Applied Acoustics 76 (2014) 359–365

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Damping of flexural vibrations in turbofan blades using the acoustic black hole effect

E.P. Bowyer, V.V. Krylov *

Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Received 13 December 2012
Received in revised form 25 August 2013
Accepted 4 September 2013
Available online 26 September 2013

Keywords:
Vibration damping
Turbofan blades
Acoustic black hole effect
Wedges of power-law profile

ABSTRACT

The results of the experimental study into the damping of flexural vibrations in turbofan blades with trailing edges tapered according to a power-law profile are reported. Trailing edges of power-law profile (wedges), with small pieces of attached absorbing layers, materialise one-dimensional acoustic black holes for flexural waves that can absorb a large proportion of the incident flexural wave energy. The experiments were carried out on four model blades made of aluminium. Two of them were twisted, so that a more realistic fan blade could be considered. All model blades, the ones with tapered trailing edges and the ones of traditional form, were excited by an electromagnetic shaker, and the corresponding frequency response functions have been measured. The results show that the resonant peaks are reduced substantially once a power-law tapering is introduced to the blade. An initial study into the aerodynamic implications of this method has been carried out as well, using measurements in a closed circuit wind tunnel. In particular, the effects of the trailing edge of power-law profile on the airflow-excited vibrations of the fan blades have been investigated. It has been demonstrated that trailing edges of power-law profile with appropriate damping layers are efficient in reduction of the airflow-excited vibrations of the fan blades. The obtained results demonstrate that power-law tapering of trailing edges of turbofan blades can be a viable method of reduction of blade vibrations.

1. Introduction

One of the major causes of turbofan blade failure in jet engines is the flow-induced vibrations of the blades resulting in their high cyclic fatigue [1]. The reduction of blade vibrations would bring lower stress levels into the blade and ultimately a longer fatigue life. Vibrations in fan blades arise as a result of the combination of many vibration sources. One of the main contributing sources is that caused by a fluctuating lift force that acts on the blade aerofoil as it rotates. Other sources include atmospheric turbulence and viscous wake interaction along with turbulence from the engine mechanical components. All these factors result in generation of fan blade vibrations at a variety of resonant frequencies that are dependent on engine design. For that reason, a frequency specific damping system cannot be successfully implemented. Therefore, a broadband frequency damper would be an ideal solution as it would allow for variation in resonant peak frequencies brought about by varying engine designs.

There are two widely used methods of damping structural vibrations. The first one is based on the addition of layers of highly absorbing materials to the surface of the structure in order to increase energy dissipation of propagating (mostly flexural) waves [2–4]. The second method provides the suppression of resonant vibrations of finite structures via reducing reflections of structural waves from their free edges [2,5]. There are also several specific damping methods used on jet engine fan blades, each presenting individual problems. Amongst these methods are slip damping, gas damping, and damping wires [6,7].

A new method of damping flexural vibrations based on the so-called 'acoustic black hole effect' for flexural waves in wedge-like structures has been recently developed and investigated [8–10]. This method has been initially applied to one-dimensional plates of power-law profile (wedges), the tips of which having to be covered by narrow strips of absorbing layer [8,9]. Ideally, if the power-law exponent is equal or larger than two, the flexural wave never reaches the sharp edge and therefore never reflects back [8–11]. With the addition of small pieces of absorbing materials helping to overcome problems associated with the geometry of real manufactured wedges, this constitutes the acoustic black hole effect. It has been established theoretically [8,9] and confirmed experimentally [10,12–15] that this method of damping structural vibrations is very efficient. It has been also pointed out [10] that this method can be easily incorporated into existing designs of turbofan blades by modifying the natural taper that is already present at the trailing edges of existing turbofan blades.

* Corresponding author. Tel.: +44 1509 227216.
E-mail address: V.V.Krylov@lboro.ac.uk (V.V. Krylov).

0003-682X/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apacoust.2013.09.009

This paper describes the results of the experimental investigation of damping flexural vibrations in model turbofan blades with their trailing edges modified to have the power-law shapes, following the idea proposed in [10]. Such trailing edges materialise one-dimensional acoustic black holes for flexural waves, and they are expected to result in substantial reduction in wave reflections from the edges and in efficient suppression of resonant vibrations of the blades. All model blades, the ones with tapered trailing edges and the ones of traditional form (reference samples), were excited by an electromagnetic shaker, and the corresponding frequency response functions have been measured. An initial study into the aerodynamic implications of this method has been carried out as well, using measurements in a closed circuit wind tunnel. In particular, the effects of the trailing edge of power-law profile on the airflow-excited vibrations of the fan blades have been investigated.

