EFFECT OF ACOUSTIC RESONANCE CONDITION ON WAKE GENERATED ROTOR BLADE GUST RESPONSE

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ABSTRACT

Unsteady aerodynamic blade row response is generally categorized based on the far field acoustic response. For a cascade in a subsonic flow, the unsteady flow is superresonant when pressure disturbances propagate away from the cascade unattenuated. When the pressure disturbances decay exponentially with distance, the cascade is subresonant. At an acoustic resonance, a point where subresonant and superresonant regions meet, the pressure disturbances propagate energy along the blade row, i.e., the energy is propagated in a purely tangential direction.

INTRODUCTION

Turbomachine blade row aeroelastic and aeroacoustic response are driven by unsteady aerodynamic phenomena, currently analyzed by linearized unsteady aerodynamic models in which the unsteady flow is considered to be a small perturbation of a uniform, unsteady, or nonuniform steady flow. These linearized models must be validated by experiment to establish their accuracy in predicting the blade row unsteady aerodynamics. The far field solution characteristics are critical. Namely, the particular combination of unsteady flow conditions may result in various wave propagation modes.

Unsteady aerodynamic blade row response is generally categorized based on the far field acoustic response. For a cascade in a subsonic flow, the unsteady flow is superresonant when pressure disturbances propagate away from the cascade unattenuated. When the pressure disturbances decay exponentially with distance, the cascade is subresonant. At an acoustic resonance, a point where subresonant and superresonant regions meet, the pressure disturbances propagate energy along the blade row, i.e., the energy is propagated in a purely tangential direction.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>b</td>
<td>Rotor blade semichord</td>
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<tr>
<td>(C_p)</td>
<td>Rotor blade steady pressure coefficient</td>
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<td>(C_p)</td>
<td>Rotor blade unsteady pressure coefficient</td>
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<td>(C_{dp})</td>
<td>Rotor blade unsteady pressure difference coefficient</td>
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<td>(C_p)</td>
<td>Rotor blade acoustic wave unsteady pressure coefficient</td>
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<td>(i)</td>
<td>Rotor blade mean incidence angle</td>
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<td>(k)</td>
<td>Reduced frequency = (ob/V)</td>
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<td>(P)</td>
<td>Digitized ensemble averaged unsteady pressure</td>
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<td>(P_S)</td>
<td>Rotor blade surface steady pressure</td>
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<td>(P^+)</td>
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<td>(u^+)</td>
<td>Streamwise gust first harmonic component</td>
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<td>(v^+)</td>
<td>Streamwise periodic unsteady velocity</td>
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<td>(V_x)</td>
<td>Mean axial velocity</td>
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<td>Absolute velocity vector difference from mean value</td>
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<td>(\Delta W)</td>
<td>Total unsteady velocity</td>
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<td>(\dot{\beta})</td>
<td>Relative mean flow angle</td>
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<td>(\Delta \beta)</td>
<td>Relative flow angle difference from mean value</td>
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<tr>
<td>(\omega)</td>
<td>Forcing function frequency</td>
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Acoustic resonances exist for specific combinations of steady flow conditions, cascade geometries, and interblade phase angle $\beta$ and reduced frequency $k$ values. For a subsonic inlet Mach number, the unsteady flow and cascade geometry conditions which specify the acoustic resonant interblade phase angle value $\beta^*$ is given in Equation 1. At positive and negative interblade phase angle values, acoustic resonances bracket the wave propagating superresonant region. When either $\beta > \beta^*$ or $\beta < \beta^*$, the cascade is subresonant and the waves decay [9].

$$\beta^* = \frac{2kM}{(C/S)(1 - M^2)} \left( \frac{\alpha_o + \gamma}{\sqrt{1 - M^2 \cos^2(\alpha_o + \gamma)}} \right)$$

(1)

where $\beta^*$ is the acoustic resonant interblade phase angle, $M$ denotes the Mach number, $k = \omega C/2U$, $C/S$ is the cascade solidity, $\gamma$ is the cascade stagger angle and $\alpha_o$ is the mean flow incidence angle.

