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Coaxial Rotor Broadband Noise Prediction in Hover

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ABSTRACT

This paper presents an efficient prediction of coaxial rotor broadband noise, particularly trailing-edge noise. The method combines a newly developed iterative coaxial rotor BEMT, a viscous panel method, an empirical wall pressure spectrum, and Amiet's trailing-edge noise model. Aerodynamic data including the induced velocity and angle of attack on each rotor are calculated by the iterative BEMT. Then, turbulent boundary layer flows, such as the boundary layer thickness, skin friction coefficient, pressure gradient, etc., are computed by a viscous panel code, XFOIL. Based on these boundary layer parameters, the wall pressure spectrum near the trailing edge is computed by Lee's semi-empirical model. Finally, trailing-edge noise is predicted by Amiet's model from the wall pressure spectrum. This method provides fast computations for aerodynamics and acoustics for coaxial rotors. Acoustic predictions can be performed for various design and operating conditions including the effect of rotor-to-rotor separation distance. In addition to the overall noise of the combined rotor system, each rotor's contributions to noise can be analyzed. A small-scaled untwisted rotor is selected to analyze aerodynamics and aeroacoustics. It is found that the noise contribution from each rotor is about the same at small separation distances. At large separation distances, the lower rotor generates higher noise levels than the upper rotor mainly due to the change in rotor distance with respect to the observer. The detailed boundary-layer flow properties are investigated on both rotors.

INTRODUCTION

A coaxial rotor has distinctive advantages over a single rotor. A counter-rotating rotor cancels out the yaw moment generated by each rotor so that the torque balance is met without a tail rotor. A removal of tail rotor enables the design of the vehicle system to be simpler and provides additional space in the tail. Auxiliary propellers can often be installed in the tail of the coaxial rotorcraft, which provides an additional propulsive force and enables a high-speed flight of rotorcraft (Ref. 1).

Recently, a lift-offset coaxial rotor has gained a renewed interest in military rotorcraft operation. A lift-offset coaxial rotor is designed to provide additional lift on the advancing side of each rotor (Refs. 2,3). This concept provides higher lift on the advancing side and lower lift on the retreating side. A reduced angle of attack on the retreating side helps mitigate dynamic stall and, hence, allows the rotorcraft to fly at a much faster speed compared to conventional helicopters without the issues due to dynamic stall. Numerical studies on a lift-offset coaxial rotor can be found from references (Refs. 4–12).

Coaxial rotor noise is categorized into tonal noise and broadband noise. Tonal noise occurs due to periodic blade motion (thickness noise) or unsteady blade loading (loading noise).

Loading noise becomes dominant at low tip speeds especially when the rotor tip vortex interacts with the same rotor blades (self-BVI) or with other rotor's blades (rotor-to-rotor BVI). In addition, an abrupt change in the loading when two blades cross over causes impulsive noise (blade crossover noise) (Ref. 13). This aerodynamically induced noise for a coaxial rotor has been investigated using low-fidelity models (lifting-line mode) (Refs. 5,6,10–12,14), medium-fidelity models (vortex transport model) (Ref. 4), and high-fidelity computational fluid dynamics (CFD) (Refs. 7,8) in high-speed forward flight.

Broadband noise in subsonic vehicles is mainly generated by the interaction between surfaces and flow turbulence. Turbulence arises from the atmosphere, rotor wake, or boundary layer. When atmospheric turbulence or rotor wake flows interact with the blade, pressure fluctuations at the leading edge generate broadband noise (leading-edge noise) (Ref. 15), which is particularly important at low frequencies. A turbulent boundary layer on the blade itself generates high-frequency dominant broadband noise named trailing-edge noise (Ref. 16).

Trailing-edge noise is generated by the scattering of turbulent boundary layer flows by a sharp trailing edge. This noise has been studied for several decades (Refs. 16–19). Even though rotorcraft trailing-edge noise has also been studied a priori, most of the studies were limited to a single rotor. Studies on trailing-edge noise in multirotor vehicles were recently pub-

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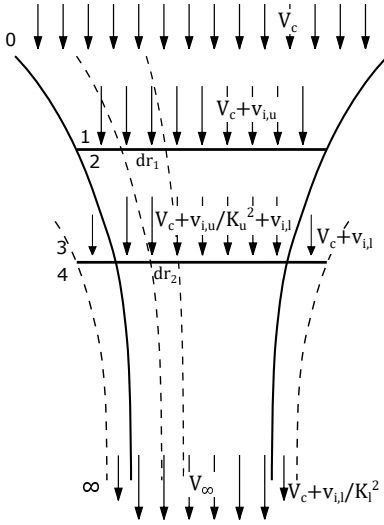


Fig. 1. Wake contraction for a coaxial rotor.

lished (Ref. 20). However, to the authors' best knowledge, trailing-edge noise was not studied or analyzed in a coaxial rotor. In a coaxial rotor, the upper and lower rotors are influenced by each other, which yields different aerodynamics and flow fields compared to a single rotor. In addition, the performance and interactional aerodynamics of a coaxial rotor are highly dependent on blade design, desired thrust values, separation distance, etc. Therefore, the effect of the rotor design and operating condition on broadband noise would be important. The contribution from each rotor on noise should be understood and analyzed.

The goals of this paper are to develop a fast predictive tool for coaxial rotor trailing-edge noise and to analyze broadband noise in different design and operating conditions including the axial separation distance between two rotors.

