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A CHARACTERIZATION OF ROTATING STALL BEHAVIORS IN HIGH AND LOW SPEED CENTRIFUGAL COMPRESSORS

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ABSTRACT

The characterization of the instabilities of two centrifugal compressors, one low speed and one high speed, which exhibit the type of flow instabilities typical of most industrial compressors is described. The low speed compressor exhibits a stable rotating stall that initiates from a separation region located near the impeller blade midchord. In the high-speed compressor, two spatially coherent disturbances are observed prior to surge initiation. These are shown to be consistent with a 9 mode and a 1 mode rotating stall located at or near the diffuser.

INTRODUCTION

On the performance map of a compression system, the operating range is bounded by the surge and choke lines. The barrier posed by the surge line is of particular interest due to its proximity to the maximum efficiency points of the compressor. At operating points beyond the surge line, flow instabilities such as surge and/or rotating stall dominate the compressor behavior. These unstable operating conditions represent dangerous unsteady aerodynamic excitations to impeller and diffuser vanes, as discussed by Haupt et al. [1] and Jin et al. [2,3]. Because of this, much research activity has been directed at developing an understanding of compressor instabilities and the development of techniques to extend stable operating range. To date, this effort has largely focussed on axial compression systems, including the work of Day [4], McDougall et al. [5] and Garnier et al. [6]. In these, rotating stall has been determined to play a significant roll in surge initiation.

In centrifugal compressors, the instability pathologies are more complex, and the role of rotating stall in surge initiation less well understood. Rotating disturbances in centrifugal compressors have been described by terms such as inducer stall, impeller stall, diffuser stall, fast and slow stall, progressive stall, and abrupt stall. These terms are based on the observed origin, speed, growth, or the location of maximum disturbance amplitude. However, a detailed understanding of the stalled flow field is still far from being accomplished. And yet, if success in rotating stall and surge detection and suppression is to be achieved, an understanding of the mechanism of the initiation process is crucial. Toward this end, this paper describes experiments directed at characterizing the instability pathologies of centrifugal compression systems. The goal of these experiments is to determine the nature of rotating stall behavior exhibited across different classes of radial flow turbomachinery and to determine the role rotating stall plays in surge initiation in high speed centrifugal compressors. These investigations are performed in the Purdue Low Speed Centrifugal Research Compressor (PLCRC) and the Purdue High Speed Centrifugal Research Compressor (PHCRC).

FACILITIES

Purdue Low Speed Centrifugal Research Compressor

The Purdue Low Speed Centrifugal Research Compressor (PLCRC), Figure 1, features a shrouded mixed flow impeller with 23 backswept blades and a variable geometry 15-vane diffuser. The nominal operating speed for the impeller is 1,790 rpm, the impeller diameter is 75.8 cm, resulting in a tip speed of 68.6 m/s. The design pressure ratio is 1.02 and flow rate is 2.4 kg/sec. Lawless and Fleeter [7] provide a detailed description of this facility. The dominant instability exhibited in this machine is rotating stall, typical for low tip speed centrifugal compressors.

Purdue High Speed Centrifugal Research Compressor

The Purdue High Speed Centrifugal Research Compressor (PHCRC), Figure 2, features a titanium impeller with 15 blades, 15 splitter blades, and a 22-vane diffuser. The impeller has a nominal operating speed of 48,450 rpm, and a diameter of 21.6 cm, resulting in a tip speed of 334 m/s. The maximum pressure ratio is 5.4 and a maximum mass flow rate of 5.5 lbm/sec (2.5 kg/sec). A detailed description of the facility is given by Shook et al [8]. At the higher speed lines, deep surge is the dominant instability encountered.

EXPERIMENTAL TECHNIQUE

Fourier analysis of signals from an array of circumferentially distributed, simultaneously sampled microphones has proven effective in identifying spatially coherent phenomena such as rotating stall [7]. In such a technique, the Fourier transform is performed in the spatial domain on a simultaneous signal from each microphone in an array. The resultant harmonics correspond to wave numbers or modes propagating around the compressor annulus, and thus directly correspond to the number of cells in the rotating stall event. However, for this technique to be successful, the signal-to-noise ratio must be improved by bandpass filtering around the frequency of the event.

To identify the frequency of the stall event, a joint-time frequency analysis is performed on a single pressure transducer or microphone signal. The joint time-frequency analysis consists of a Fourier transform on a fraction of the data, or window, and then repeating the process by advancing the window by a short time. The resultant spectra then form a transient plot of the instability frequencies.