Although these acoustic resonances are critical to obtaining mathematically correct predictions from linearized unsteady flow models, they are a subject of some controversy. For example, Gerolymos, Blin, and Quinnou [1990] developed an Euler solver and obtained good agreement with vibrating transonic cascade data. However, this code did not exhibit any particular behavior at acoustic resonance conditions. Experimentally, superresonant flow wave propagation behavior has been shown by Buffum and Fleeter [1991a, 1991b] to have a significant effect on obtaining valid two-dimensional oscillating cascade data. The question has also been raised as to the significance of acoustic resonances in actual blade rows.

Of particular interest herein is a rotor blade operating in a multiblade row environment. The interaction of this rotor with distorted flow fields generated from vanes, struts, obstructions or inlet flow distortions, for example, generates propagating acoustic waves. These unsteady interactions are specified by the reduced frequency $k$ and the relative number of upstream excitations $N_{\text{excitations}}$ and downstream rotor blades $N_{\text{blades}}$ which specifies the interblade phase angle value $\beta$.

$$\beta = 2\pi \frac{N_{\text{excitations}} \pm 2nm}{N_{\text{blades}}}$$

(2)

where $m$ is an integer.

These rotor interactions generate acoustic waves which propagate upstream and downstream. Depending on the interaction, i.e., the relative number of upstream excitations and downstream rotor blades, either a subresonant or a superresonant flow condition results. In the subresonant regime, the acoustic wave is attenuated whereas in the superresonant flow regime it propagates upstream and downstream.

In this paper, multistage axial flow compressor acoustic resonance conditions, including both subresonant and superresonant unsteady aerodynamic response in the immediate vicinity of an acoustic resonance, are experimentally investigated. This is accomplished by means of a series of experiments directed at quantifying these acoustic resonance and subresonant and superresonant blade row interaction phenomena in terms of their effect on the rotor blade row periodic unsteady pressure response. First the first stage rotor row periodic unsteady pressure response to a downstream stator-rotor interaction generated acoustic wave is studied. Then, the gust unsteady aerodynamic response of the first stage rotor row due to IGV wakes, with the IGV instrumented first stage rotor itself configured to generate subresonant and superresonant conditions is considered.

**RESEARCH COMPRESSOR**

The Purdue Axial Flow Research Compressor models the fundamental turbomachinery unsteady aerodynamic multistage interaction phenomena which include the incidence angle, the velocity and pressure variations, the aerodynamic forcing function waveforms, the reduced frequency, and the unsteady blade row interactions. The compressor is driven by a 15 HP DC electric motor at a speed of 2,250 RPM. For the baseline configuration, each identical stage contains 43 rotor blades and 31 stator vanes having a British C4 airfoil profile, with the first stage rotor inlet flow field established by a variable setting inlet guide vane (IGV) row of 36 airfoils. The overall compressor and airfoil characteristics are defined in Table 1.

The first stage rotor row is instrumented, with the first stage stator and second stage rotor row removed to assure that potential effects do not affect the instrumented blade row data. The propagating acoustic wave is generated by fixing the number of third stage rotor blades and varying the number of second stage stator vanes to obtain superresonant flow conditions form this downstream stator-rotor interaction. The IGV's and instrumented first stage rotor row combination is such that their interaction is far removed from the acoustic resonant condition.

To investigate the gust unsteady aerodynamic response of the first stage rotor row due to IGV wakes, with the IGV instrumented rotor interaction generating subresonant and superresonant conditions, the number of first stage rotor blades is maintained constant and the number of IGV's is varied. Also, the downstream second stage stator and third stage rotor combinations are configured to operate far from an acoustic resonance.

**INSTRUMENTATION**

The compressor aerodynamic performance is determined utilizing a 48 port Scanivalve system, thermocouples, and a venturi orifice to measure the required pressures, temperatures and flow rate, respectively. The Scanivalve transducer is calibrated each time data are acquired, thus automatically compensating for zero and span shifts of the transducer output. A 95% confidence interval, root-mean-square error analysis of 20 samples is performed for each steady data measurement.

Both steady and unsteady rotor blade row data are required. The steady data quantify the rotor row mean inlet flowfield and the resulting rotor blade midspan steady loading distribution. The unsteady data define the periodic aerodynamic forcing function and the resulting midspan blade surface periodic unsteady pressure distributions.

