Analysis and reduction of blade passing noise of a VTOL aircraft

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ABSTRACT

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

INTRODUCTION

Recent development of unmanned aircraft, 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 aircraft in a wind tunnel. This device is a radial drum or centrifugal fan that draws air in vertically and dispels it radially, 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 (Figure 2). The skirt also has the ability to direct the air with a horizontal component giving rise to the thrust force. Unlike other craft which are capable of VTOL, this device accelerates the air radially as opposed to axially, resulting in a more compact vehicle footprint, higher lift/power ratio and safer VTOL.

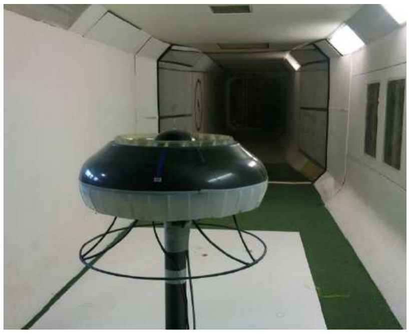

Figure 1. Image of Entecho VTOL aircraft

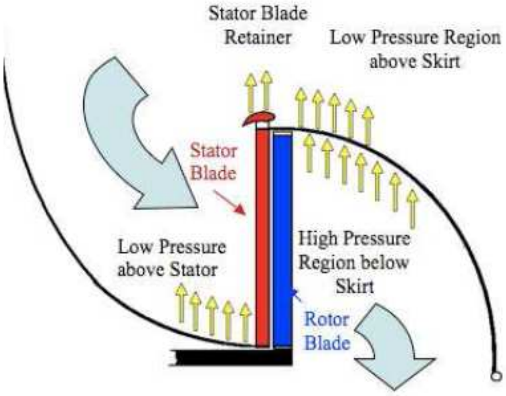

Figure 2. Illustration diagram of lift generation

The centrifugal fan in the aircraft 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.

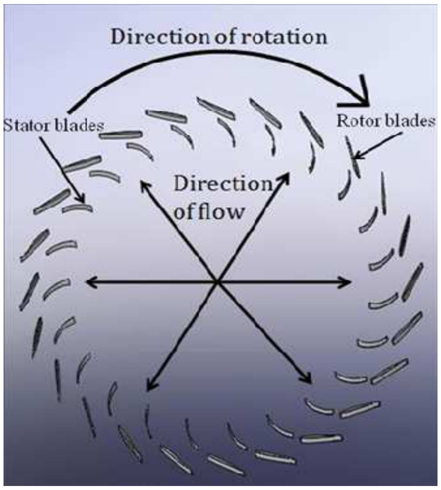

Figure 3. Rotor and stator blades in the VTOL aircraft

Measured noise of the aircraft demonstrates that the aircraft noise is dominated by its blade passing components attributing 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 aircraft (mupod) for different configuration of the aircraft components, tested at a constant angular velocity of the rotor.

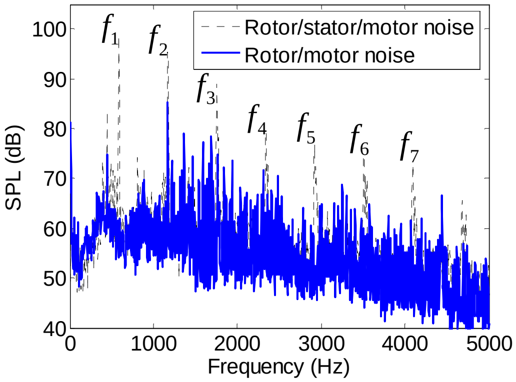

Figure 4. Sound pressure spectra (dB re 20 μPa) of Entecho VTOL aircraft (mupod) at 1500 rpm rotor speed

The dashed curve in Figure 4 is from the completely assembled mupod. Noise for this case is contributed by the electrical motors, turbulent noise generated by the blades passing the flow and blade passing noise due to rotor and stator blade interaction. The difference of the overall sound pressure level (dBA) between these two cases is approximately 10 dB. 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 attributed to the blade passing event.

