AN INVESTIGATION OF THE EFFECT OF TIP VORTEX MASS INJECTION ON BLADE VORTEX INTERACTION

Frank N. Coton, Richard B. Green, Juliana Early and Wang Tongguang
Department of Aerospace Engineering
University of Glasgow
Glasgow, G12 8QQ

Abstract

This paper describes an experimental research programme to evaluate the potential of small blown jets to modify the core of the tip vortex trailed from a rotor blade. The objective is to demonstrate that the vorticity distribution in the core can be significantly altered in such a way that the peak velocities are significantly reduced and the core radius increased. Initially, Particle Image Velocimetry (PIV) is used to demonstrate and quantify the effectiveness of the technique. Subsequently, Blade Vortex Interaction (BVI) tests are conducted to simulate main rotor interaction by placing an instrumented blade in the path of the convecting vortex. By studying the interaction with and without the jets being activated, it is possible to assess the potential of the method to ameliorate unwanted BVI effects.

1. Introduction

A lifting surface of finite span produces trailed vorticity as a result of the spanwise loading distribution on the surface. Generally, this vorticity rolls up into a coherent tip vortex which can retain its structure for a considerable distance behind the lifting surface. If an object rapidly passes through or close to the vortex, the object interacts with the vortex in such a way that it is subject to unsteady fluctuating loads. For flight vehicles, these interactions create additional undesirable effects such as noise emission and structural vibration. When the lifting surfaces of helicopter rotor systems are involved, the phenomenon is termed Blade-Vortex Interaction (BVI) and occurs when the tip vortices trailed from the rotor pass close to, or impact directly with, any of the blades in the main rotor or tail rotor systems. In some flight conditions BVI can be particularly severe and is manifest as high-frequency impulsive loads on the rotor blades.

The importance of BVI has been recognised for many years and has been the focus of several experimental[1-4] and numerical[5,6] studies. Of these, most have concentrated on main rotor BVI although some, have considered the interaction of the main rotor wake with the tail rotor[7,8].

For almost as long as the helicopter has existed, there has been an impetus to reduce the aerodynamic noise which it produces. Much of the early research progressed on a trial-and-error basis because the basic noise generation mechanisms were not fully understood. As understanding of main rotor interactions developed, however, emphasis became centred on increasing the core size and reducing the core velocity of the tip vortex. In essence, the approach has been to effectively prematurely age the vortex. In recent years, this type of research has also been supported by interest from the fixed wing community in reducing the spacing between passenger aircraft to boost throughput at airports.

Basically, there are three mechanisms which result in vortex decay. The first, viscous diffusion, occurs naturally but at a rate which is too slow to prevent rotorcraft interactions from occurring. If, however, an effective means could be found to accelerate this process, significant benefits could accrue. The second mechanism is that of vortex bursting, or breakdown. In aeronautics this is, generally, identified with delta wing type flows and is associated with the body geometry and streamwise pressure gradients experienced by the vortex structure. Unfortunately, the conditions which result in the onset of breakdown do not occur naturally in the flow field of the helicopter tip vortex and could not easily be artificially introduced. The final mechanism which promotes vortex decay is through the amplification of natural flow instabilities such as the Crow[9] instability. Techniques which utilise this effect rely on introducing additional regions of discrete vorticity into the domain of the tip vortex to promote the instability.

Given the above, it is not surprising that much effort has been directed towards modification of the vortex structure at source. Many techniques, including active mechanical excitation of the Crow instability, have been used but the most promising methods so far fall neatly into two distinct categories. The first involves controlling the vortex structure by geometric definition of the blade tip profile. Several tip profile variants have been proposed as methods of either enlarging the vortex core or reducing core velocities. Others, such as the Subwing Tip[10] and the Westlands Vane Tip[11] have been shown to produce multiple cores which although resulting in multiple sub-interactions, reduce the overall severity of the gross interaction[12]. Generally, however, successful modification of the tip profile to reduce BVI has been accompanied by either a rotor thrust or drag penalty.