The inlet flow field, both steady and unsteady, is measured with a rotating cross hot-wire probe. Disturbances in the stationary frame-of-reference, i.e., the IGV wakes, are the unsteady aerodynamic forcing functions to the first stage rotor row. The rotor periodic unsteady inlet flow field generated by these disturbances is measured with a cross hot-wire mounted in the rotor frame-of-reference. The probe is axially mounted 30% of rotor chord upstream of the rotor leading edge plane. A potential flow field analysis determined this axial location to be such that leading edge potential effects are negligible for all steady loading levels. The probe is angularly aligned to obtain rotor relative velocity and flow angle data. The cross hot-wire probe was calibrated and linearized for velocities from 18.3 m/sec to 53.4 m/sec and ±35 degrees angular variation, with the accuracy of the velocity magnitude and flow angle were determined to be 4% and ±1.0 degree, respectively. Centrifugal loading effects on the rotating hot-wire sensor resistances and, thus, the responses found to be negligible.
The detailed steady aerodynamic loading on the rotor blade surfaces is measured with a chordwise distribution of 20 midspan static pressure taps, 10 on each surface. The static pressure at the rotor exit plane, measured with a rotor drum static tap, is used as the blade surface static pressure reference. These static pressure measurements are made using a rotor based 48 port constant speed drive Scanivalve system located in the rotor drum.

The measurement of the midspan rotor blade surface unsteady pressures is accomplished with 20 ultra-miniature, high response transducers embedded in the rotor blades at the same chordwise locations as the static pressure taps. To minimize the possibility of flow disturbances associated with the inability of the transducer diaphragm to exactly maintain the surface curvature of the blade, a reverse mounting technique is utilized. The pressure surface of one blade and the suction surface of the adjacent blade are instrumented, with transducers embedded in the nonmeasurement surface and connected to the measurement surface by a static tap. The embedded dynamic transducers are both statically and dynamically calibrated. The static calibrations show good linearity and no discernible hysteresis. The dynamic calibrations demonstrate that the frequency response, in terms of gain attenuation and phase shift, are not affected by the reverse mounting technique. The accuracy of the unsteady pressure measurements, determined from the calibrations, is ±4%.

The rotor-based static pressure Scanivalve transducer, rotating cross hot-wire probe and 20 blade surface dynamic pressure transducers are interfaced to the stationary frame-of-reference through a 40 channel slip ring assembly. On-board signal conditioning of the transducer output signals is performed to maintain a good signal-to-noise ratio through the slip rings. The remaining 17 channels of the slip-ring assembly are used to provide excitation to the transducers and on/off switching to the Scanivalve DC motor.

**DATA ANALYSIS**

**Steady Data**

The rotor blade surface static pressure data, measured with the rotor-based Scanivalve system, are defined by a root-mean-square error analysis of 20 samples with a 95% confidence interval. The reference for these midspan blade pressure measurements is the static pressure at the exit of the rotor measured on the rotor drum. Thus, the blade surface and the reference static pressures are measured at different radii. Hence, a correction for the resulting difference in the radial acceleration is applied in calculating the blade surface static pressure coefficient.

\[
C_p = \frac{P_{\text{s, exit}} - P_{\text{static}}}{1/2 \rho U_t^2}
\]  

where \(U_t\) is the rotor blade tip speed.

**Periodic Data**

The periodic data of interest are the first harmonic components of the aerodynamic forcing function to the first stage rotor blade row together with the resulting rotor blade surface unsteady pressures and unsteady pressure differences. These are determined by defining a digitized ensemble averaged periodic unsteady aerodynamic data set consisting of the rotating cross hot-wire probe and blade surface dynamic pressure transducer signals at each steady operating point. In particular, these time-variant signals are digitized with a high speed A-D system at a rate of 100 kHz and then ensemble averaged.

The key to this averaging technique is the ability to sample data at a preset time, accomplished by an optical encoder mounted on the rotor shaft. The microsecond range step voltage signal from the encoder is the data initiation time reference and triggers the high speed A-D multiplexer system. To significantly reduce the random fluctuations superimposed on the periodic signals of interest, 200 averages are used. A Fast Fourier Transform (FFT) algorithm is then applied to these ensemble averaged signals to determine the first harmonic component of the unsteady aerodynamic forcing function and the resulting rotor blade surface first harmonic unsteady pressures and pressure differences.

