ANALYSIS AND REDUCTION OF BLADE PASSING NOISE OF THE ENTECHO MUPOD

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Rotor-stator interaction has been identified as the dominant noise source of the Mupod, a vertical take-off and landing aircraft, developed by Entecho, a WA company. This paper reports field measurement results of blade passing noise of the Mupod together with its analysis and control. The blade passing event was simulated in a wind tunnel experiment. The flow speed, rotor blade position and rotor stator blade spacing were varied while the chord-wise pressure distribution of the leading surface of the rotor blade was measured by an array of 6 flush mounted microphones. The features of the pressure distribution on the rotor blade influenced by an upstream stator blade were used for the qualitative analysis of the sound radiation from the Mupod. The result of the reduction of the blade passing noise using angled stator blades is also presented.

INTRODUCTION

Recent development of an unmanned aircraft (the Mupod), capable of vertical takeoff and landing (VTOL) and flight through air, by a WA company, Entecho, has stimulated this research on analysis and control of noise radiated from the aircraft. Figure 1 is a photo of the Mupod in a wind tunnel. This device includes a centrifugal fan that draws air in vertically and dispels it radially and vertically, providing a means to lift and propel this craft through the air. The air from the fan is contained and directed by a skirt, which expels most of the air vertically giving rise to the predominant lift force. This is illustrated in Figure 2 where a cross section of the Mupod is shown to describe the inlet air flow (the arrow towards the stator) towards the stator blade. The skirt in the down stream of the rotor blade (Figure 2) also has the ability (through changing its shape) to direct the air flow from the the rotor (the blue arrow from the rotor) with a horizontal component giving rise to the thrust force. Unlike other craft that are capable of VTOL, the Mupod accelerates the air radially as opposed to axially, resulting in a more compact vehicle footprint, higher lift/power ratio and safer VTOL.

Figure 1. Image of the Entecho Mupod.

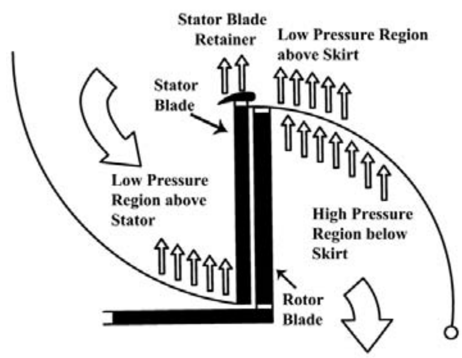

Figure 2. Illustration diagram of lift generation in the cross section of the Mupod.

The centrifugal fan in the Mupod consists of a rotor with equally spaced rotor blades and upstream stator blades that provide axial moment balance and structural support. Figure 3 shows the configuration of the rotor and stator blades and the flow in the radial direction.

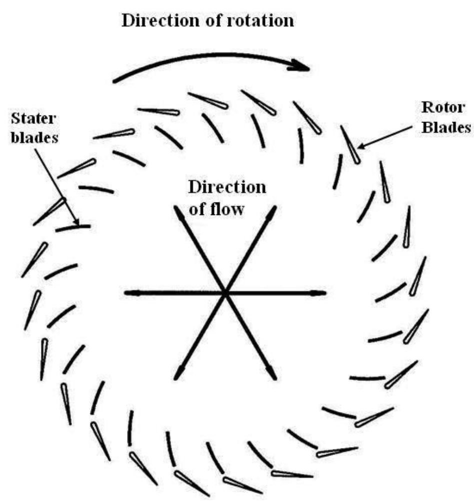

Figure 3. Rotor and stator blades in the Mupod.

Measured noise demonstrates that the Mupod noise is dominated by its blade passing components attributed to the aerodynamic interaction between the rotor and stator blades. Figure 4 shows the noise spectra (measured at 1 m away from the source and at the same height with the source) of the Mupod for two different configurations, tested at a constant angular velocity of the rotor.

