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Aerodynamic and Aeroacoustic Characterisation of Isolated Rotor in Hover and Transition to Forward Flight

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The characteristics of aerodynamic noise and thrust of an isolated tilt-rotor system were experimentally investigated at hover and multiple tilting positions of the rotor disc. In this study, the effects of rotational speed, freestream flow velocity, and tilt angle were examined in an anechoic wind tunnel. Load measurements and far-field acoustic pressure measurements were performed in static condition and under freestream velocities ranging from 8 m/s to 24 m/s. Tests were conducted at a rotor diameter-based advance ratio between 0 and 0.3, and at rotor shaft tilt angle spanning from 0° to 30°. The aerodynamic coefficients, the sound power spectral density and the sound pressure level were studied and discussed. The results demonstrate dependency between the loading and noise signatures to the rotor tilting position. At a settings of rotation speed and freestream inflow velocity, the results show a significant noise attenuation at a higher tilting angle while maintaining a similar directivity of far-field noise radiation. However, at the same setting of rotational speed and inflow velocity, the aerodynamic thrust generating capability of the rotor is adversely affected by the rotor disc tilting angle.

I. Nomenclature

θ	=	far-field observation angle [°]
α	=	rotor disc tilting angle [°]
BPF	=	blade passing frequency [Hz]
OASPL	=	Overall sound pressure level [dB]
T	=	thrust in the z direction [N]
Q	=	torque along the z direction [Nm]
D	=	rotor diameter [m]
R	=	rotor radius [m]
A	=	area of the rotor disc [m ²]
n	=	rotor rotation speed in [rev/s]
N	=	rotor rotation speed in [rev/min]
Ω	=	rotor rotation speed in [rad/s]
ρ	=	air density [kg/m ³]

II. Introduction

URBAN Air Mobility (UAM) is a modern air transportation system that is developed to provide a faster and more efficient mobility in urban landscapes. Over the years, we have witnessed a growing interest in this technology and various concepts have been proposed. Many of which exhibit a common features in their design architecture, which is to takeoff, landing and travel long distances quickly. A combination of vertical lift capability and fixed-wing lifting body are commonly employed in the design to meet the envisaged operation of UAM. A tilt-rotor system is one of the examples of design concept that utilises a set of rotor blades to generate vectored thrust. This allows the vehicle to transition its operation from the rotorcraft mode to fixed-wing aircraft mode. During this transition, the flow field around

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the rotor becomes more complex, causing intricate aerodynamic interactions between airflow and the rotor blade surfaces.

One of the ubiquitous features of rotor aerodynamics in transition flight is the lack of symmetry between the advancing and retreating blade sides of the rotor. Rotor disc encounters a highly non-uniform inflow, which consequently varies the blade's angles of attack around the azimuth and hence fluctuates the loading on the advancing and retreating blades [1]. The influence of tilting angle is imperative for rotor blades that are transitioning from hovering to forward flight operation, as this could severely change the loading of the rotor. Previously conducted aerodynamic investigations on tilt-rotor system, such as found in [2–7], have observed unsteady loading responses by the system. They attributed it to the non-linear aerodynamic characteristics which occur due to the non-axial inflow operating conditions.

As the tilting angle increases relative to the inflow direction, the rotor blade's thrust and power are expected to decrease at a given rotation rate [8]. Due to the unique flight segment, the noise characteristics of a tilt-rotor system varies depending on the loading condition experienced by the rotor. There are two main contributors of this occurrence, firstly due to the changing of direction of the rotating axis, and secondly the resulting unsteady airflow around rotor during the tilting process. Additionally, the rotor loading could be further perturbed by blade vortex interactions. This occurs when a blade passes through tip vortex or unsteady wake generated by the preceding blade [9]. This results in blade vortex interaction noise that consists of high amplitude tonal noise, which is repeated exactly at the harmonics of the blade passing frequency (BPF), which is defined as the product of the number of rotor blade and the rotational frequency, at every blade revolution [10].