The unsteady inlet flow field to the rotor row is measured with the rotating cross hot-wire probe which quantifies the relative velocity and flow angle. The velocity triangle relations depicted in Figure 1 are then used to determine the unsteady inlet flow field to the rotor. In particular, the streamwise and transverse velocity components, \(u^+\) and \(v^+\), respectively. These are then Fourier decomposed to determine the first harmonic of the streamwise and transverse gust components, \(\hat{u}^+\) and \(\hat{v}^+\).

The various unsteady aerodynamic gust mathematical models reference the gust generated airfoil aerodynamic response to a transverse gust at the leading edge of the airfoil. However, in the experiments described herein, the time-variant data are referenced to the initiation of the data acquisition shaft trigger pulse. Thus, for consistency with the models, the periodic data are further analyzed and referenced to a transverse gust at the leading edge of the first stage rotor blade. This is accomplished by assuming that: (1) the aerodynamic forcing function remains fixed in the stationary reference frame; and (2) the forcing function does not decay from the rotating hot-wire probe axial location to the rotor row leading edge plane.

Two types of unsteady pressure data were measured and analyzed. The first type is the acoustic wave unsteady pressure generated by a downstream stator-rotor interaction and operation in the superresonant flow regime and measured by the instrumented first stage rotor row. These data are referenced to the second stage stator vane wake generated transverse first harmonic gust as defined by the following equation.

\[
C_{pr} = \frac{\rho \hat{\bar{P}}_r}{\rho \bar{V}^2 \hat{v}^+} (4)
\]

where \(C_{pr}\) is the acoustic wave unsteady pressure coefficient, \(\rho \hat{\bar{P}}_r\) is the acoustic wave unsteady pressure, \(\hat{v}^+\) is the second stage stator vane wake generated transverse gust first harmonic and \(\bar{V}_s\) is the mean axial velocity.

The second type is the unsteady pressure acting on the first stage rotor row due to the upstream IGV wakes \(V_{x,1}\) and \(V_{y,1}\) from the IGV row and first stage rotor interaction operate in either a subresonant or a superresonant flow environment. The rotor blade surface unsteady pressure data, measured with the embedded high response pressure transducers, are analyzed to determine the first harmonic of the chordwise distribution of the unsteady pressure coefficient \(C_p\) and the unsteady pressure difference coefficient \(C_{\Delta p}\). These are defined in Equation 5 and are specified from the Fourier coefficients of the digitized ensemble averaged dynamic pressure transducer signals.

\[
C_p = \frac{\rho \hat{\bar{P}}_r}{\rho \bar{V}^2 \hat{v}^+} (5)
\]

\[
C_{\Delta p} = C_p, \text{ pressure} - C_p, \text{ suction}
\]

where \(\bar{V}_s\) is the harmonic transverse gust component, \(\bar{V}_x\) is the mean axial velocity and \(\hat{\bar{P}}_r\) is the relative mean flow angle. The normalization with \(\hat{\bar{P}}_r\) is used to correlate the effects of incidence angle changes on unsteady lift response per the work of Manwaring and Fleeter [1990].

The final form of the gust generated rotor blade row unsteady aerodynamic data define the chordwise distribution of the harmonic complex unsteady pressure and pressure difference coefficients. Also included as a reference where appropriate are predictions from the transverse gust analysis of Smith [1972]. This model analyzes the unsteady aerodynamics generated on a flat plate airfoil cascade at zero incidence by a transverse gust convected with an inviscid, subsonic, compressible flow.
RESULTS

To investigate multistage axial flow compressor acoustic resonance conditions, a series of experiments are directed at quantifying these acoustic resonance and subresonant and superresonant blade row interaction phenomena in terms of their effect on the rotor blade row periodic unsteady pressure response. First the first stage rotor row periodic unsteady pressure response to a downstream stator-rotor interaction generated acoustic wave is studied. Then, the gust unsteady aerodynamic response of the first stage rotor row due to IGV wakes, with the IGV-instrumented first stage rotor itself configured to generate subresonant and superresonant conditions is considered.