2. Manufacturing of experimental samples

Four model fan blade samples were machined out of aluminium block, Fig. 1(a), using a CNC (Computer Numerically Controlled) milling machine operating at a cutter speed of 1200 rpm. The NACA 1307 aerofoil was used as a base model and then manipulated to form non-engine-specific model fan blades, Fig. 1(b). Two of the samples were then twisted, so that the effect of adding an acoustic black hole onto a more realistic fan blade could be considered. The dimensions of the fan blade are given in Table 1. When a twist was added to the blade, this was done after manufacturing of the blade and the modified trailing edge.

The main problem encountered when utilising this method of manufacturing was the complexity of the aerofoil combined with the modified trailing edge (a wedge of power-law profile). Recreating identical twists in the blade was also difficult. The four manufactured samples used for testing consisted of a straight reference fan blade (Fig. 2(a)), a straight fan blade with a trailing edge (wedge) of power-law profile (Fig. 2(b)), a twisted reference fan blade (Fig. 2(c)), and a twisted fan blade with a trailing edge (wedge) of power-law profile (Fig. 2(d)).

3. Experimental set up

Two experimental set ups were utilised in the acquisition of results of this investigation. The first one was used to acquire a vibration response. This set-up has been designed to allow nearly free vibration of the sample blades and to introduce minimal damping to the system, see Fig. 3(a). The excitation force was applied centrally on the blade using an electromagnetic shaker via 'glue' and fed via a broadband signal amplifier. The response was recorded by an accelerometer (B&K Type 4371) attached to one surface, directly in line with the force transducer (B&K Type 8200), also attached using 'glue', Fig. 3(b). The acquisition of the point accelerance was utilised using a Bruel & Kjaer 2035 analyser and amplifier. A frequency range of 0–9 kHz was used.

Table 1
Blade dimensions.

Length	Root chord	Tip chord	Twist angle	Wedge length
300 mm	100 mm	120 mm	11°	43.5 mm

The second experimental set up utilised a closed circuit wind tunnel to produce flow visualisation diagrams of the fan blades when placed in an airflow, Fig. 4. The wind tunnel was run at its maximum speed of 30.4 m/s. Although this speed is not a true representation of normal jet engine flow speed, it is sufficient to get some important information on the effect of power-law profile of the trailing edge on the blade aerodynamic performance, especially at engine start/wind up.

In order for the white flow visualisation patterns to be clearly visible on the final photographs, the blades were spray painted black. The samples were secured in the working section of the wind tunnel, and the flow visualisation fluid painted on to the blade. The wind tunnel was then ran up to speed and the flow was allowed to stabilize. At this point, with the tunnel still running, a still was taken of the blade. This process was performed on the top and underside of the blade and at 0° and 10° to the airflow.

For both experiments, the damping layer attached to the trailing edge of power-law profile consisted of a single 40 mm × 300 mm piece of ducting tape attached to the profiled side of the wedge. This damping layer had a loss factor of 0.06.

4. Results and discussion

4.1. Introduction of a trailing edge of power-law profile to a straight fan blade

This section considers the introduction of a trailing edge of power-law profile to a model fan blade and examines whether this could produce an 'acoustic black hole effect', as seen in previously tested steel plate samples [14]. Two types of samples were tested: a straight reference blade and a straight blade with a machined trailing edge of power-law profile (one-dimensional (1D) 'acoustic black hole'). As discussed in the introduction, it has already been ascertained that an additional damping layer is required to provide an 'acoustic black hole effect', therefore all samples with trailing edges (wedges) of power-law profile also had a damping layer attached to the wedge tips.

A comparison of a straight blade with and without a power-law profile at the trailing edge is shown in Fig. 5. Like in the previous work [14], the addition of a power-law profile to the trailing edge of an aluminium fan blade shows the same trends that were seen in steel plates. There is no difference between the two samples below 1.4 kHz. After this point, an increase in the reduction of the resonant peaks is seen up until a maximum reduction of 12 dB from the reference sample at 4.2 kHz. Above this frequency the

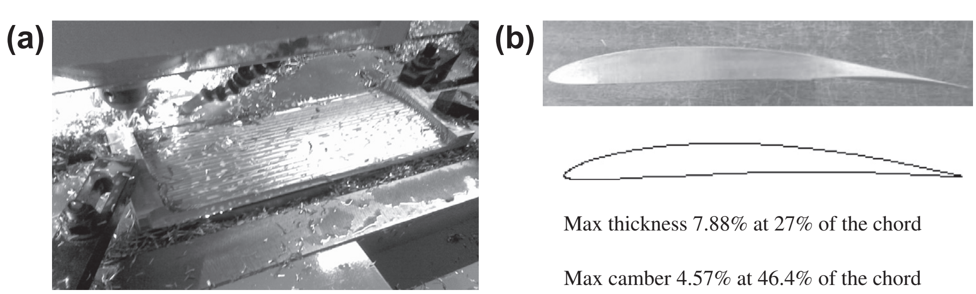

Fig. 1. Model fan blades: manufacturing of a fan blade (a), fan blade profile with (top picture) and without (lower picture) tapering according to the power-law geometry (b).

