are quite similar up to the point where the stall begins (indicated by the vertical line). Note that in the stabilizing control case, a surge behavior occurs when one-cell stall is suppressed. This condition does not erupt in the uncontrolled case, and is specific to the suppression of the one-cell stall. Note that three-cell stall is also present during the instability initiation. However, because of the high frequency of the three-cell stall event, this portion of the signal is severely attenuated compared with the 5-Hz surge oscillation.

Recovery from Fully Developed Stall

To demonstrate that the control system was able to achieve recovery from a developed stall condition, the compressor vanes were restaggered to 50 deg. In this configuration, the three-cell stall and surge events observed previously are absent, and the control was able to achieve range extension without the eruption of higher-order modes. In this build, the control system demonstrated a capability to restore system stability at flow coefficients close to the normal stalling point of the compressor. Additional throttling of the compressor, however, placed the compressor in a region of operation where the control authority was insufficient to stabilize the system, and one-cell stall would again erupt.

Recovery of the compressor from a one-cell rotating stall condition was characterized by the on-impeller microphones, with results presented in Figs. 9 and 10 for the suction and pressure surfaces, respectively. These figures show the microphone traces that have been low-pass filtered to remove the effects of vane-pass. The bottom of each figure shows a trace of the first-mode magnitude as determined with the fixed inlet microphone array. The magnitude of the pressure oscillations because of the stall was greatest at the midchord location. As the control system was activated, a gradual decay of the stall magnitude occurred over a span of approximately 30 revolutions.

Range Extension

The control system exhibited a limited ability to extend the stable operating range of the compressor. In determining true range extension, a repeatable means of determining the stall

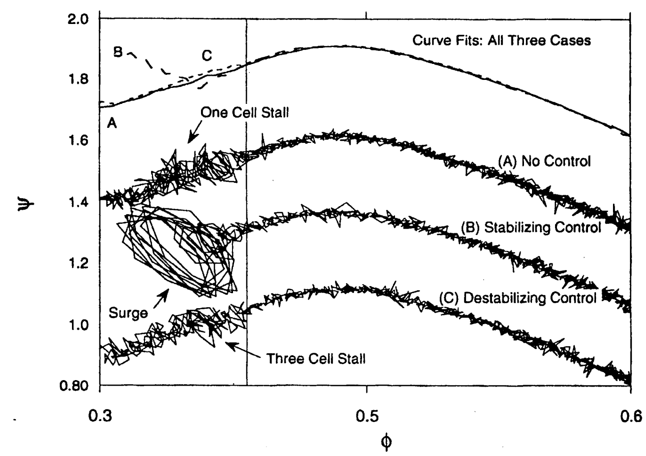

Fig. 8 Characteristics for the control, no control, and destabilizing control cases.

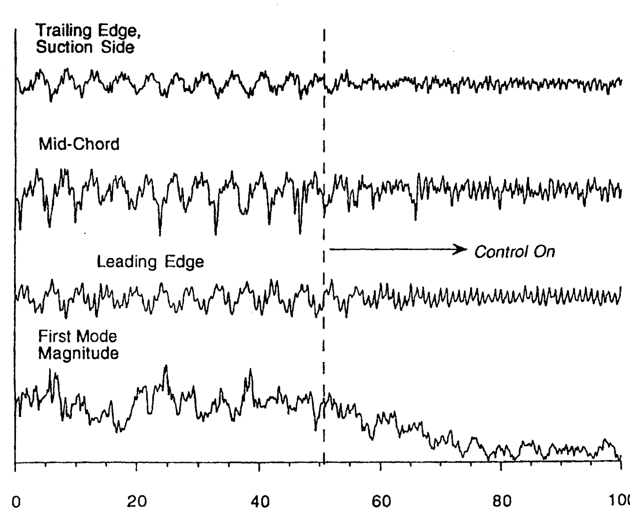

Fig. 9 Effect of control wave on stable rotating stall, suction side.