Aerodynamic data including the induced velocity and angle of attack on each rotor are calculated by the iterative BEMT. Then, turbulent boundary layer flows, such as the boundary layer thickness, skin friction coefficient, pressure gradient, etc., are computed by XFOIL. Based on these boundary layer parameters, the wall pressure spectrum near the trailing edge is computed by Lee's semi-empirical model. Finally, trailing-edge noise is predicted by Amiet's model from the wall pressure spectrum. This method provides fast computations for aerodynamics and acoustics for coaxial rotors. Acoustic predictions are performed in a platform of UCD-QuietFly for various design and operating conditions of a coaxial rotor including the effect of rotor-to-rotor separation distance.

NUMERICAL APPROACHES

Iterative Blade Element Momentum Theory

In this section, a recently developed iterative BEMT approach (Ref. 21) that solves the upper and lower rotors simultaneously will be briefly reviewed.

Figure 1 shows the control volume with two rotors. The climb velocity, V_c , is included for axial flight. For hover, V_c is zero.

Let us define y as the radial distance of a streamtube at the tip, $K_t = y_\infty/y_1$ as the tip vortex contraction ratio from 1 to ∞ in the presence of the lower rotor, $K_u = y_3/y_1$ as the tip vortex contraction ratio from the upper rotor to the lower rotor, and $K_l = y_\infty/y_3$ as the tip vortex contraction ratio for the lower rotor from 3 to ∞ .

The far downstream velocity within the slipstream of the upper rotor becomes

$$V_\infty = V_c + \frac{v_{i,u}}{K_t^2} + \frac{v_{i,l}}{K_l^2} \quad (1)$$

where $v_{i,u}$ and $v_{i,l}$ are the induced velocities by the upper and lower rotors at each rotor plane, as shown in Fig 1. Outside the slipstream of the upper rotor, $v_{i,u}$ becomes zero.

The inflow ratios for the upper (λ_u) and lower rotors (λ_l) can be derived as

$$\lambda_u = K_t^2 \sqrt{\lambda_c^2 + \frac{1}{r_u dr_u} \left(\frac{dC_{T_u}}{F} + \frac{dC_{T_l}}{K_u^2} \right)} + (1 - K_t^2) \lambda_c - K_u^2 \lambda_{i,l} + A \lambda_{i,l} \quad (2)$$

and

$$\lambda_l = \begin{cases} K_l^2 \sqrt{\lambda_c^2 + \frac{1}{r_l dr_l} \left(K_u^2 dC_{T_u} + \frac{dC_{T_l}}{F} \right)} + (1 - K_l^2) \lambda_c - B \lambda_{i,u} & \text{for } r_l \leq K_u r_{u,tip} \\ K_l^2 \sqrt{\lambda_c^2 + \frac{1}{r_l dr_l} \left(\frac{dC_{T_l}}{F} \right)} + (1 - K_l^2) \lambda_c & \text{for } r_l > K_u r_{u,tip} \end{cases} \quad (3)$$

where F is the Prandtl's tip loss effect, $r_{u,tip}$ is the non-dimensionalized tip radius of the upper rotor, and A and B are empirical constants. r denotes the non-dimensional radial distance that is normalized by the blade radius. λ_c is the normalized climb velocity by the tip speed. The detailed derivation of Eqs. (2)–(3) can be found in a reference (Ref. 21).

Empirical constant, A , in Eq. (2) has been added to include the effect of the lower rotor on the upper rotor. This constant is multiplied by $\lambda_{i,l}$ so that the effect of the lower rotor depends on the magnitude of the induced velocity of the lower rotor. Since the induced velocity of the lower rotor varies as a function of the radial distance and the axial separation distance, the effect of the lower rotor on the upper rotor also varies with the rotor radial and axial separation distances. Empirical constant, B , in Eq. (3) has been added to augment the effect of the upper rotor on the lower rotor when the area is within the influence zone of the upper rotor wake. This empirical constant is multiplied by the induced velocity of the upper rotor. Since the induced velocity of the upper rotor is a function of the radial and separation distances, the effect of the upper rotor on the lower rotor is also a function of the radial and separation distances. It was found that A of 0.5 and B of 0.12 provide the closest agreement with the measurement data for untwisted rotors.

Equations (2)–(3) describe the momentum equations. They can be combined with a standard blade element theory, in which the sectional forces are determined from the inflow, rotor pitch, and blade local twist angle, to construct BEMT. This