The second method of vortex control which has shown promise has been the use of some form of air injection at the blade tip[13]. Early studies of this type relied on high levels of blowing to achieve any significant levels of vortex control but more recent studies, using discrete jets, have demonstrated that significant changes can be made to the vortex structure with relatively low levels of blowing. For example, Gowanlock et al.[14], have recently shown that selective use of discrete jets oriented in the spanwise direction, can reduce the peak rotational velocities in the tip vortex by as much as 50% on a model rotor, even at blowing coefficients as low as $C\mu = 0.0033$. Similarly, Liu et al.[15] computed the benefits of blowing air at 5% of the freestream speed from a spanwise slot positioned near the tip trailing edge on the upper surface of a rotor blade. They postulated that pulsed blowing from this type of slot could be useful in reducing the higher harmonic loads and noise during a BVI encounter.

The present study also examines the potential to modify the tip vortex structure by air injection in the region of the blade tip. In this case, however, the air is injected both horizontally and vertically behind the tip trailing edge in an attempt to expand the vortex core during the roll-up phase. To examine the effectiveness of the technique, the vortex structure is interrogated using Particle Image Velocimetry (PIV) and it is shown that, not only is the core expanded, the peak rotational velocities are also reduced. The results from a second series of tests, where the vortex undergoes a parallel interaction with a stationary blade, are then presented. These results demonstrate that the severity of the interaction is reduced by the tip blowing.

2. Methods

The experiments were conducted in the Glasgow University 1.15m x 0.85m low speed wind tunnel. This is a closed return facility with a working section length of 1.8m and is capable of speeds up to 33m/s. The interaction vortex was produced using a single bladed rotor placed in the settling chamber of the wind tunnel[16]. The tip vortex system produced by this rotor has been shown, via hot-wire anemometry and PIV, to exhibit the same characteristic features as a helicopter main rotor[17] and so provided the basis for interaction studies. The design of the vortex generator has been previously detailed by Copland[16] but will, for convenience, be summarised here. The vortex generator is essentially a rotor of radius 0.75m that has a single rectangular planform blade of chord 0.1m with a NACA 0015 cross section. During rotation, the blade pitch is varied using a spring-loaded pitch link running on a cylindrical cam configured such that the blade pitch varies in four equivalent (90^o) phases of azimuth. The first phase sets the blade at zero incidence while the blade is pointing into the settling chamber (45^o azimuthal travel on either side of the wind tunnel centre line). In the next two phases of motion, the blade is pitched from zero to 10^o, before traversing the working section at a constant 10^o incidence. In the final 90^o phase, the spring loaded pitch link forces the blade to overcome its aerodynamic and inertial loads and follow the cam as it returns to zero degrees.

The rotor assembly is mounted on a vertical rotating shaft that is supported by bearings which are installed in an external framework above and below the wind tunnel contraction. Also located on this framework is a DC electric motor that is used to drive the rig. During operation the rotational speed is monitored by an optical sensor located on the main shaft. The rotor assembly is shown in Fig. 1. Where it may be observed that, during operation, the rotor shaft is enclosed by aerodynamic fairings.

The air required for the tip injection system is supplied from the laboratory compressed air supply and is piped to a rotating valve mechanism at the top of the rotor shaft. An air pipe then leads from this valve through the hollow rotor shaft and out to the blade itself as shown in Fig. 2.

Fig. 1. Vortex Generator in Settling Chamber

Fig. 2. Air supply pipe entering blade

The particular blade used in this study was specially constructed to include internal ducting to carry the air to the tip jets. The tip jet arrangement consisted of a cylindrical extension tube of diameter 6.5mm and length 8mm that protruded from the tip trailing edge. The air jets emanated from four holes of diameter 0.79mm spaced at 90 degree intervals around the tube. The tip extension is shown in Fig. 3.