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

NOISE ANALYSIS

Blade passing noise

Asuming a rotor blade rotates at a constant angular velocity in an air flow, it experiences aerodynamic forces. In return 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 radiated sound pressure at observation location $\vec{r}_o$ by the reaction force $\vec{F}$ at the blade passing location $\vec{r}_s$ is described by [1]:

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

where $R = |\vec{r}_o - \vec{r}_s|$, $[\;]_\tau$ indicates that quantities inside are evaluated at the retarded time $\tau = t - R/c$ and c is the speed of sound. It is noted that the retarded time in Equation (2) does not include Mach number. It 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 illustrate the blade passing noise. The reaction force $\vec{F}$ at $\vec{r}_s$ and instant τ generates sound pressure at $\vec{r}_o$ and t:

$$p(\vec{r}_o, t) = -\frac{1}{2\pi}\frac{(\vec{r}_o - \vec{r}_s)\cdot\vec{F}(\tau)}{|\vec{r}_o - \vec{r}_s|^3}. \tag{3}$$

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

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

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 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 frequency of the Entecho VTOL aircraft (Mupod), which has N_R equally spaced rotor blades. If we ignore the effect of aerodynamic interaction between the rotor blades on the blade passing near the stator, the only change of the time history of the force in (4) is to replace Ω by $\frac{1}{T} = N_R\Omega$ as 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:

$$p(\vec{r}_o, t) = -\frac{1}{2\pi}\frac{y_o F_{yo}}{\left|\vec{r}_o - \vec{r}_s\right|^3}\sum_{k=-\infty}^{\infty} C_k e^{j2\pi k\frac{\tau}{T}} \qquad (5)$$

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

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

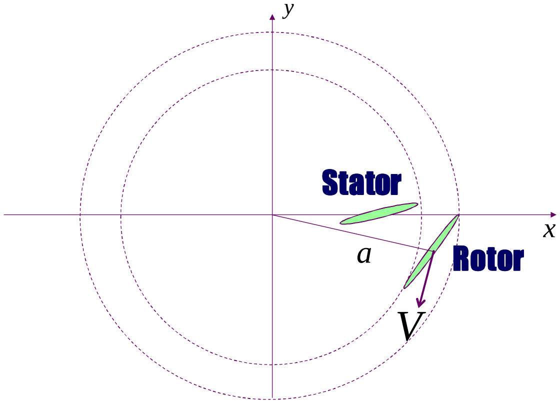

Figure 5. The top view of a rotor blade passing a stator blade

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 may also exist, the general features of blade passing frequency component sound pressure due to the component force of N_R equally spaced rotor blades passing a stator blade are qualitatively explained using this simple analysis.

Overall blade passing noise

The craft actually has N_S 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 position of the first stator blade is defined at $\vec{r}_{s1} = (a, 0, 0)$, then the position of the n_s^{th} (increasing in the anti-clockwise direction) stator blade is

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

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

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

Thus when Equation (3) and the superposition principle are used to calculate the total sound pressure produced by the blade passing at each stator blade, the phase of each blade passing event is also contributed by the distance $\left|\vec{r}_o - \vec{r}_{sn_s}\right|$ 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 [2] indicated that blade passing noise from axial fans can be reduced by optimising the relative phases of the noise from each stator blade, and an optimal combination of the numbers of rotor and stator blades may be found that resulting 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 VTOL aircraft considered here after the properties of the blade passing forces are understood.

Properties of the blade passing force

Although general features of the blade passing noise and its control are analysed using the interference of component sound from each blade passing and a simple form of the force time history, accurate prediction 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 was $380 \times 260 mm^2$

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

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 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 is located upstream. Since this surface pressure contributes to the blade reaction force to the air, so to reduction in the radiated sound pressure (see Equation (3)), is expected with the removal of the stator blade in the craft. This may explain the noise reduction observed in Figure 4.