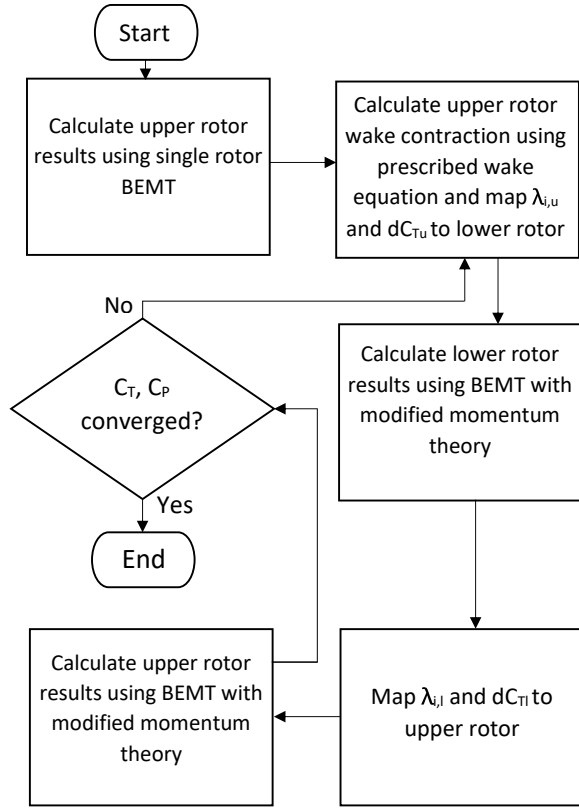


Fig. 2. Flow chart of the iterative BEMT method

BEMT can be solved for each rotor. However, it is worthwhile noting that the upper rotor inflow solution is influenced by the lower rotor thrust and lower rotor inflow in Eq. (2). Similarly, the lower rotor inflow is affected by the upper rotor thrust and upper rotor inflow in Eq. (3). Therefore, an iterative approach is required to solve these coupled equations. For example, for the upper rotor BEMT calculation, the lower rotor thrust and the lower rotor inflow ratio are known a priori from an earlier iteration or the initial assumption of zero for both. Then, the upper rotor BEMT determines the upper rotor thrust and the upper rotor inflow ratio. For the lower rotor BEMT calculation, the upper rotor thrust and the upper rotor inflow ratio are given from an earlier iteration or the initial assumption of zero for both. Then, the lower rotor BEMT determines the lower rotor thrust and the lower rotor inflow ratio. The rotor-to-rotor iteration is continued until the thrusts and the inflow ratios for both rotors are fully converged. A flow chart of the iterative BEMT incorporating the prescribed wake is shown in Fig. 2.

Since a streamtube contracts from the upper rotor to the lower rotor, the radial locations following the streamtube are not the same for both rotors. Furthermore, the influenced radial locations may not be on the designated control points, at which the aerodynamic data are defined. Therefore, a numerical interpolation is required on each rotor blade when coupling the upper rotor BEMT and lower rotor BEMT. In order to determine the radial contraction for the upper rotor work, or K_u , Landgrebe's prescribed wake (Ref. 22) is used.

Trim process

In the coaxial rotor, two trim conditions are considered. The first one is the balanced torque or $C_{Q_u} = C_{Q_l}$ where C_{Q_u} is the torque of the upper rotor and C_{Q_l} is the torque of the lower rotor. The second trim condition is the required total thrust or $C_{T_u} + C_{T_l} = C_{T_{req}}$ where C_{T_u} and C_{T_l} are the thrust of the upper and lower rotors, respectively, and $C_{T_{req}}$ is the required thrust. We use Broyden's Method to find the collective pitch angles (θ_u and θ_l) of the upper and lower rotors to meet these trim conditions.

Trailing-edge noise

A rotor trailing-edge code named UCD-QuietyFly is used to predict coaxial rotor broadband noise. In this program, wake-blade interaction noise (leading edge noise) is not accounted for. The flow is assumed to be transitioned to a turbulent flow near the leading edge. First, the iterative BEMT provides the relative velocity, including the induced inflow and tangential inflow, and angle of attack at each radial section on both rotors. Based on these input conditions, the boundary layer parameters including the boundary layer thickness, displacement thickness, momentum thickness, skin friction coefficient, pressure gradient, and edge velocity, are computed near the trailing edge at each blade section on both rotors using XFOIL (Ref. 23), which is a viscous panel code. Then, a semi-empirical wall pressure spectrum developed by Lee (Ref. 24) is used to compute the wall pressure spectrum near the trailing edge using boundary layer parameters, which will be shown later.

Finally, Amiet's model (Ref. 16) is used to predict trailing edge noise from each section on both rotors. The Doppler effect and coordinate transformation due to the rotation of sources are included in the prediction. The power spectral density (PSD) of each section changes with the azimuth angle; hence, it is azimuthally averaged by

$$S_{pp} = \frac{N_B}{2\pi} \int_0^{2\pi} \left(\frac{\omega}{\omega_d} \right)^2 \bar{S}_{pp} d\phi, \quad (4)$$

in which $\bar{S}_{pp}$ is the acoustic PSD at an observer location (X, Y, Z) of each surface of an airfoil. The Doppler-shifted frequency ω_d at the observer is related to the source frequency ω using

$$\frac{\omega_d}{\omega} = \frac{1}{1 + M_r \left(\frac{X}{R_s} \right)}. \quad (5)$$

Note that $M_r = \Omega r / c_o$ is the rotational Mach number of the blade section. X has the direction pointing from leading edge to trailing edge shown in Fig. 3, and R_s is the distance between the blade section and an observer. A full equation for Eq. (5) is given as

$$S_{pp} = \left(\frac{\omega}{c_o} \right)^2 c^2 \Delta r \left(\frac{1}{32\pi^2} \right) \frac{B}{2\pi} \int_0^{2\pi} D_\phi |L|^2 I_r \Phi_{pp} d\phi. \quad (6)$$

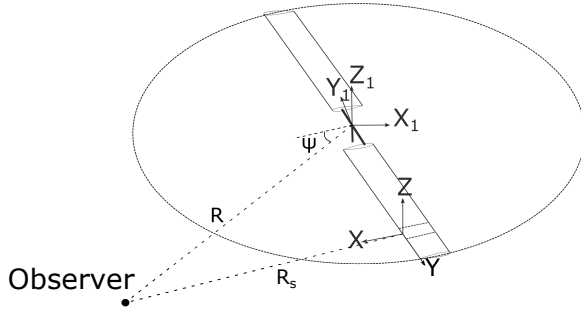


Fig. 3. Global coordinates

where c_0 is the speed of sound, c is the chord length, Δr is the sectional distance, B is the number of blades, D_ϕ is the directivity function, L is the loading function, l_r is the spanwise correlation length, and Φ_{pp} is the wall pressure spectrum, which is computed by the semi-empirical model. The loading term L is given by Amiet (Ref. 25). All other detailed functions can be found from references (Refs. 26, 27).

