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Broadband Noise reduction from a mini-UAV propeller through boundary layer tripping

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ABSTRACT

The reduction of radiated noise from mAV (miniature Aerial Vehicle) and small UAV (Unmanned Aerial Vehicle) platforms is of significant consideration as they start to perform more diverse roles in close proximity to populated areas. This paper examines a possible noise reduction technique for a small size propeller with a short chord length (15~30mm) operating at low Reynolds numbers. A series of static and wind tunnel tests have been conducted to investigate the mechanism behind a large broadband noise reduction achieved in static test conditions. It has been found that a leading edge boundary layer trip can produce a large reduction in broadband noise in simulated cruise conditions, with no evidence of performance detriments. Preliminary conclusions suggest that both a strong source of laminar boundary layer noise along with turbulent boundary layer noise mechanisms are present on the suction surface of the propeller blade, along with the existence of a laminar separation bubble on the blade surface during simulated cruise conditions. The introduction of a boundary layer trip appears to eliminate the laminar separation bubble and result in a large broadband noise reduction. It is believed that the elimination of the laminar separation bubble removes the strong laminar boundary layer noise source, and reduces the noise generated by the turbulent boundary layer. The leading edge trip has proved successful in achieving a broadband reduction which results in a repeatable 6-7dB(A) reduction at the sample location, which corresponds to an overall reduction in SWL by up to 4dB in static tests.

NOMENCLATURE

k	wave number, 1/m
r	radius, m
δ	boundary layer thickness, m
δ^*	boundary layer displacement thickness, m
mAV	mini Aerial Vehicle
UAV	Unmanned Aerial Vehicle
U	freestream velocity, m/s
V	freestream velocity, m/s
c	chord, m
v	viscosity, m^2/s
β	boundary layer instability waves angular frequency
$\underline{h}$	height of trip strip, mm
T	thrust, g
l	length, mm
LAeq	A weighted Equivalent Noise level, dB
r/R	Radial Position/Blade Radius
SPL	Sound Pressure Level, dB
SWL	Sound Power Level, dB

INTRODUCTION

mAV (miniature Aerial Vehicle) (~1m wing span) platforms are beginning to see use in a large and ever increasing variety of roles that are in close proximity to populated areas. As these platforms are now incorporating quiet electric motors, propeller noise is becoming an increasingly significant component of the platforms noise. In a military context noise reduction may be the only way to increase survivability of these small platforms, while for the increasing civil market any noise reduction that can be achieved on these platforms will broaden the range of missions that can be performed in a regulatory environment with increasingly stricter rules. These aircraft operate with low RPM (3000-7000) values, which reduces the strength of the traditionally dominant blade passage noise and in turn increases the importance of the contribution from the broadband aerofoil self noise. This paper examines a possible noise reduction technique for a mAV propeller operating with a short chord length (15~30mm) and at low Reynolds numbers. The understanding gained from this study could also be applied to other applications of low Reynolds airfoil sections that exhibit similar characteristics, with small wind turbines being one candidate in this category. This series of experimental investigations into mAV propeller noise has shown that a leading edge boundary layer trip can produce a large reduction in broadband noise in simulated cruise conditions. Test results also show that this noise reduction technique also produces either similar or improved propeller performance.

Traditionally boundary layer trips are used to eliminate laminar boundary layer (LBL) noise, by forcing the laminar boundary layer to transition and become turbulent. However, in this investigation the test conditions provide an environment which is highly turbulent, making it difficult for any laminar boundary layer not to naturally transition to turbulent. The technique examined in this paper looks into boundary layer trips in the form of a straight strip of adhesive tripping tape applied to the suction surface of the propeller, which avoids some of the delicate installation issues of leading edge serrations that were implemented in the studies of Longhouse (1977), Soderman (1973), and Hersh, Soderman and Hayden (1974). It was concluded in many of these studies that the presence of a turbulent boundary layer on the full scale airfoil sections (>100m) meant that any laminar boundary layer noise that was present during testing on small chord length sections would not exist at full scale. It is for this reason that boundary layer transition strips have not seen any extensive practical use outside of the laboratory. Similar reductions to what have been found in this current investigation as a result of boundary layer tripping for scaled tests are presented in Grosche and Stiewitt (1978), and Paterson and Amiet (1982). In each of these cases the reduction was explained as the elimination of laminar vortex shedding, which was justified by the acoustic wavelengths of the emitted tones being almost equal length to the blade chord, and that the peak frequencies fitted well with the prediction of laminar vortex shedding noise proposed by Fink (1974). In each of the experiments the vortex shedding noise was then removed by tripping the boundary layer with a leading edge trip. However, this was only possible when the surface of the blade exhibited a fully laminar boundary layer.