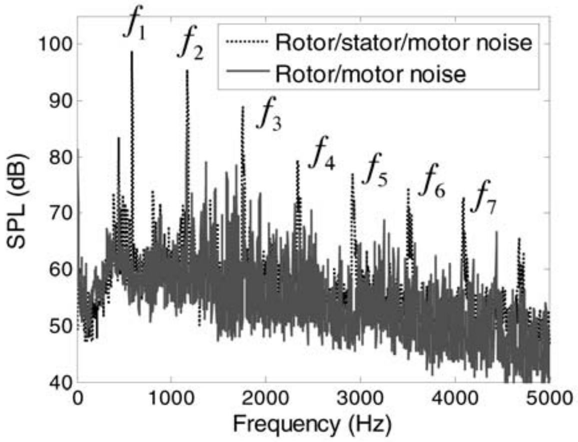

Figure 4. Sound pressure spectra (dB re 20 μPa) of Entecho VTOL aircraft (Mupod) at 1500 rpm rotor speed.

The dashed curve in Figure 4 is from the completely assembled Mupod. Noise for this case is contributed by the electric motors, turbulent noise generated by the blades passing the flow and blade passing noise due to rotor and stator blade interaction. The peak sound levels corresponding to the blade passing event are readily identified at the blade passing frequencies and its harmonic frequencies, which can be determined from

$$f_k = kN_R\Omega \tag{1}$$

where k = 1, 2, 3..., Ω and N_R are respectively the rotational frequency and number of rotor blades.

The solid curve in Figure 4 is from the Mupod with the stator blades removed. This is the case where rotor and stator interaction is removed. A significant difference in overall noise level is evident for this configuration. The large sound level for the first case is clearly attributed to the blade passing event.

The blade passing event of the Mupod is analysed in this paper. The understanding of the blade passing mechanism has led to a recommended change to the Mupod configuration that has significantly reduced the blade passing noise.

NOISE ANALYSIS

Blade passing noise

When a rotor blade rotates at a constant angular velocity in an air flow, it experiences aerodynamic forces. In turn the reaction force from the rotating blade accelerates the surrounding air and generates pressure disturbances in the air as sound waves. A specific case of interest of the force transfer from blade to the air is when the blade passes a closely placed obstruction such as a stator blade. During this blade passing, the force on the air in the vicinity of the rotor blade often increases significantly. The work by Curle [1], Ffowcs Williams and Hawkings [2] have provided the mathematical and physical foundation for understanding aerodynamic sound when boundary surfaces are present. For the radiated sound pressure at observation location $\vec{r}_o$ by the reaction force $\vec{F}$ at the blade passing location $\vec{r}_3$, Morse and Ingard [3] provided the following expression:

$$p(\vec{r}_o, t) = -\frac{1}{4\pi}\nabla_{\vec{r}_o}\cdot\left[\frac{\vec{F}}{R}\right]_\tau \tag{2}$$

where $R = \left|\vec{r}_o - \vec{r}_s\right|$. $[\ ]_r$ indicates that quantities inside are evaluated at the retarded time $\tau = t - R / c$, where c is the speed of sound. It is noted that the retarded time in Equation (2) does not include Mach number. This is because the sources of the the blade passing sound are located near the stators and have no relative motion with the observer.

A single rotor blade passing a stator (Figure 5) is considered first to demonstrate that the blade passing noise is dependent on the reaction force (blade passing force). The reaction force $\vec{F}$ at $\vec{r}_s$ and instant τ generates pressure $p(\vec{r}_o, t)$ at $\vec{r}_o$ and time t:

$$p(\vec{r}_o, t) = \frac{1}{4\pi}\frac{\vec{R}\cdot\vec{F}(\tau)}{R^3} + \frac{1}{4\pi}\frac{\vec{R}}{cR^2}\cdot\frac{\partial\vec{F}(\tau)}{\partial\tau}. \tag{3}$$