The wall pressure spectrum Φ_{pp} is obtained by a recently developed empirical wall pressure spectrum model for non-zero gradient flows, Lee's model (Ref. 24), as

$$\frac{\Phi_{pp}(\omega)U_e}{\tau_w^2 \delta^*} = \frac{\max(a, (0.25\beta_c - 0.52)a)(\frac{\omega \delta^*}{U_e})^2}{[4.76(\frac{\omega \delta^*}{U_e})^{0.75} + d^*]^e + [8.8R_T^{-0.57}(\frac{\omega \delta^*}{U_e})]^{h^*}} \quad (7)$$

where $\beta_c = (\Theta/\tau_w)|dp/dx|$, $a = 2.28\Delta^2(6.13\Delta^{-0.75} + d)^e[4.2(\Pi/\Delta) + 1]$, $\Delta = \delta/\delta^*$, $\Pi = 0.8(\beta_c + 0.5)^{3/4}$, $e = 3.7 + 1.5\beta_c$, $d = 4.76(1.4/\Delta)^{0.75}[0.375e - 1]$, $R_T = (\delta/U_e)(v/u_\tau^2)$, $h^* = \min(3, (0.139 + 3.1043\beta_c)) + 7$, and if $(\beta_c < 0.5)$, $d^* = \max(1.0, 1.5d)$, otherwise $d^* = d$.

Finally, the far-field SPL for one side of the i^{th} section is calculated from the power spectral density S_{pp} as

$$\text{SPL}_{i(U/L)} = 10 \log_{10} \left(\frac{2\pi S_{pp}}{(2 \times 10^{-5})^2} \right), \quad (8)$$

where U and L represent the upper and lower surfaces of an airfoil, respectively. The rotor's total SPL is logarithmically summed to be

$$\text{SPL}_{\text{rotor}} = 10 \log_{10} \sum_{i=1}^N \left(10^{0.1 \text{SPL}_{iU}} + 10^{0.1 \text{SPL}_{iL}} \right), \quad (9)$$

where N is the total number of sections.

RESULTS

In this section, the validation of the iterative BEMT for untwisted rotor performance for different axial distances and the validation of UCD-QuietFly for trailing-edge noise predictions are presented. Then, coaxial rotor broadband noise is predicted by UCD-QuietFly.

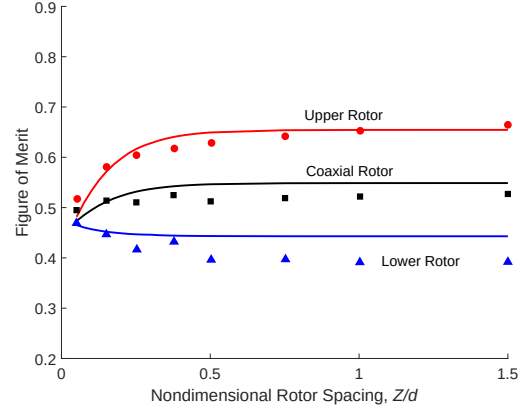


Fig. 4. Figure of merit as a function of the coaxial rotor spacing for $C_T = 0.014$. (Data source: (Ref. 28))

Iterative BEMT validation

In this subsection, Ramasamy's coaxial rotor experimental data (Ref. 28) are used to validate the iterative BEMT as a function of the axial separation distance. Ramasamy's experiment includes comprehensive and detailed performance results for a model-scaled coaxial rotor in hover.

The coaxial rotor of our choice for the validation has three blades on each rotor. The blade uses a NACA0012 untwisted airfoil. The blade radius is 2.17 ft and the chord length is 2.29 in. The root cutout is 19.1%. The rotor RPM is 800 and the tip Mach number is 0.16.

Figure 4 shows the effect of the axial separation distance on the figure of merit for the total coaxial thrust coefficient of 0.014. Both the prediction and the measurement data are included in the figure. It is found that the upper rotor shows a decrease in the figure of merit as the separation distance approaches to zero. For the lower rotor, the figure of merit is much lower than that of the upper rotor, and it remains constant for most separation distances except near zero separation distance, in which it slightly increases. The iterative BEMT prediction captures the trend of the figure of merit for the upper rotor and lower rotor as a function of the separation distance. For the upper rotor, the prediction is in good agreement, but for the lower rotor, the prediction is slightly overpredicted. Both the measured and predicted figures of merit for the upper rotor converge to that for the isolated rotor for a large separation distance or Z/d greater than 0.5.

