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Experimental study of damping flexural vibrations in tapered turbofan blades

E. P. Bowyer, J. M. Lister, V. V. Krylov and D. J. O'Boy

Loughborough University, Ashby Road, LE11 3TU Loughborough, UK
e.bowyer@lboro.ac.uk

In this paper, the results of the experimental investigations into damping of flexural vibrations in turbofan blades with trailing edges tapered according to a power-law profile are reported. 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 NACA 1307 aerofoil was used as a base model for experimental samples. This model was modified to form four samples of non-engine-specific model fan blades. Two of them were then 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 fan blades with power-law tapered edges have the same pattern of damping that can be seen for plates with attached wedges of power-law profile, when compared to their respective reference samples. The resonant peaks are reduced substantially once a power-law tapering is introduced to the sample. 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 fan blade failure in jet engines is from the undamped vibration of the blades resulting in a high cyclic fatigue [1]. To reduce the vibration in the blades would result in lower stress levels on the blade and ultimately in a longer fatigue life. Vibration in fan blades arises as a result of the combination of many vibration sources. One of the main contributing sources of the harmonic force on the blade is that caused by a fluctuating lift force that acts on the blade aerofoil as it rotates about the central annulus in front of the stationary stator row. Other sources include atmospheric turbulence and viscous wake interaction along with turbulence from mechanical components such as pitot tubes and struts. All these factors result in a variance of fan blade resonance dependent on engine design, so a frequency specific damping system could not be widely implemented.

Due to the variance of fan blade resonance for the reasons mentioned above, a broad frequency damper would be ideal solution as it would allow for variation in resonant peak frequencies brought about by varying engine designs. Two traditional methods of damping structural vibrations are the addition of layers of highly absorbing materials to the structure in order to increase energy dissipation of propagating waves [2-4] and the suppression of resonances of structures via reduction of reflections of structural waves from their free edges [5]. There are also some damping methods used specifically on jet engine fan blades, each presenting individual difficulties [6,7]. These methods include slip damping, gas damping and damping wires.

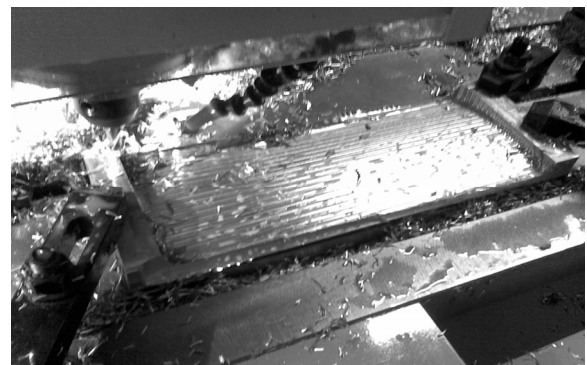
A new method of damping structural vibrations based on the 'acoustic black hole effect' for flexural waves in wedge-like structures has been recently developed and investigated [8-10]. As was pointed out in [10], one of the advantages of this method is that it can be easily incorporated into existing blade designs, utilizing the natural taper at the trailing edge of the aerofoil. This method has been initially applied to one-dimensional plates of power-law profile (wedges), the tips of which had 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]; this constitutes the 'acoustic black hole effect'. It has been established theoretically [8,9] and confirmed experimentally [10,12,13] that this method of damping structural vibrations is very efficient.

This paper looks at the integration of wedges of power-law profile initially onto the trailing edge of a straight and then twisted fan blade, and at their effects on the damping

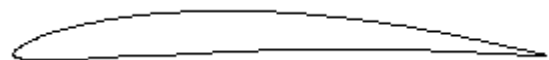
of flexural vibrations in the blade. An initial investigation into the aerodynamic implications of this method has been carried out as well, utilising a flow visualisation technique.

2 Manufacturing of experimental samples

Four fan blade samples were machined out of aluminium block, Figure 1(a), using a CNC (Computer Numerically Controlled) milling machine operating at a cutter speed of 1200 rpm.



(a)



Max thickness 7.88% at 27% of the chord
Max camber 4.57% at 46.4% of the chord

(b)

Figure 1: (a) Manufacturing of a fan blade, (b) Fan blade profile with (top picture) and without (lower picture) wedge of power-law profile

The NACA 1307 aerofoil was used as a base model and then manipulated to form a non engine specific model fan

blades. 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. The power-law exponent for a wedge was $m = 2.2$. When a twist was added to the blade, this was done after manufacturing of the blade and wedge.