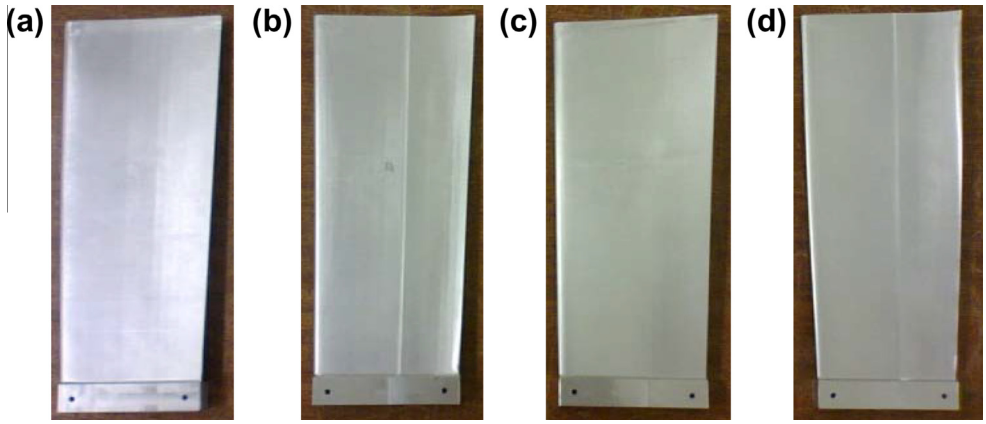

Fig. 2. Experimental samples: (a) reference fan blade – straight, (b) fan blade with power-law wedge – straight, (c) reference fan blade – twisted, and (d) fan blade with power-law wedge – twisted.

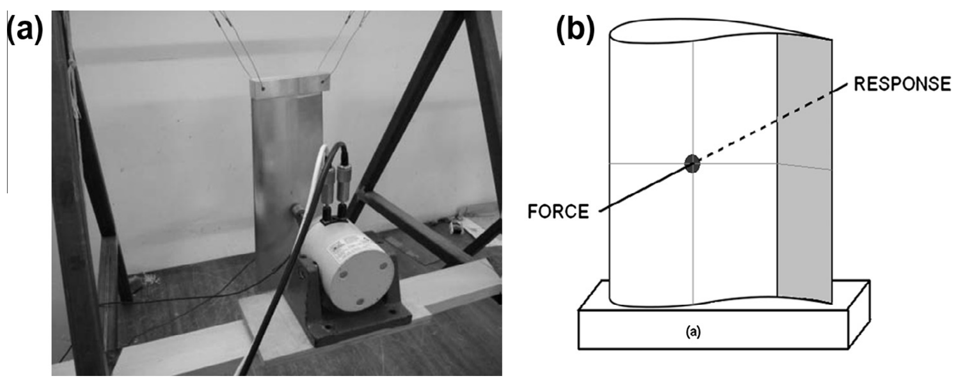

Fig. 3. Experimental set up (a), locations of the shaker (Force) and of the accelerometer (Response) on an experimental sample (b).

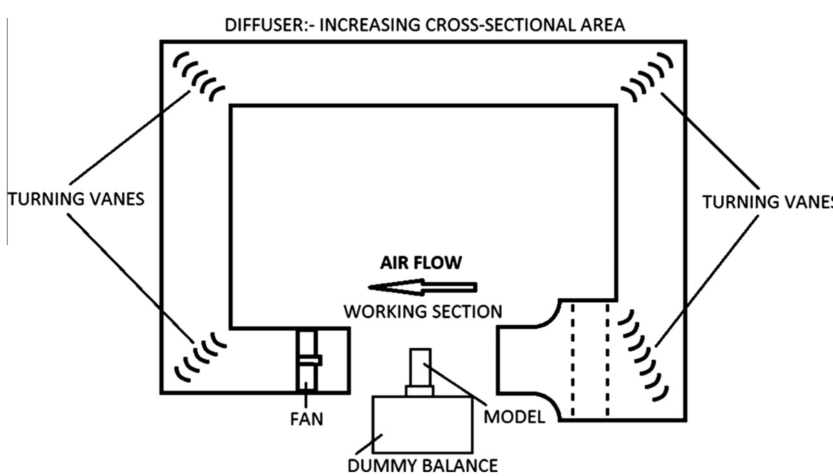

Fig. 4. Closed circuit wind tunnel.

response is smoothed, with resonant peaks heavily damped if not completely removed.