Figure 5 shows the rotor thrust as a function of the rotor separation distance. For the separation distance larger than 0.5, the lower rotor carries only about 70% of the upper rotor thrust. As the separation distance decreases, the lower rotor thrust increases and approaches 100% at near zero distance. The prediction shows about 10% higher thrust ratio for the lower rotor at a large separation distance. However, overall, the iterative BEMT accurately predicts this thrust ratio trend. It is clearly seen that the upper rotor decreases and the lower rotor thrust increases as the separation distance decreases.

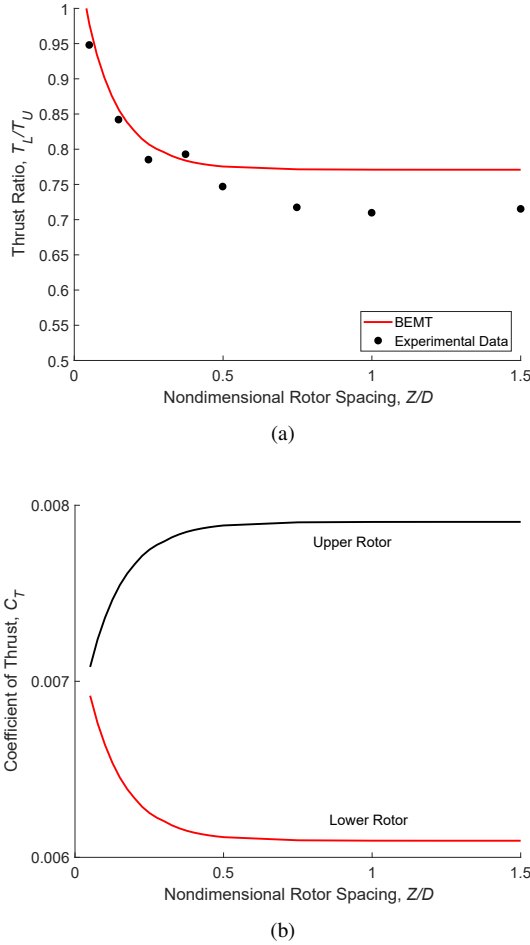


Fig. 5. Ramasamy Untwisted coaxial rotor thrust as a function of the rotor spacing for $C_T = 0.014$.: (a) thrust ratio and (b) thrust coefficient for the upper and lower rotors. (Data source: (Ref. 28))

Validation for trailing-edge noise predictions

Now that aerodynamics has been validated based on the iterative BEMT, aeroacoustic solver (UCD-QuietFly) is validated for trailing-edge noise predictions in this subsection.

First, airfoil trailing-edge noise data is used to validate UCD-QuietFly. Benchmark Problems for Airframe Noise Computations (BANC) (Ref. 29) case 3 is used for the validation. In this case, a NACA0012 airfoil with the chord length of 0.4 m and the span length of 1 m is used. The freestream velocity is 53 m/s and the angle of attack is 6 degrees. The observer is located at 1 m above the trailing edge. For this airfoil validation case, the turbulence convective velocity $U_c = 0.7U_\infty$ and spanwise turbulence lengthscale $l_r = 1.0U_c/\omega$ are used. For both the measurement and prediction, the flow is enforced to transition to turbulent near the leading edge.

One-third octave band sound pressure levels (SPLs) are presented in Fig. 6 in which error bars of ± 3 dB are included, as reported in reference (Ref. 29). The prediction has a good match with the measurement at an entire frequency range, which demonstrates the validity of the numerical approach

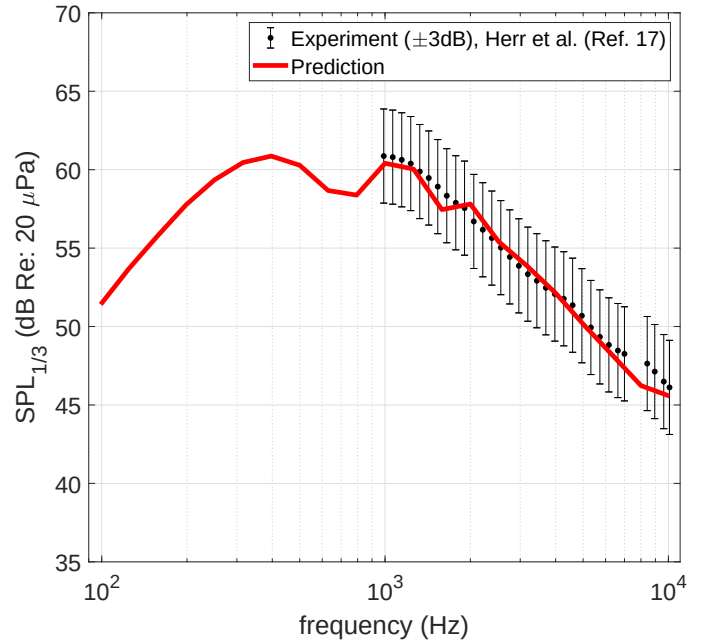


Fig. 6. Validation of airfoil trailing-edge noise prediction against measurement (Ref. 29).

involving the boundary-layer flow parameters from XFOIL, Lee's wall pressure spectrum model in Eq. (7), and the Amiet model in Eq. (6).