For simplicity, we assume the sound generated by a single force component $\vec{F}(\tau) = [0F_y(\tau)\ 0]^T$ only at position $\vec{r}_s = (a, 0, 0)$, where $F_y(\tau)$ is modelled by impulses:

$$F_y(\tau) = \begin{cases} F_{yo}, & \frac{n}{\Omega} \le \tau \le \frac{n}{\Omega} + \Delta T, \quad n = 0, \pm 1, \pm 2, ... \\ 0 & otherwise \end{cases} \tag{4}$$

In Equation (4), ΔT is the duration of blade passing wherein the force is assumed to be a constant. Equations (4) and (3) lead to the time history of sound pressure in the form of a series of pressure impulses with period of $1/\Omega$. This gives rise to the fundamental frequency (blade passing frequency) Ω of the sound pressure.

The above analysis is extended to the blade passing noise and frequencies of the Entecho Mupod, which has N_R equally spaced rotor blades. If we only consider the aerodynamic interaction when the rotor and stator blades are very close, the time history of the force on air near a stator blade can still be expressed by Equation (4), but with Ω replaced by $N_R\Omega$. This is because the stator is passed by N_R rotor blades in one cycle of rotation. As a result, radiated sound by the N_R rotor blades passing the stator blade is described by the discrete frequency components of sound pressure at zero frequency $k = 0$, blade passing ($k = 1$) and its harmonic ($k > 1$) frequencies:

$$p(\vec{r}_o, t) = \frac{1}{4\pi}\frac{y_o F_{yo}}{R^2}\sum_{k=-\infty}^{\infty} C_k\left(\frac{1}{R} + \frac{j2\pi k}{cT}\right)e^{j2\pi k\frac{\tau}{T}} \tag{5}$$

where y_o is the location of the observer on the Y axis and

$$C_k = \left(\frac{\Delta T}{T}\right)\frac{\sin(\pi k\Delta T/T)}{\pi k\Delta T/T}e^{-j\pi k\Delta T/T}\ . \tag{6}$$

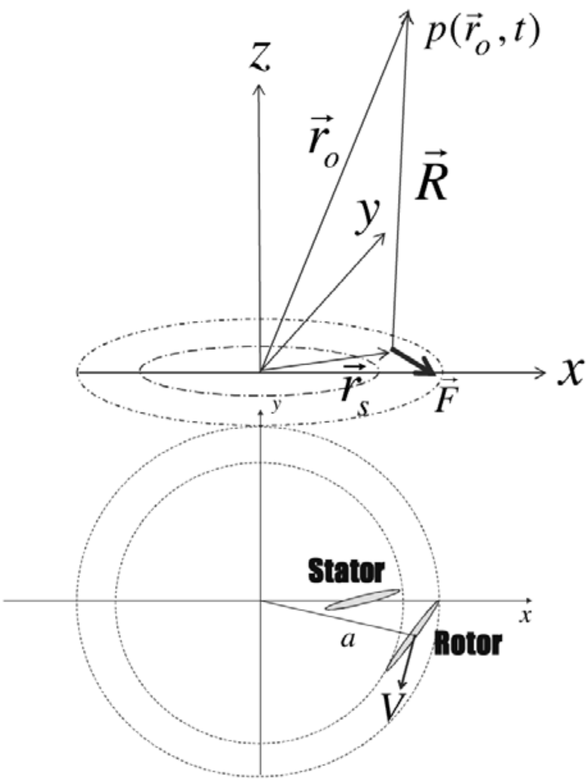

Figure 5. Coordinates for blade passing sound generated by a blade passing force.

Although the practical reaction force during the blade passing event may have a more complicated time history than a series of simple rectangular impulses and multiple force components, the general features of blade passing frequency component sound pressure due to the component force of equally spaced rotor blades passing a stator blade are qualitatively explained using this simple analysis.