Length	Root chord	Tip chord	Twist Angle	Wedge length
300mm	100mm	120mm	11 deg	43.5 mm

Table 1: Blade dimensions

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

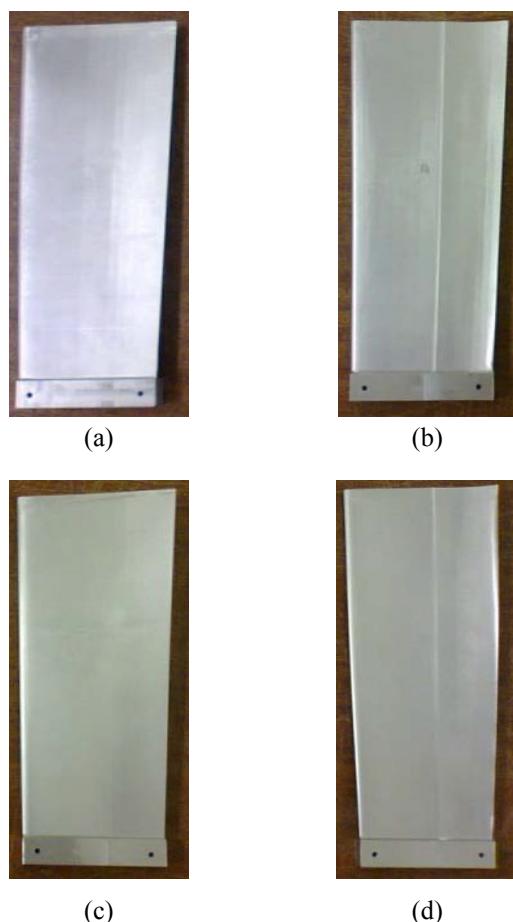


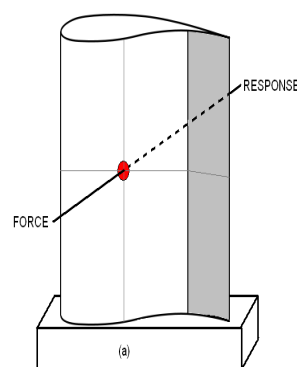
Figure 2: (a) Reference fan blade - straight, (b) Fan blade with power-law wedge - straight, (c) Reference fan blade - twisted, (d) Fan blade with power-law wedge - twisted

3 Experimental set up

Two experimental set ups were utilised in the acquisition of results for this paper. The first experimental set was used to acquire a vibration response. This set-up has been designed to allow nearly free vibration of the sample blades (i.e. to eliminate clamping of edges), take the weight off the edges and introduce minimal damping to the system, see Figure 3(a).



(a)



(b)

Figure 3: (a) Experimental Set up, (b) Locations of the shaker (Force) and of the accelerometer (Response) on an experimental sample

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', Figure 3(b). The acquisition of the point acceleration was utilised using a Bruel & Kjaer 2035 analyser and amplifier. A frequency range of 0- 9 kHz was investigated.

The second experimental set up utilised a closed circuit wind tunnel to produce flow visualisation diagrams of the fan blades when placed in an air flow, Figure 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 engine running speed, it is sufficient to get a basic indication of the effect of a power-law wedge on the trailing edge of the fan blade, especially at engine start/wind up.

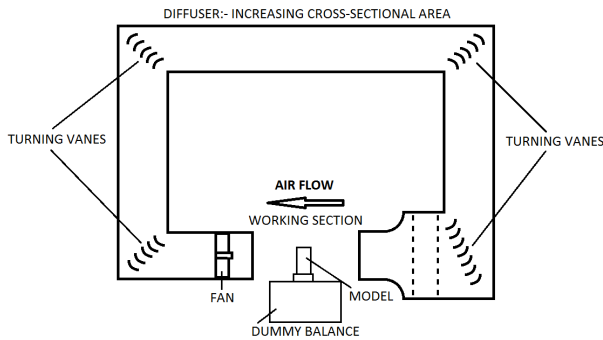


Figure 4: Closed circuit wind tunnel

In order for the white flow visualization 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 visualization 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 degrees to the airflow.

For both experiments, the damping layer attached to the trailing edge of power-law profile consisted of a single 40mm x 300mm 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 wedge of power-law profile to a straight fan blade

This section looks at the introduction of a wedge of power-law profile to a fan blade and examines whether this could produce an ‘acoustic black hole effect’, as seen in previously tested steel samples [10,12,13]. Two types of samples were tested: a straight reference blade and a straight blade with a machined wedge of power-law profile (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 a wedge also had a damping layer attached to the wedge tip.

A comparison of a straight blade with and without a power-law profile wedge is shown in Figure 5. As was seen in the previous work [12], the addition of a wedge of power-law profile to the end of an aluminum fan blade, shows the same trends 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 response is smoothed, with resonant peaks heavily damped if not completely removed.