Measurements of the convecting tip vortex were made using a particle image velocimetry (PIV) system based on a Spectra-Physics Nd:Yag laser. By operating the laser in a double-pulsed mode, two images of the flow field can be obtained with very small time separation (35μs). A standard cross-correlation and sub-pixel peak detection routine can then be used to determine the mean velocity at various locations in the region of interest. The flow was seeded with 1-2μm oil smoke particles distributed throughout the flow. The laser light was passed through an optical arrangement which converted the beam into a laser sheet which was passed through the working section and illuminated the flow seeding. The particle displacements could then be recorded using a Kodak Megaplus ES 1.0 camera of 1k x 1k resolution. Further details of the PIV system used in this study are presented in Ref. 18.

Fig. 3. Tip jet arrangement

The vortex generator produces a curved, three-dimensional vortex that convects through the wind tunnel working section. A NACA 0015 blade of chord 152.4mm and overall span 944mm was placed in the path of the convecting vortex during the second phase of the work in order to study the interaction of the vortex with the blade. The blade, which was set at zero incidence, was instrumented at 78.5% span with a chordal array of 30 miniature Kulite pressure transducers mounted around the surface of the blade. The transducers were connected to surface orifices of 1mm diameter. Pressure data for each transducer were recorded using a BE256 data logger at 20 kHz sampling rate. For each case, sixteen phase locked blocks of 2018 samples per transducer were collected. The data presented in this paper represent the average of the sixteen cases. As shown in Fig. 4, the blade was mounted horizontally from a support structure located on the side wall of the wind tunnel working section that allowed the blade to be raised and lowered. The blade extended into the working section such that the transducer array was located at 225mm from the tunnel centreline (Fig. 5). Previous hot-wire measurements[17] have shown this location is well outside the turbulent wake of the vortex generator support shaft.

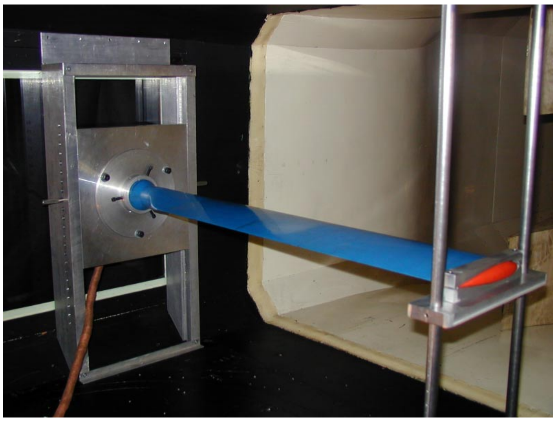

Fig. 4. Blade support structure

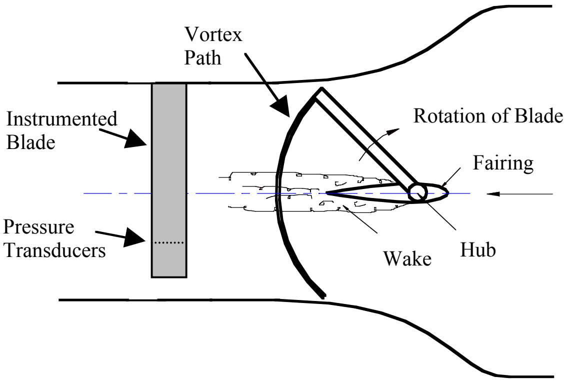

Fig. 5. Schematic of test set-up

For all tests the freestream velocity was fixed at 20m/s and the rotational speed of the vortex generator was 540 RPM. These settings had been previously identified by Doolan et al.[19] to provide a clear, well defined tip vortex structure in the working section which is parallel to the blade leading edge at the measurement location. Based on these conditions, the nominal interacting blade Reynolds number was 2×10^5.

3. Flowfield Measurements

The first series of tests involved examining the effect of the tip jets on the cross sectional structure of the tip vortex. To do this, PIV measurements were made in the working section of the wind tunnel for the baseline case of no blowing and with blowing on. No direct measurements of the blowing coefficient were made for the rotating blade but measurements on a stationary wing showed a similar effect on the tip vortex to that discussed below, with a momentum blowing coefficient of around $c\mu = 0.004$.