Migliore and Oerlemans (2004) investigated the use of tripping for the elimination of intense narrowband peaks in the trailing edge spectra on wind turbine airfoil sections in an anechoic wind tunnel (Migliore and Oerlemans 2004). The elimination of the tones was explained by the suppression of the laminar boundary layer, and the "disruption of the feedback mechanism responsible for laminar boundary layer vortex shedding" (Migliore and Oerlemans 2004:8). However, in contrast to the findings in Migliore and Oerlemans (2004) where such tones did not appear in the presence of strong upstream turbulence (Turbulence Intensity ~9%), in this current investigation a noise reduction by boundary layer tripping was still found to exist at turbulence levels of a similar high magnitude. Possible reasons to explain these differing results are presented in this paper. This investigation looks into the possible mechanisms that are occurring on the propeller blade, and develops a picture of what the sources of noise are that are being reduced through boundary layer tripping are believed to be.

EXPERIMENTAL INVESTIGATION

A series of static and wind tunnel tests have been performed at the National Acoustics Laboratories (NAL), Chatswood, NSW over 2006-2008. The experiments have been performed to further analyse the mechanisms that are involved in the broadband reduction that was achieved through boundary layer tripping, and whether or not it would be possible to reproduce these reductions in simulated flight conditions.

Static Tests

A series of static tests, where the propeller is tested with no incoming airflow other that the flow induced by the propeller, were conducted in both anechoic conditions and the quiet 'Sound Shell' environment. The initial reductions that were found in anechoic conditions were at 3500RPM and 5000RPM, and were found to be repeatable in the quiet test environment of the Sound Shell. The measurements were taken using a B&K 2250 SLM using a 4189 ½" Free Field Microphone, recorded onto a ZOOM H4 Handy Recorder at 44.1kHz for analysis. Measurements were taken at 1.7m from the propeller, which was located out of the near field for the frequency range of concern for the investigation which was above 1kHz. The near field limit was calculated to be 321Hz, based on *kr*>10. A directivity pattern for the static tests was established for the 3500RPM condition in anechoic conditions, showing a strong dipole characteristic (Figure 1a. and 1b.) where the strongest source location in front of the rotating propeller on the axis of rotation. (90 degree position in Figure 1.). This was the microphone sample location used for the comparative anechoic tests. To verify that any reductions that were obtained by the single microphone sample position were not strongly directionally dependant and prevent false conclusions, 21 equally spaced sample positions over a 1.7m sphere were used to look at both the sounds power of the propeller and the directivity of the propeller noise (Leslie, 2006).

The propeller examined in this study is the Master Airscrew 10x5. It was chosen due to the simplicity of the Clark Y airfoil section used, and its simple profile shape which allowed for geometry modifications to be completed without complex parameter variation becoming a consideration.