Overall blade passing noise

The Mupod actually has N_S (different from N_R) equally spaced stator blades as shown in Figure 3. Consequently, the total sound pressure is due to the superposition of all sound produced by the N_R blade passing events in the vicinity of the N_S stator blades.

If the the first stator blade is located at $\vec{r}_{s1}$ = (a, 0, 0), then the position of the n_s^{th} (increasing in the anti-clockwise direction) stator blade is described as

$$\vec{r}_{sn_s} = \left(a\cos\frac{2\pi(n_s-1)}{N_S}, a\sin\frac{2\pi(n_s-1)}{N_S}, 0\right) \tag{7}$$

and the time delay between the adjacent blade passing events (for clockwise rotation of the rotor) is

$$\Delta\tau = \tau_{n_s} - \tau_{n_s-1} = -\frac{1}{N_S\Omega}\ . \tag{8}$$

Thus when Equation (3) and the superposition principle are used to calculate the total sound pressure produced by the blade passing at all stator blades, the phase of each blade passing event is also contributed by the distance $|\vec{r}_o - \vec{r}_{sn_s}|$ in the retarded time τ_{n_s}. The magnitude of blade passing noise from each stator also depends on the orientation between the force vector $\vec{F}_{n_s}(\tau_{n_s})$ and the position vectors $\vec{r}_o - \vec{r}_{sn_s}$.

Huang's work on the noise control of axial fans [3] indicated that blade passing noise from axial fans can be reduced by optimising the relative phases of the noise from each stator blade. An optimal combination of the numbers of rotor and stator blades may be found that results in minimum noise radiation to certain directions (based on spatial interference of radiated sound) and at certain blade passing frequencies. A similar approach can be undertaken for the Mupod after the properties of the blade passing forces are understood.

Properties of the blade passing force

It is clear that any further analysis of the blade passing noise must require the property of the blade passing forces. However, neither experimental nor numerical data of such forces are available for the specific blade passing of the Entecho Mupod.

A preliminary experiment has been conducted in a wind tunnel to measure the surface pressure on a stationary rotor blade located downstream from a stator blade. Six mini-microphones were flush mounted along the chord of the rotor blade (see Figure 6). The pressure was measured on the rotor blade at 13 different angular positions (see Figure 7) on an arc simulating the rotor path. The minimum clearance between the blades was 2mm. The angle of the trailing edge of the stator blade was -30° to the direction of the incoming air flow. The orientation angle of the rotor blade was -70° from the radial direction. Both rotor and stator blades were made of wood. The dimensions of the blades are listed in Table 1. The area testing cross sectional area of the wind tunnel working section was 380 x 250 mm^2.

Table 1. Dimensions of rotor and stator blades

	Chord length	Thickness	Blade length
Rotor	49mm	10mm	260mm
Stator	47mm	10mm	260mm

Figure 8 shows the sound pressure level measured by the microphone (mic 1) near the leading edge of the rotor blade at three flow speeds. The result shows an increase of pressure up to 15dB when the rotor blade is placed in the vicinity of the stator blade. The location of the rotor blade is given by its angular location on a circle of radius 210 *mm*, where the angular position of zero corresponds to rotor blade position 7 in Figure 7.

The distributed sound pressures (with and without the effect of the upstream stator) along the chord of the rotor blade for rotor position 7 are shown in Figure 9. The increase in the sound pressure level near the trailing edge of the blade when the stator is absent is due to the unsteady flow generated near the trailing edge of the rotor. With the influence of the stator, the pressure distribution on the rotor blade finds its maximum level near the leading edge of the blade. An increase in peak pressure by 15dB near the leading edge of the blade is evident for the case where the stator blade is located upstream. Since this surface pressure contributes to the blade reaction force to the air, the reduction in the radiated sound pressure (see Equation (3)) is expected if the stator blades in the craft are removed. This explains the noise reduction observed in Figure 4.