Acoustic Wave Generated Rotor Row Response

The first stage rotor blade row unsteady pressure response to upstream propagating acoustic waves generated by the superresonant interactions of a far downstream stator and rotor row is quantified. Varying the number of second stage stator row vanes while maintaining the number of third stage rotor blades enables subresonant and superresonant flow regimes to be established. In particular, superresonant flow regimes are established with a second stage stator row with 38, 39, 40 and 41 vanes and a third stage rotor row with 43 blades, while subresonant flow regimes are established with a second stage stator row with 36 and 37 vanes and a third stage rotor row of 43 blades. For these configurations, the corresponding reduced frequency values range from 4.76 to 5.42 while interblade phase angles range from -58.6° to -16.7°. The reduced frequency is minimally affected by this range in the number of vanes while the interblade phase angle is greatly affected and, thus the effects shown by variation in the number of vanes corresponds generally to interblade phase angle variations.

To demonstrate the generation of an upstream traveling acoustic wave, Figure 2 shows the Fourier decomposition of a typical first stage rotor blade surface unsteady pressure signal generated by the far downstream stator and rotor operating in a superresonant stator-rotor configuration consisting of 38 vanes and 43 blades, with a Mach number of 0.08 at an RPM of 2,250. This unsteady pressure measurement, located at 5% chord on the first stage rotor blade suction surface, clearly shows the strong frequency content due to the upstream traveling 38 per rev acoustic wave, with the amplitude being approximately one-third that of the 36 per rev IGV wake generated first harmonic amplitude.

Blade Surface Steady Pressures

A compressor operating condition corresponding to the lowest obtainable first stage rotor blade steady loading level is utilized, corresponding most closely to the flat plate cascade model. For this compressor configuration, this lowest loading condition is defined by a first stage rotor row mean incidence of approximately -3.5°. Figure 3 shows the chordwise distribution of the first stage rotor blade surface steady pressure coefficient with the downstream stator-rotor operating in a superresonant flow condition generated by a downstream configuration with 38 stator vanes and 43 rotor blades. The area between the pressure and suction surface steady pressure data is numerically integrated to determined the steady loading level. Figure 3 also shows the negligible variation of steady loading when the number of downstream stator vanes is varied to obtain subresonant and superresonant flow conditions. Therefore the blade steady loading and thus the surface steady pressure is unaffected by the upstream propagating acoustic wave generated by downstream superresonant stator-rotor interactions.

Rotor Row Periodic Unsteady Inlet Flow Field

Figure 4 shows the Fourier decomposition of the periodic unsteady inlet flow field entering the first stage rotor row and measured with the rotor-based cross hot-wire probe when the far downstream stator and rotor are in a superresonant condition with 38 vanes and 43 rotors. The periodic unsteady flow field, defined by the nondimensional streamwise and transverse gust components, shows the strong harmonic content due to the 36 IGV wakes upstream of the rotor row. However, frequency content due to the 38 per rev superresonant upstream propagating acoustic wave is not found.

Three other downstream stator-rotor configurations, 39, 40 and 41 vanes, also give superresonant acoustic conditions. In all of these, however, the acoustic wave is not sensed. Thus, the upstream propagating acoustic wave does not affect the IGV wake generated periodic unsteady flow field entering the first stage rotor row.

Rotor Row Unsteady Pressure Response

Figures 5 and 6 show the first stage rotor blade row pressure and suction surface unsteady pressure response to the upstream propagating acoustic wave generated by the four superresonant stator-rotor configurations. For each configuration, both the pressure and suction surface show nearly constant unsteady pressure magnitude and linear phase chordwise distributions, with the magnitude decreasing as the number of vanes is increased from 38 to 41 and the linear phase distributions remaining relatively unaffected. The linear chordwise distribution of these phase data correspond to a convected wave speed of approximately 352 m/sec, which corresponds to the speed of an upstream traveling acoustic wave, i.e., the speed of sound minus the mean axial flow velocity. Since the pressure and suction surface unsteady pressure chordwise distributions are nearly identical in magnitude and phase, the magnitude of the unsteady pressure difference is nearly zero for each of the vane configurations. Thus, the unsteady lift due to upstream propagating acoustic waves is minimal.