The next validation problem is helicopter noise (Ref. 30). The helicopter has two blades with the rotor radius of 6.7 m and the blade linear twist of -10 degree. The tip Mach number in hover is 0.67 and the thrust coefficient is 0.0036. A NACA0012 airfoil is used. The observer is 5 rotor diameters from the hub with an elevation angle of $\Psi = 26.7^\circ$. The UCD-QuietFly prediction is presented in Fig. 7 along with the measurement and the prediction by Kim and George (Ref. 31). The results show that UCD-QuietFly has a good match with the measurement in the mid- and high-frequency range in which trailing-edge noise is expected to be the dominant noise source. The low-frequency noise is thought to be irrelevant to trailing-edge noise. In addition, Fig. 7 shows that UCD-QuietFly is more accurate than Kim and George's prediction for the entire frequency range.

Coaxial rotor broadband noise prediction

Figure 8 shows a comparison of total one-third octave band trailing-edge sound pressure levels (SPLs) of a coaxial rotor for various axial separation distances. The noise is measured at ten rotor radii below the upper rotor. It is shown that noise slightly increases with increasing the separation distance at the entire frequency range. Comparing $z/D=0.08$ and 1.5, however, the noise difference is only about 3 dB.

Figure 9 shows the noise contributions from the upper and lower rotors as well as the total noise at various z/D locations. It is found that, at a small separation distance, the upper and lower rotors generate similar noise levels with a peak frequency of around 3 kHz where the maximum noise occurs.

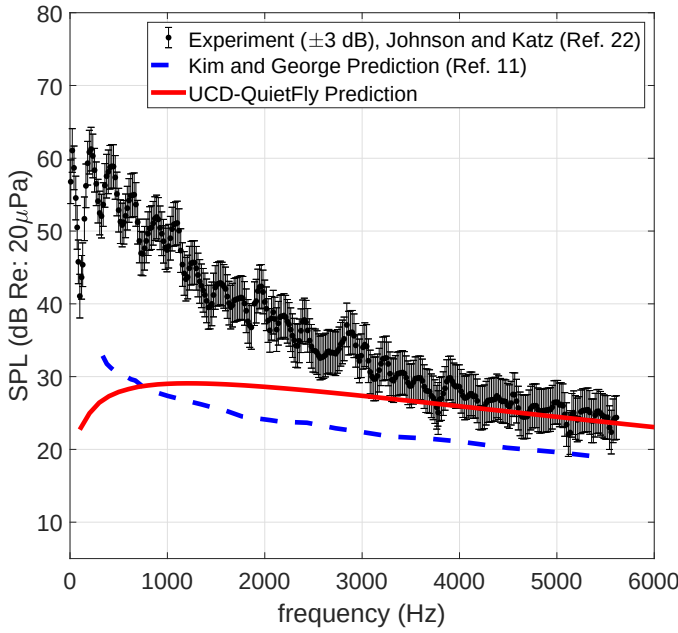


Fig. 7. Comparison of UCD-QuietFly prediction with measurement by Johnson (Ref. 30) and prediction by Kim and George (Ref. 31).

In this case, the coaxial rotor trailing-edge noise is almost the same as the summation of the noise from two isolated rotors. As the axial distance increases, however, lower rotor noise increases. As a result, total noise increases with increasing the axial distance, as shown in Fig 9.

Figure 10 and 11 show the suction side (upper surface) and the pressure side (lower surface) one-third octave band SPLs for both rotors. First of all, the suction side SPL is higher than the pressure side SPL for both rotors. Secondly, the upper rotor shows very similar results for different separation distances while the lower rotor shows higher noise at larger separation distances.

Figures 12 and 13 show the total vertical induced velocity on the rotor disk and angle of attack as a function of the blade radius at various separation distances. As the separation distance decreases, the induced velocity on the upper rotor increases due to higher influence from the lower rotor. This leads to the reduction in angle of attack (AoA) with decreasing the separation distance. For the lower rotor, the induced velocities are very similar for all separation distances except the transition region between 0.09 and 0.1 of r/R where the upper rotor tip vortex meets with the lower rotor. Note that the lower rotor has the higher induced velocity due to the addition of the upper rotor wake. In other words, the upper rotor AoA is slightly higher than the lower rotor AoA. Even though the induced velocities are similar at various z/D values on the lower rotor, AoA still varies due to the change in the collective pitch angle that is determined by the trim solution as discussed earlier and shown in reference (Ref. 21). Overall, the change of AoA is about 1 degree between $z/D = 0.08$ and 1.5. This small change in AoA would make little impact on the noise results as shown in Fig. 10, in particular the upper rotor noise. This result indicates that the effect of the change in the sepa-

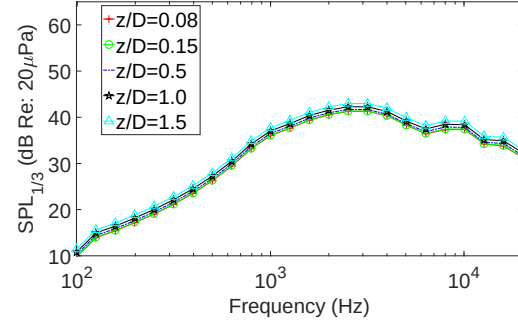


Fig. 8. Total trailing-edge noise from a coaxial rotor at various separation distances ($z/d = 0.08, 0.15, 0.5, 1.0, 1.5$).

ration distance on the lower rotor noise may not be attributed to the flow change, but the geometrical distance between the source and observer. As the separation distance increases, the lower rotor is moved closer to the ground while the upper rotor location is fixed so that the noise level increases.