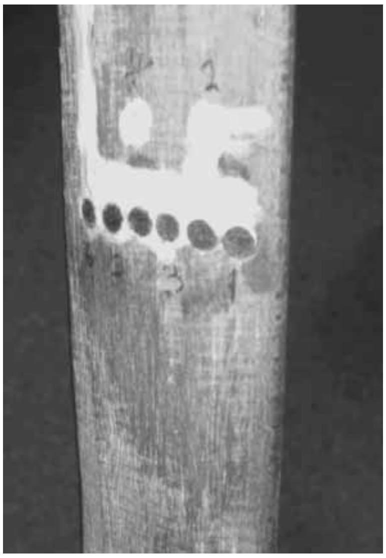

Figure 6. Rotor blade with flush mounted microphones and their locations.

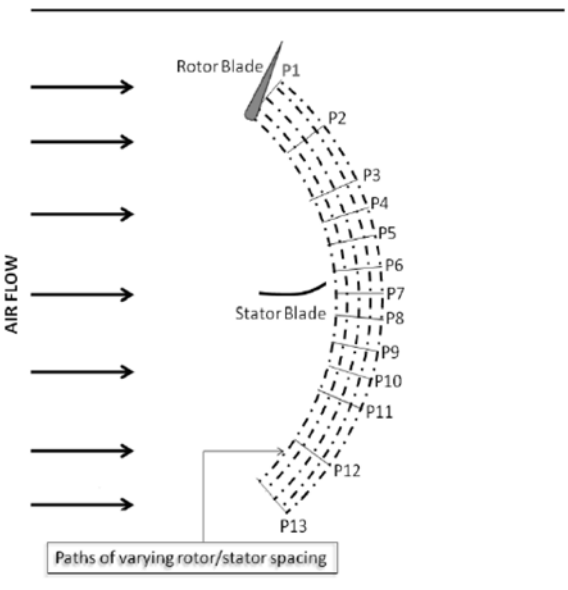

Figure 7. Rotor blade positions for surface pressure measurement.

Observations from Figures 8 and 9 also provide data for further analysis of the blade passing noise using quasi-steady approximation for the force estimation [4], where the effect of the rotor blade speed on the characteristics of the force is ignored. Figure 8 shows that the effective angular range where the blade passing force is significant is about 0.1 (rad).

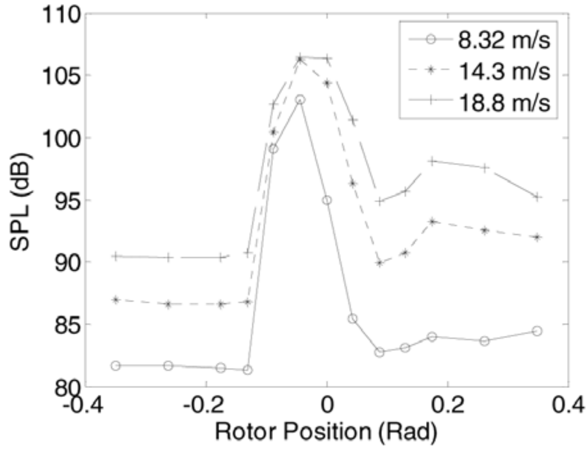

Figure 8. Pressure near the leading edge of the rotor blade at different angular positions.

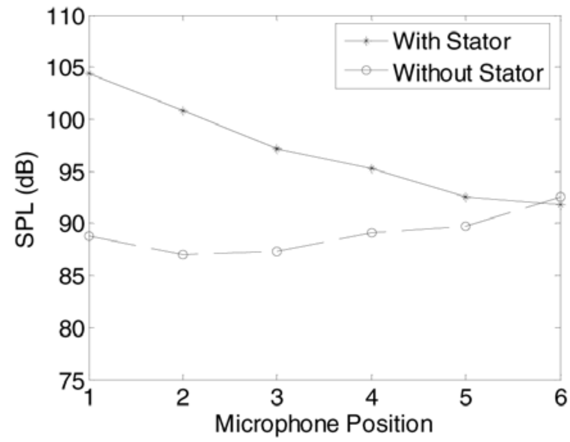

Figure 9. Pressure distribution along the chord of the rotor blade when rotor blade is located at position P7.

