EFFECT OF ADJACENT BLADE OSCILLATION ON THE FORCES ON A BLADE OF A COMPRESSOR CASCADE

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Abstract
The current trend of aircraft engines is one towards attaining high isentropic efficiency while minimizing its weight. This leads to a state where the blades are highly loaded and consequently susceptible to vibrations. High cycle fatigue caused as a result of such self-excited flutter or forced vibration due to defects in the air stream are detrimental to the engine. An understanding of the onset of instabilities is essential to predict their occurrences to avoid a catastrophic failure during operation or costly redesign during the development phase. The critical parameters in turbomachine aeroelasticity are the reduced frequency and the interblade phase angle. The damping of the system is known to be a function of the phase difference between the blade forces and the blade motion. In the present study, a linear cascade of five blades is considered to understand the effect of harmonically varying boundary conditions. The second and fourth blades of the cascade are subjected to torsional oscillation by an external mechanism. The third blade, considered as the reference, is stationary and instrumented. The unsteady pressure along the reference blade surface is measured simultaneously with the loads acting on the blade. The unsteady pressures are measured using a multi-sensor pressure scanner by multiplexing and the loads are measured using a five-channel strain gage balance. The blade displacement is determined from the integrated accelerometer signal mounted on an oscillating blade. The experiments are conducted at a low-subsonic speed and multiple oscillation frequencies. The cascade is set at zero incidence and four stagger angles. The effect of inter-blade phase angle is included as the oscillation of the walls adjacent to the reference blade. The phase difference between the harmonic motion of the neighboring walls and the pressure and load signals on the reference blade is related to the damping characteristics of the reference blade. The variation in damping is studied for the range of blade motion phase difference angles and reduced frequencies. The effect of the phase difference between the oscillating blades is seen to strongly affect the damping characteristics of the reference airfoil.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$C_m$</td>
<td>Moment coefficient about the blade oscillation axis, with neighboring blades oscillating</td>
</tr>
<tr>
<td>$C_{m0}$</td>
<td>Moment coefficient about the blade oscillation axis, with neighboring blades stationary</td>
</tr>
<tr>
<td>$\overline{C_p}$</td>
<td>Unsteady pressure coefficient defined with respect to inlet freestream static pressure</td>
</tr>
<tr>
<td>$C_p$</td>
<td>Steady pressure coefficient defined with respect to inlet freestream static pressure</td>
</tr>
<tr>
<td>$k$</td>
<td>Reduced frequency</td>
</tr>
<tr>
<td>PD</td>
<td>Phase difference between oscillating blades</td>
</tr>
<tr>
<td>$U$</td>
<td>Inlet freestream velocity</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Blade oscillation angular frequency</td>
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Introduction
The requirements in the design of modern turbomachinery blades are tending towards designs with thinner blades and high loading to reduce the number of stages so
as to minimize the weight. Although this results in engines with superior thrust to weight ratios, this also leads to aerodynamically induced vibrations in the blades. These vibrations over time can lead to fatigue or catastrophic failure (Srinivasan [1]). Hence, an understanding of the effect of the conditions leading to an instability involving the aerodynamic and structural forces is required.

Aeroelastic instability is due to an unfavorable interplay between the inertial, aerodynamic and elastic forces (Cox et al. [2]). The unfavorable condition results when the net energy added to a solid body is more than that dissipated in a cycle. In contrast to the aeroelasticity of a fixed-wing, there is a strong coupling in case of turbomachines due to the presence of multiple vibrating blades in the vicinity of a blade (Paranjpe [3], Fleeter [4] and Frsching [5]). A systematic way to study aeroelastic instabilities is to perform controlled oscillation experiments on a cascade of blades. In one method (Crawley [6]), all the blades of a cascade are subjected to oscillation with a constant phase difference between them, known as the travelling wave method. An alternative method was proposed by Hanamura et al. [7] that involved the oscillation of a single blade at a time and obtaining the same results. Studying the aerodynamics of vibrating blades in a linear cascade is one of the fundamental experiments to understand the effect of forced response.

In the present study, the loads on a stationary airfoil, with oscillating neighboring blades are studied. The oscillation is prescribed at specific frequencies and phase angle difference between the neighboring blades.