4.2. Introduction of a trailing edge of power-law profile to a twisted fan blade

After observation of the promising results for a straight fan blade described in the previous section, the next step was to introduce a power-law profile onto a trailing edge of a twisted (11°) blade and compare the results with those for a twisted reference blade. The straight and twisted reference blades where also compared. Needless to say that a twisted blade more accurately represents the real world engine fan blades these samples are emulating. This section thus looks at the combined effect of the addition of a power-law profile and twisting of the blade on the damping performance of the samples.

Fig. 6 shows the measured accelerance for a twisted reference blade compared to a straight reference blade. Below 1 kHz there is correlation in the resonances, however after this there is little to no duplication of resonant frequencies. The reason for this is

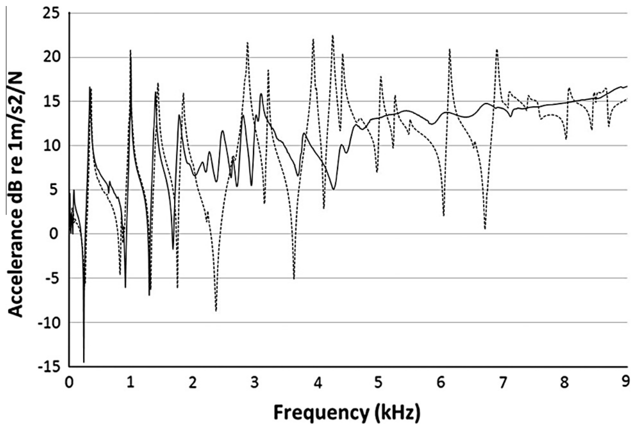

Fig. 5. Measured accelerance for a reference fan blade (dashed line) compared to the case of a fan blade having a wedge of power-law profile with damping layer (solid line).

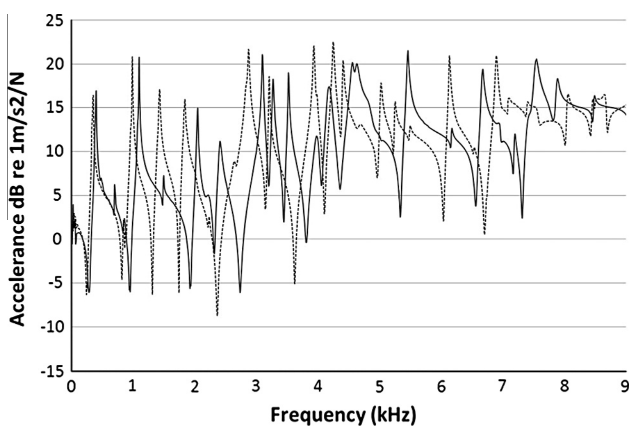

Fig. 6. Measured accelerance for a reference fan blade – twisted (solid line) compared to the case of a reference fan blade – straight (dashed line).

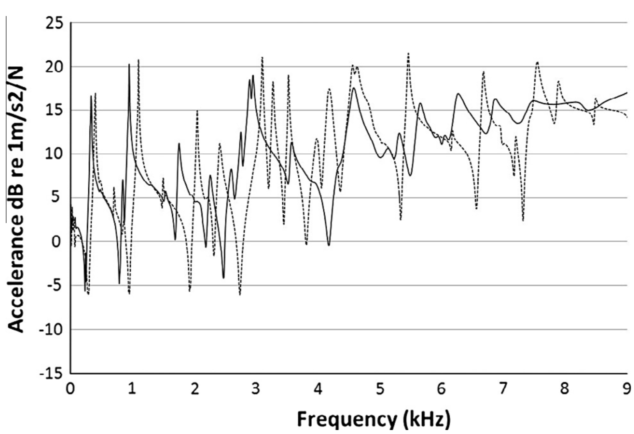

Fig. 7. Measured accelerance for a reference fan blade-twisted (dashed line) compared to the case of fan blade having a wedge of power-law profile with damping layer-twisted (solid line).

that twist in the blade modifies the plate modes, that are no longer pure flexural, resulting not only in peak shifts but in entirely different resonances. This observation confirms the need for the experiments on twisted fan blades in order to investigate whether the damping method based on the acoustic black hole effect can be applied to a more realistic blade structure.