LOW SPEED CENTRIFUGAL STALL INITIATION

To investigate rotating stall initiation in the PLCRC, the spatial Fourier analysis is applied to the signals from an array of microphones mounted in the O.D. endwall of the compressor inlet. For comparison with these data, an impeller blade is also instrumented with miniature microphones. A comparison of the impeller blade mounted microphone signals and the magnitude of the first spatial mode, i.e. the one-cell stall, characterized by the inlet microphone array as the compressor is throttled into rotating stall is shown in Figure 3. The stall pressure oscillations are clearly of greatest magnitude in the mid-chord region, with the apparent development of a stall cell denoted by Point A. Of significance is that the stall cell appears to develop before the beginning of the rise of the mode magnitude trace and also prior to the significant disruption of the leading and trailing edge transducers.

Prior researchers working in axial compressors have suggested the existence of weak oscillations, or 'modal waves' in the compressor flow field prior to stall. These modal waves are regarded as a precursor to the eruption of a finite stall cell. However, such weak spatially coherent disturbances at the inlet of this centrifugal machine appear to be the remnants of a discrete stall cell in the blade passage further downstream. This view is reinforced by Particle Image Velocity (PIV) measurements in the impeller passages at a stable operating point during rotating stall. PIV is a technique that provides instantaneous, whole field, high resolution velocity data. Two pulses of a laser light source illuminate a seeded flow, thereby producing a double exposed image of the seed particles. Captured either by a digital camera or on film, the double-exposed image is then transferred to an analysis computer for instantaneous computation of the whole velocity field.

The PIV measurement location is a region from 55% to 80% meridional chord, which intersects the suction surface at 80% span and the pressure surface at 30% span. A sketch of the measurement plane is shown in Figure 4. This measurement plane closely follows a meridional streamline and avoids the suction side corner separation zone. The relative passage velocities in and out of stall are shown in Figure 5. A region of near zero relative velocity, the stall cell, is observed in the stalled flow-field near the suction surface at 60% meridional chord in the blade passage. This is near the same point that the cell formation was tracked by the on impeller microphones in the stall initiation results.

HIGH SPEED INSTABILITY INITIATION

Similar throttle-down experiments are performed in the high-speed facility. Again, an array of microphones located in the inlet is employed, as well as pressure transducers distributed in the compressor diffuser. Figure 6 shows a joint time-frequency analysis of the signal from a single transducer mounted in the diffuser endwall during the compressor throttling. A discrete frequency is observed near 1450 Hz, Point A, and continues until the first surge cycle. Also observed is a lower frequency disturbance near 500 Hz, Point B, prior to the initial surge cycle, Point C.

To determine the location of the disturbances within the research compressor, the magnitudes of the Fourier analyses of transducer signals located along the compressor stage are compared. The results for the disturbance centered at 1,482 Hz are shown in Figure 7. The maximum signal strength is in the diffuser. It is interesting that the next largest magnitude occurs in the endwall of the plenum. The attenuated magnitude at the impeller inlet indicates that the source of the disturbance is located at or near the diffuser rather than in the impeller flow passages, as was the case in the low speed machine. A similar comparison of the joint time-frequency analyses for the 520 Hz disturbance shows the diffuser to again be the location of maximum amplitude.

Spatial Fourier analyses are performed on the signals from the inlet and diffuser transducer arrays. The signals are filtered around the frequencies identified in the above-described joint time-frequency analyses. The results show the presence of two distinct modes, a 9 mode and a 1 mode, corresponding to the disturbances observed at 1,482 Hz and 520 Hz respectively. Figure 8 shows the spatial mode magnitudes for the 1 mode at 520 Hz and the 9 mode at 1,482 Hz along with the plenum pressure. The 9 mode magnitude increases a significant time prior to the 1 mode and the first surge event. Namely, the one mode increases at t = 800 impeller revolutions corresponding to the first mild surge cycle. The appearance of the 1 mode has minimal effect on the 9 mode, with both existing simultaneously. A similar phenomena occurs at t = 850 revolutions, which corresponds to the first deep surge cycle. As the surge cycle progresses, the 1 mode magnitude continues to increase until the pressure rise begins to recover. During the recovery portion of the surge cycle, there is minimal amplitude of either the 1 or 9 mode. Both modes reappear at t = 950 revolutions as the next surge cycle begins.

