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Acoustics Analysis of a Quiet Helicopter for Air Taxi Operations

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ABSTRACT

This paper investigates tonal noise and broadband noise for rotor designs used on urban air mobility vehicles. The rotor aerodynamics in edge-wise forward flight is calculated using the blade element theory, coupled with a dynamic inflow model and the moment-balance trim analysis. Loading noise and thickness noise are obtained using the lifting-line loading distribution and the dual-compact thickness noise model in PSU-WOPWOP. With the forward flight capability developed in UCD-QuietFly, broadband noise is obtained, including trailing-edge noise, trailing-edge bluntness noise, and airfoil stall noise. The air taxi designs, with varied tip speeds and the same mission specifications, are studied for their tonal noise and broadband noise. First, it is found that broadband noise is the dominant noise source for the rotor designs with low tip speeds and fewer blades, while tonal noise is dominant for the high-tip-speed designs. Second, for human hearing, A-weighting maintains the importance of broadband noise while reduces tonal noise significantly. Third, broadband noise is the dominant noise source for the rotor out-of-plane observers, while tonal noise is dominant for the in-plane observers. Fourth, both tonal noise and broadband noise increase proportionally with increasing the forward speed. Finally, low tip speed and more blades are found to be the preferable design features in terms of psychoacoustic metrics.

NOTATION

A_{cs}	airfoil cross-sectional area	N_q	number of blades
c	speed of sound in the undisturbed medium, m/s	N_i	number of sections per blade
C_f	skin friction coefficient	$(n)!!$	double factorial of n, $(n)(n-2)(n-4)...$
C_T	rotor thrust coefficient	OASPL	overall sound pressure level, dB
dP/dx	boundary layer pressure gradient, Pa/m	p'	tonal acoustics pressure, Pa
f	frequency, Hz	p'_L	loading noise acoustic pressure, Pa
f_{mod}	modulations frequency, Hz	p'_T	thickness noise acoustic pressure, Pa
$\mathbf{F}$	fluctuation strength, vacil	q	blade index
H_j^r	factorial combination	R	rotor radius, m
i	blade section index	$\mathbf{R}$	roughness, asper
$\vec{l}$	blade surface loading vector, N/s	r	distance between $\vec{y}$ and $\vec{x}$
l_r	blade surface loading in the radiation direction, $\vec{l} \cdot \hat{r}$, N/m	$\hat{r}$	unit vector in the radiation direction
l_M	blade surface loading in the motion direction, $\vec{l} \cdot \hat{M}$, N/m	$\bar{r}$	non-dimensional blade radial location
L_{BBN}	broadband noise level, dB	r, m	harmonic number
$[L]$	influence matrix	j, n	polynomial number(shape function index)
L_i^q	lift on the q_{th} blade i_{th} section, N	SPL	sound pressure level, dB
ΔL	overall modulation depth, dB	t	observer time, s
ΔL_E	specific modulation depth, dB/Bark	$\bar{t}$	non-dimensional time, Ωt
m	modulation factor	U_e	boundary layer edge velocity, m/s
M_r	March number in the radiation direction, $\vec{M} \cdot \hat{r}$	V_i	inflow velocity, m/s
$[M]$	apparent mass matrix	V_∞	rotor forward velocity, m/s
		w	inflow ratio, $V_i/\Omega R$
		$\vec{x}$	observer position, m
		X_2, Y_2, Z_2	observer global coordinate system
		$\vec{y}$	sound source position, m
		α_j^r, β_j^r	induced flow coefficients
		α_{sh}	rotor shaft angle of attack, deg
		α_{tpp}	rotor tip-path-plane angle of attack, deg
		λ_i	inflow ratio

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μ	advance ratio
v	local fluid velocity on the blade surface, m/s
v_n	normal component of fluid velocity, m/s
δ^*	boundary layer displacement thickness, m
Ω	rotational speed, rad/s
ϕ_j^r	radial expansion function
ψ	azimuth angle, deg
ρ_∞	air density in the undisturbed medium, kg/m^3
τ	retarded time, s
τ_n^m	loading coefficients

INTRODUCTION

Urban Air Mobility (UAM) is a concept that passengers and cargo are transported in urban areas mainly using Vertical Take-off and Landing (VTOL) aircraft. As this concept has been studied for recent years, multiple VTOL designs were created. For example, Silva et al. (Ref. 1) at NASA designed three configurations, such as quadcopter, side-by-side, and lift-cruise, with the same mission specifications of carrying six passengers. A recent multidisciplinary optimization (Ref. 2) of NASA's eVTOL conceptual designs (Ref. 1) shows that the minimum cruise flight altitude should be about 1700 ft. Although many UAM aircraft designs have multi-rotor configurations with a distributed power system, Johnson (Ref. 3) presented a quiet single-rotor helicopter for urban air taxi operations, as shown in Fig. 1. A quiet helicopter was designed with variations of the number of blades, solidity, and RPM. Other various UAM VTOL designs were also released by the companies, such as Hyundai Motor Company (Ref. 4) and Joby Aviation (Ref. 5).



Fig. 1: Quiet Air Taxi Configuration. (Ref. 3)

NASA UAM market study (Ref. 6) presented that noise is one of the top barriers to a successful UAM market due to its negative public acceptance. The VTOL company Uber (Ref. 7) suggested that UAM VTOL vehicles should have a noise level (L_{Amax}) less than 62 dB(A) at an altitude of 500 ft or 67 dB(A) at 250 ft, and the authors have demonstrated that these noise targets can be challenging (Ref. 8). Jia and Lee (Refs. 9, 10, 11) studied tonal noise of quadrotor and side-by-side configurations of VTOL aircraft. Petingill and Zawodny (Ref. 12) investigated broadband noise of small-scale drone rotors using the BPM model. Thurman et al. (Ref. 13) used the lattice-Boltzmann method–very-large-eddy simulation (LBM-VLES) to predict noise from a DJI-9450 drone rotor in hover and found that broadband noise is the dominant noise source above 1 kHz. Smith et al. (Ref. 14) studied

the effect of increasing number of rotors on multicopter tonal noise by coupling the rotor aerodynamics software Rensselaer Multicopter Analysis Code (RMAC) (Ref. 15) and the acoustics software PSU-WOPWOP (Refs. 16, 17).

By its frequency characteristics, rotorcraft noise can be categorized into tonal noise and broadband noise, where rotor tonal noise is important in the forward direction (Ref. 18), while rotor broadband noise propagates in the downward (or plane-normal) direction (Ref. 19).

Rotor tonal noise is the dominant noise source at the low- and mid-frequency range, and has the discrete-frequency characteristics. It consists of various sources, such as steady loading noise, and thickness noise, unsteady Blade-Vortex-Interaction (BVI) noise, and high-speed impulsive noise. Loading noise is generated by the accelerating force in the fluid caused by the moving blade, while thickness noise is generated by the displacement of fluid. Loading and thickness noise can be solved by the numerical computation of Farassat's Formulation 1A (Refs. 20, 21) of the Ffowcs Williams and Hawkings equation (Ref. 22). This method is widely used in acoustics simulation software, including PSU-WOPWOP (Refs. 16, 17) and ANOPP (Refs. 23). At the onset of BVI noise, it becomes the most dominant tonal noise so that the accurate prediction of the blade and vortex interaction is critical in assessing UAM noise. High-speed impulsive noise is due to the shock wave that occurs in the transonic flow (Ref. 24), but this type of noise is rare on the low-tip-speed UAM aircraft. In general, it is straightforward and easy to predict rotor tonal noise when BVI noise is not present.

Historically more research efforts have been devoted to tonal noise compared to broadband noise, since the noise detection in the forward direction is important to military helicopters, and conventional civil helicopters that have high tip speeds make tonal noise a dominant noise source. However, the thriving of the UAM market has brought serious interest to the research on rotorcraft broadband noise, which has been demonstrated to be important for the over-head position (Ref. 25). In addition, the rotor broadband noise dominated the mid-to high-frequency range (Ref. 26), which is in the sensitive frequency range of human hearing, as manifested in the A-weighting (Ref. 27).