Fig. 7 shows the results for the twisted reference blade compared to the twisted blade with a trailing edge of power-law profile. It can be seen that a damped response similar to that observed for the straight blades is clearly viable. Below 1.4 kHz there is little to no damping, although an obvious peak shift is already visible. Between 1.4 and 6.8 kHz there are reductions in the resonant peaks of 3–10 dB, with some resonances damped completely. A maximum reduction of 10.5 dB from the reference plate by the profiled sample can be seen at 4.1 kHz. After 6.8 kHz the response is smoothed, with resonant peaks heavily damped if not completely removed.

The observed fact that the effect of the power-law profile trailing edges on the straight blade is more visible than on the twisted blade (see Figs. 5 and 7) can be explained by the coupling of flexural and in-plane vibrations in twisted blades. As a result of such coupling, pure flexural waves do not exist in twisted blades. Instead, quasi-flexural waves generated by an electromagnetic shaker contain a significant proportion of the wave energy that is associated with in-plane vibrations. This part of the wave energy is not influenced by the acoustic black hole effect, which takes place for pure flexural waves only [8,9]. Therefore, the reduction of the reflection coefficient of such complex waves containing both flexural and in-plane displacements from the power-law profile trailing edges is smaller than in the case of straight blades. This makes the effect of the power-law profile trailing edges on the straight blade more visible.

In order to ascertain that all the damping seen in the blades was due to the combined effect of the trailing edge (wedge) of power-law profile and of the damping layer, and not due to the damping layer alone, the twisted reference blade was tested with and without a damping layer, and the results were compared. Fig. 8 shows the results for the comparison of the twisted reference blade with and without a damping layer. Below 2 kHz little to no damping is seen. The next resonant peak at 2.4 kHz shows the maximum reduction of 3 dB by the reference blade with the damping layer. After this frequency, there is just a minor reduction of the peak amplitudes for the reference plate with damping layer, by about 1 dB over the remainder of the frequency range. This result confirms unequivocally that the substantial damping seen above in the power-law profiled blade samples is due to the effect of a one-dimensional acoustic black hole.

4.3. Flow visualisation for a fan blade with a trailing edge of power-law profile

This section describes the results of the flow visualisation for the straight fan blade. The fan blade was at an arbitrary incline

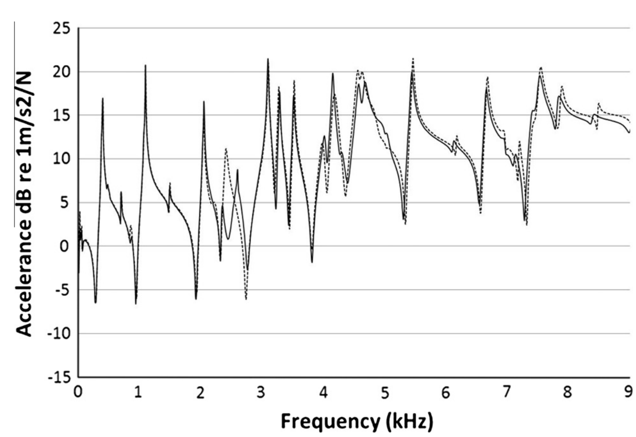

Fig. 8. Measured accelerance for a reference fan blade (twisted) with a damping layer (solid line) and without a damping layer (dashed line).

of 10° to the airflow. The aim of this investigation was to prove that, with adaptation of the damping layer attached to the wedge of power-law profile, the airflow over the underside of the blade could be returned to a similar state as that seen for the reference blade.

Fig. 9 shows the progression of the flow visualisation tests from a reference fan blade to a fan blade with a trailing edge of power-law profile and a specifically shaped damping layer. Looking at the reference fan blade (Fig. 9(a)), one can see that the flow visualisation shows a laminar flow across the blade surface, with no separation. The effects on the airflow of the presence of the power-law trailing edge are immediately obvious (Fig. 9(b)) from the flow visualisation. It shows a clear transition line and lamina separation bubble, and the flow then reattaches towards the trailing edge of the blade.

The same type of the damping layer, as used in the vibration test above, was then attached, and the test was carried out. From Fig. 9(c), a clear line of transition can be seen between the upstream laminar flow and the turbulent flow after the start of the damping layer. This flow is too turbulent to reattach to the blade. It is worth noting that with the damping layer attached in this way there is a step between the blade surface and the damping layer. This step is responsible for the increased turbulence of the airflow in the profiled area.