**Experimental Setup**

The cascade considered for the study consisted of a NACA 65 series airfoil, Standard Test Configuration 1 (Bölcs et al. [8]), with a camber angle of 10° and chord 152 mm. The cascade consists of five airfoils with a spacing of 60.5 mm. The span of the blades is 300 mm. The test section is placed at the end of a wind tunnel capable of delivering air between 25 m/s to 40 m/s. The central blade is instrumented with a five-channel strain gage balance for unsteady load measurements. The neighboring blades were oscillated with a cam and follower mechanism to enable controlled sinusoidal oscillations at prescribed amplitude and phase.

In the previously reported study (Babu et al. [9]) the unsteady loads were measured in terms of the total forces and moments acting on the reference.

The purpose of the present study is to examine the unsteady blade surface pressure distribution together with the loads. For this, the central blade (blade 0) is instrumented with pressure taps at the mid-span location. The location of the pressure taps is given in Table-1. A negative value of the non-dimensional distance implies suction surface and hence, the point 0 corresponds to the Leading Edge (LE) of the blade and the points +1 and -1 coincide at the Trailing Edge (TE). As the loads are also being measured simultaneously, the blade taps cannot be rigidly fixed to the stationary frame. To minimize the forces due to blade tappings, flexible tubes were used to interface the blade taps and the pressure transducer which is in the fixed frame.

In order to obtain the displacement information of the oscillating blades, a laser displacement sensor is employed. The laser beam falls on a reflective coating made on an arm rigidly fixed to blade +1. The reflected light is sensed by the laser displacement sensor unit and the distance is estimated with a response of 1 ms. An accelerometer is also mounted on this blade. Post-measurement, the accelerometer data was discarded as the laser displacement sensor provided a better signal-to-noise ratio. Figs.1-3 show the details of the setup.

The blade unsteady static pressures were measured with the ESP 32 HD pressure scanner at a sampling rate of 500 samples per second per port. The range of the sensor

| Table-1 : Location of Static Pressure Taps Along the Blade |
|---------------------------------|------------------|
| Non-dimensionalised Locations of Pressure Taps |
| Suction Surface | Pressure Surface |
| TE | LE |
| -0.70 | 0.18 |
| -0.65 | 0.22 |
| -0.49 | 0.27 |
| -0.44 | 0.32 |
| -0.32 | 0.40 |
| -0.27 | 0.45 |
| -0.24 | 0.52 |
| -0.20 | 0.55 |
| -0.15 | 0.61 |
| -0.10 | 0.67 |
| LE | TE |
is ±34.5 kPa and has a manufacturer specified static accuracy of 17 Pa for the calibration order used here. As the device multiplexes across all ports (at the rate of 16,000 per second), the time correction due to the delay in multiplexing is incorporated in the calculations. The loads from the strain-gage balance were also measured simultaneously together with one component of the accelerometer signal, both at 16,000 samples per second. To ensure the signals are acquired at the set times, all acquisitions were triggered and timed by the same hardware clock.

In the present case the experiments were performed for a constant velocity (29 m/s), three frequencies (9, 12 and 15 Hz), four stagger angles (0°, 15°, 30°, 45°) and with a phase difference (PD, as shown in Fig.2) of 0° to 315° in steps of 45°. The stagger is defined with respect to the axial direction and is representative of the blade setting angle for all the blades, when the oscillating blades are in their mean position. In total, a total of 108 test conditions were conducted, but only a sub-set of the results are presented here.

Performance parameters

The primary quantities of interest are the unsteady amplitude and phase of the loads acting on the central blade (blade 0). The load considered is the moment on the central airfoil (blade 0). For the present study, the phase of oscillation of blade +1 is taken as a reference for other periodic signals. When a boundary is moving at a given frequency, the inertial forces are expected to vary with the same frequency, but with a phase lag. A typical signal of a dynamic property (force acting on the blade or pressure on the surface of the blade) will therefore follow the periodic disturbance but with a phase delay. When the blade motion is also superimposed within the same time scale, the performance parameter namely phase difference is evident. In order to compute this, the Fourier transform is applied to the force signal. This not only gives the magnitude of the signal at all frequencies, but also the phase with respect to a reference. In order to obtain the phase angle of the dominant frequency in the signal, the phase corresponding to the frequency of maximum magnitude is determined. This angle minus the phase angle of the blade displacement signal of blade +1 (which is set as zero) gives the phase difference between the load and displacement signals. In other words, the time-dependent fluctuating pressure at a given location $x$ is decomposed as $\overline{C}_p(x) + C_p \sin (\omega t + \phi)$, where the magnitude of the fluctuating pressure ($C_p$) and the phase lead ($\phi$) are obtained from the Fourier coefficients.