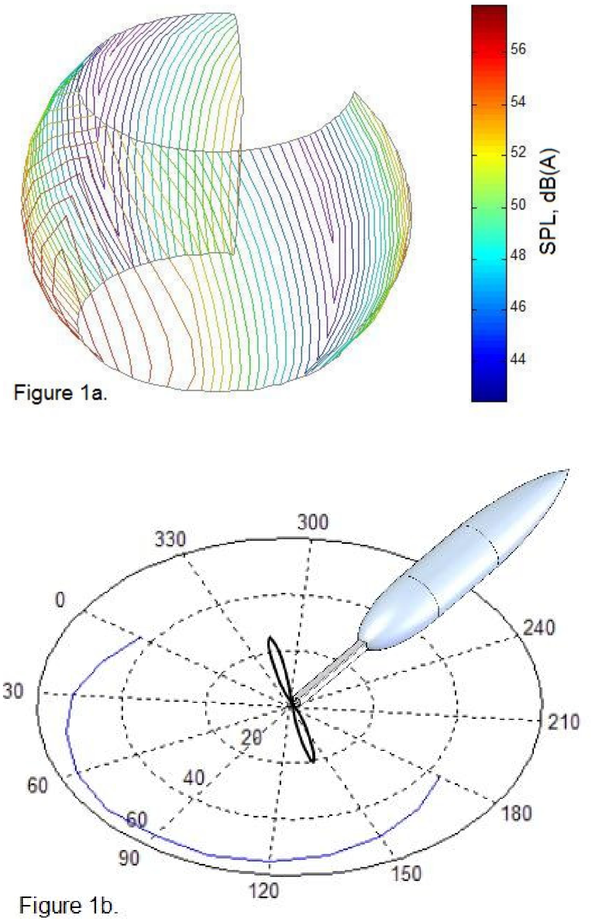

Figure 1a.) Directivity Pattern, LAeq at 1.7m, 3500RPM, Anechoic Conditions, Master Airscrew 10x5 Propeller. b.) Directivity Pattern in single plane in front of propeller, LAeq at 1.7m, 3500RPM.

Wind Tunnel Tests

The preliminary wind tunnel study was conducted in the recently created "silent" airflow system primarily designed for measuring the acoustical properties and aerodynamic performance of acoustic louvers (Fishburn et al 2007). It was modified to be utilised as an open jet wind tunnel for these tests. The tunnel is situated within the Sound Shell of the facility, which is a 58x50m hall with 280mm thick concrete walls, and is vibrationally isolated from the rest of the facilities structure. The tunnel exhibited sufficiently low background noise levels to test the propellers. However, the outlet turbulence intensity was significantly high (2.6% at 6m/s, 7.2% at 13.5m/s) even after methods to reduce the turbulence intensity were implemented. The tunnel outlet is 610mm x 610mm, and is capable of producing up to a maximum continuous airspeed of 20m/s following the installation of a set of turbulence screens.

The wind tunnel tests were completed using a single microphone sample location, similar to the static tests, for quick comparison of modifications. The location of the sample microphone was at 45 degrees to the propeller face at 1.7m. This sample location was used to allow the measurements to be taken at the location of the strongest source without placing the microphone in the airflow. Placing the microphone in the airflow was avoided because it would have disturbed the propeller inflow which would then generate extraneous noise. The measurements were taken using the same equipment as the static tests for consistency. Measurements were taken inside the main hall of the NAL Sound Shell, due to the location of the exhaust outlet of the 'silent' airflow system. With the exception of the reflective floor surface, all reflective surfaces were kept at a minimum of twice the measurement distance from the microphone location, so as to allow the direct field from the propeller to be dominant in the samples. The only exception to this was a low concrete wall at approximately the measurement distance to the rear of the test rig, which was heavily padded for all tests (Figure 2.). Measurements were conducted with and without the absorptive padding, which revealed a negligible contribution from the reflections in the spectrum.

Figure 2. Wind Tunnel Measurements Setup

The test rig (Figure 3.) was designed to minimise its contribution to the background noise levels, and to avoid interfering with the propeller aerodynamically during operation. It was designed to minimise potential acoustic reflections which were found to affect results in the first test rig design. It was also carefully designed to avoid possible separation or shedding noise coming from the test rig itself when it was immersed in the airflow of both the tunnel and propeller slipstream.

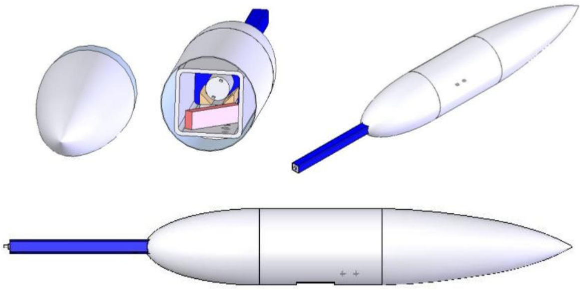

Figure 3. Test Rig Design

Results to confirm that the test rig was designed to contribute adequate background noise levels are presented in Figure 4. The background levels were at least 10dB for all frequencies above 100Hz. The test rig generated noise levels were at least 8dB below the measured propeller levels for all frequencies in the frequency range of interest above 1kHz.