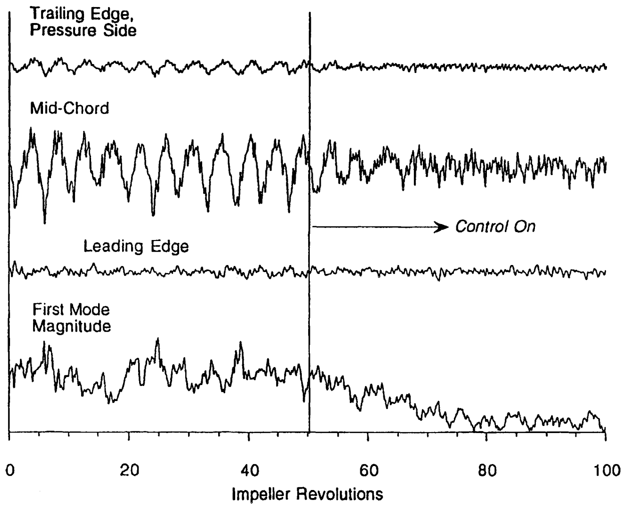

Fig. 10 Effect of control wave on stable rotating stall, pressure side.

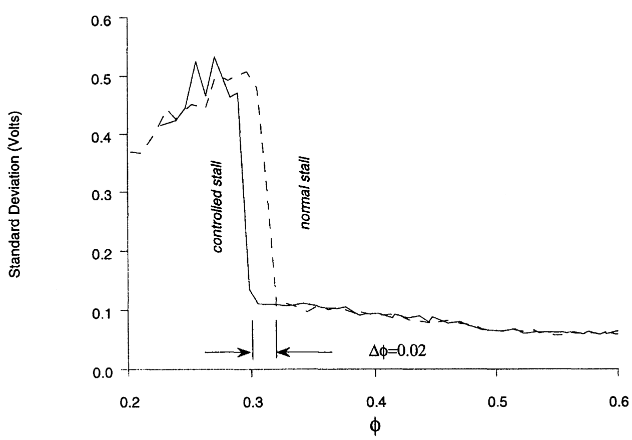

Fig. 11 Standard deviation of inlet microphone signals.

point was required. With the compressor vanes configured to achieve a single-cell stall pathology (15 vanes, 50-deg stagger), this was achieved by calculation of the standard deviation of 500 sample running averages from the signal trace of a single inlet microphone. As stall was characterized by an increase in the low-frequency unsteadiness in the flow, the rise in the signal standard deviation provided a repeatable indication of the stall point. The results are shown in Fig. 11, where a shift in stalling flow coefficient of approximately 6% was observed. The range extension for the 70-deg vane stagger build showed significantly less improvement in operating range. Rather, the control system primarily served to transform the compressor from a one- to a three-cell stall.

Summary and Conclusions

The active control of first-mode rotating stall has been successfully demonstrated for a low-speed centrifugal compressor. The stall control was implemented by introducing a phased inlet distortion into the compressor. This distortion was introduced by an array of 12 air-injection ports located in the compressor endwall.

The control system was not only able to suppress the eruption of the first mode in the compressor during stall initiation, but was also capable of bringing the compressor out of a fully developed rotating stall. The controller was also capable of destabilizing the compressor and accelerating the eruption of the first spatial mode.

With the compressor diffuser vanes set to 70 deg of stagger, the successful suppression of the first spatial mode resulted in the development of a higher-order stall condition, and the range extension was minimal. Better range extension was achieved when a diffuser build that exhibited no higher-order modes was employed; however, the increases in stall margin was still small. The maximum change in stalled flow coefficient achieved was approximately 6%.

The use of the air-injection jets to control rotating stall brings up the obvious question as to whether the control was addressing large- or small-length scale disturbances. The evidence presented here demonstrates that the air jets are effective when introducing a circumferential flow distortion into the compressor inlet annulus at a frequency near or at the stall frequency. The increased response at these frequencies is also demonstrated at flow coefficients near the stalling point of the compressor but with the compressor still clearly exhibiting stable operation. The amplitude of these excited modes increased as the stall point was approached. This supports the system view of stall initiation as a gradual reduction in system damping as the flow coefficient is reduced. Finally, the phase sensitivity of the controller suggests that the control is acting on a circumferential scale, rather than that of the impeller blade spacing. If the stabilizing behavior were attributed to a local effect, such as the elimination of a local separation zone, the destabilizing behavior demonstrated when the control phasing was changed would not be expected.

In conclusion, the practical application of control systems such as that demonstrated here requires further study into the control of multiple spatial modes, increasing control authority, and application to high-speed machines. However, even in the limited context presented here, such control systems are useful tools in investigations into the physical nature of stall phenomena.

Acknowledgments

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