Rotor driven system exhibits a relatively complex sound generating mechanism. With the ever-increasing complexity in the design of UAM, the development of low-noise of rotor system continues to be an important topic of scientific interest. While there are preponderance preceding works done on rotor noise study, such as found in [11–15], majority of these investigations only involved analysis of rotor acoustics at a single fixed position. Nevertheless, the fundamental mechanism of aerodynamically generated rotor noise remain consistent regardless of the rotorcraft configurations [16–18]. Generally, the rotor noise source is contributed by the nature of fluid volume displacement, steady forces acting on the blade, circumstantially non-uniform loading, and non-linear broadband generation [19].

This paper presents the preliminary experimental results on the aerodynamic and aeroacoustic performance of isolated rotors in hover and transition forward flight conditions. Additionally, the effects of the freestream velocity and rotational speed are also addressed. This paper is organized as follows: Sec. III explains the aeroacoustic facility, experimental rig and the techniques used; Sec. IV provides the results of the experiments in two main parts, i.e., aerodynamic performance and rotor noise. Finally, Sec. V reports the conclusion of this manuscript.

III. Experimental Setup

The aerodynamic loading and far-field noise measurements were conducted at non-axial inflow conditions in the aeroacoustics facility at The University of Bristol. A 12x4-inch, two-bladed rotor was used in this study and was tested at a variety of tilting angle between 0° to 30° . The rotor was driven by a 40A speed-controlled brushless motor, and powered by a DC bench power supply, regulated up to a maximum of 25V. Electrical current was measured at the power supply as the throttle setting of ESC was varied to change the speed of the motor. The rotor blade rotation speed was obtained by measuring the electrical pulse signals from one of the three wires of the BLDC motor. Additionally, tachometer signal was obtained using DT-2234C+ reflective optical sensor which gave a one-per-revolution signal of the motor casing for an accurate reading of the rotation speed. The rotor was positioned in the middle of the open jet nozzle and centered approximately 60 cm away from the nozzle exit. The schematics of the test rig and the experimental set up are as illustrated in Fig. 1.

A. Experimental Facility

The open-jet anechoic wind tunnel is a closed-circuit type of wind tunnel that provides a simulation of free-flight air. The nozzle used in present studies has a dimension of 0.5 m width and 0.775 m height. It is capable of a maximum reliable speed between 5 m/s to 40 m/s with a turbulence intensity of 0.2%. The free jet is exhausted into a 7.9-m long airtight anechoic chamber with a cross-section of 5.0m width and 4.6 m height. The facility is equipped with a 23-element linear array of $\frac{1}{4}$ " diameter GRAS model 40PL free-field microphones. The microphones are installed on a polar arc, located 1.75 m on top of the working section along the center line of the nozzle and spans from 40° to 150° at 5° interval, as presented in Fig. 2. For a more detailed description of the facility, the interested reader is referred to Mayer et al. [20].

Fig. 1 Schematics of the isolated tilt-rotor test rig. (a) The details of the test set up configuration, nozzle and far-field microphone array (b) The details of assembled components.

Fig. 2 Picture of isolated rotor in hover and transition flight experimental set up : (A) rotor at $\alpha = 0^\circ$, (B) jet collector, (C) far-field microphone array, (D) rotor at non-zero tilting angle, and (E) wind tunnel nozzle.

B. Data Acquisition

The noise data was acquired using a National Instruments PXIe-1082 data acquisition system, which comes with 8 slots and 64 channels in total. The noise measurements were performed for 16 s at a sampling frequency of 2^{16} Hz. Additionally, six components of aerodynamic forces were acquired using a mini40 multi axis force and torque transducer. The load measurements were performed for 16s at a sampling frequency of 2^{13} Hz. Background noise data was also acquired to quantify and visualise other undesirable noise sources, such as background flow noise, reflective surfaces and unloaded electrical motor noise [21].