The nondimensional acoustic wave unsteady pressure amplitude as a function of the number of vanes is compared to the flat plate cascade prediction in Figure 7. The acoustic wave amplitude is obtained from the blade surface unsteady pressure constant magnitude chordwise distributions. The prediction of the number of vanes at which resonance occurs is fairly the data show that resonance occurs at an interblade phase angle generated with between 37 and 38 vanes per stator row (s between -50.2° and -41.8°), while the flat plate cascade model predicts the resonance to occur at 38.4 vanes (s equal to -38.5°). However, there is very good trendwise agreement between the data and the prediction, with the magnitude of the superresonant acoustic wave increasing as resonance is approached and the acoustic wave greatly attenuated in the subresonant environment.

IGV Wake Generated Rotor Row Response

The gust unsteady aerodynamic response of a rotor row due to IGV wakes, with the IGV-instrumented rotor itself configured to generate subresonant and superresonant conditions is investigated. The acoustic conditions are achieved by varying the number of IGV’s and maintaining the number of first stage rotor blades. In particular, subresonant and superresonant acoustic environments were established two ways: (1) by changing the number of vanes while maintaining the number of rotor blades, thereby altering the unsteady stator-rotor interactions and the interblade phase angle and (2) by varying the Mach number without changing the blade row interactions.
Subresonant flow regimes are established for an IGV row with 35, 36 and 37 vanes and a first stage rotor row with 43 blades, while superresonant flow regimes result with IGV rows with 38, 39 and 41 vanes and a first stage rotor row with 43 blades. For these configurations, the corresponding reduced frequencies range from 4.63 to 5.42 and the interblade phase angles range from -67.0° to -16.7°. The reduced frequency is minimally affected by this range in the number of vanes while the interblade phase angle is greatly affected and, thus, the effects shown by variation in the number of vanes corresponds generally to interblade phase angle variations.

The flat plate cascade unsteady lift coefficient phase prediction differs greatly from the data in both the subresonant and superresonant flow regime. The predicted phase decreases slightly as the number of vanes is increased, with a sharp decrease in phase near the resonant condition. However, the data show an increase in phase as the number of vanes is increased, with no sharp decrease near the resonance condition. Also, the predicted phase is generally 90° to 150° greater than the data.

Unsteady Pressure Difference

Figure 11 shows the complex unsteady pressure difference coefficient data for the three subresonant flow condition configurations generated with 35, 36, and 37 IGV's, while Figure 12 shows the analogous data for the three superresonant flow condition configurations with 38, 39 and 41 IGV's. The chordwise variations of the magnitude data for both near resonant flow conditions are almost identical, with the magnitude generally decreasing with increasing chord except in the quarter and aft chord. In the region about the quarter chord, the data show a large decreased magnitude whereas in the aft chord the data show an increased magnitude. In accordance with the previously presented unsteady lift magnitude trends, the magnitude data increase with an increasing number of vanes and an increasing interblade phase angle in the subresonant environment and decrease with an increasing number of vanes and interblade phase angle in the superresonant environment.

The complex unsteady pressure difference coefficient phase data also show nearly identical chordwise trends, with the data generally increasing with an increase in the number of vanes and the interblade phase angle. The exceptions are once again in the quarter chord and aft blade regions. At quarter chord, the large decrease in the phase data diminishes as the acoustic resonance condition is approached for both the subresonant and superresonant environments. In the aft blade, the phase data decrease, with the decrease becoming increasingly sharp as the number of vanes and interblade phase angle are increased.

Pressure Surface Unsteady Pressures

Figures 13 and 14 show the first stage rotor row pressure surface IGV wake generated first harmonic unsteady pressure response in the subresonant and superresonant flow regimes. The trends of the magnitude data with chordwise position are nearly identical for both flow environments, with a generally decreasing magnitude with increasing chord distribution except for a large decrease in magnitude at quarter chord. The pressure surface magnitude data exhibit the same variation with the number of vanes and interblade phase angle as did the unsteady lift and unsteady pressure difference magnitude data, i.e., the magnitude data increase in both the subresonant and superresonant environments as the number of vanes and interblade phase angle approach their resonant values.