CONCLUSIONS

Characterization of the instabilities of two compressors, one low speed and one high speed, which typify the type of flow instabilities exhibited by most industrial compressors has been described. The low speed compressor exhibited a stable rotating stall that initiated from a separation region located near the impeller midchord. That this instability was easily detected near the mid-chord region prior to any significant periodicity being detected by sensitive microphone arrays located at the inlet to the compressor was of specific interest. Namely, this suggests that what might be considered to be modal wave precursors if observed in absence of on-impeller data are in actuality the remnants of a small but finite stall cell located upstream in the flow passage.

In the high speed compressor, two spatially coherent disturbances were observed prior to surge initiation. These were shown to be consistent with a 9 mode and a 1 mode rotating stall condition. An analysis of the signal strengths from different transducers indicated that the disturbance was located at or near the vaned diffuser. No strong indication of impeller stall, as was seen in the low speed machine, was seen to precede the surge event.

In summary, two centrifugal machines of vastly different tip speed classes were shown to exhibit some type of rotating disturbance consistent with rotating stall. In the case of the high speed compressor, this phenomenon was a precursor to an eventual deep-surge condition. Although this does not confirm that stall initiates such events, it provides some of the first experimental evidence of its existence in high speed centrifugal compressors prior to surge.

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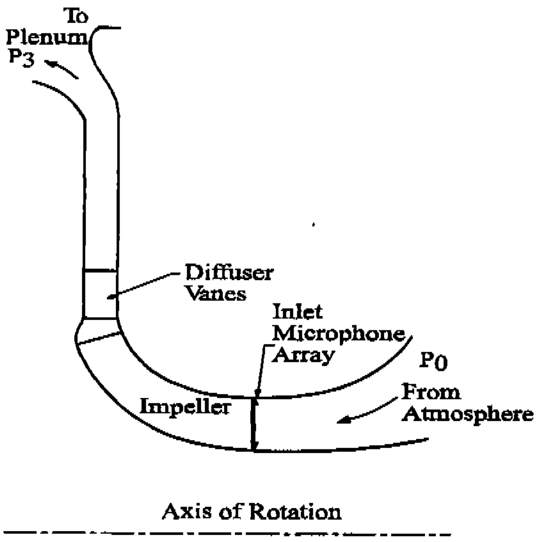