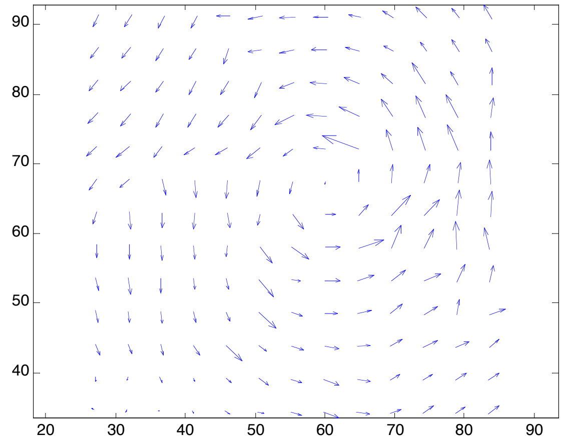

Fig. 6a. Vortex velocity distribution (no blowing)

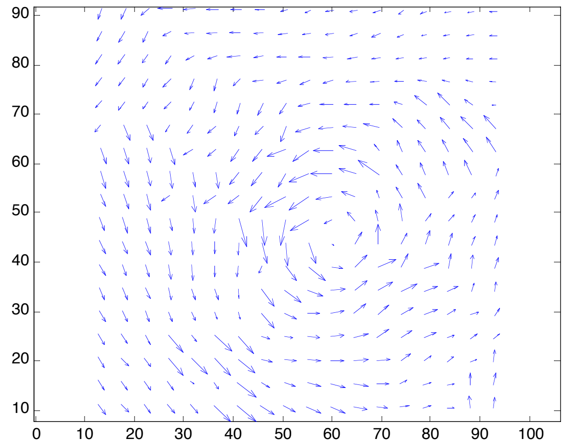

Fig. 6b. Vortex velocity distribution (blowing on)

A cross-sectional view of the tip vortex velocity field for the baseline case is presented in Fig. 6a. In this figure the mean flow velocity has been removed to allow the structure of the vortical flowfield to be more clearly displayed. As may be expected, given the manner in which the vortex was generated, the flowfield is not entirely symmetrical but, nevertheless, the tip vortex clearly dominates the image. A similar general pattern is evident in Fig 6b where the flowfield corresponding to the blowing case is presented. This time, the number of velocity vectors plotted is higher although the flowfield apparently exhibits the same basic features as before. In fact, the peak velocity in this case is 7.2m/s compared with 9.61m/s in the baseline case and this peak velocity is located further from the centre of the vortex indicating that the vortex core diameter may also have increased.

Further information on the effect of the blowing on the vortex core may be obtained when the vorticity levels are compared. Figure 7 shows the distribution of vorticity in the vortex core in the baseline case compared with that in the blowing case. It is immediately obvious, from this figure, that the peak vorticity levels in the vortex core are consistent with the trend in tangential velocity and have been greatly reduced as a result of blowing.

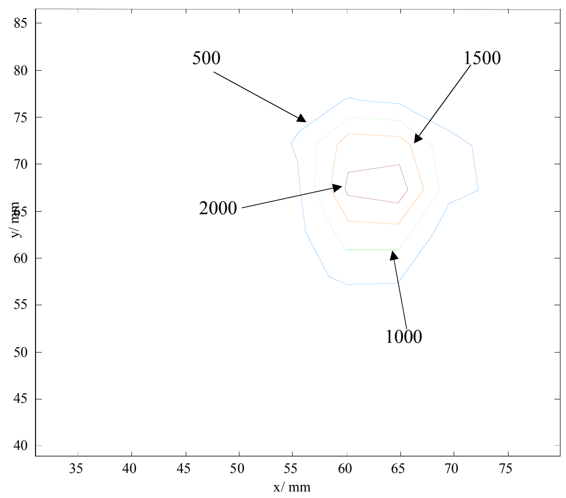

Fig. 7a. Vortex vorticity field (no blowing)