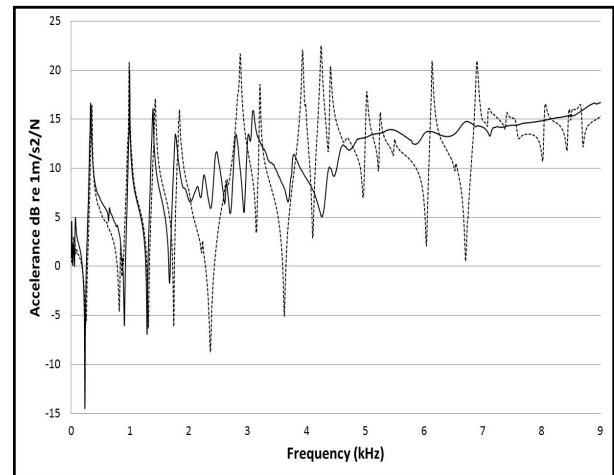


Figure 5: Accelerance for Reference fan blade (dashed line) compared to fan blade with a wedge of power-law profile with damping layer (solid line)

4.2 Introduction of a wedge of power-law profile to a twisted fan blade

After observation of a promising result on a straight fan blade, the next step was to apply the wedge of power-law profile onto a twisted (11 degrees) blade and compare the results to those for a twisted reference blade. The straight and twisted reference blades were also compared. A twisted blade more accurately represents the real world engine fan blades these samples are emulating. This section thus looks at the effect of the addition of a power-law wedge, and also at the effect of twisting the blade has on the damping performance of the samples.

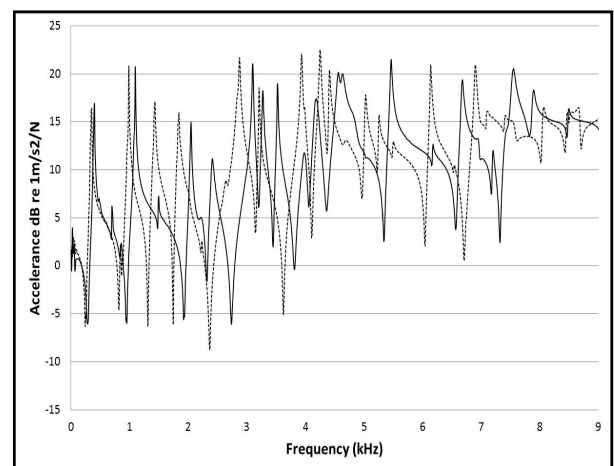


Figure 6: Accelerance for Reference fan blade – twisted (solid line) compared to Reference fan blade – straight (dashed line)

Figure 6 shows the results 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 that twist in the blade creates different kind of interaction between the plate modes, 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.

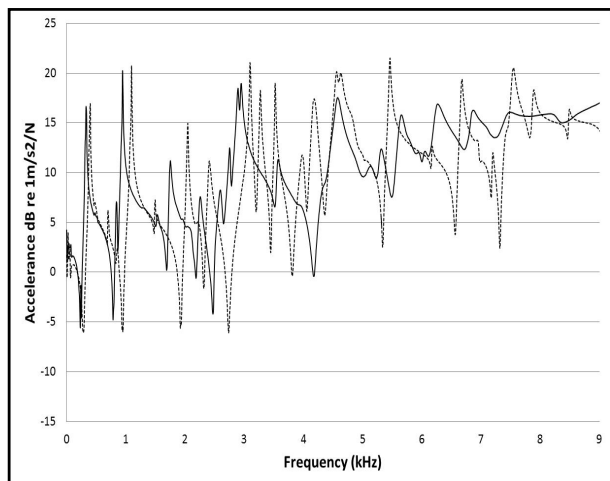


Figure 7: Accelerance for Reference fan blade – twisted (dashed line) compared to Fan blade with wedge of power-law profile and damping layer – twisted (solid line)

From Figure 7 it can be seen that, when the twisted reference blade is compared to the twisted blade with a wedge of power-law profile, 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 – 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 blade 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

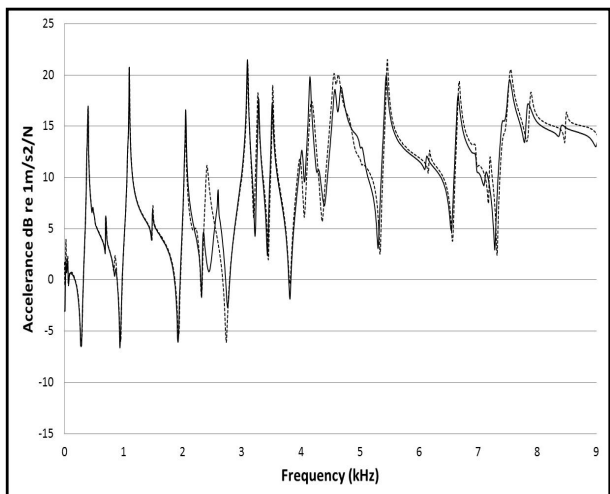


Figure 8: Accelerance for Reference fan blade (twisted) with a damping layer (solid line) and without a damping layer (dashed line)

In order to ascertain that all the damping seen in the blades above was due to the combined effect of the 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.