One could expect that any deviation in profile from the original design specification of the blade will not only have the increased turbulence and increased drag, as seen above. It will also result in lower efficiency and will also affect the airflow into the next stage of the engine. An obvious possible solution to the flow turbulence problem seen in Fig. 9(b and c) would be to recreate the flow pattern seen in Fig. 9(a), i.e. the original profile of the blade has to be restored. One method of partly achieving this is to shape the damping layer in order to recreate the original profile. This was achieved by building up layers of the damping material which, when covered by a layer of damping material of the same width as the wedge, would reproduce the original profile. The final diagram (Fig. 9(d)) shows the resultant flow over the blade with this shaped damping layer. There is still a clear line of transition but the flow quickly reattaches to blade. This line of transition will always be seen with the ridge at the edge of the damping layer. This result shows that if the damping layer could be more effectively blended into the blade the line of transition would disappear and a laminar flow would cover the blade.

One should keep in mind that, although for the experimental model samples described above the damping tape can be attached as strips of visco-elastic polymeric layer, this would not be practical for a real world jet engine due to high temperatures of the airflow. It would be more realistic therefore to incorporate a different type of damping layer in this case. One possible solution to the above-mentioned transition problem and the one just mentioned would be a shaped layer made of an alloy with a greater loss factor that could be cast on to the blade at manufacture [10], thus ensuring a strong bond and continuous surface with no transition visible between the blade and damping layer.

4.4. Investigation of airflow-excited vibrations of the fan blades

In order to gain an insight into the effects of the trailing edge of power-law profile on the airflow-excited vibrations of the fan blades, the blades were placed in the airflow and their vibration response was recorded in terms of acceleration. The blades were tested at 0° and 10° of incidence to the airflow. The attached damping layer was of the 'built up' type, to reshape the blade profile as described previously. The more realistic twisted fan blades were used for this investigation.

Again, the wind tunnel was run at a maximum speed to give the fastest airflow possible. Although this air speed is not representative of actual engine speed, it can allow for initial conclusions to be drawn and for insight to be given into the periods of start-up and run-down on a jet engine. As it is known from the literature, the periods of start-up and run-down cause significant vibration and fatigue of the fan blades.

The first thing to note is that, as expected, the greater the angle of incidence to the airflow, the greater the amplitude of the response. This can be seen from Fig. 10, where a comparison of the reference blade is made at 0° and 10° of incidence to the airflow. This result is also compared to the response of the bench to the airflow, thus allowing for confidence in the responses being emanated from the samples and not the bench.

Indeed, there are two resonances visible in the fan blade samples: one at 60 Hz and one at 350 Hz, the bench has only one at 60 Hz. The blade inclined at 10° shows an increase in response of 0.8 m/s^2 and 0.7 m/s^2 respectively at each resonance, when compared to the blade at normal incidence. Although the bench resonance corresponds to the first resonance seen in the other two samples, the amplitude of the response is negligible in comparison to the responses from the fan blades. It can therefore be concluded that the resonances seen are those of the blade and not of the bench. The subsequent results in this section show the responses of the blades inclined at 10° to the airflow. The blades at normal incidence follow the same trends, but with a lower amplitude response.

Fig. 11 shows a comparison of the vibration responses for a twisted fan blade having a trailing edge of power-law profile inclined at 10° to the airflow, with and without a built up damping layer. The blade with a built up damping layer shows a reduction

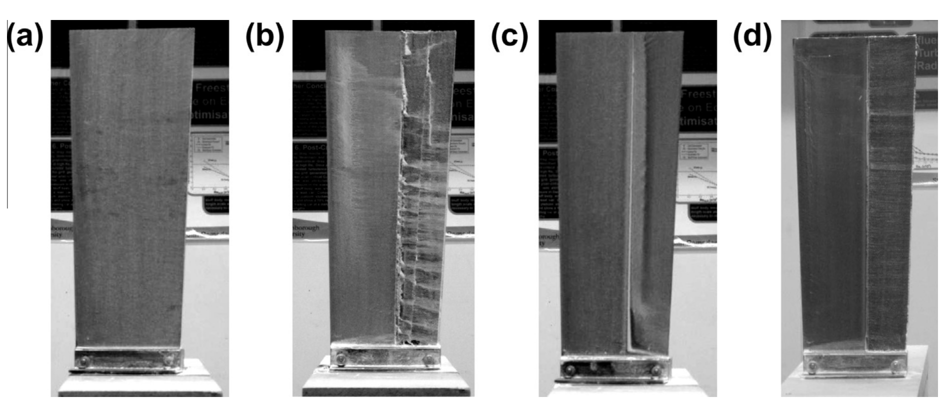

Fig. 9. Flow visualisation diagram for: (a) reference fan blade, (b) fan blade with a power-law wedge, (c) fan blade having a power-law wedge with a single damping layer, and (d) fan blade having a power-law wedge with a shaped damping layer.