The prediction models of rotorcraft broadband noise are mainly based on two different approaches: the physics-based acoustics model and the empirical noise model. First, the physics-based acoustics models, such as the Amiet model (Ref. 28) and the Howe model (Ref. 29), are developed from the theories of edge-scattering of pressure fluctuations on an airfoil. As for their advantages, these models are capable of offering fundamental explanations of the noise generation mechanism, which provides the flexibility to investigate complicated acoustic scattering processes, such as the serrated trailing-edge (Ref. 30). However, the physics-based models still depend on the input of the wall pressure spectrum (Ref. 31). Second, the empirical broadband noise models are determined by curve-fitting the measured broadband noise in conjunction with a proper scaling, such as the semi-empirical

BPM model (Ref. 32). These empirical models tend to accurately predict broadband noise for the airfoils that were used in the model development, but they reveal little noise mechanisms and require additional measurements for different airfoils, such as cambered airfoils.

For UAM VTOL in the hovering flight, the authors presented the new method, namely UCD-QuietFly (Refs. 19 and 8), to predict rotor trailing-edge broadband noise, which combines Blade Element Momentum Theory (BEMT), XFOIL panel method (Ref. 33), Lee's wall pressure spectrum model (Refs. 31 and 34), and Amiet's trailing-edge noise model (Ref. 28), and considers rotor blades' full motions. The rotorcraft aerodynamics is solved by the BEMT to obtain the local velocity and angle of attack along the blade span. For each blade section, the far-field noise is obtained from the Amiet trailing-edge noise model, which requires the coordinate transformations to include rotor blade motions.

In this paper, the recent developments in UCD-QuietFly are presented to predict rotorcraft broadband noise in trimmed forward flight with the applications to UAM aircraft. The trimmed rotor forward flight aerodynamics is calculated using the Peters-He dynamic inflow model (Ref. 35), the force-moment balance trim solution (Ref. 36), and the blade element theory. Broadband noise and tonal noise of the quiet air taxi design are compared in various vehicle operating conditions and observer locations. The psychoacoustics metrics of the time variation of broadband noise are also studied.

METHOD AND FORMULATION

This section presents the Peters-He dynamic model to calculate the inflow of a trimmed rotor in a steady forward flight. Next, rotor tonal and broadband noise prediction approaches are presented. As the detailed theories in UCD-QuietFly can be found in Refs. 8, 19, and 37, the newly developed theories in UCD-QuietFly for the advancing rotor are only presented in this section. Lastly, the psychoacoustics models used to calculate fluctuation strength and roughness are briefly described.

A. Rotor Forward Flight Analysis

The inflow distribution of a trimmed forward flight is calculated using the Peters-He dynamic inflow model (Ref. 35). The normalized inflow velocity w shown in Eq. (1) is written as a combination of multiple states,

$$w(\bar{r}, \psi, \bar{t}) = \sum_{r=0}^{\infty} \sum_{j=r+1, r+3, \dots}^{\infty} \phi_j^r(\bar{r}) [\alpha_j^r(\bar{t}) \cos r\psi + \beta_j^r(\bar{t}) \sin r\psi] \quad (1)$$

where ϕ is the radial expansion shape function, and α and β are the induced flow coefficients to be determined in the model. The radial shape function $\phi(\bar{r})$ is described as

$$\phi_j^r(\bar{r}) = \sqrt{(2j+1)H_j^r} \sum_{q=r, r+2, \dots}^{j-1} \bar{r}^q \frac{(-1)^{(q-r)/2} (j+q)!!}{(q-r)!! (q+r)!! (j-q-1)!!} \quad (2)$$

with

$$H_j^r = \frac{(j+r-1)!! (j-r-1)!!}{(j+r)!! (j-r)!!} \quad (3)$$

These induced flow coefficients are formulated in Eq. (4), where $*$ means the time derivative, and the τ vectors contain the rotor loading coefficients. In a trimmed steady forward flight, the unsteady coefficients α^* and β^* are zeros, and the loading coefficients are averaged over one rotor revolution.

$$\begin{aligned} [M] \begin{bmatrix} \vdots \\ \{\alpha_j^r\} \\ \vdots \end{bmatrix}^* + [L^c]^{-1} \begin{bmatrix} \vdots \\ \{\alpha_j^r\} \\ \vdots \end{bmatrix} &= \begin{bmatrix} \vdots \\ \{\tau_n^m\}^c \\ \vdots \end{bmatrix} \\ [M] \begin{bmatrix} \vdots \\ \{\beta_j^r\} \\ \vdots \end{bmatrix}^* + [L^s]^{-1} \begin{bmatrix} \vdots \\ \{\beta_j^r\} \\ \vdots \end{bmatrix} &= \begin{bmatrix} \vdots \\ \{\tau_n^m\}^s \\ \vdots \end{bmatrix} \end{aligned} \quad (4)$$

On the right-hand side of Eq. (4), the loading coefficient matrices can be expressed in Eq (5), where q is the blade index, i is the blade element index, and L_i^q is the rotor normal force on the q_{th} blade and i_{th} section. The same shape function shown in Eq. (2) is used in Eq. (5) with r and j replaced by m and n .

$$\begin{aligned} \tau_n^{0c} &= \frac{1}{2\pi\rho\Omega^2 R^4} \sum_{q=1}^{N_q} \left[\sum_{i=1}^{N_i} L_i^q \phi_n^m(\bar{r}_i) \right] \\ \tau_n^{mc} &= \frac{1}{\pi\rho\Omega^2 R^4} \sum_{q=1}^{N_q} \left[\sum_{i=1}^{N_i} L_i^q \phi_n^m(\bar{r}_i) \right] \cos(m\psi) \\ \tau_n^{ms} &= \frac{1}{\pi\rho\Omega^2 R^4} \sum_{q=1}^{N_q} \left[\sum_{i=1}^{N_i} L_i^q \phi_n^m(\bar{r}_i) \right] \sin(m\psi) \end{aligned} \quad (5)$$

B. Tonal Noise Prediction

The equations of Farassat's Formulation 1A, that consist of thickness noise p'_T and loading noise p'_L , is given as

$$p'(\vec{x}, t) = p'_T(\vec{x}, t) + p'_L(\vec{x}, t) \quad (6)$$

$$\begin{aligned} 4\pi p'_T(\vec{x}, t) &= \int_{f=0} \left[\frac{\rho_{\infty}(\dot{v}_n + v_{\dot{n}})}{r|1-M_r|^2} \right]_{ret} dS \\ &+ \int_{f=0} \left[\frac{\rho_{\infty} v_n (r\dot{M}_r + c(M_r - M^2))}{r^2|1-M_r|^3} \right]_{ret} dS \end{aligned} \quad (7)$$

$$\begin{aligned} 4\pi p'_L(\vec{x}, t) &= \frac{1}{c} \int_{f=0} \left[\frac{\dot{l}_r}{r|1-M_r|^2} \right]_{ret} dS \\ &+ \int_{f=0} \left[\frac{l_r - l_M}{r^2|1-M_r|^2} \right]_{ret} dS \\ &+ \frac{1}{c} \int_{f=0} \left[\frac{l_r(r\dot{M}_r + c(M_r - M^2))}{r^2|1-M_r|^3} \right]_{ret} dS \end{aligned} \quad (8)$$

The acoustics software PSU-WOPWOP (Ref. 16) will be used to directly obtain the solutions of loading noise in Farassat's Formulation 1A. The blade local loading l , as a function of the blade radial location and the azimuth angle, is calculated by blade element theory (BET) for the trimmed forward flight condition. The azimuthally dependent loading also provides the unsteady loading $\dot{l}$ at each time step. However, BET is a lifting-line-based method that does not have the surface normal velocity v_n on the blade surface. To calculate the thickness noise, the compact thickness noise formulation (Refs. 38, 39) is used. Lopez (Ref. 38) gave the compact thickness formulation of Farassat Formulation 1A as

$$4\pi p'_T(\vec{x}, t) = \int_{f=0} \left[\frac{\rho_\infty A_{cs}}{1-M_r} \frac{\partial}{\partial \tau} \left\{ \frac{1}{1-M_r} \frac{\partial}{\partial \tau} \left(\frac{1}{r(1-M_r)} \right) \right\} \right] dy_{ret} \quad (9)$$

where A_{cs} is the airfoil cross-sectional area, and this equation can be solved with the blade geometry and the aerodynamic results from BET. PSU-WOPWOP (Refs. 16, 17) has the capability to calculate thickness noise using the dual-compact thickness noise formulations (Ref. 39), in which the blade-geometry-dependent loading is applied on two lines and the tip and root areas to represent the geometry of a rotor blade.