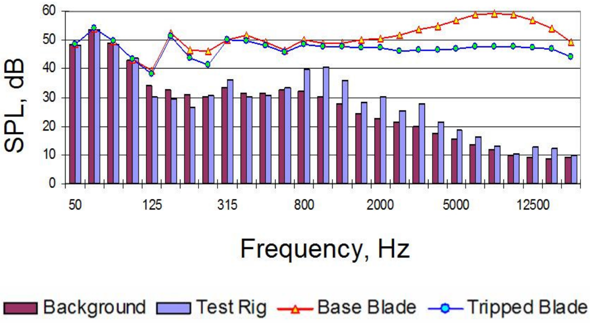

Figure 4. Background Noise Comparison

Airspeeds and turbulence intensity levels were obtained using a single sensor hot-wire sampling at 200Hz. The hot-wire sensor was calibrated with a pitot-static tube. The pitot-static tube was sampling at the same rate as the hot-wire sensor and had been calibrated using known pressures. Based upon velocity samples taken across a horizontal plane passing through the propeller axis, 25cm infront of the propellers plane of rotation, it was determined that the propeller was operating within the outlet jet core with a 65% radial length clearance from the tip to the shear layer of the wind tunnel outflow jet. This was done so as to avoid any interaction between the shear layer and the propeller which would generate noise.

The operational test points that were examined in the experiments were based upon results from model flight tests, and the predicted highest efficiency point of the propeller for 5000, 6000, and 7000RPM, which are the upper limits of mAV RPM range. The focus of the project has been upon the cruise condition, which the aircraft will operate in for the majority of its flight regime, and so this will be the state that the propeller should optimally be designed for. The optimum efficiency condition was determined using the Propeller analysis program BETPAT (Jagenberg 2004), which uses a blade element method. This program integrates the accurate airfoil section data from the 2D Panel Method program XFOIL (Drela 1989), with a Blade Element Method to analyse the aerodynamic performance of a propeller. During each of the samples the mean thrust value was recorded from a balance at the base of the test rig for comparison against predicted thrust values. Checking the predictions from this program against the experimental results, it was found that the predicted thrust values were within 10% of the measured values.

Flow Visualisation

Due to the size restrictions of the propeller, pressure taps to determine boundary layer properties were not feasible. Visualisation of the surface flow was found to be the most effective method to determine the existence and location of laminar separation and reattachment. It was determined that a mixture of kerosene and titanium dioxide would reveal the clearest full picture of the surface flow. Using this method the bubble position was compared to predictions. This was to try and use a 2D panel method such as XFOIL (Drela 1989) to determine the actual nature of the boundary layer in the discrete regions shown by the visualisation tests. Laminar separation bubble positions were distinguished by observing chord wise sections of pure radial flow which occurred directly after a cleared section of the blade surface where separation took place. The reattachment location was determined by chordwise discontinuity of the titanium dioxide, which was then followed by streaks that contained both radial and chordwise components. An illustration of how the separation and attachment locations were determined can be seen in Figure 5.

Figure 5a.

Figure 5b.

Figure 5. 5000 RPM, Static Test Conditions, Master Airscrew Propeller, a.) The separation bubble location is clearly visible, b.) The trip strip is at 10% chord (h=0.12mm). The removal of the separation bubble can be seen.

RESULTS AND DISCUSSION

Each of the test cases where a significant broadband noise reduction was achieved correlated with the observation of a laminar separation bubble on the suction surface of the blade via the visualisation tests. The noise reduction only occurred in the cases where the tripping of the boundary layer was ahead of the laminar separation location, and the laminar separation bubble was eliminated (Figure 5.). A summary of the significant overall LAeq level reductions that were achieved through these various tripper designs is summarised in Figure 6.

Static Tests

A series of 4 static test investigations were conducted. The first set of tests was a general UAV (Unmanned Aerial Vehicle) propeller noise exploratory series, the second being an extension of the first series examining a number of boundary layer tripping variables. The final two static tests were incorporated into the wind tunnel tests for comparative purposes. The following will outline significant findings.

The initial anechoic tests found that for a trip with a thickness close to the boundary layer thickness, when placed in front of a laminar separation position on an airfoil section will result in a significant broadband noise reduction. At 3500RPM, a SPL reduction of 5~6dB(A) at the measurement location was repeatable in multiple test environments, which corresponded to an overall SWL reduction of 4dB. It was found that if a trip was placed in the same chordwise position on the pressure side of the aerofoil, that there was no significant added reduction. This helped to point towards the conclusion that the suction surface boundary layer is dominant in broadband noise production. These findings were then coupled with the visualisation results, which showed that the tripper was removing the laminar separation bubble on the suction surface in the cases where the noise reduction occurred. These results together supported the view that the noise mechanism that was being modified was either the trailing edge boundary layer thickness on the suction surface being changed (due to the trip which affected the way the boundary layer interacted with the trailing edge), or that the source of noise production was related to the bubble itself.