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

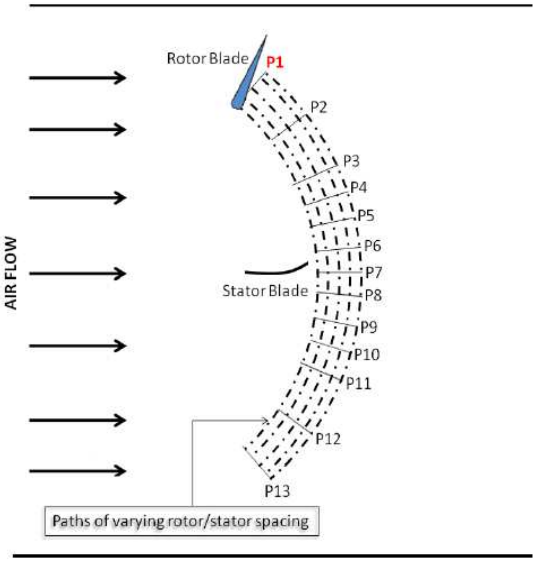

Figure 7. Rotor blade positions for surface pressure measurement

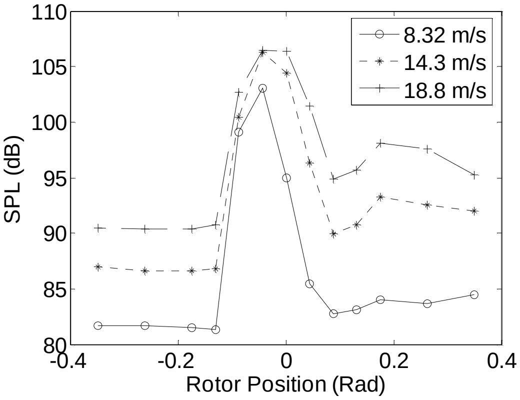

Figure 8. Pressure near the leading edge of the rotor blade at different angular positions

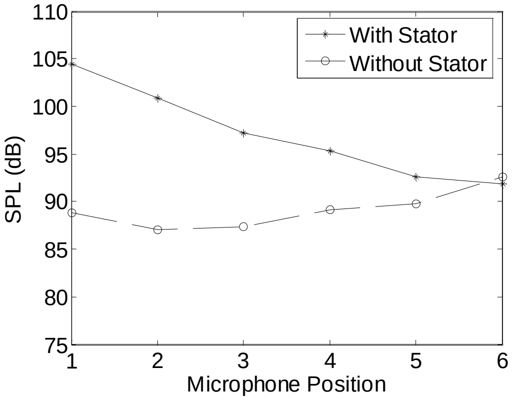

Figure 9. Pressure distribution along the chord of the rotor blade when rotor blade is located at position 7

Observation of Figures 8 and 9 also provides data for further analysis of the blade passing noise using quasi-steady approximation for the force estimation [3], where the effect of the rotor blade speed on the characteristics of the force is ignored. From Figure 8 the angular range where blade passing force has a peak value is determined to be 0.02π. Such range yields the duration in the time history, where peak force is detected $\Delta T = \frac{0.02}{\Omega}$. Figure 9 indicates that most blade forces are contributed by the pressure over approximately the fisrt quater of the chord length from the leading edge.

The pressure on the stationary rotor blade may not correctly represent 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 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 craft's blade passing noise. 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 involves in the blade passing event . The location of the force can be approximated as a point at the leading edge of the blade and close to the trailing edge of the stator. If the rotor blade is parallel to the stator blade, then the area is 1/4 chord times of 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. For this case, the duration ΔT is also the shortest ($\frac{0.02}{\Omega}$). 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 craft (see Figure 11), the force magnitude $F_{yo,A}$ during blade passing can be significantly reduced due to the reduced area per unit time at blade passing. The blade passing duration is increased to

$$\Delta T_A = \frac{0.02}{\Omega} + \frac{L \tan \vartheta}{2\pi a \Omega} \qquad (9)$$

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

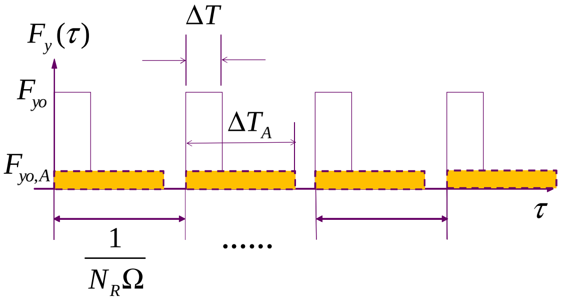

Figure 10. Illustration of time history of forces during blade passing. Solid impulses: stator blade is parallel to the rotor blade; dashed impulses: stator blade is at the angle to the vertical rotor blade

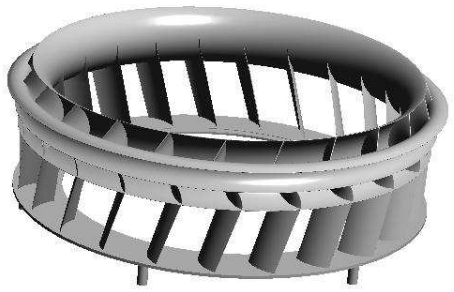

Figure 11. Angled stator for the VTOL aircraft with a blade angle of 15 degrees

Intuitively, the reduction of blade passing noise by using the angled stator blades can be understood from Figure 10. Increasing the stator's 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 may result 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.

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

Figure 12 provide more details of $|C_k|$ as a function of $\Delta T_A / T$. There are only two regions of $\Delta T_A / T$ ($\Delta T_A / T \rightarrow 0,1$) where all the blade passing components can be reduced. Design for $\Delta T_A / T \rightarrow 0$ is not feasible because of the inherent non-zero blade passing duration ($\frac{0.02}{\Omega}$ as observed experimentally). However, design of $\Delta T_A / T \rightarrow 1$ can be achieved by using an angled stator as illustrated by Equation (9).