C. Broadband Noise Prediction

Rotor broadband noise is predicted using UCD-QuietFly Refs. (8,19,37), whose architecture is shown in Fig. 2. The airfoil-self noise sources, including trailing-edge noise, trailing-edge bluntness noise, and airfoil stall noise, are predicted based on each blade section and summed for the entire rotor. In the current study, the blade sectional velocity and angle of attack, calculated using BET, are the inputs to UCD-QuietFly.

One major contribution of this paper is an extension of the advanced rotor broadband noise tool, UCD-QuietFly, to forward flight and detailed analyses of rotor broadband noise for various operating conditions. Obtained from the trimmed rotor forward flight analysis, the time-dependent blade local velocity $U_\infty(r, \psi, q)$ and angle of attack $AoA(r, \psi, q)$ are the inputs to UCD-QuietFly, where r is the blade radial position, ψ is the azimuth angle, and q is the blade index.

The emission time τ of each blade section is associated with the angular velocity Ω and azimuthal angle ψ by

$$\tau = \frac{\psi}{\Omega} \quad (10)$$

Due to the different distances from each blade section to the observer, each blade section has a different emission time. The relationship between the emission time and the observer time can be described as

$$t - \frac{|\vec{x}(t) - \vec{y}(\tau)|}{c} - \tau = 0 \quad (11)$$

where $\vec{x}(t)$ is the observer coordinate at the observer time t , and $\vec{y}(\tau)$ is the blade section coordinate at the emission time τ . A two-blade rotor in forward flight and a moving observer with the same forward speed are shown in Fig. 3.

According to Fig. 3, the distance of $|\vec{x}(t) - \vec{y}(\tau)|$ required in Eq. (11) is calculated as

$$|\vec{x}(t) - \vec{y}(\tau)| = \sqrt{[(X_2 - r \cos \psi \cos \alpha_{sh}) + V_\infty(t - \tau)]^2 + [Y_2 - r \sin \psi \cos \alpha_{sh}]^2 + [Z_2 - r \cos \psi \sin \alpha_{sh}]^2} \quad (12)$$

where ψ and α_{sh} are the rotor azimuth angle and shaft angle of attack, respectively. To calculate the observer time of each blade section, the quadratic equation shown in Eqs. (11)-(12) is solved using the Newton-Raphson root finding method.

Broadband noise of each blade section is calculated in terms of sound pressure level $SPL(f, \tau)$ at the emission time, and the sound pressure level $SPL(f, t)$ at the observer time is saved at observer times following Eq. (11). After the calculations of every time step and blade section, the sound pressure levels at the same observer time t are summed to have total broadband noise. Note that Eq. (11) is a general equation, but the forward flight calculation in (12) is used to calculate the attached observer that moves with the vehicle.

D. Psychoacoustics Metrics

The time variation of broadband noise causes the fluctuations of noise amplitude. The two psychoacoustics metrics that characterize such fluctuations are fluctuation strength (amplitude modulation) and roughness. Based on the psychoacoustics models developed by Fastl and Zwicker (Ref. 40), the noise fluctuations with the modulation frequency under 20 Hz are categorized as the amplitude modulations with the fluctuation strength, while the fluctuations with the modulation frequency over 20 Hz are categorized as roughness.

The fluctuation strength and the roughness are calculated using Eqs. (13) and (14).

$$\mathbf{F} = \frac{5.8(1.25m - 0.25)[0.05(L_{BBN}) - 1]}{(f_{mod}/5)^2 + (4/f_{mod}) + 1.5} \text{ vacil} \quad (13)$$

where L_{BBN} is the broadband noise level, f_{mod} is the modulation frequency in Hertz, and m is the modulation factor determined from the overall modulation depth $\Delta L = 20 \log[(1 + m)/(1 - m)]$.

$$\mathbf{R} = 0.3 \frac{f_{mod}}{1000} \int_0^{24Barks} \Delta L_E(z) dz \text{ asper} \quad (14)$$

where $\Delta L_E(z)$ is the specific modulation depth at the z_{th} critical band. The human hearing system processes the noise spectrum according to the critical bands, and in the current study, the critical bands are approximated by the one-third-octave bands.

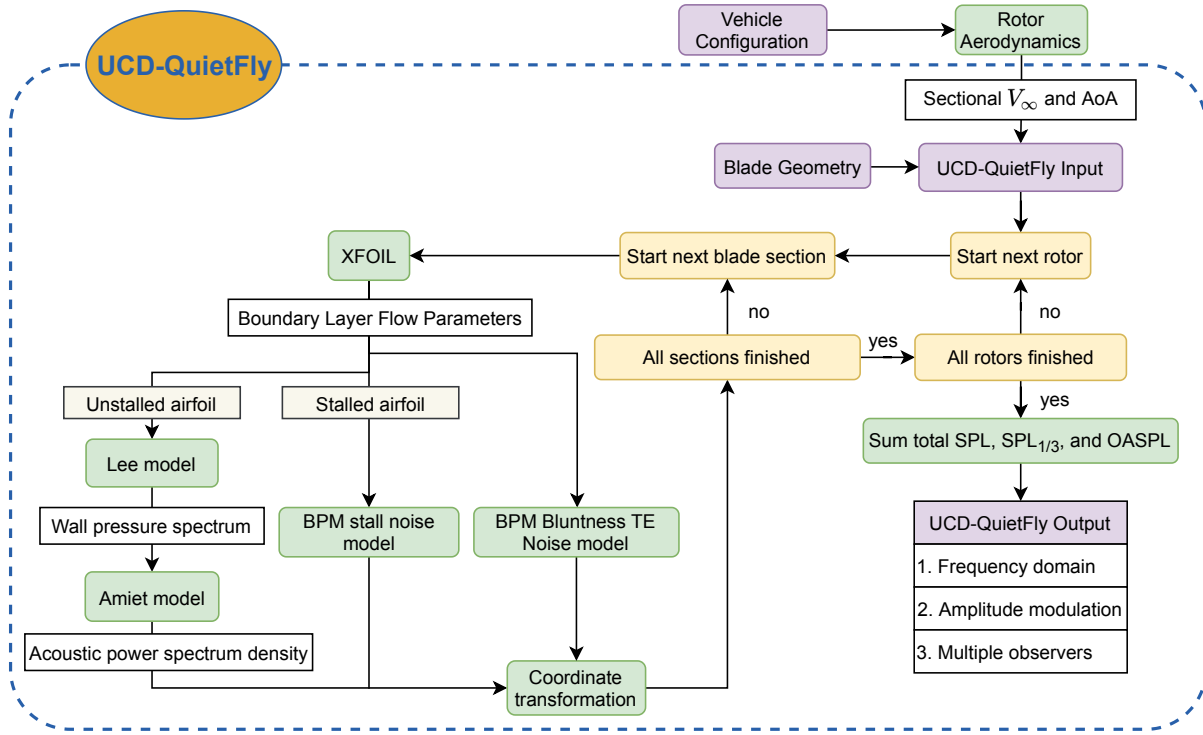


Fig. 2: Rotor broadband noise prediction code UCD-QuietFly methodology.

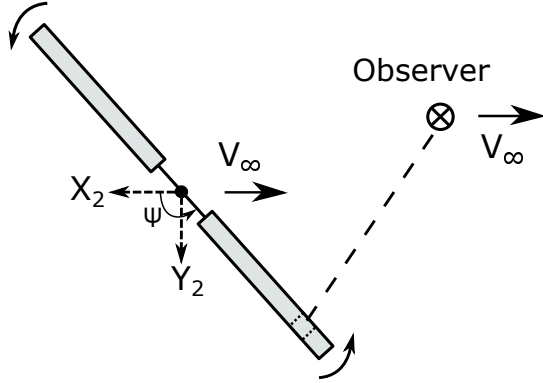


Fig. 3: Top view of a two-bladed rotor in forward flight.