In order to justify the above statement and understand the effect of flow parameters on noise, the detailed flow data near the trailing edge is investigated. Since the suction side contributes more to total trailing-edge noise than the pressure side, we will focus on the suction side for both rotors to investigate the detailed boundary-layer flows. Again, the boundary-layer parameters were obtained from XFOIL. Figure 14 shows the boundary-layer edge velocity at $x/c = 0.99$ on the suction side as a function of the blade radius at multiple separation distances where x and c denote the streamwise location and the chord length. The edge velocity increases with increasing the blade radial position for both rotors. It is shown that the separation distance changes the edge velocity very little for both rotors.

Figure 15 shows the streamwise pressure gradient at $x/c = 0.99$ on the suction side as a function of the blade radius at multiple separation distances. The pressure gradient increases toward the blade tip. However, it changes very little with the separation distance. Figure 16 shows the boundary-layer displacement thickness at $x/c = 0.99$ on the suction side as a function of the blade radius at multiple separation distances. As the separation distance decreases, the displacement thickness decreases on the upper rotor and increases on the lower rotor. This is consistent with the AoA behavior as shown in Fig. 13, i.e., the smaller AoA, the smaller displacement thickness. Figure 17 shows the skin friction coefficient at $x/c = 0.99$ on the suction side as a function of the blade radius at multiple separation distances. As the separation distance reduces, the skin friction coefficient increases on the upper rotor and decreases on the lower rotor. This is also consistent with the AoA behavior. As AoA increases with increasing the separation distance, the flow tends to be more likely be separated so that the skin friction approaches to zero. On both rotors, the skin friction coefficients are positive so that the flow is fully attached. It is shown that the skin friction coefficients rapidly increase near the tip region.

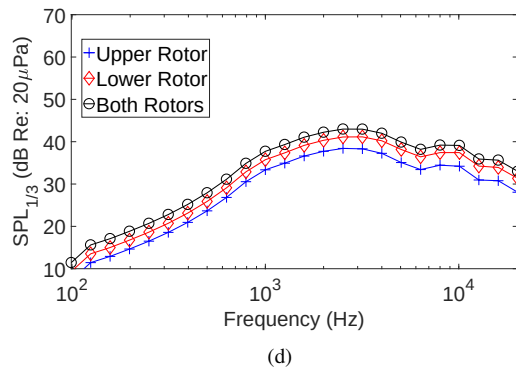
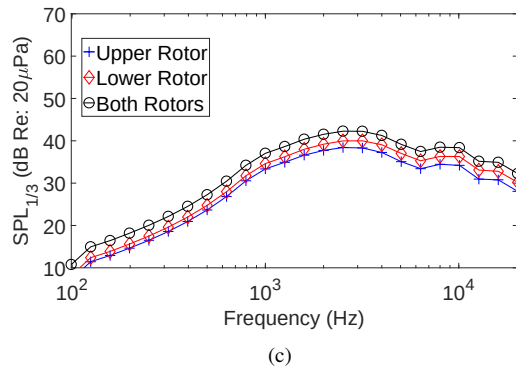
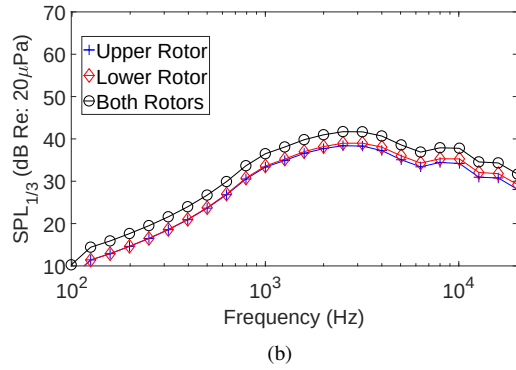
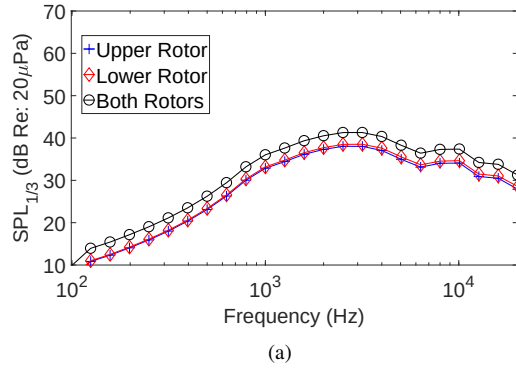


Fig. 9. Trailing-edge noise from a coaxial rotor at various separation distances: (a) $z/D=0.08$, (b) $z/D=0.5$, (c) $z/D=1.0$, and (d) $z/D=1.5$.

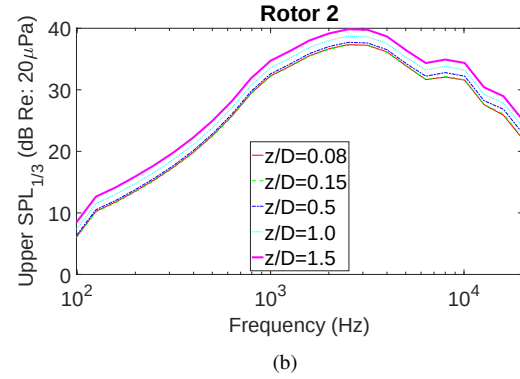
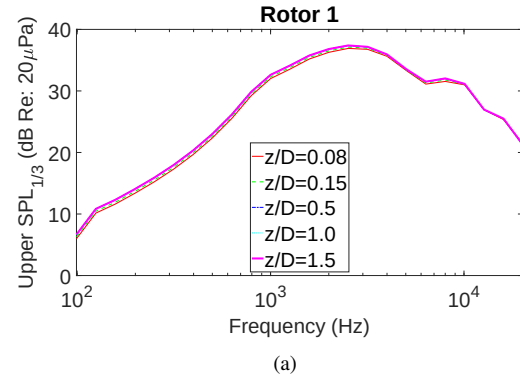


Fig. 10. Trailing-edge noise on the suction side at various z/D locations: (a) upper rotor and (b) lower rotor.