The surface pressure is non-dimensionalized with respect to the inlet dynamic pressure, with the inlet freestream static pressure as the reference. The moment factor is the ratio of the unsteady moment with the adjacent blades oscillating to the mean of the steady moment when the blades are not oscillating, with all other parameters set at identical conditions.

Results and Discussion

Firstly the effect of stagger on surface pressure distribution will be considered. The effect of the phase difference between the oscillating blades will be considered next. Finally the effect of the input parameters on the moment factor is presented.

Effect on Surface Pressure

In order to ensure a nominal incidence on the rotating blades, the blade chords of an axial compressor are staggered with reference to the axial direction. For perturbations from the transverse direction, this results in a flow where only a fraction of the blade surface along the chord is influenced. The effect is augmented for higher stagger angles.
Figure 4 shows the variation of surface pressure coefficient for different staggers, all at the same reduced frequency ($k = 0.15$) and the neighboring blades oscillating in phase ($PD = 0^\circ$). In Fig.4(a), we can see that, for all cases, the effect of the oscillating blades is higher on the suction surface than on the pressure surface. This is due to the flow field having lower pressure near the suction surface. Further, in the lowest stagger case, the influence of the neighboring blades is maximum on the suction surface at a point near the leading edge. As the stagger increases this point shifts away from the leading edge, to almost up to the mid-chord. The magnitude of influence at this region is also significantly high at higher staggers.

The maximum unsteady pressure along the suction surface is seen to increase with stagger with the exception of stagger $30^\circ$. This irregularity is perhaps due to a momentary misalignment in the blade oscillation during the moment of blade oscillation, leading to a smaller amplitude of oscillation. This can be seen from diminished the pressure side response also. However, the occurrence of maximum unsteady pressure amplitude on the suction surface is in a region between that of stagger $15^\circ$ and $45^\circ$. Fig.4(b) shows the phase difference between the pressure signal and the displacement signal of blade $+1$. It is to be noted that this phase difference is between the specified pressure and the displacement of blade $+1$, and the notation PD is reserved for the phase difference between the displacement of blade $-1$ and blade $+1$. The phase angle is wrapped to within $\pm 180^\circ$. The figure therefore indicates that the suction surface is nearly in phase with the blade motion. And the pressure surface is nearly out of phase. This is evident when the position of the moving blade with respect to the reference blade is viewed (Fig.2). At a stagger of $30^\circ$, the point on the suction surface close to the leading edge is seen to be completely out of phase with the displacement of the adjacent blade.

The same plot is also shown for the case $k = 0.25$ for the same PD = $0^\circ$ in Fig.5. The primary observation by contrasting with Fig.4 is that the magnitudes of influence are now reduced with the trend essentially the same. The phase plots also show an identical trend.

Having considered the case with the neighboring blades oscillating in phase, we next see the case when they are oscillating out of phase at low and high reduced frequencies (Figs.6 and 7). Fig.6 shows the surface pressure distribution for the case similar to that of Fig.4, except the phase difference between the oscillating blades is $180^\circ$. The magnitude plot (Fig.6(a)) shows a similarity to the PD = $0^\circ$ case, except a reduced magnitude. Comparing the phase plots (Figs.4(b) and 6(b)), we see that the fact that the blades are nearly in phase with the blade oscillating adjacent to the respective surface, except near the suction side leading edges of the high stagger cases.

Figures 7(a) and (b) show the variation for the case $k = 0.25$ and PD = $180^\circ$. A prominent difference from the in-phase oscillation case is the presence of higher magnitude response on the pressure side of the reference blade. The phase plot shows a near-identical trend compared to the lower reduced frequency case.