VALIDATIONS

This section presents the validations of the inflow distribution in forward flight, the predictions of tonal noise using PSU-WOPWOP, and the predictions of broadband noise using UCD-QuietFly. The validity of each prediction is demonstrated.

Rotor Inflow Validation

The validation of the rotor forward flight analysis is shown in Fig. 4, where the inflow distribution is calculated for a 2MRTS rotor using the Peters-He model (Ref. 35). The prediction is validated against the inflow measured by the laser velocimeter (Ref. 41). It is shown that the predicted inflow distribution agrees well with the measurement, especially on

the blade tip sections that heavily contribute to broadband noise. The validation of the inflow distribution is also important for tonal noise predictions, since the inflow velocity determines the local angle of attack that gives the blade sectional loading from the 2-D airfoil aerodynamics.

Tonal Noise Validation

Figure 5 shows the validations of the tonal noise predictions by coupling the rotor forward flight analysis and PSU-WOPWOP. The validations are performed on the BO105 rotor and the Bell430 rotor, whose configurations are shown in Table 1. The three rotor cases are selected to validate the different ranges of the rotor scale, the tip speed, and the advance ratio. The 40% scale BO105 rotor acoustics measurements (cases 1 and 2) were carried out by Brooks et al. (Ref. 42) in the Duits-Nederlandse Wind Tunnel in the forward flight configurations. The helicopter flight test of Bell430 (case 3) was performed by Snider et al. (Ref. 25) to obtain the noise data. Since the forward flight analysis uses a lifting-line theory and does not include the rotor-to-rotor interactions, the first blade passing frequency (BPF) noise level is the dominant peak for tonal noise in the simulation, and higher-harmonic noise associated with the rotor-to-rotor interactions, such as blade-vortex-interaction (BVI), are not captured.

Broadband Noise Validation

Since UCD-QuietFly has been validated on various rotor cases with different scales (Refs. 8, 19, 37) in hover flights,

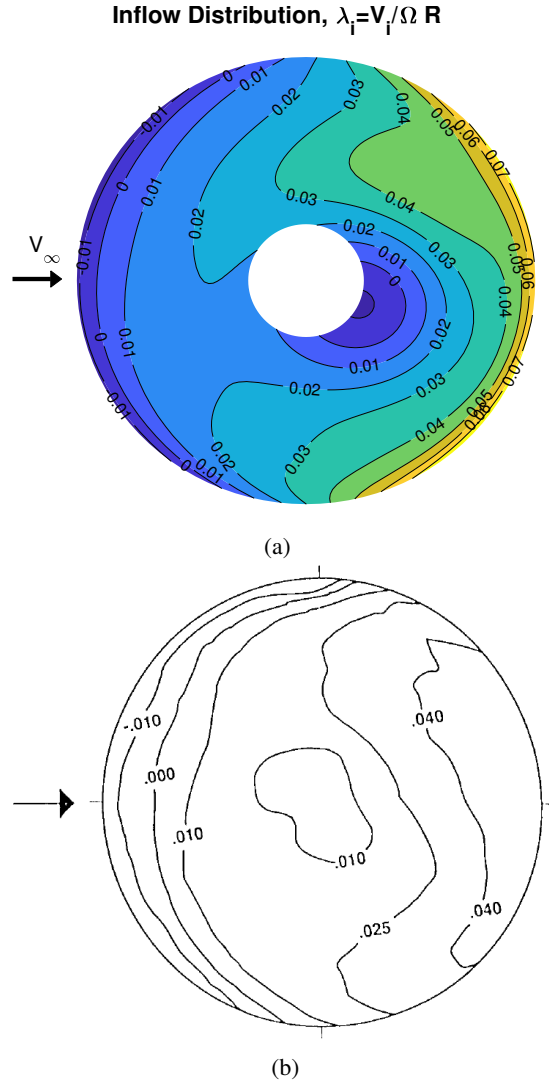


Fig. 4: Validation of rotorcraft forward flight inflow distribution on 2MRTS rotor at $\mu = 0.15$: (a) prediction, and (b) measurement (Refs. 41, 35).

Table 1: Validation rotor cases

Parameter	Case 1	Case 2	Case 3
Rotor name	BO105	BO105	Bell430
Scale	40%	40%	full
Rotor radius[ft]	6.56	6.56	21
Number of blades	4	4	4
RPM	1050	525	349
Advance Ratio	0.086	0.173	0.27
Thrust Coefficient	0.0044	0.0044	0.0047
Observer-hub distance [ft]	23.4	23.4	492
Obs. elevation angle [deg]	90	90	-90

only one additional validation case is shown in this paper in Fig. 6 for the BO-105 40 % scale rotor (case 2) in forward flight. The narrow-band sound pressure level (SPL) prediction of broadband noise is compared with the wind tunnel acoustics measurements (Ref. 42). The comparisons confirm that the predictions from UCD-QuietFly well capture the

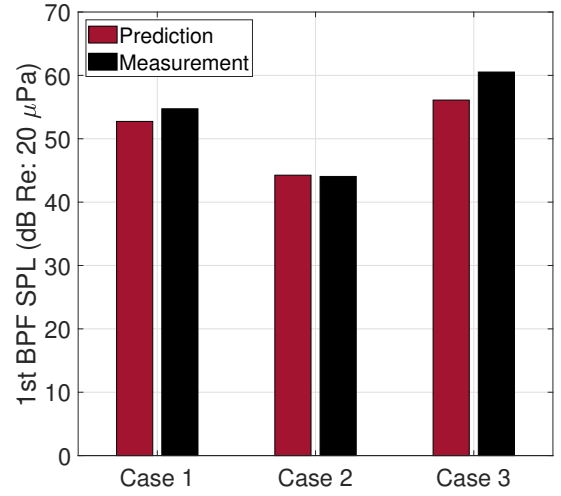


Fig. 5: Validations of tonal noise predictions. Rotor specifications are given in Table 1.

mid- to high-frequency (5-15 kHz) range on the noise spectrum, where airfoil-self broadband noise, such as trailing-edge noise, is dominant.

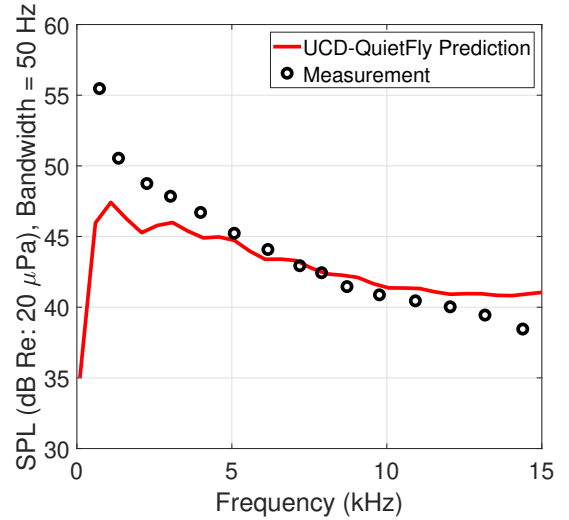


Fig. 6: Validation of UCD-QuietFly on forward flight rotor of Case 2 shown in Table 1, compared with the measurement of Brooks et al. (Ref. 42).

RESULTS

The quiet air taxi designs are analyzed in this paper for their tonal noise, broadband noise, and psychoacoustic importance. Given in Table. 2, the air taxi conceptual configurations are designed by Johnson (Ref. 3) with different rotational tip speeds but the same disk loading and forward speed. With the reduced blade tip speed, the rotor solidity is increased by increasing the number of blades to maintain the same payload and forward speed. Therefore, the acoustics analysis in this paper studies the combined effects of multiple design parameters, including the rotational speed, the rotor solidity, and the advance ratio. Since the configurations have the same mission specification, the current acoustic analysis has a more

practical value than investigating the individual effect of each design parameter on rotor broadband noise (Ref. 19).