IV. Result and Discussion

A. Aerodynamic Performance

In present work, the rotor blade was configured in asymmetrical and non-axial inflow, and set to tilt forward from hovering position to tilting position. The mean inflow velocity, U was set between 8 m/s to 24 m/s, and the rotor rotation speed, N was varied from 4000 rpm to 5500 rpm. This corresponds to a range of advance ratio, μ between 0.09 to 0.34. The rotor aerodynamic performance was evaluated using the thrust and torque data obtained from the load cell and then normalized to the non-dimensional coefficients of thrust (C_T) and power (C_P). The mathematical expressions of the coefficients, power and advance ratio are given as,

$$C_T = \frac{T}{\rho(R\Omega)^2 A}, \quad (1)$$

$$C_Q = C_P = \frac{P}{\rho(R\Omega)^3 A}, \quad (2)$$

$$P = \Omega Q, \quad (3)$$

$$\mu = \frac{U \cos \alpha}{\rho R}. \quad (4)$$

Figure 3 demonstrates the effect of varying rotor tilting angle on the time-averaged aerodynamic coefficients for rotor operating at 5000 rpm. The figure is constructed with the advance ratio on the horizontal axis and the mean thrust and power coefficients on the vertical axes. Between 0° to 15° of tilting angle as shown in Fig. 3(a), the results exhibit a steady increase of thrust coefficient with increasing advance ratio. Meanwhile, the C_T results appear to be less affected by the advance ratio at 20° . However, at the two highest settings of tilting angle (25° and 30°), the advance ratio is shown to be giving a detrimental effect towards C_T . The power coefficient results, as plotted in Fig. 3(b), demonstrate only minute changes over the range of advance ratio at the lower setting of tilting angle, between 0° to 4° . Further increase of tilting angle, from 6° to 20° , is shown to also increase the value of C_P with respect to the advance ratio. Similar to the behaviour observed for C_T , at 25° and 30° tilting, the rotor blade shows a sudden drop of power coefficient starting from approximately 0.15 advance ratio.

Fig. 3 (a) Thrust coefficient and (b) power coefficient of rotor operated at $N = 5000$ rpm and tilting angle $\alpha = 0^\circ$ to $\alpha = 30^\circ$.

The time-averaged thrust and power coefficients are plotted at a fixed setting of 5000 rpm rotation speed and 24 m/s inflow velocity in Figs. 4(a) and (b), respectively. The tilting of rotor is shown to have a significant influence in reducing the thrust generating capability as the tilting angle increases. In contrast, the rotor experiences an increasing effect of the power coefficient with every increase of tilting angle, up to a maximum level at $\alpha = 20^\circ$. However, as the tilting angle further increased to 25° and 30° , the coefficient of power of the rotor drops significantly.

Fig. 4 (a) Thrust coefficient and (b) power coefficient of rotor operated at $N = 5000$ rpm and $U=24$ m/s inflow.

Fig. 5 Comparison of OASPL(dB) at varying rotation speed $4000 \text{ rpm} < N < 5500 \text{ rpm}$, for hovering angle $\alpha = 0^\circ$ (a,b,c) and $\alpha = 30^\circ$ (d,e,f) at freestream velocities of $0 \text{ m/s} < U < 24 \text{ m/s}$.