This range yields the blade passing duration $\Delta T = \frac{0.1}{2\pi\Omega}$. Figure 9 indicates that most blade forces are contributed by the pressure over approximately the first quarter of the chord length from the leading edge.

The pressure on the stationary rotor blade in the wind tunnel may not be a correct representation of that on the rotating blades. Because of the increased relative velocity, the change in the momentum in the air near the area of blade passing may be increased, so too the relative magnitude of the force components. Nevertheless, the confined angular region of pressure rise in the vicinity of the stator blade and pressure concentration near the leading edge of the rotor blade during blade passing are features useful for the following qualitative analysis of control of blade passing noise.

REDUCTION OF BLADE PASSING NOISE

Noise control mechanism

The above analytical and experimental results are used to assist the control of the blade passing noise of the Mupod. Equation (4) shows that the main characteristics of the force during blade passing are the duration of blade passing ΔT and force magnitude F_{yo}. The F_{yo} can be approximately estimated by the pressure (during blade passing) integrated over a surface area near the leading edge of the rotor blade. This area equals 1/4 of the rotor's chord multiplied by the length of stator section (in the stator length) which is involved in the blade passing event. The location of the force can be approximated as a point at the leading edge of the rotor blade and close to the trailing edge of the stator blade. If the rotor blade is parallel to the stator blade, then the effective blade passing area is 1/4 chord times the height of the stator L. For this case the force magnitude is the largest as the blade passing area per unit time is the largest. When the blade passing area is the largest, the blade passing duration ΔT is also the shortest ($\frac{0.1}{2\pi\Omega}$). The magnitude and duration of the force for this parallel blade configuration is illustrated in Figure 10 by rectangular pulses with solid boundaries.

If angled stator blades are used for the Mupod (see Figure 11), the force magnitude $F_{yo,A}$ during blade passing can be significantly reduced due to the reduced blade passing area per unit time. The blade passing duration is increased to

$$\Delta T_A = \frac{0.1}{2\pi\Omega} + \frac{L\sin\vartheta}{2\pi a\Omega} \tag{9}$$

where ϑ is the angle between the stator blade and the vertical direction (see Figure 11) and L is the length of the stator blade. Those features of the blade passing force due to the use of an angled stator are illustrated in Figure 10 by the dashed pulses.

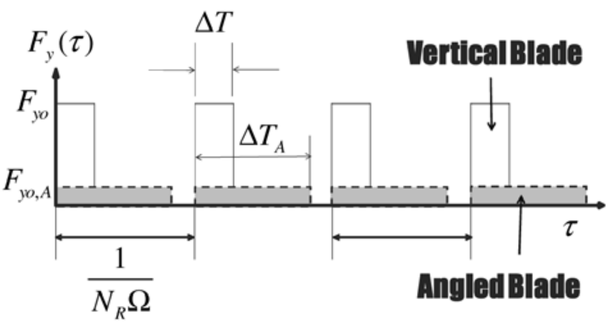

Figure 10. Illustration of time history of forces during blade passing. Solid impulses: stator blade is parallel to the rotor blade; dashed impulses: stator blade is at an angle to the vertical rotor blade.

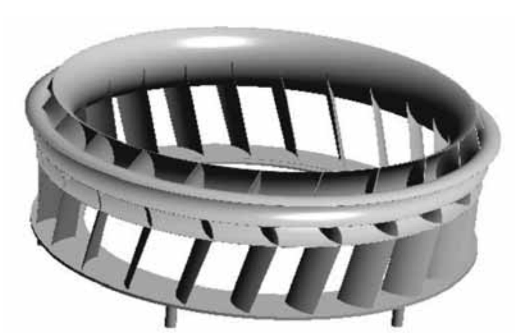

Figure 11. Angled stator for the VTOL aircraft with a blade angle of 15 degrees.

