Abstract

Vibration related issues like flutter can significantly limit the performance of aircraft engines and cause unwarranted cost and time overruns. The increased demand for more powerful yet compact engines has resulted in the use of relatively thin and long blade rows, which are more susceptible to such vibration related issues. Flutter refers to an aeroelastic instability in which the motion of the blade interacts with the flow to generate the unsteady fluid loads that can sustain or possibly grow its oscillations, which can ultimately lead to structural failure. The severe consequences that follow the phenomenon of flutter has triggered substantial interest in flutter studies. Linear cascades that represent a particular span section of the rotor have proven to be a reliable tool for such flutter studies. Although several studies pertaining to flutter have been reported in the literature, only a few of them have concentrated on linking the flutter characteristics to the corresponding unsteady flow field around the blade. With this in mind, in the present work, detailed experimental study of bending mode flutter in two representative cascades, one operating in stalled conditions at low Reynolds number ($\sim 10^4$) incompressible flow, and the other at transonic conditions has been carried out. The main focus of the work is on simultaneous measurements of flutter characteristics and the unsteady flow field around the blade that can help in understanding the unsteady flow features that contribute to flutter. The blade oscillations are forced and the flutter characteristics are deduced in terms of the energy transfer to the blade from the measured unsteady loads, and the flow field is measured with the help of PIV in both the cases, in addition to high-speed shadowgraphy for the transonic case.

In the low Reynolds number cascade case, three blades in the cascade were oscillated with arbitrary phase difference between adjacent blades referred to as Inter Blade Phase Angle (IBPA). The response of the flow to these imposed oscillations is measured in terms of unsteady loads on the central blade in the cascade, and this is used to quantify the mean energy transfer to the blade from the fluid over an oscillation cycle. The parameters varied in this case include the reduced frequency (k) (up to 0.1) and the Inter Blade Phase Angle (IBPA), the latter being varied from $+180^\circ$ to -180° in steps of 45°. The experiments were conducted at three different post stall incidence angles of the blades in the cascade to assess the influence of blade loading on flutter behaviour. In each case, IBPA and k have been varied and contours plots of the excitation have been obtained in the plane of IBPA and k, showing the region of excitation, with the results indicating that most of the excitation occurs around IBPA of $+90^\circ$. Fluid excitation at lower k values for specific IBPA cases of $+45^\circ$ and $+90^\circ$ was observed, indicating the influence of reduced frequency (k) and Inter Blade Phase Angle (IBPA) on cascade stability. Also, an increased blade loading is observed to significantly increase the extent of excitation or damping. To understand the contribution from oscillating adjacent blades, experiments involving a single blade oscillating in a cascade have also been performed. PIV measurements at different IBPA values show that there exists significant differences in the phase of the separated unsteady shear layer dynamics with respect to the blade motion between excitation (flutter) and damping (no flutter) cases. The PIV measurements also clearly show the effect of the time-varying inter-blade spacing on the shear layer dynamics, with the shear layer tending to separate at instances when there is a large inter-blade spacing, compared to the instances when the inter-blade spacing is small, this being important for cases with different IBPA values.

For the transonic cascade case, in order to facilitate flutter studies at flow conditions that are realistic to aircraft engine components, a new blow-down transonic cascade facility has been developed as part of the present work. The facility is equipped with a mechanism that can oscillate the central blade in the cascade at realistic reduced frequency (k) of about 0.1. The parameters varied in this case include the reduced frequency (k) up to 0.1 and the static pressure ratio (SPR) across the cascade. The SPR in these transonic cases alters the passage shock position, which is seen to have a large effect on the corresponding flutter characteristics of the blade. Four SPR cases of 1.05, 1.25, 1.35 and 1.55 are considered for flutter studies of which the first three have a passage shock, while the SPR = 1.55 case corresponds to an unstarted cascade with a detached shock at the leading edge. The experimental results indicate striking differences in the flutter behaviour between the started and unstarted cascade cases. While both the cases show excitation at lower k values ($k \approx 0.05$), in the unstarted cascade, an additional regime of huge excitation is observed at relatively higher k values, with the excitation values in this case being about an order of magnitude higher that that at lower k values. A large PIV data set has been obtained simultaneously with unsteady loads in select cases. High-speed shadowgraphy visualizations have also been carried out at different reduced frequencies for both a started cascade case with passage shock, and an unstarted cascade case with a detached leading edge shock. The results indicate that the shocks oscillate in response to the blade motions, with the phase between the shock motion and the blade motion being dependent on the reduced frequency and SPR. In particular, differences are seen in the phase of the shock motion with respect to the blade motion between the excitation and damping cases, and also between started and

unstarted cascade cases. These measurements also show striking differences in the shock phase between the two excitation cases of the unstarted cascade case, indicating differences in the underlying mechanisms responsible for the two excitation regimes observed at lower and higher frequencies, respectively. Specifically, when the blade is at the suction side extreme location, the detached leading edge shock is found to be located upstream of its mean location in the low frequency excitation case, while the shock is located downstream of the mean location at the higher frequency excitation regime.

In summary, the measurements indicate that the unsteady shear layer and its phase relation with the blade motion is the deciding factor for stall flutter at low Reynolds numbers, while it is the phase of the unsteady shock motions with respect to the blade motion that is crucial in the transonic cascade case.