Figure 1. Flowpath of the low speed centrifugal compressor

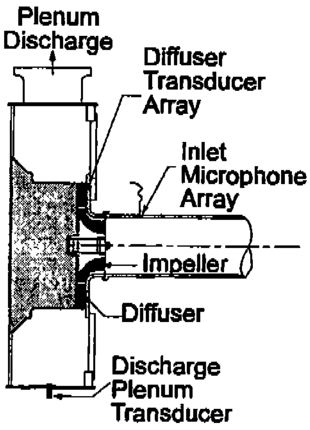


Figure 2. High speed cnetrifugal research compressor

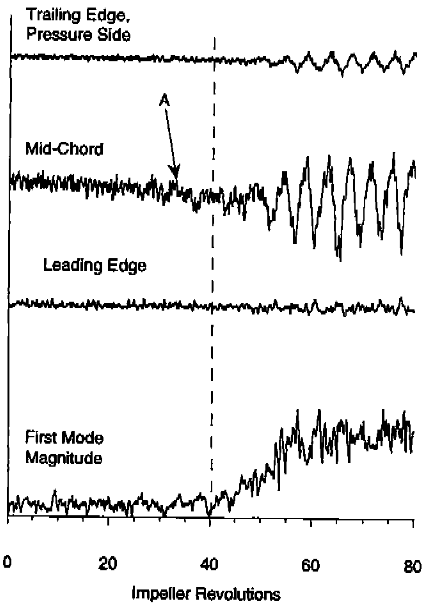


Figure 3. Stallling behavior of the low speed compressor

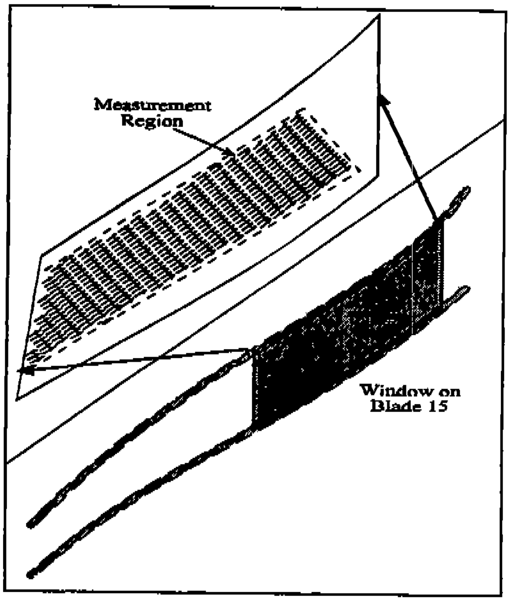
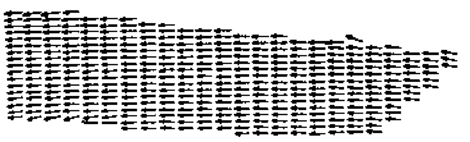
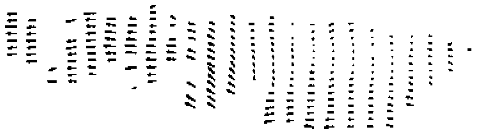


Figure 4. Impeller flowpath measurement region



(a) Stable flow



(b) Rotating Stall

Figure 4. Velocity Vectors near midspan during (a) stable operation and (b) rotating stall

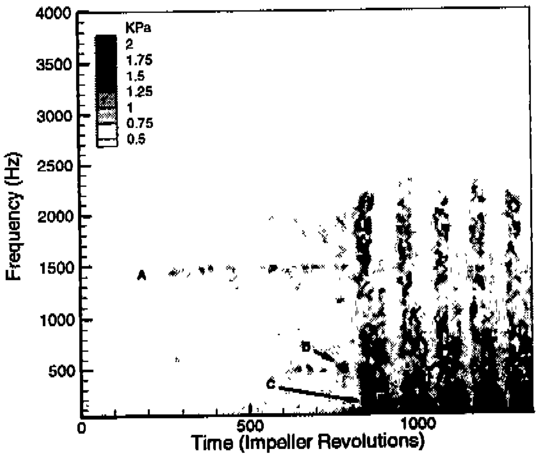


Figure 5. Joint time-frequency analysis for a single diffuser pressure transducer with surge chamber diffuser

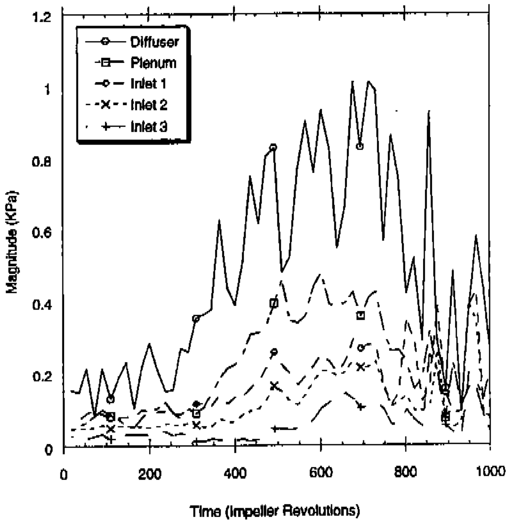


Figure 6. Fourier transform magnitudes for the disturbance at 1482 Hz at the plenum, diffuser and along the impeller inlet

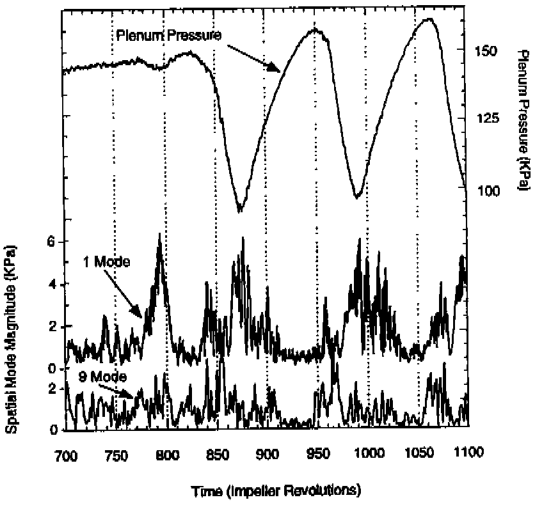


Figure 7. Spatial mode magnitudes from a diffuser transducer and plenum pressure