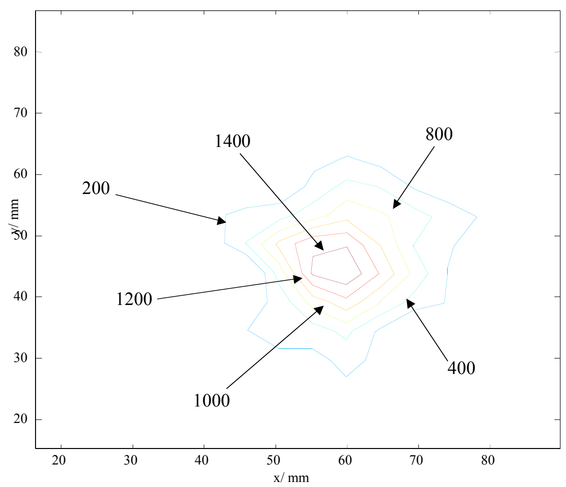

Fig. 7b. Vortex vorticity field (blowing on)

4. BVI Experiments

During the blade vortex interaction experiments, the blade was initially located 20mm below the anticipated location of the vortex core and then moved upwards in 10mm steps towards and through the core position. During interaction, the pressures were measured at 30 chordal locations and these pressures were then integrated to give the normal force coefficient, Cn.

Figure 8a shows the variation of normal force 20mm below the nominal core location for the baseline condition and with the blowing switched on. This figure illustrates the typical Cn behaviour during the interaction. Initially, the blade experiences an upwash as the vortex approaches its leading edge. This upwash produces a gradual rise in Cn. When the vortex passes over the leading edge and moves past the quarter chord, the Cn drops dramatically as the the leading edge becomes exposed to downwash and the trailing edge to upwash. Subsequently, as the vortex passes over the remainder of the chord and further downstream, the Cn gradually recovers to its pre-interaction level.

For the blade positioned at 20mm below the nominal core location, the two Cn curves are very similar with the only significant differences apparent prior to the interaction. These differences are most likely due to wander in the vertical position of the vortex produced by the generator. It is, however, interesting that the magnitude of the gradient of the Cn response during interaction is slightly greater when the blowing is on.

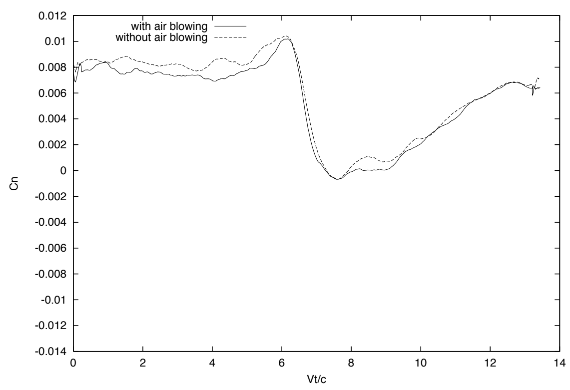

Fig. 8a. Normal force coefficient response during BVI for blade 20mm below nominal core location

As the blade is moved closer to the vortex in Fig. 8b (10mm below), the severity of the interaction increases. The magnitude of this increase is, however, noticeably reduced by the blowing. In particular, the drop in Cn as the vortex passes over the leading edge region is short-lived in comparison to the non-blowing case. There is also a slight reduction in the gradient of the Cn drop during the interaction.

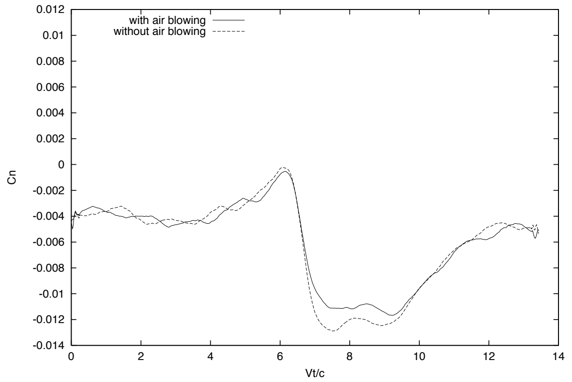

Fig. 8b. Normal force coefficient response during BVI for blade 10mm below nominal core location

A further 10mm increase in blade height again produces a similar effect (Fig. 8c) with both the magnitude and gradient of the Cn response during interaction being reduced. This blade position corresponds to the nominal vortex core location.