B. Rotor Noise

1. Effect of Rotation Speed (N)

In this section, the effect of blade rotation speed will be addressed. It is expected that the blade rotation speed will take effect in shifting the frequency of acoustics signal, as the blade pass frequency is a function of the rotation speed. Figure 5 presents the directivity of the overall sound pressure level (OASPL) for rotation speed of $4000 \text{ rpm} \leq N \leq 5500 \text{ rpm}$ at rotor tilting angles of 0° and 30° for freestream velocities of 0 m/s , 8 m/s and 24 m/s . The directivity of noise radiation can be observed across the far-field polar observation angle, θ , between 40° to 150° . The results demonstrate how rotation speed significantly impacts the sound pressure level for the rotor in hover and tilting. Considering the results at $\alpha = 0^\circ$, Figs. 5(a), (b), and (c), an apparent increase of the OASPL value is evident as the rotational speed increase and the velocity increase. The dipolar directivity patterns show a more symmetric pattern around the center, polar angle of 90° , for all rotational speeds at freestream velocities of 0 m/s and 24 m/s . However, at freestream velocity of 8 m/s , Fig. 5(b), the OASPL patterns become more directive towards the upstream. For tilting angle of $\alpha = 0^\circ$, Figs. 5(d), (e), and (f), the dipolar sound radiation patterns show a fast decay at the downstream observation points, i.e., $\theta > 90^\circ$, for the static condition and for the freestream velocity of $U=8 \text{ m/s}$. The comparison of energy distribution at the harmonics of blade pass frequency for rotor at 4000 rpm and 5500 rpm is analysed from Fig. 6. The blade rotation speed demonstrates a notable influence on the frequency of the sharp tonal peaks in the spectra. It appears that the BPF

Fig. 6 Power spectral density of the far-field pressure fluctuations for rotor in hover and tilting flight at (a) $\alpha = 0^\circ$ (b) $\alpha = 10^\circ$ and (c) $\alpha = 30^\circ$ over a freestream inflow velocity range of $0 \text{ m/s} < U < 24 \text{ m/s}$.

and its higher harmonics shifted at higher blade rotation speed.

Fig. 7 Overall sound pressure level directivity comparisons for rotor in hover and tilting flight at (a) $\alpha = 0^\circ$ (b) $\alpha = 10^\circ$ and (c) $\alpha = 30^\circ$ over a velocity range of $0 \text{ m/s} < U < 24 \text{ m/s}$.

2. Effect of freestream Inflow Velocity (U)

The far-field noise measurements acquired at varying inflow velocity are expected to increase the sound pressure level and shift its directivity pattern. Figure 6 shows the power spectral density (PSD) of the pressure fluctuations measured at the polar angle 90° for rotor at three different rotor disc positions of $\alpha = 0^\circ$, $\alpha = 20^\circ$ and $\alpha = 30^\circ$ tilting. Each of the frequency spectra is compared against various inflow velocity ($0 \text{ m/s} < U < 24 \text{ m/s}$) and the unloaded motor noise. The PSD results at $\alpha = 0^\circ$ demonstrate that the measured spectra are dominated by the tonal (narrowband) peaks at the 1st blade passing frequency (BPF) and its higher harmonics for all freestream velocities. Considering the PSD levels at the 1st BPF at the rotational speed of $N=4000$ rpm, one can conclude that the increase in freestream velocity elevates the radiated noise monotonically. The results at the higher rotational speed display a similar trend. Moreover, the results demonstrate that regardless of the rotor tilting angle, the energy distributions across the spectra appear to be dominated mainly by rotor noise at the highest inflow velocity operation. As the tilt angle increases, the magnitude of the PSD at higher harmonics of the 1st BPF reduces. The reduction of the noise level is more prominent at $N=5500$ rpm, Fig. 6(d), compared to the results at $N=4000$ rpm, Fig. 6(c). At the highest tilting angle, $\alpha = 30^\circ$, a significant reduction at the levels of the higher harmonics PSD is evident. It is also worth noting that, at the highest freestream velocity, the broadband energy content displays a marked increase at the low frequency region. Additionally, the differences in PSD level between the highest and the lowest inflow velocity setting appears to be relatively attenuated

at higher tilting positions.