Intuitively, the reduction of blade passing noise by using the angled stator blades can be understood from Figure 10. Increasing the stator's blade angle not only reduces the blade passing force, but also increases the blade passing duration. As ΔT_A is increased towards the blade passing period $T = \frac{1}{N_R\Omega}$, the force approaches a constant. This results in a significant reduction in noise components at the blade passing frequency and its harmonic frequencies. Mathematically this mechanism of reducing blade passing noise is also observed from Equation (6), i.e.

$$\lim_{\Delta T_A/T\to 1} C_k = \begin{cases} 0, & k\neq 0 \\ 1, & k=0 \end{cases}. \tag{10}$$

Figure 12 provides more details of $|C_k|$ as a function of $\Delta T_A/T$. There are only two regions of $\Delta T_A/T$ ($\Delta T_A/T \to 0,1$) where all the blade passing components can be reduced. Design for $\Delta T_A/T \to 0$ is not feasible because of the inherent non-zero blade passing duration ($\frac{0.1}{2\pi\Omega}$) as observed experimentally. However, design of $\Delta T_A/T \to 1$ can be achieved by using an angled stator as illustrated by Equation (9).

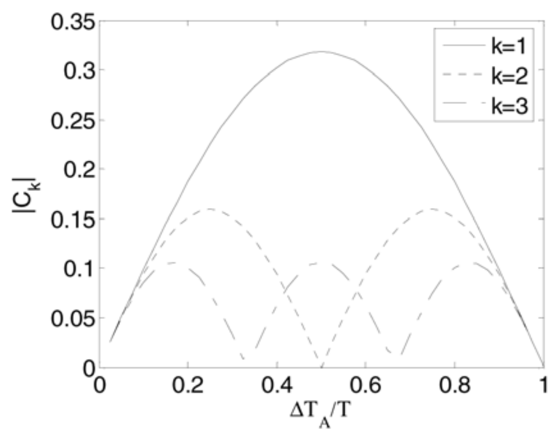

Figure 12. $|C_k|$ as a function of $\Delta T_A/T$.

Experimental confirmation

A comparison experiment was conducted to measure radiated sound pressure at 1.5m away from the Mupod. The first measurement was for the noise from the Mupod with the normal configuration where the stator blades are parallel to the rotor blades. In the second measurement, the normal stator was replaced by a stator with a blade angle of 15 degrees from the rotor blades. The test was conducted at three different motor speeds.

The sound pressure spectra for these two measurements and for motor speed at 1500rpm are shown in Figure 13. The results demonstrate that the angled stator significantly reduces the blade passing noise.

The Mupod used for the test has a rotor diameter of a = 206mm, $N_R = 24$, $L = 84.8mm$ and $\Omega = 25Hz$. This configuration results in T of 0.0017s. The inherent blade passing duration when rotor and stator blades are parallel is $\Delta T = 0.0006s$. The estimated increase of blade passing duration due to the 15 degree angled stator blade is $\frac{L \sin \vartheta}{2\pi a \Omega} = 0.0007s$. As a result, $\Delta T_A / T = 0.76$, This indicates that the angled stator blades almost doubled the blade passing duration and made $\Delta T_A / T$ approach the unity limit.