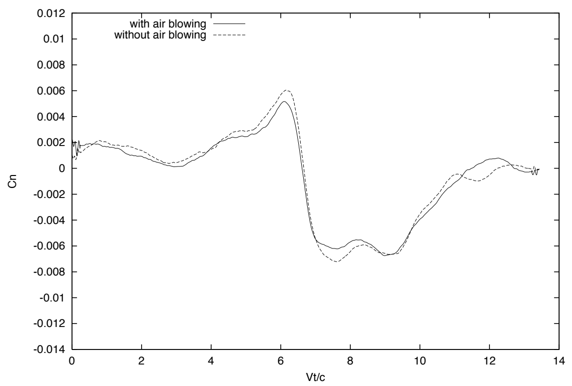

Fig. 8c. Normal force coefficient response during BVI for blade at the nominal core location

Figure 8d, with the blade located 10mm above the nominal vortex core location, exhibits the most severe Cn response of all the blade positions for both the baseline and the blowing case. Interestingly, however, there is little difference in this case between the baseline and the blowing cases either in terms of the magnitude of the Cn response or its gradient.

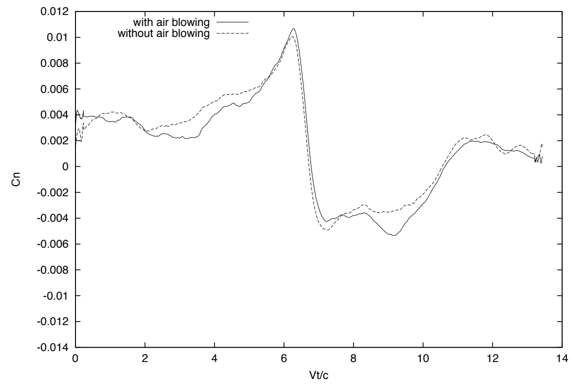

Fig. 8d. Normal force coefficient response during BVI for blade 10mm above nominal core location

Finally, the Cn responses for the blade positioned 20mm above the nominal vortex core are presented in Fig 8e. In a similar manner to the 20mm below case, the major differences in the two curves occur during the early stages of the interaction.

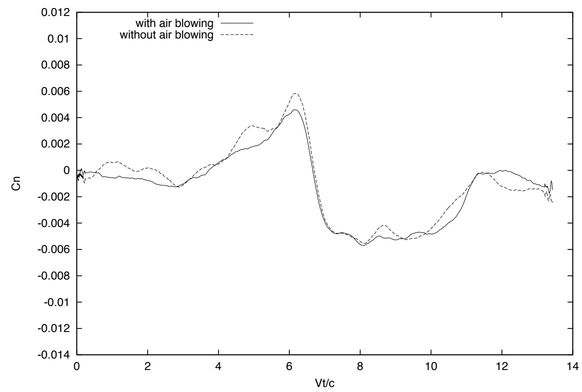

Fig. 8e. Normal force coefficient response during BVI for blade 10mm above nominal core location

The severity of a blade vortex interaction may be characterised both in terms of the magnitude of the response and rate of change of the loading during the interaction. For the data presented in Fig. 8, the magnitude of the response has been determined by evaluating the absolute difference, ΔCn, between the maximum and minimum Cn values in each case. The variation of this ΔCn parameter with blade position is presented in Fig. 9 for both the baseline and blowing cases.