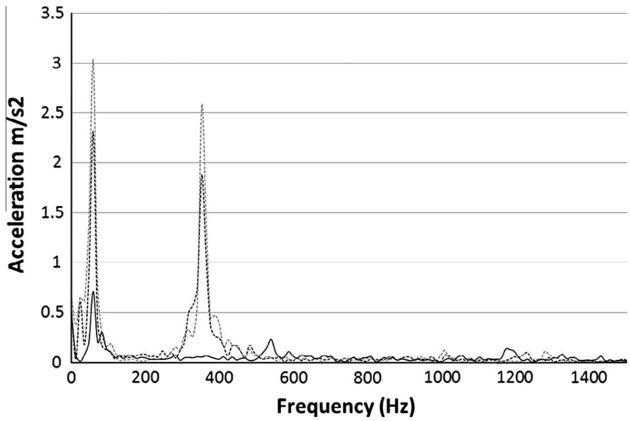

Fig. 10. Measured acceleration of the reference fan blade in the airflow at 0° (dashed dark grey line) and 10° (dashed light grey line) of incidence to the airflow compared to the bench (solid line).

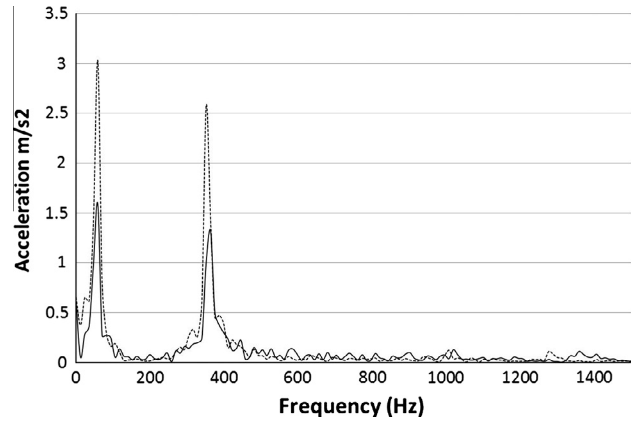

Fig. 12. Measured acceleration for a twisted reference blade (dashed line) compared to the twisted blade with a wedge of power-law profile and built up damping layer (solid line).

in peak amplitude of 0.7 m/s^2 and 0.5 m/s^2 at 60 Hz and 360 Hz respectively, when compared to the same blade without a damping layer.

The observed larger suppression of low frequency resonant peaks under air flow excitation (Figs. 10 and 11) in comparison with the case of electromagnetic shaker excitation (Figs. 5 and 7) can be explained as follows. The exciting dynamic forces applied to the blade in both these cases are very different. The electromagnetic shaker excitation represents the simplest case of concentrated force with equal amplitudes at all frequencies in the range considered. In fact, the blade frequency response to such a force represents the frequency spectrum of the Green's function for the blade under consideration (with or without power-law tapering) for the chosen points of excitation and observation. It reflects the well-documented fact that the acoustic black hole effect is less efficient at low frequencies [8–10], and its efficiency increases with the increase of frequency. Contrary to the above-mentioned case of electromagnetic shaker excitation, the dynamic forces acting on the blade under air flow excitation are much more complex [1]. These are distributed aerodynamic forces, e.g. lift forces, due to the air flow fluctuations and flow-blade aero-elastic interaction. Unlike in the case of electromagnetic shaker excitation, with the force frequency spectrum having equal amplitudes at all frequencies in the observation range, the air flow-induced forces have predominantly low-frequency spectra, as it can be seen from Figs. 10 and 11 – only two resonant peaks are excited, at 60 Hz and at 360 Hz. Apparently, the introduction of acoustic black holes to blade tails reduces the resulting aerodynamic forces applied to the blades, which results in much more significant reduction of the low-frequency resonant peaks in comparison with the case of electromagnetic shaker excitation. Of course, this is only a hypothesis. A more detailed experimental investigation of the acoustic black hole effect for fan blades under air flow excitation would be desirable in the future, including possible effects of self-excited vibrations (aero-elastic flutter) at high flow speeds.