The unsteady pressure phase data are relatively unaffected by the number of vanes and the interblade phase angle in the subresonant environment but show large effects in the superresonant environment. As the number of vanes increases from 35 to 37 in the subresonant region, the phase data decrease slightly with increasing chord except near the quarter chord where these data are increased in value. In the superresonant environment, while the chordwise trends still remain relatively unaffected by the number of vanes, the phase data generally increase with an increase in the number of vanes and interblade phase angle. The exception again is in the quarter chord region, where the decrease in phase becomes larger as the number of vanes and the interblade phase angle decreases in the subresonant environment and increases in the superresonant environment.

Suction Surface Unsteady Pressures

The first stage rotor blade suction surface IGV wake generated first harmonic unsteady pressure response is shown in Figures 15 and 16 for the subresonant and superresonant conditions. Once again, the
The suction surface phase data are affected by the number of vanes and interblade phase angle in the subresonant environment as well as in the superresonant environment, in contrast to the corresponding pressure surface data. The suction surface phase data chordwise trends are nearly identical for both the subresonant and superresonant conditions, with the phase data remaining generally constant along the chord except in the aft chord region where there is a decrease. As the number of vanes and interblade phase angle is increased, the phase data increase, with the decrease in the aft chord region becoming larger.

**Mach Number Effects**

In the previous section, the gust unsteady aerodynamic response of a rotor row due to IGV wakes, with the IGV-instrumented rotor itself configured to generate subresonant and superresonant conditions, was investigated. This was accomplished by varying the number of IGV's while maintaining a constant number of rotor blades and , thus, varying the reduced frequency and the interblade phase angle. In addition to the reduced frequency and interblade phase angle, the Mach number is also a key parameter for acoustic resonance, Equation 1. Therefore the effect of Mach number on the acoustic environment of the first stage rotor row periodic unsteady aerodynamic response is also experimentally investigated. This is accomplished by first configuring the compressor such that it operates in the subresonant flow regime nearest to the resonance, i.e., with 37 IGV's and 43 first stage rotor blades. The Mach number is then varied while maintaining the reduced frequency constant by changing the rotor speed and thus the flow through the compressor. Note that in these experiments the interblade phase angle is maintained constant at -50.2° as the number of IGV's and first stage rotor blades are fixed at 37 and 43 respectively. Four Mach numbers are considered, with three 0.072, 0.077 and 0.081, resulting in subresonant flow conditions and one, 0.085 resulting in a superresonant flow condition.

Figure 17 shows the comparison of the complex unsteady lift coefficient data and flat plate cascade prediction as a function of the Mach number. The prediction and data correlation results are similar to the previous results. Namely, the prediction of the Mach number where resonance occurs, 0.105, is only in fair agreement with the data, which shows the resonance between Mach number values of 0.081 and 0.085. Also, in the subresonant flow regime, the unsteady lift magnitude data and prediction are in good agreement, with both having approximately the same values and increasing with increasing Mach number. For the superresonant flow condition, the magnitude data and corresponding unsteady lift prediction show only fair agreement, with a large decrease in both as compared to the subresonant values. Once again, the phase prediction exhibits very poor correlation with the data. The prediction is relatively constant with Mach number except near the resonance condition. However, the phase data increase as the Mach number is increased, with no indication of the large phase variation near the resonance condition as shown by the prediction. Also, the predicted phase is greater than the data by approximately 90°.

Figure 18 shows the rotor blade unsteady pressure difference coefficient data chordwise distributions in the subresonant and superresonant flow regimes. Both the magnitude and phase data trends are unaffected by the acoustic environment, with these trends also corresponding to those previously found by varying the number of vanes and interblade phase angle. The magnitude data follow the near resonant trends of the unsteady lift data, i.e., the unsteady pressure difference magnitude data increase with increasing Mach number in the subresonant regime and are greatly reduced in the superresonant regime. Also, as the Mach number is increased, the phase data values are increased except in the quarter-chord region in the superresonant environment, where the decrease in phase becomes larger.