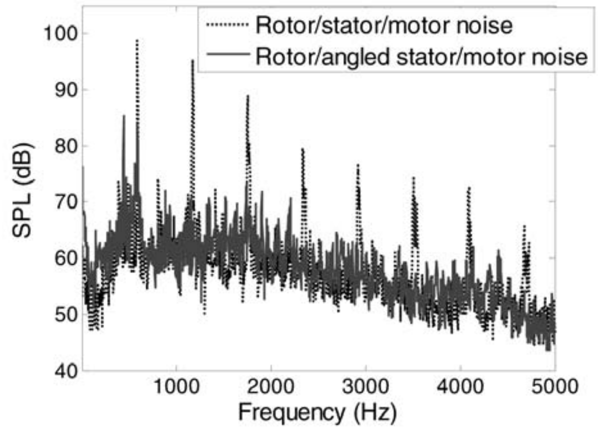

Figure 13. Comparison of sound pressure spectra of Entecho VTOL aircraft (Mupod) at 1500 rpm. Dotted curve: Mupod with normal stator blades; solid curve: Mupod with angled stator blades.

Further confirmation of the effectiveness of the blade passing noise reduction using angled stator blades is shown in Figure 14, where overall dBA level of the Mupod with normal stator and with angled stator are compared at three different rotor speeds. Up to 10 dB noise reduction is observed for all the rotor speeds.

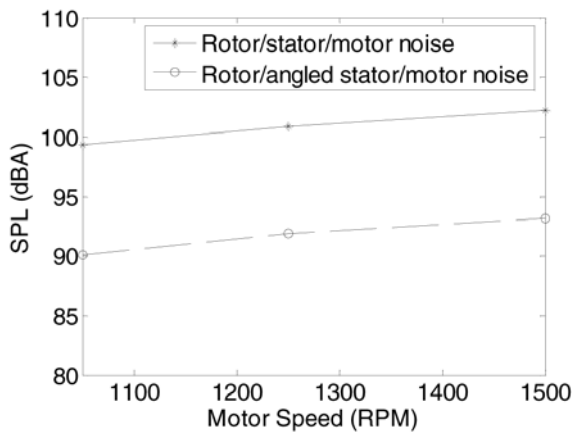

Figure 14. Comparison of overall A-weighted noise levels of the Mupod sound radiation at three different speeds. Solid curve: Mupod with normal stator; dashed curve: Mupod with angled stator.

CONCLUSIONS

Analytical and experimental approaches have been used to study the blade passing noise radiated from an Entecho Mupod. The blade passing sources are spatially stationary sources and the blade passing force plays a dominant role in producing the radiated noise. The features of the force are characterised by the duration of the peak blade passing force and the distribution of the blade passing pressure. Wind tunnel measurement of the blade passing pressure on a stationary rotor blade has provided some preliminary information of the blade passing duration and pressure distribution. This understanding of the blade passing force (which is the surface intergration of the blade passing pressure) and the analytical model of the blade passing noise provides a useful explanation for the effective reduction of blade passing noise using angled stator blades.

Future work includes the measurement of the blade passing force when relative motion between rotor and stator blades is involved. In this paper, the blade passing duration through a stator blade is obtained from a quasisteady approximation and based on measured pressure on a stationary rotor blade downstream from a stator blade. Further experiment is required to study the effect of blade size, angle of attack and relative velocity between rotor and stator blades on the blade passing force.

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REFERENCES

[1] N. Curle, "The influence of solid boundaries upon aerodynamic sound", Proceedings of the Royal Society of London. Series A, Vol.231(1187), 505-514, (1955).

[2] J. E. Ffowcs Williams and D. L. Hawkings. "Sound generation by turbulence and surfaces in arbitrary motion', Proceedings of the Royal Society of Lon-don. Series A, Vol.264(1151), 321-342, (1969).

[3] P. M. Morse and K. U. Ingard, "Theoretical Acoustics", McGraw-Hill Book Co. New York, (1968).

[4] L. Huang, "Characterizing computer cooling fan noise", J. Acoust. Soc. Am 114(6), 3189-3199, (2003).

[5] D. Olivari, "An investigation of vortex shedding and galloping induced oscillation on prismatic bodies", Journal of Wind Engineering and Industrial Aerodynamics, 11, 307-319, (1983).