A. Air Taxi Tonal and Broadband Noise Comparison

The tonal and broadband noise predictions at the vehicle overhead position are shown in Fig. 7, where A-weighting is applied for the adjustment of human hearing. The total noise level is the logarithmic summation of tonal and broadband noise. It is seen that the high tip speed designs of 700, 650, 600, and 550 ft/s rotors have higher tonal noise levels than the lower tip speed designs, since the high tip speed rotors have a higher blade loading derivative that contributes to loading noise. Thickness noise is weak when the observer is directly beneath the rotor. However, an increase in tonal noise is observed from the tip speed of 650 to 600 ft/s, and from 500 to 450 ft/s, due to the destructive and constructive interference between the blades, which will be discussed. On the other hand, since broadband noise is highly dependent on the tip speed, the broadband noise level is observed to decrease linearly with decreasing the rotor tip speed. For the designs with the tip speed higher than 550 ft/s, the tonal noise overall sound pressure level (OASPL) is higher than that of broadband noise, while the broadband noise level exceeds tonal noise for the low tip speed designs. In the current study, since tonal noise is dominated by the first BPF, which is less than 100 Hz, A-weighting significantly reduces the tonal noise levels as shown in Fig. 7(b). However, since broadband noise has its peak levels near 2 kHz frequency, A-weighting has little effect on its noise levels. Therefore, broadband noise is demonstrated to be the dominant noise source at the overhead position regarding human hearing.

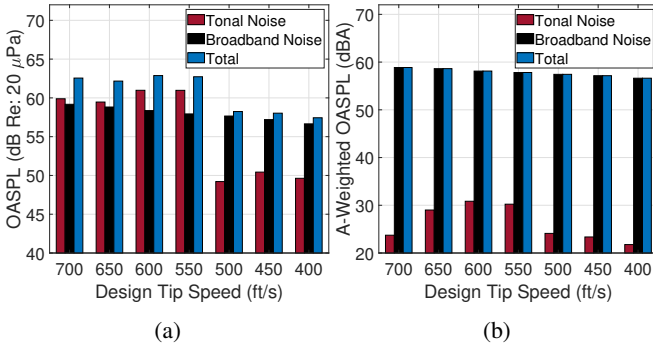


Fig. 7: Predictions of tonal and broadband noise of the quiet air taxi designs at -90° elevation angle and 492 ft observer-hub distance (vehicle overhead position): (a) OASPL, and (b) A-weighted OASPL.

The acoustic pressures of loading noise predicted on the cases of design tip speeds of 600 ft/s (4 blades) and 650 ft/s (3 blades) are shown in Figs. 8 and 9, where the time windows of one rotor revolution are used. The loading noise acoustic pressure contribution from each blade and the total loading noise acoustic pressure are shown on the same observer time range. It is observed that although the acoustic pressure peak of a single blade of the 600 ft/s tip speed case is lower than

that of the 650 ft/s tip speed case, the 600 ft/s tip speed case has the higher total loading noise acoustic pressure. The destructive interference is seen on the 650 ft/s tip speed case, where the positive pressure peak of one blade occurs at the same observer time of the negative pressure peak of another blade.

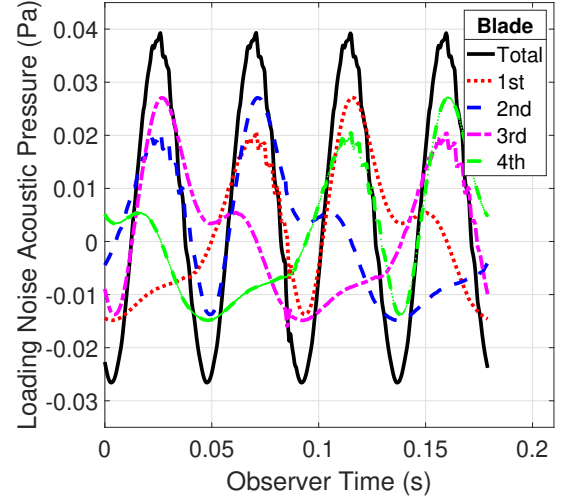


Fig. 8: The blade contributions of loading noise acoustic pressure for the design tip speed of 600 ft/s. The observer is at -90° elevation angle and 492 ft observer-hub distance (vehicle overhead position)

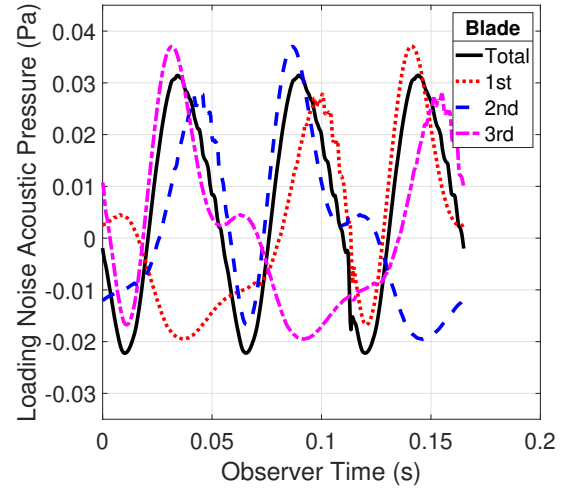


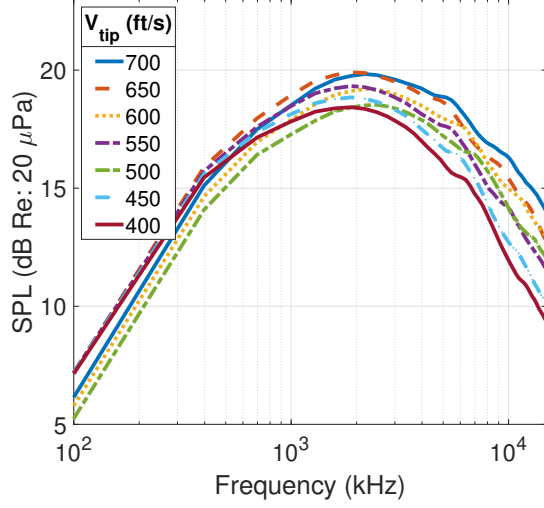
Fig. 9: The blade contributions of loading noise acoustic pressure for the design tip speed of 650 ft/s. The observer is at -90° elevation angle and 492 ft observer-hub distance (vehicle overhead position)

The narrow-band SPL predictions of broadband noise for the air taxi conceptual designs are given in Fig. 10, where the high-frequency noise level increases with the higher design tip speed. It is also confirmed that the broadband noise peaks are near 2 kHz frequency, which is the most sensitive frequency range for human hearing.

At a different observer location of -45° elevation angle and

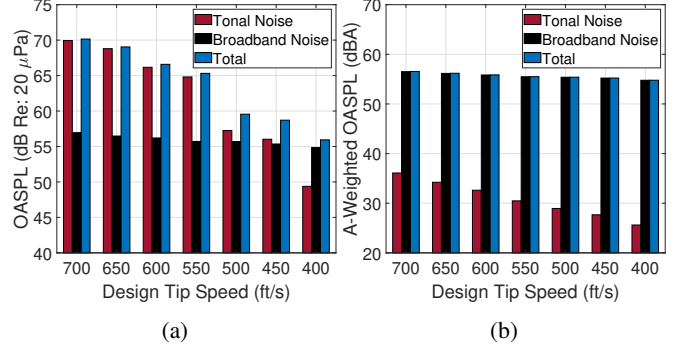
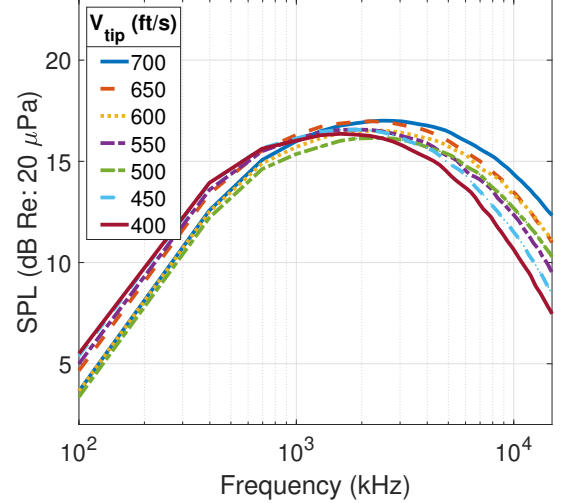
Table 2: Quiet air taxi rotor design configurations (Ref. 3)