In the present study, the local influence of adjacent blade motion is studied in terms of surface static pressure of the central blade, which is stationary. As the reference blade is stationary, it is not possible to comment on the aeroelastic stability of the system in terms of aerodynamic damping, as the work done on the blade is zero when it is not in motion. Also, the actual stability of a blade will be the sum of the influence of the motion from all the blades, summed accounting for their respective phases. However, from the presented results the regions of maximum unsteady pressure coefficient can be identified as the regions that are substantially influenced by the adjacent blade motion, and hence may be identified as a potential contributor to aeroelastic instability.

**Effect on Moment**

The effect of the parameters on the moment of the blade is considered here. Due to the effect of the neighboring blades oscillating in torsional mode, the torsional force on the stationary reference blade is of interest. To present all the results concisely, the results for the four staggers will be considered separately, comparing the effect of reduced frequency within each. This will be done for the moment magnitude and the phase difference with respect to blade $+1$.

Figure 8 shows the variation of the moment factor with the phase difference angle between the oscillating blades. The point at $0^\circ$ is also plotted at $360^\circ$ for better visualization. The asymmetry in the values about $180^\circ$ even in the zero stagger case is due to the camber of the blades. The key point of note is that there is a strong dependence of the integrated moment on the phase difference between the neighboring blades. A change in magnitude for the same PD between different staggers is also seen. The $45^\circ$ stagger case shows a significantly large magnitude compared to
the lower stagger cases. This can be attributed to the large variation in the magnitude of $C_p$ along the chord for this stagger (as seen in Fig.8(a)).

The phase difference of the moment loads is shown in Fig.9 for different stagger. The non-linear nature of the dependence on loading on inter-blade phase angle (Carta and St. Hilaire [11]), and therefore the phase difference PD is evident from the nature of the plots. It can be seen that for the highest reduced frequency considered ($k = 0.25$), the moment is leading the phase for nearly all cases. As the stagger increases, the amount of leading angle reduces considerably. The amount of leading or lagging has a direct bearing on the damping of a cascade in travelling wave vibrations. But the extent of influence depends on the magnitude of the loads at those conditions. Therefore, the phase and the magnitude plots have to be evaluated in unison.

**Conclusion**

Experiments are performed on a linear cascade with two oscillating airfoils adjacent to an instrumented airfoil. The unsteady loads and blade surface pressures are measured together with the reference blade displacement. The phase difference of the response with respect to the blade motion shows the extent of influence due to the specific conditions on a local region of the blade surface. The magnitude and phase of the influence is seen to depend on the geometry (stagger) along with the phase difference between the oscillating blade and frequencies. In case of staggered blades, the region of interest is confined to the portion of the blade that is adjacent to the oscillating surface. This results in a marked variation of the pressure influence, resulting in a large moment on the stationary blade.

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**References**


Fig. 1 Schematic of the Setup

Fig. 2 Details of the Nomenclature of Blades and Phase Angle Difference Definitions

Fig. 3 Photograph of the Test Section at 45° Stagger, Showing the Mounting of the Balance, and Point of Measurement of the Laser Displacement Sensor

Fig. 4 The Surface Pressure Coefficient on the Reference Blade for the Case $k=0.15$ and PD=0°, Showing the (a) Magnitude, and (b) Phase Difference
Fig. 5 The Surface Pressure Coefficient on the Reference Blade for the Case $k=0.25$ and $PD=0^\circ$, Showing the (a) Magnitude, and (b) Phase Difference

Fig. 6 The Surface Pressure Coefficient on the Reference Blade for the Case $k=0.15$ and $PD=180^\circ$, Showing the (a) Magnitude, and (b) Phase Difference

Fig. 7 The Surface Pressure Coefficient on the Reference Blade for the Case $k=0.25$ and $PD=180^\circ$, Showing the (a) Magnitude, and (b) Phase Difference
Fig. 8 Variation of the Magnitude of Moment Factor with the Blade Phase Difference Angle for the Staggers
(a) 0° (b) 15° (c) 30° and (d) 45°

Fig. 9 Variation of the Phase Difference of Moment Factor with the Blade Phase Difference Angle for the Staggers
(a) 0° (b) 15° (c) 30° and (d) 45°