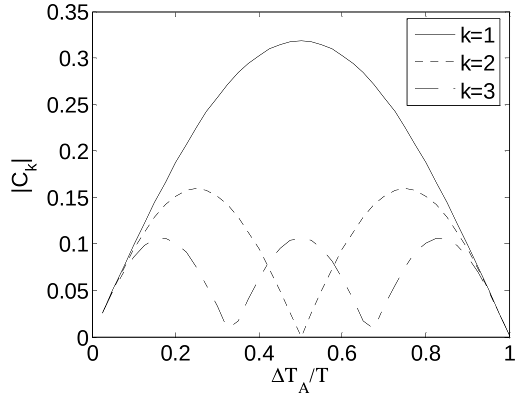

Figure 12. $|C_k|$ as a function of $\Delta T_A / T$

Experimental confirmation

A comparison test was conducted to measure radiated sound pressure at 1.5m away from the mupod. The first measurement was for the noise from the craft with normal stator where stator blades are parallel to the rotor blades. In the second measurement, the normal stator was replaced by an angled 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. Comparing the results demonstrates 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 results in a value for T of $0.0017s$. The inherent blade passing duration $\Delta T = 0.0008s$. The estimated increase of blade passing duration due to the 15 degree angled stator blade is $\frac{L \tan \vartheta}{2\pi a \Omega} = 0.0007s$. As a result, $\Delta T_A / T \approx 0.88$ which indicates that the angled stator almost doubled the blade passing duration and this was accompanied by a significant smoothing of the time history of the blade passing force.

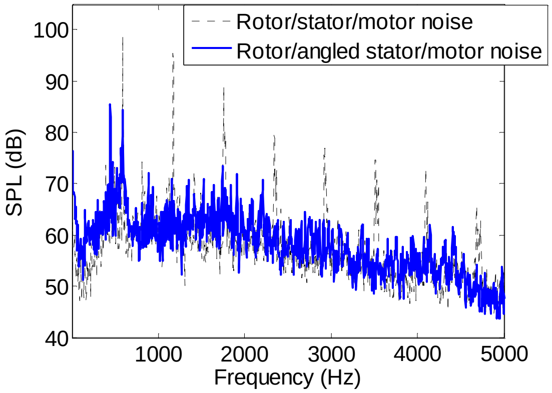

Figure 13. Comparison of sound pressure spectra of Entecho VTOL aircraft (Mupod) at 1500 rpm. Dotted curve: Mupod with normal stator blades; solid curve mupod with angled stator blades.

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 at all the rotor speeds.

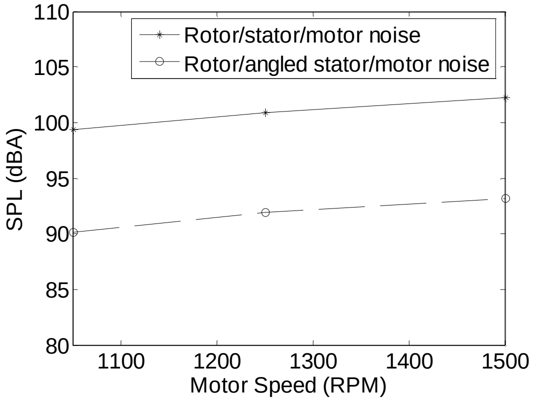

Figure 14. Comparison of overall A-weighted noise levels of the mupod sound radiation at three different speeds. Solid curve: mupod with normal stator; dashed curve: mupod with angled stator.

CONCLUSIONS AND FUTURE WORK

Analytical and experimental approaches have been used to study the blade passing noise radiated from an Entecho VTOL aircraft. The blade passing sources are spatially stationary sources and the time history of the blade passing forces plays an important role in producing the radiated noise. The features of the force's time history 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 force 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 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 rotor blade moves around the stator blade. Accurate prediction of the blade passing sound relies on the accuracy of the force. In this paper, the blade passing duration through a normal rotor blade is assumed to be 10% of the total duration that the rotor blade experience pressure fluctuation. This assumption cannot be justified before the effect of blade size, angle of attack and relative velocity between rotor and stator blades on the blade passing force is studied. Nevertheless, once this nomimal blade passing duration is known, an optimal angle of the rotor blade can be determined by solving ϑ from $\Delta T_A = T$.

ACKNOWLEDGEMENTS

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