Rotational Tip Speed [ft/s]	700	650	600	550	500	450	400
Rotor radius [ft]	16.96	17.07	17.09	17.25	17.27	17.64	18.39
Number of blades	3	3	4	4	6	6	8
Solidity	0.0411	0.0477	0.0559	0.0666	0.0805	0.0994	0.1258
Advance ratio	0.246	0.269	0.29	0.319	0.361	0.395	0.411
Blade passing frequency [Hz]	19.7	18.2	22.4	20.3	27.6	24.4	27.7

Fig. 10: Narrow-band SPL predictions of broadband noise at the elevation angle of -90° (vehicle overhead position).

observer-hub distance of 492 ft in front of the rotor, tonal noise and broadband noise are predicted for the seven conceptual designs as shown in Fig. 11. Compared to the observer directly beneath the rotor, the observer at -45° elevation angle experiences significantly higher tonal noise, due to the presence of the thickness noise that propagates in the forward direction. Broadband noise level is slightly reduced at -45° elevation angle compared to -90° , since rotor broadband noise has the dipole directivity pattern with the maximum noise level at -90° elevation angle (Ref. 19). However, A-weighting still shows the dominance of broadband noise regarding human hearing in Fig. 11(b). Regarding the narrow-band SPL of broadband noise, Fig. 12 shows that as the design tip speed is increased, low-frequency broadband noise decreases while high-frequency broadband noise increases. When the design tip speed is reduced, the blade chord length and the number of blades are increased, and the larger chord length results in the increase of low-frequency broadband noise. Although Fig. 12 shows the opposite trends for the low- and high-frequency ranges, the broadband noise OASPL uniformly increases with increasing the tip speed, since the OASPL calculation considers all frequencies equally while the logarithmic spectrum emphasizes the low frequencies.

The tonal and broadband noise directivities of the 450 ft/s tip speed design are shown in Fig. 13, where the observer-hub distance is 5 rotor radii. With the same observer-hub distance, it is shown that the rear side has a higher broadband noise level

Fig. 11: Predictions of tonal and broadband noise of the quiet air taxi designs, at -45° elevation angle and 492 ft observer-hub distance: (a) OASPL, and (b) A-weighted OASPL.Fig. 12: Narrow-band SPL predictions of broadband noise at the elevation angle of -45° and the forward position of the vehicle.

than the forward side, since the retarded-time effect reduces the noise propagation distance for the rear side and increases the propagation distance for the forward side, as the observer is attached to the rotor in forward flight. On Fig. 13(b), broadband noise is biased towards the starboard side, since the advancing blade has a higher local velocity than the retreating blade. Although the retreating blade experiences a higher local angle of attack, the flow velocity effect is more dominant for broadband noise. Tonal noise is observed to be dominant in the in-plane directions, primarily contributed by the presence of thickness noise. Comparing their relative importance, broadband noise is more important to the observer underneath

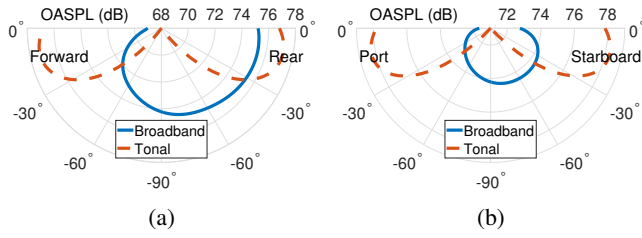


Fig. 13: Noise directivity in the downward region of the design tip speed of 450 ft/s and the observer-hub distance of 5 rotor radii: (a) port side view, and (b) rear view.

the vehicle while tonal noise is dominant in the forward direction. Tonal noise is shown to have the same directivity patterns in the forward and rear directions. Note that the broadband noise OASPL shown in Fig. 13 is not weighted, and A-weighting will greatly reduce the tonal noise level. However, tonal noise maintains its dominance for the in-plane observer at a long observer distance, due to atmospheric absorption loss in high-frequency broadband noise, which is not considered in the current study.

The sectional OASPL contours of broadband noise are shown in Fig. 14. The rotor flight conditions are given in Table 2, and the observer is 492 ft away from the rotor hub and at the elevation angle of -90° . The noise contours show that the OASPL increases with increasing the design tip speed. The starboard side with the advancing blade generates higher broadband noise than the retreating blade, due to the higher flow speed on the advancing blade. Although Fig. 14 shows the noise contributions from the single blades and the lower tip speed designs have more blades, the overall broadband noise trend given in Fig. 7 still demonstrates the lower broadband noise levels for lower design tip speed.

The contours of the boundary layer parameters for the 700 ft/s tip speed case are shown in Fig. 15. The parameters are taken at 99% of the chord length, which are used to calculate trailing-edge noise. The advancing side is shown to have significantly larger boundary layer edge velocity than the retreating side, which makes the higher broadband noise level on the advancing side as shown in Fig. 13. The upper surface of the advancing side has smaller displacement thickness than the retreating side due to the cyclic pitch. The inboard region on the retreating side shows large displacement thickness due to the reverse flow, but the noise contribution from this inboard region is small. The pressure gradient contours shows a similar trend as the boundary layer edge velocity, since the two parameters are proportionally related. The pressure gradient contours also show a discontinuity at the blade tip section, where the two different airfoils are connected. Since the values of the skin friction coefficient are not in the same order of magnitude, especially in the inboard region of the retreating side, the contours of $\log(C_f)$ are given in Fig. 15. It is shown that the skin friction coefficient is larger at the tip section on both the upper and lower surfaces, and the inboard region on the retreating side has small values due to the reverse flow.

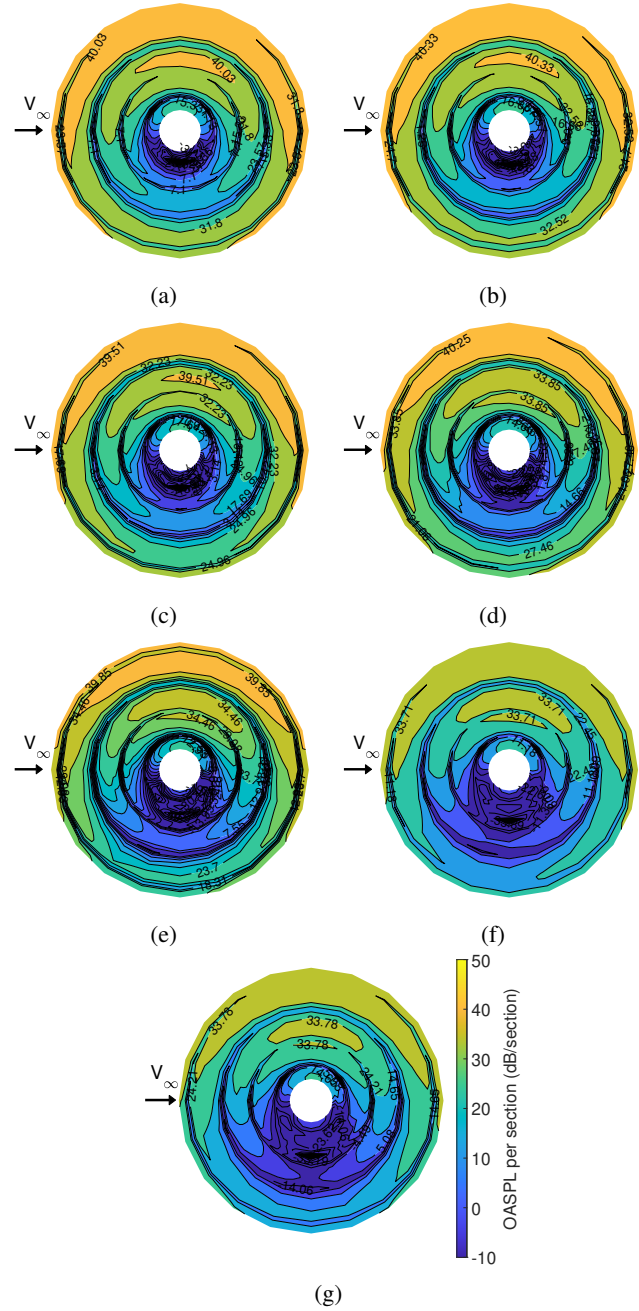


Fig. 14: Sectional OASPL contours, at the observer-hub distance of 492 ft and the elevation angle of -90° : (a) 700 ft/s, (b) 650 ft/s, (c) 600 ft/s, (d) 550 ft/s, (e) 500 ft/s, (f) 450 ft/s, and (g) 400 ft/s.