It was also noted that if the tripper height was increased significantly past the calculated boundary layer thickness at the tripper location, no noise reduction would be experienced, and in some cases there was a broadband noise increase.

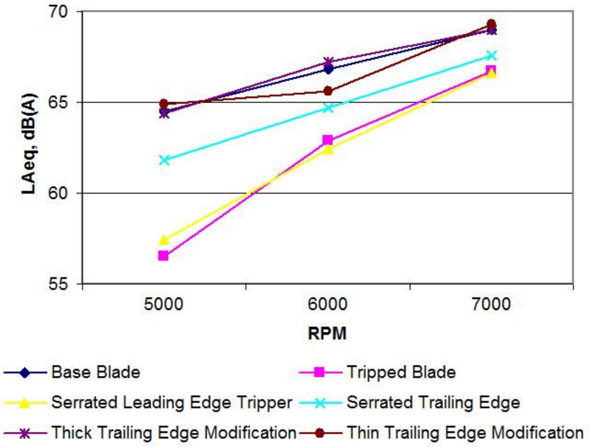

Figure 6. Trailing Edge Modifications, when operating at optimum propeller efficiency (~60%, with ~1.5degree Angles of Attack at 0.8r/R). (All trippers are length 3mm. Thick trip h= 0.12mm, Thin trip h=0.049mm. Leading edge trips located at 10% chord)

Wind Tunnel Testing

The wind tunnel testing has taken place in two series of tests. The first was an extensive investigation into tripper parameters. This involved altering the tripper thickness, and leading and trailing edge positions. The second focused upon the effects of the operational environment, and a further investigation into the underlying mechanism through various tripper placements. These investigations showed that this broadband reduction was achievable in a variety of operating conditions, with the RPM, inflow velocity and resulting turbulence levels all being variables. An outline of the some key parameter variations is shown in Table 1., in order of increasing LAeq level.

Table 1.Variation in Tripper Parameters, 5000RPM, V=10m/s

Config.	*LA_{eq}*	*%c*	*l(mm)*	*h(mm)*	*T(g)*
1	59.31	10%	3	0.120	119
2	60.08	20%	3	0.120	66
3	60.82	10%	3	0.049	112
4	61.61	10%	6	0.049	112
5	63.58	20%	3	0.049	125
6	64.02	10%	9	0.049	100
B	66.00	-	-	-	105

Source: (Leslie 2008)

Note: *%c*= Leading edge position of tripper as % of chord

One significant finding which is yet to be fully explained was the effect of the length of the boundary layer trip. This variation was found for both the static and wind tunnel tests, and can be seen in Table 1. It appeared that there was a maximum tripper length before the beneficial effects weakened. This maximum beneficial length appeared to correlate with the location of the trailing edge of the tripper when it exceeded the reattachment point of the original separation bubble that was removed. Currently, the only hypothesis is that the backwards step at the trailing edge of the trip may be a source of further disturbance to the turbulent boundary layer close to the trailing edge. The step may contribute to increasing the turbulent boundary layer displacement thickness at the trailing edge, and as a result increase the TBL-TE (Turbulent Boundary Layer – Trailing Edge) noise compared with the non-tripped condition. However, so far no evidence has been found to support this conclusion.

Based upon a combination of the static and wind tunnel tests, a picture of the noise reducing mechanism of the noise source has slowly been developed. The following outlines the findings and conclusions which have helped to narrow down the noise mechanism which is being reduced.

Turbulent Boundary Layer- Trailing Edge (TBL-TE)

The initial explanation as a result of the testing was that the main noise source would have to be TBL-TE noise. This was due to there being strong evidence that there was a reattached turbulent boundary layer at the trailing edge and so any laminar boundary layer noise would be almost non-existent. The 2D Panel method XFOIL was used to calculate the approximate aerodynamic boundary layer conditions that would exist on the propeller. The calculated results were then matched against the visualisation test results. To match the visualisation results to the calculated XFOIL results the predicted locations of laminar separation and reattachment were matched to the observed. When the location of the discontinuities in the flow obtained from the visualisation results (Figure 5.) were matched with the locations where the skin friction coefficient was calculated to become less than zero, it was determined that the aerodynamic conditions used for the calculations were similar to those being experience by the section of the propeller blade. However, using XFOIL this technique would only work successfully at much lower turbulence levels (<3%) than those measured for the freestream on the test conditions. The justification for the successful matches is that there would be a decrease in turbulence intensity in the propellers inflow stream tube, which was also supported in Paterson and Amiet (1979). It was calculated that for all the matched cases the boundary layer would transition as it passed over the separation bubble, and then would reattach as a turbulent boundary layer. The measured high free stream turbulence also provides support to the conclusion that any reattachment of the boundary layer would have to be turbulent.