Figure 7 presents the overall sound pressure level (OASPL) directivity results for rotor at three different rotor disc positions of $\alpha = 0^\circ$, 20° , and 30° over freestream velocity range of $0 \text{ m/s} < U < 24 \text{ m/s}$. The results demonstrate the influence of varying freestream velocity on the measured far-field sound pressure level. At $\alpha = 0^\circ$, the radiated noise levels increase with an increase in the freestream velocity. Increasing the tilting angle to $\alpha = 10^\circ$ does not have a significant effect on the directivity patterns and the magnitude of the OASPL. However, at $\alpha = 30^\circ$, the magnitude of the noise radiation reduces drastically. It is also worth noting that, at higher speed settings, between 12 m/s to 24 m/s , the OASPL directivity pattern appears to be less affected by the magnitude of inflow velocity. However, a symmetrical directivity profile is observed about the rotor axis, relative to the data at 0 m/s and 8 m/s .

Fig. 8 Effect of tilting angle on the radiated noise spectra at 90° microphone for angles of $0^\circ < \alpha < 30^\circ$ at $N = 5500 \text{ rpm}$ at freestream velocities of (a) $U = 0 \text{ m/s}$ and (b) $U = 24 \text{ m/s}$. A close-up look for the 1st BPF is presented on the top-right corner of the each sub-figure.

3. Effect of Rotor Disc Tilting Angle (α)

Due to the nature of highly non-uniform inflow and retardation in thrust generating capability, rotor disc at higher tilting angles is expected to reduce the rotor noise level and influence its signature. The results are presented for rotor operating at 5500 rpm and with tilting angle of $0^\circ \leq \alpha \leq 30^\circ$. Figures 8(a) and (b) display the noise spectra at the static condition and at the presence of the freestream of $U = 24 \text{ m/s}$. The results are displayed at the rotational speed of $N = 5500 \text{ rpm}$. In order to better visualize the effect of tilting angle, a close-up look at the 1st BPF is provided. At the static condition, the PSD results indicate a limited effect on the broadband noise. However, the tilting angle has a significant effect on the noise radiated at the 1st BPF. The results suggest that an increase in the tilting angle reduces the PSD levels up until $\alpha = 20^\circ$. Beyond $\alpha = 20^\circ$, a slight increase in the PSD results are evident. Considering Fig. 8(b),

PSD results demonstrate a prominent influence of rotor disc tilting on the level of tonal and broadband content across the entire spectra at $U = 24$ m/s. The results show that the PSD level at the 1st BPF reduces as the tilting angle increases. Moreover, the broadband noise radiation is attenuated significantly with the increase of the tilting angle

Figure 9 compares the directivity trends of overall sound pressure level for rotor at different tilting positions during operation at the static condition and the highest setting of inflow speed. In contrast to the trend shown during static operation in Fig. 9(a), the region of maximum acoustic radiation demonstrates uniformly distributed profiles over the periphery of the source of rotor in Fig. 9(b). However, at a fixed operational setting of rotor blade rotation speed and freestream inflow velocity, a slight asymmetric shift of directivity is observed with increasing tilting angle. Similar asymmetry of the rotor sound field is observed in previous numerical work other authors, such as found in [22–24].

Fig. 9 Effect of tilting angle on the overall sound pressure level for $0^\circ < \alpha < 30^\circ$ at $N=5500$ rpm at freestream velocities of (a) $U=0$ m/s and (b) $U=24$ m/s.

V. Conclusion

This paper aims at understanding the complex aeroacoustics and aerodynamics characteristics of an isolated tilt-rotor system in hover and transition to forward flight. The loading and noise response to the change in rotation speed, freestream inflow velocity and tilting angle were investigated. The findings indicate a profound influence of the tilting angle during non-axial inflow on the resulting loading and acoustics signatures. At a fixed setting of rotational speed and inflow speed, the results show a significant noise attenuation with tilting angle while maintaining a similar directivity pattern. However, at the same setting of rotation speed and freestream inflow velocity, the aerodynamic thrust generating capability of the rotor also reduces at a higher tilting position. This can potentially be speculated to be one of the trade-offs between attenuating rotor noise to the aerodynamic performance of the rotor blade. To further assess the benefits and characteristics of a tilt-rotor system in aeroacoustics applications, further aerodynamic testing is required for the quantification of the flow field around the rotor blade.

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