Figures 19 and 20 show the effect of subresonant and superresonant environments on the rotor blade pressure and suction surface IGV wake first harmonic unsteady pressure response. Once again, the trends of the data magnitude and phase are relatively unaffected by the acoustic environment. The exception is the unsteady pressure magnitude response in the front and aft suction surface in the superresonant environment with Mach number 0.085, where the magnitude is greatly decreased. The magnitude data follow the trends previously shown by the unsteady pressure difference data, with the magnitude increasing as the resonance is approached from the subresonant regime and reduced sharply in the superresonant regime. As the Mach number is increased, the phase data also increase in value, with the suction surface data increasing at a slightly greater rate than the pressure surface data.

**SUMMARY AND CONCLUSIONS**

A series of experiments have been performed to investigate multistage axial flow compressor acoustic resonance conditions, including both subresonant and superresonant unsteady aerodynamic response in the immediate vicinity of an acoustic resonance. In particular, these experiments quantified these acoustic resonance and subresonant and superresonant blade row interaction phenomena in terms of their effect on the rotor blade row periodic unsteady pressure response. Subresonant and superresonant acoustic environments were established by changing the number of vanes while maintaining the number of rotor blades, thereby altering the unsteady stator-rotor interactions and the interblade phase angle and by varying the Mach number without changing the blade row interactions. First the first stage rotor row periodic unsteady pressure response to a downstream stator-rotor interaction generated acoustic wave was studied. Then, the gust unsteady aerodynamic response of the first stage rotor row due to IGV wakes, with the IGV-instrumented first stage rotor itself configured to generate subresonant and superresonant conditions was considered. Results of these experiments are summarized in the following.

**Acoustic Wave Unsteady Pressure Response**

* The pressure and suction surfaces have the same constant magnitude and linear phase variation chordwise distributions.

* The prediction of the number of vanes and the interblade phase angle at which acoustic resonance occurs is fair, with the prediction and data differing by approximately one vane and 8°.

* There is very good trendwise agreement between the acoustic wave unsteady pressure prediction and data, with the superresonant environment magnitude increasing as resonance is approached and then sharply reduced to negligible values in the subresonant environment.
IGV Wake Generated Rotor Row Response Near Resonance

* The correlation of the unsteady lift coefficient data with the predictions was very good in the subresonant flow regime, with the correlation of these data in the superresonant flow regime only fair. In both acoustic environments, the correlation of the phase data were poor, both in value and trend.

* The subresonant and superresonant acoustic environments affect the rotor blade surface unsteady pressure difference magnitude and phase data, with the magnitude data increasing as the resonance condition is approached from either the subresonant or superresonant flow regimes.

* On the individual rotor blade suction and pressure surface, the IGV wake generated unsteady pressure magnitude data increase in value as the acoustic resonance condition is approached from either the subresonant or superresonant flow regimes, reflecting the unsteady lift and unsteady pressure difference results. Also, the corresponding phase data increase in value as the acoustic resonance is approached from the subresonant flow regime.

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Figure 2. Fourier decomposition of 5% suction surface chord unsteady pressure signal

Figure 3. Blade surface steady pressures and downstream generated acoustic wave effect on rotor steady loading

Figure 4. FFT of near acoustic resonance rotor periodic unsteady flow

Figure 5. Pressure surface unsteady pressure response to an acoustic wave
Figure 6. Suction surface unsteady pressure response to an acoustic wave

Figure 7. Data-prediction correlation of acoustic wave amplitude

Figure 8. Near acoustic resonance operation effect on blade steady loading

Figure 9. Variation of streamwise and transverse harmonic gusts with number of IGV's
Figure 10. Correlation of the gust generated unsteady lift coefficient versus vane number

Figure 11. Subresonant flow vane number effect on blade unsteady pressure difference

Figure 12. Superresonant flow vane number effect on blade unsteady pressure difference

Figure 13. Subresonant flow vane number effect on blade pressure surface response
Figure 14. Superresonant flow vane number effect on blade pressure surface response

Figure 15. Subresonant flow vane number effect on blade suction surface response

Figure 16. Superresonant flow vane number effect on blade suction surface response

Figure 17. Correlation of gust generated unsteady lift coefficient versus Mach number
Figure 18. Near resonant Mach number effect on blade unsteady pressure difference

Figure 19. Near resonant Mach number effect on pressure surface unsteady response

Figure 20. Near resonant Mach number effect on suction surface unsteady response