The calculated aerodynamic conditions for the match cases were used to further examine of the boundary layer characteristics. From these results it was found that that if transition was forced to occur where the tripper is located instead of letting the separation bubble form, there would be a reduced boundary layer displacement thickness at the trailing edge. If the trailing edge boundary layer thickness was reduced, this would correspond to reduction in the radiated Turbulent Boundary Layer- Trailing Edge (TBL-TE) noise (Brooks et al 1989). Separation noise was disregarded as a significant contributor, which was supported by prediction models (Figure 7.), as the calculated angles of attack of the blade are too low for a significant amount or full separation to occur. This assumption was also supported by the strong correlation between the predicted thrust values and the measured values. However, the calculated reductions that would result from the predicted change in boundary layer displacement thickness as a result of tripping are presented in Figure 7. The figure shows that the reduction that would be achieved by a change in boundary layer displacement thickness would not have the significant broadband reduction that this tripped test results show, and would also not be over the same range of frequencies.

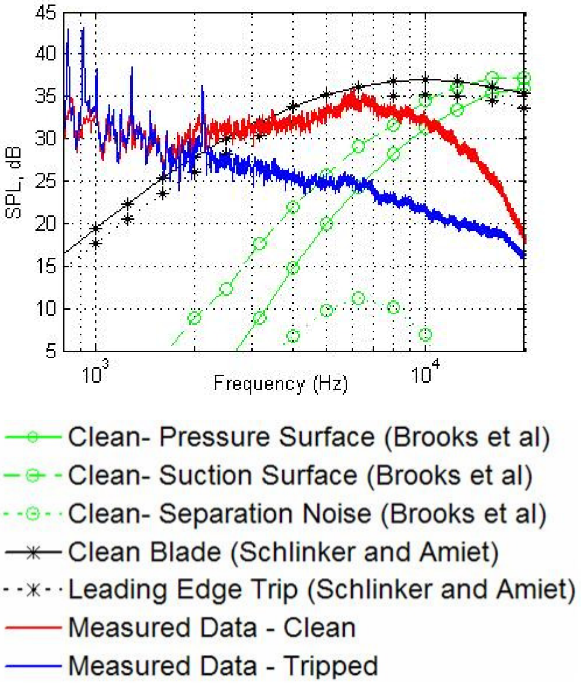

Figure 7. TBL-TE Prediction, 5000RPM, 10m/s. Tripped data comparison against TBL-TE prediction in Brooks et al. TBL-TE model (Brooks et al 1989), and Schlinker and Amiet TBL-TE model (Hubbard 1990). Based on a tripper thickness of 0.12mm, at 10% chord, and XFOIL δ calculations. Clean= No tripper applied to the blade surface.

Laminar Boundary Layer-Vortex Shedding (LBL-VS)

The alternative explanation for the noise mechanism that is being modified would then be that the noise was coming from Laminar Boundary Layer-Vortex Shedding. Traditionally this noise is results from an entirely or almost entirely laminar boundary layer. Usually an aeroacoustic feedback loop is established when the T-S (Tollmien-Schlichting) boundary layer oscillations are amplified and radiated acoustically at the trailing edge. These radiated acoustic waves are then in phase with the boundary layer waves and so reinforce and amplify these frequencies as they are convected along the blades surface. This forms an aeroacoustic feedback loop which reinforces a single frequency and radiates as tone, or a region of tones in the case of a propeller. The presence of any disruption on the surface which forces the laminar boundary layer to transition will result in the break down of the aeroacoustic feedback loop, eliminating the laminar boundary layer tonal noise (Oerlemans 2004).

The measured broadband reduction region was then checked against the predicted range of tones that should be radiated from the blade based upon the chord length, and speed variation along the blade. The predicted laminar boundary layer vortex shedding region based upon the findings in Fink (1974) using Equation 1., can be seen in Figure 8. The only discrepancy is that the reduction continues up to frequencies higher than that predicted for vortex shedding.

$$f = (1/2\pi(1.73))(\beta\delta^*/U)U^{3/2}\,1/\sqrt{c\nu} \qquad (1)$$

(Fink, 1974)

β = The instability angular frequency ~0.18 for low Reynolds numbers.