B. Effects of Advance Ratio

The air taxi configuration of 450 ft/s tip speed is used to study the effect of advance ratio on its acoustics. The observer is 492 ft from the rotor hub with the elevation angle of -90° (vehicle overhead position). The advance ratio is varied from 0.25 to the maximum design advance ratio of 0.442. Since the rotor is fixed-RPM and variable-pitch, the higher advance ratio represents the higher forward speed. The rotor trim solutions are solved for each value of the advance ratio. It is seen in Fig. 16 that both tonal noise and broadband noise increase

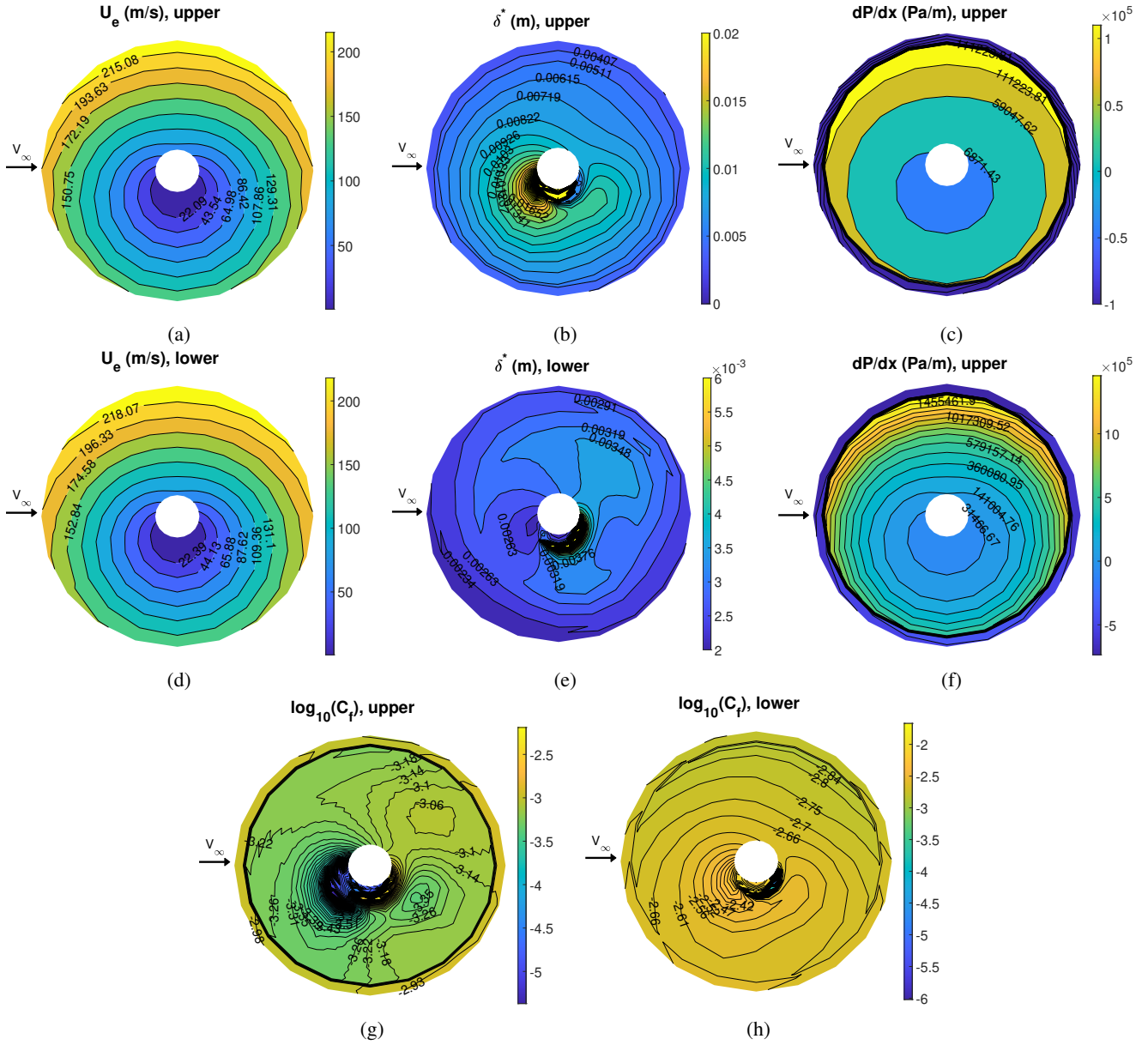


Fig. 15: Contours of the boundary layer parameters taken at 99% of the blade chord length for the 700 ft/s tip speed case: (a) boundary layer edge velocity on the upper surface, (b) displacement thickness on the upper surface, (c) chord-wise pressure gradient on the upper surface, (d) boundary layer edge velocity on the lower surface, (e) displacement thickness on the lower surface, (f) chord-wise pressure gradient on the lower surface, (g) skin friction coefficient on the upper surface, and (h) skin friction coefficient on the lower surface.

proportionally with increasing the advance ratio, and the relative importance between tonal noise and broadband noise remains unchanged. The narrow-band SPL of broadband noise is shown in Fig. 17, where broadband noise increases for all the frequency ranges with increasing the advance ratio. To achieve the helicopter lateral moment balance, the increasing advance ratio results in higher local velocity and lower angle of attack on the advancing side, and lower local velocity and higher angle of attack on the retreating side. Since flow speed is the primary effect on broadband noise in vehicle operations, the increased velocity on the advancing side contributes to higher total broadband noise. In addition, tonal noise in-

creases with the higher forward speed, due to the larger blade loading and loading derivative on the advancing blade. It is interesting to observe that the difference (ΔOASPL) between tonal and broadband noise remains the same for the varied advance ratio, which suggests the same forward-speed scaling for the two noise sources.

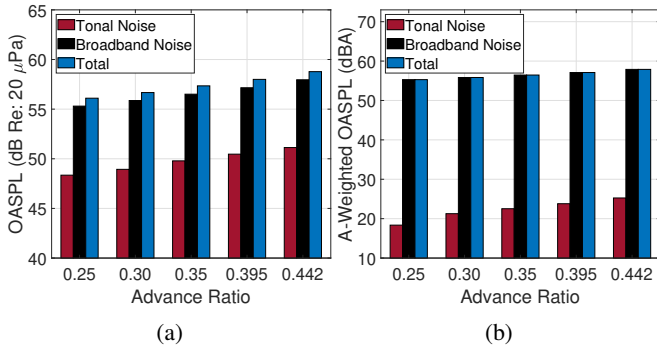


Fig. 16: Predictions of tonal and broadband noise of the 450 ft/s tip speed design for varied advance ratio: (a) OASPL, and (b) A-weighted OASPL.

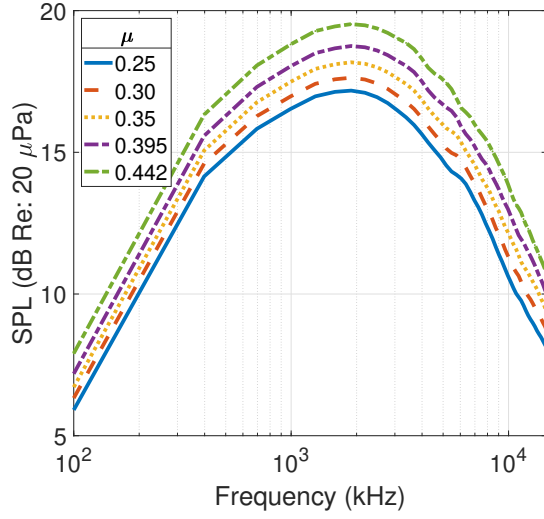


Fig. 17: Narrow-band SPL predictions of broadband noise of the 450 ft/s tip speed design for varied advance ratio.