Figure 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 presence of the 1D ‘acoustic black hole’.

4.3 Flow visualisation for a fan blade with a wedge of power-law profile

This section describes the preliminary results of the flow visualisation for the straight fan blade. The fan blade is at an arbitrary incline of 10 degrees 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.

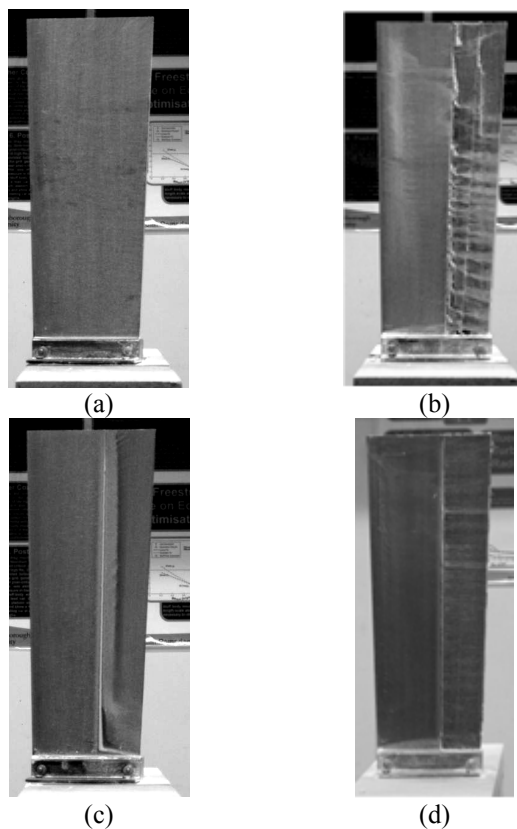


Figure 9: Flow visualisation diagram for (a) Reference fan blade, (b) Fan blade with power-law wedge, (c) Fan blade with power-law wedge with single damping layer and (d) Fan blade with power-law wedge and shaped damping layer

Figure 9 shows the progression of the flow visualisation tests from a reference fan blade to a fan blade with a wedge of power-law profile covered by a specifically shaped damping layer. Looking at the reference fan blade (Figure 9(a)), one can see that the visualisation shows laminar flow across the blade surface with no separation. The effects on

the airflow of the presence of the uncovered wedge are obvious (Figure 9(b)). One can see 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 (see Figure 9(c)). One can see a clear line of transition 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 wedge area.

One could expect that any deviation in blade profile from the original design specification will not only have the increased turbulence and increased drag, as seen above. It will also result in lower efficiency and will affect the airflow into the next stage of the engine. An obvious possible solution to the flow turbulence problem seen in Figures 9(b) and (c) would be to recreate the flow pattern seen in Figure 9(a) via restoring the original profile of the blade. One method of partly achieving this is to shape the damping layer in order to recreate the original profile. This was achieved in this work by building up layers of the damping material to reproduce the original profile. The final diagram (Figure 9(d)) shows the resultant flow over the blade with this shaped damping layer. It can be seen that 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. 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.

Another important remark is that, although for the experimental samples described above the damping tape can be attached as strips of visco-elastic polymeric layer, this would not be practical for real world engines due to high temperatures of the air flow. It would be more realistic 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 to use an alloy with a greater loss factor that could be cast onto the blade at manufacture [10], ensuring a strong bond and continuous surface with no transition visible between the blade and damping layer.

5 Conclusions

The results of this work show that incorporating wedges of power-law profile along with the attached damping layers into trailing edges of fan blades, which forms 1D acoustic black holes, represents an effective method of damping flexural vibrations in the blades. The maximum damping achieved in a straight fan blade was 12 dB, and 10.5 dB was achieved in the twisted fan blade.

Using flow visualisation, it can be seen that power-law profiled wedges can be incorporated into the trailing edges of real world fan blades. When an appropriate shape of covering damping layer is applied, the aerofoil can be restored to its original profile, with limited to no interruption in flow over the blade surface.

These initial results show that the use of 1D acoustic black holes in engine fan blades could be a viable way of

reducing flexural vibration in the blades, thus reducing internal stresses on the blades and increasing their fatigue life.

Acknowledgements

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