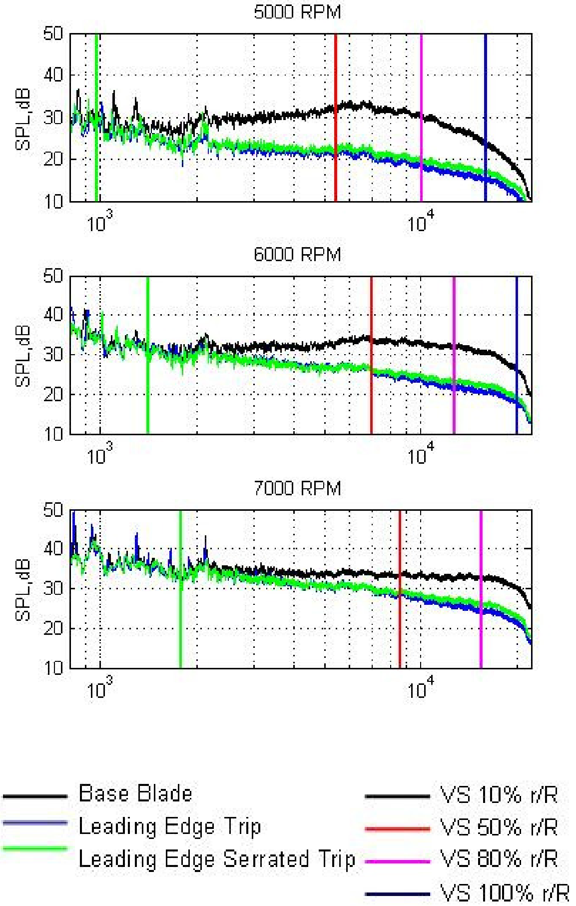

Figure 8. Boundary Layer Trips, and the predicted Vortex-Shedding frequencies ranges, from 10% radius to the blade tip (100%)

Presented in Figure 9., are the results of when the trailing edge is modified aft of the laminar separation bubble. This was done by applying tripping tape along the trailing edge, making sure the leading edge of the tape is aft of the reattachment location found from the visualisation results. This was done as an attempt to break any aeroacoustic feedback loop that was present on the suction surface of the propeller without removing the laminar separation bubble, plus modify the boundary layer thickness at the trailing edge. The noise reductions that are achieved with the trailing edge modification, shown in Figure 9., are nowhere near the same magnitude as those achieved when the bubble is eliminated. The continued presence of a laminar separation bubble following the trailing edge modification was verified through visualisation tests. Instead the modifications fitted much more closely with the reductions that were expected from a modification to the trailing edge boundary layer thickness, and the TBL-TE noise that is produced. Based upon this it can be concluded that the source of the broadband bump that is eliminated through boundary layer tripping has to be upstream of the trailing edge, even though there contribution from the trailing edge boundary layer thickness.