C. Broadband Noise Amplitude Modulation and Psychoacoustics

The amplitude modulations of broadband noise are calculated on the seven air taxi designs listed in Table. 2, and the time range for all the test cases is 2 rotor revolutions. The observer is 5 rotor radii from the rotor hub, and the elevation angle is -45° in the forward direction. The time variations of the noise spectrum are shown in Fig. 18, where the number of noise peaks in two revolutions corresponds to the number of blade passages. The noise spectrum qualitatively shows that the characteristics of the modulations diminishes with increasing the number of blades and decreasing the design tip speed. To quantify the significance of the fluctuations, the fluctuation strength and the roughness of the seven cases are calculated using Eqs. (13) and (14) in Figs. 19 and 20. Figure 19 shows that the fluctuation strength becomes negligible for the design tip speed lower than 600 ft/s, since the modulation depth ΔL is less than 3.52 dB according to Eq. (13). These small modulation depths are caused by two factors. First, the maximum noise peaks are reduced for the low tip speed cases. Second, the high modulation frequencies make the edge of the noise signature of one blade overlaps with those of its adjacent

blades, as shown in Fig. 18. Figure 20 shows that the rotor designs with the higher tip speed and fewer number blades create a more severe sensation of roughness. Given that all seven cases achieve the same missions, low-RPM rotors with more blades are preferable from a psychoacoustic point of view.

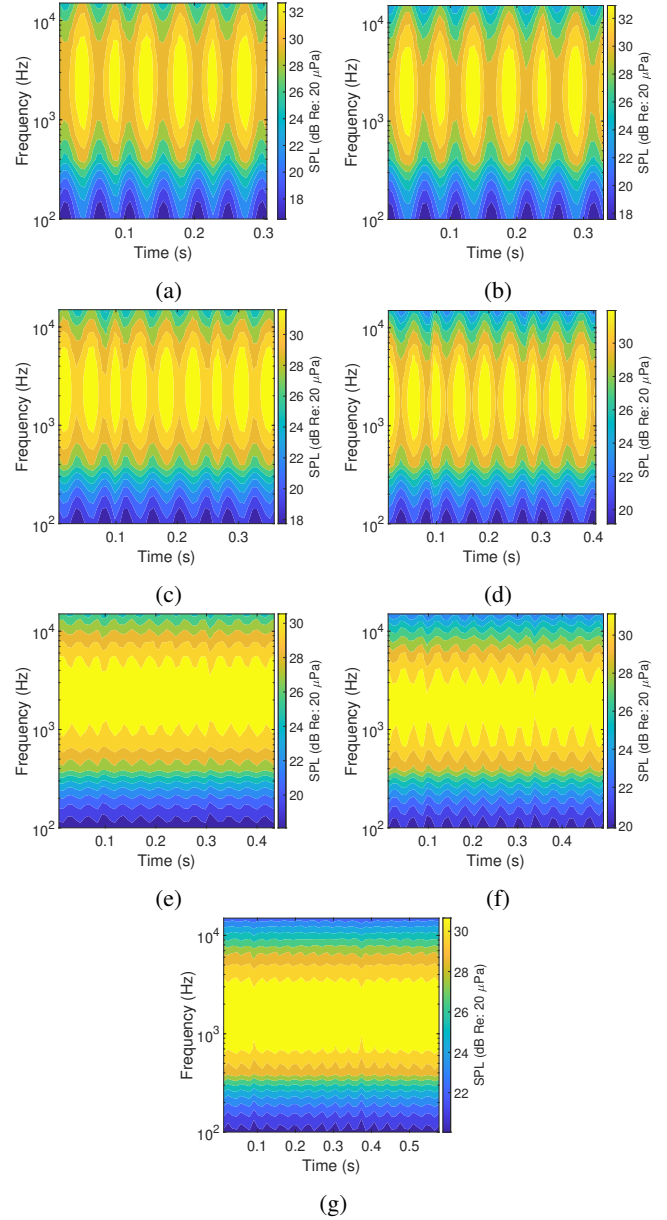


Fig. 18: Time variation of the broadband noise spectrum at 5 rotor radii observer distance and -45° forward elevation angle, for the design tip speeds of: (a) 700 ft/s, (b) 650 ft/s, (c) 600 ft/s, (d) 550 ft/s, (e) 500 ft/s, (f) 450 ft/s, and (g) 400 ft/s.

CONCLUSIONS

The acoustics analysis procedure for rotorcraft in the cruise flight is developed to predict both tonal noise and broadband noise. This method couples the dynamic-inflow blade element theory (BET), PSU-WOPWOP, and UCD-QuietFly. The

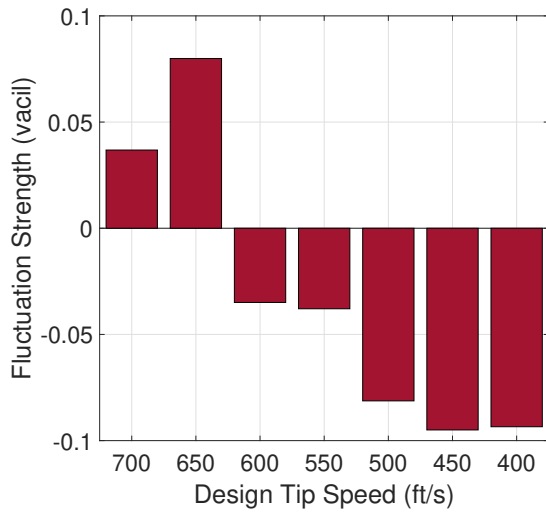


Fig. 19: Fluctuation strengths of the rotor designs at 5 rotor radii observer distance and -45° forward elevation angle.

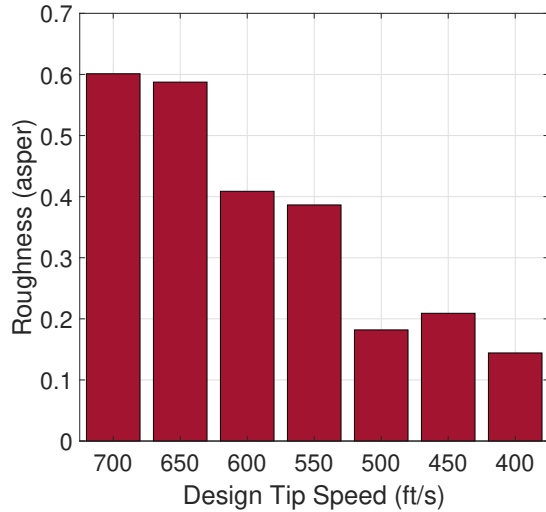


Fig. 20: Roughness of the rotor designs at 5 rotor radii observer distance and -45° forward elevation angle.

acoustics sources included in this study are steady thickness noise, loading noise, trailing-edge noise, trailing-edge bluntness noise, and airfoil stall noise. Investigating the quiet air taxi designs (Ref. 3), the major findings are concluded as follows:

- At the vehicle overhead position, broadband noise is the dominant noise source for the rotor designs of low tip speed and more blades, while broadband noise and tonal noise have comparable levels for the rotors with high tip speed and fewer blades. In the forward region of the rotor, tonal noise is the dominant noise source for high-tip-speed design, while broadband noise and tonal noise have comparable levels for the rotors with low tip speed.
- On the A-weighted spectrum adjusted for human hearing, broadband noise is demonstrated to be the dominant noise source in the out-of-plane directions. Note that blade-vortex-interaction noise and atmospheric ab-

sorption are not included in the current study, which may alter this conclusion in certain cases.

- Broadband noise is demonstrated to be biased towards the rear and starboard directions, due to the retarded time effect and the higher velocity on the advancing blade.
- In the study of the effect of the advance ratio on the rotor acoustics, the relative importance of tonal noise and broadband noise remains unchanged for varying forward speeds. Both the tonal and broadband noise levels are shown to increase proportionally with increasing the advance ratio.
- Psychoacoustics metrics of fluctuation strength and roughness were calculated on broadband noise of the air taxi designs, which shows that the fluctuation strength on rotorcraft is negligible when the modulation depth is less than 3.52 dB that is caused by the high blade passing frequency. The sensations of both fluctuation and roughness reduce with decreasing the design tip speed. Therefore, the rotor designs with low tip speed and more blades are preferable in terms of psychoacoustic metrics.

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