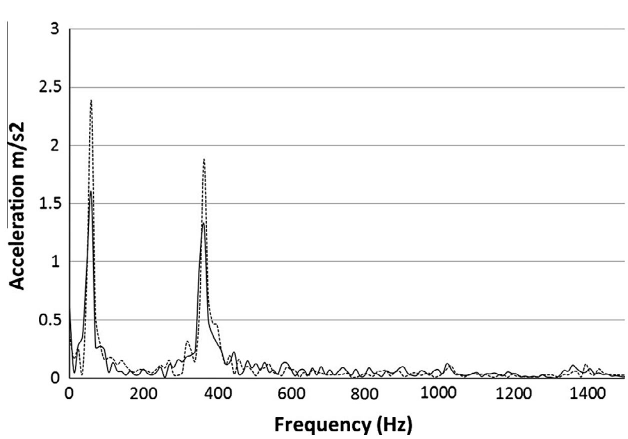

Fig. 11. Measured acceleration for a twisted fan blade having a wedge of power-law profile with (solid line) and without built up damping layer (dashed line).

Finally, Fig. 12 shows the response of the twisted fan blade with a trailing edge of power-law profile and built up damping layer compared to the twisted reference blade. The twisted fan blade with a trailing edge of power-law profile and built up damping layer shows about a 50% reduction in the level of airflow-excited vibrations when compared to the twisted reference blade. A reduction in peak amplitude of 1.4 m/s^2 and 1.25 m/s^2 at 60 Hz and 360 Hz respectively has been observed.

5. Conclusions

The results of this work show that modifying trailing edges of turbofan blades according to the power-law profile along with the attaching thin strips of damping layers, which materialises one-dimensional acoustic black holes for flexural waves, represents an effective method of damping flexural vibrations in the blades. The maximum damping achieved for the straight fan blade was 12 dB at 4.2 kHz, and the maximum damping achieved for the twisted fan blade was 10.5 dB at 4.1 kHz.

Using flow visualisation, it can be concluded that power-law profiled shapes can be implemented for the trailing edges of real world fan blades. When an appropriate built up damping layer is applied, the aerofoil can be restored to its original profile, with limited to no interruption in airflow over the blade surface.

It has been demonstrated that trailing edges of power-law profile with appropriate damping layers are efficient in reduction of airflow-excited vibrations of the fan blades.

The initial experimental results described in this paper show that the use of one-dimensional acoustic black holes in jet engine fan blades could be a viable method of reducing flexural vibration in the blades, thus reducing internal stresses in the blades and increasing their fatigue life.

Acknowledgement

The research reported here has been partly supported by EPSRC Grant EP/F009232/1.

References

[1] Rao JS. Turbomachine blade vibration. New Delhi: Wiley Eastern Limited; 1991.

[2] Cremer L, Heckl M, Ungar EE. Structure-borne sound. Berlin: Springer; 1988.

[3] Mead DJ. Passive vibration control. Chichester: Wiley; 1998.

[4] Ross D, Ungar EE, Kerwin Jr EM. Damping of plate flexural vibrations by means of viscoelastic laminae. In: Ruzicka JE, editor. Structural damping. Oxford: Pergamon Press; 1960. p. 49–87.

[5] Vemula C, Norris AN, Cody GD. Attenuation of waves in plates and bars using a graded impedance interface at edges. J Sound Vib 1996;196:107–27.

[6] Logan Jr E, Roy R. Handbook of turbomachinery. Tempe, Arizona: Marcel Dekker; 2003.

[7] Beards CF. Structural vibration – analysis and damping. Arnold; 1996.

[8] Krylov VV, Tilman FJBS. Acoustic 'black holes' for flexural waves as effective vibration dampers. J Sound Vib 2004;274:605–19.

[9] Krylov VV. New type of vibration dampers utilising the effect of acoustic 'black holes'. Acust – Acta Acust 2004;90(5):830–7.

[10] Krylov VV, Winward RETB. Experimental investigation of the acoustic black hole effect for flexural waves in tapered plates. J Sound Vib 2007;300:43–9.

[11] Mironov MA. Propagation of a flexural wave in a plate whose thickness decreases smoothly to zero in a finite interval. Soviet Phys – Acoust 1988;34:318–9.

[12] O'Boy DJ, Krylov VV, Kralovic V. Damping of flexural vibrations in rectangular plates using the acoustic black hole effect. J Sound Vib 2010;329:4672–88.

[13] Georgiev VB, Cuenca J, Gautier F, Simon L, Krylov VV. Damping of structural vibrations in beams and elliptical plates using the acoustic black hole effect. J Sound Vib 2011;330:2497–508.

[14] Bowyer EP, O'Boy DJ, Krylov VV, Horner JL. Effect of geometrical and material imperfections on damping flexural vibrations in plates with attached wedges of power law profile. Appl Acoust 2012;73:514–23.

[15] Bowyer EP, O'Boy DJ, Krylov VV, Gautier F. Experimental investigation of damping flexural vibrations in plates containing tapered indentations of power-law profile. Appl Acoust 2013;74:553–60.