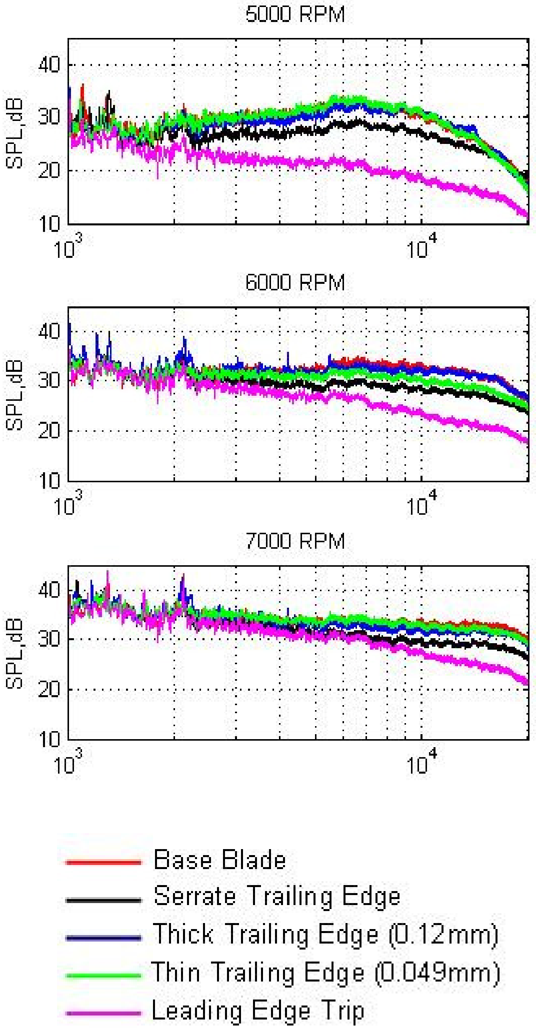

Figure 9. Trailing edge modifications, 5000RPM, 8m/s, Optimum efficiency condition (~60% propeller efficiency)

Uncertainties and Limitations

It is difficult to split up the two mechanisms (LBL-VS and TBL-TE) if they are both occurring on the blade simultaneously and are at similar levels, which appears may be the situation in this case. The predicted levels for the different mechanisms can only used as good approximations, due to the lack of good quantitative results for the inflow turbulence levels actually impinge on the blade. The fact that the effect of 3D rotation has on the aerodynamics of the blade at this size and for this particular propeller is not known should also be taken into consideration. If these were accurately known then greater certainty could be place in the predicted models, so that they could be used effectively to determine the mechanisms and ultimately the optimum tripper position for a certain propeller.

To determine the true noise source locations more sophisticated data acquisition systems are required than have been used so far in this investigation. If the noise source is to be properly located it need to be done using a phase array and individual frequencies need to be targeted, so as to pin point if the laminar boundary layer is actually radiating tonal noise components, and if not where these tones are being radiated from.

It was also suggested by Brooks et al. (1989), that there was shedding noise present when a laminar boundary layer existed for a significant portion of the airfoil surface, but not the entire chord length which deviates from the traditional simple LBL noise model. These findings are similar to those of the test cases for this current investigation, where it was observed that there was a turbulent boundary layer by the trailing edge. It was suggested that both LBL-VS and TBL-TE noise were occurring on these airfoil sections, but this point was not expanded upon further. However, it suggests that similar mechanisms to what is observed in this current investigation have also been previously observed, however it is not known if a laminar separation bubble had any significant contribution to these findings.

KEY CONCLUSIONS

The findings of this investigation support the hypothesis that there may be both LBL-VS and TBL-TE noise mechanisms occurring simultaneously, with the LBL-VS being the dominant mechanism. The LBL-VS shedding would not be a result of the formation of an aeroacoustic feedback loop linked with the trailing edge, but instead it appears that it is linked to the bubble. It is then suggested that the shear layer of the bubble is amplifying the T-S boundary layer waves, and they are then forcing the bubble to fluctuate and are radiating as an efficient dipole source of tonal noise. These tones are manifesting themselves as a large broadband hump due to the range of velocities across the propeller blade. The bubble will act as a series of point sources along the blades radius, as the propeller blade is acoustically compact chordwise but not spanwise for the frequency range of concern. The elimination of the laminar separation bubble will then eliminate this efficient dipole source, while also reducing the trailing edge displacement thickness, intern also reducing the less efficient quadrupole TBL-TE noise levels. An illustrated summary of the proposed mechanism is illustrated in Figure 10.

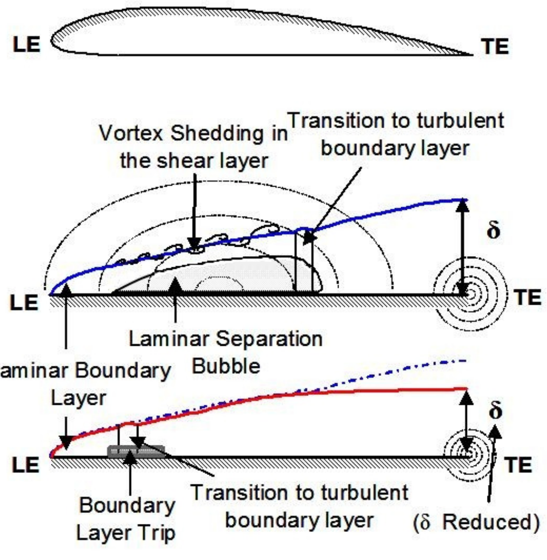

Figure 10. Explanation of Tripper modification on the aerodynamics and acoustics.

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