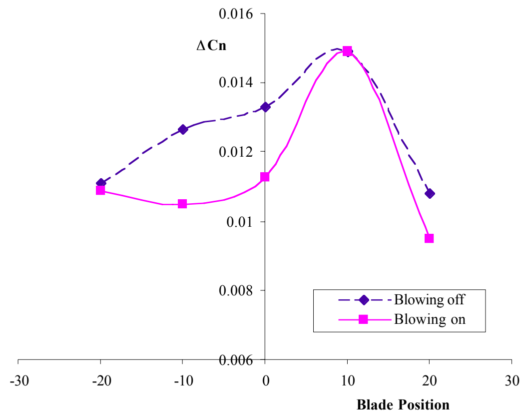

Fig. 9. Variation of peak Cn response with blade position

In general terms, the ΔCn associated with the interaction is reduced by the tip blowing. This is particularly true when the blade is positioned at or slightly below the nominal vortex core location. At these locations the magnitude of the reduction produced by the blowing is of the order of 15%. In contrast, however, the magnitude of the peak interaction, which as indicated earlier occurs when the blade is positioned 10mm above the nominal core location, appears to be unaffected by the blowing. It should be noted that this location is approximately one core radius from the nominal vortex centre.

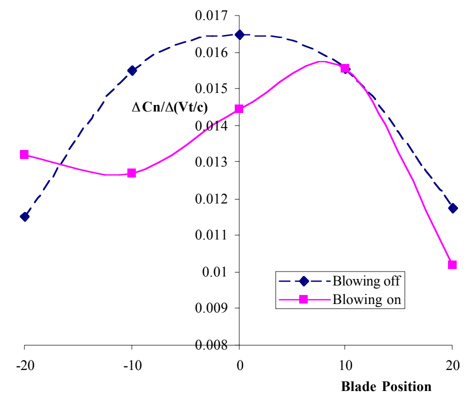

Fig. 10. Variation in interaction gradient with blade position

The variation in the peak rate of change of Cn with respect to non-dimensional time, for the range of interaction cases, is presented in Fig. 10. Interestingly, for the baseline case, the highest rate of change is experienced when the blade is located at the nominal core location. In fact, the curve is almost symmetric about this location. This behaviour is entirely consistent with that expected on the basis of simple vortex theory. The same cannot be said for the blowing case where the highest rate of change occurs when the blade is 10mm above the nominal core location and the curve exhibits no symmetry whatsoever. This may suggest that, despite positioning the air jets at 90 degree intervals around the tip extension, their effect on the vortex structure is not symmetric. In fact, given the asymmetry of the original baseline vortex, as indicated by the PIV images, this is not entirely surprising. Importantly, however, the effect produced by the tip blowing is to reduce the Cn gradient in most cases. In this respect, the result obtained when the blade was located 20mm below the nominal core location is somewhat anomalous but is inevitably associated with the manner in which the flowfield is distorted by the tip blowing.

It should be noted that the vortex core location was observed to wander by up to two core diameters between tests. The fact that the results presented here for each of the cases are an average of sixteen individual tests will, to some extent, remove the influence of the wander. Nevertheless, it cannot be assumed that the results are entirely free from this effect and it is also debatable whether the averaged results are entirely representative of the true interaction. Generally, however, it appears that the use of tip air jets may have the potential to ameliorate BVI. The present data indicate that changes can be made to the BVI response with relatively low levels of mass injection. Further work is required to establish the sensitivity of this effect to parameters such as jet diameter and velocity and also how the effect changes as the blowing coefficients are altered. In addition, the effect of tip blowing on the rotor torque and thrust needs to be investigated although, in the present case, there appeared to be no effect on the rotor torque produced by the blowing.

5. Conclusions

A series of experiments have been conducted in a low speed wind tunnel to assess the potential effect of tip air jets on blade-vortex interaction.

It has been shown that the severity of the interaction, in terms of both the magnitude of the response and the rate of change of loading, can be influenced by a relatively small amount of blowing. Generally, the effect of the tip blowing is beneficial in that it acts to reduce the severity of the interaction.

Acknowledgements

The authors wish to express their thanks to the following individuals who have in some way contributed to the present work: Dr. Con Doolan, Mr. R. Gilmour, Mr. B. Montgomery, Mr. S. Lawson, Mr. R. Cannon and Mr. R. Henderson.

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