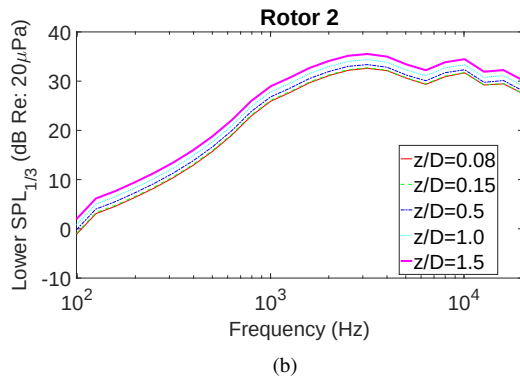
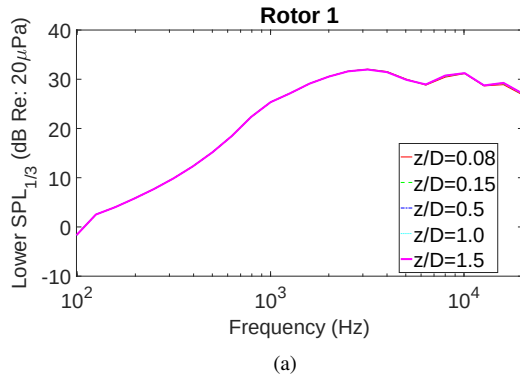
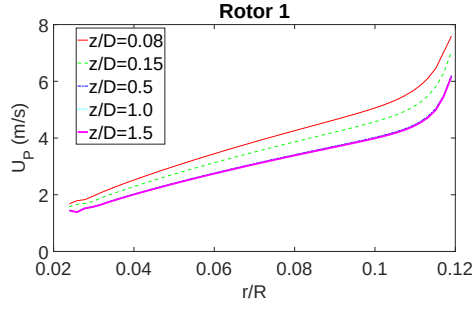
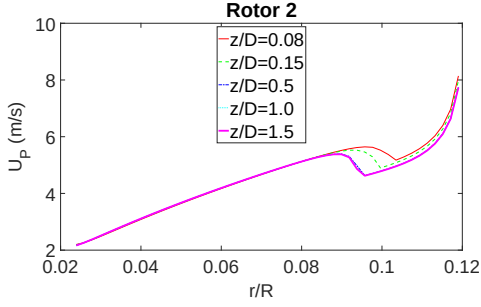


Fig. 11. Trailing-edge noise on the pressure side at various z/D locations: (a) upper rotor and (b) lower rotor.

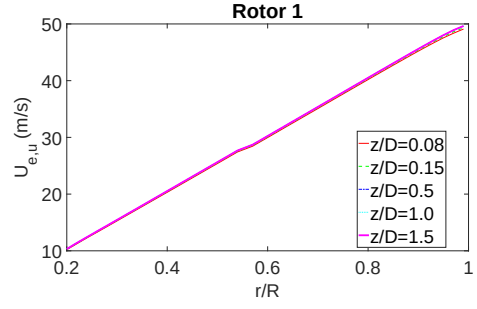


(a)

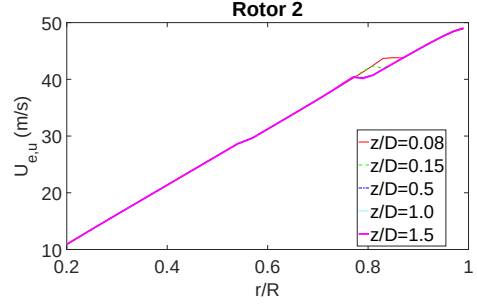


(b)

Fig. 12. Induced velocity as a function of the blade radius that is perpendicular to the rotor disk at various z/D locations: (a) upper rotor and (b) lower rotor.

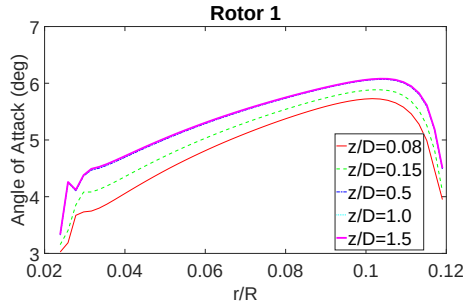


(a)

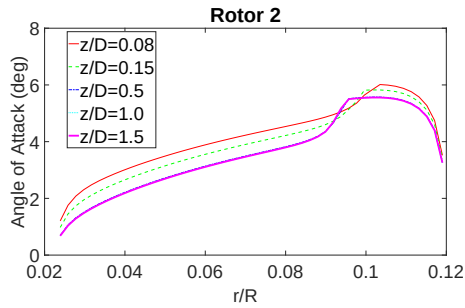


(b)

Fig. 14. Boundary-layer edge velocity (U_e) as a function of the blade radius at $x/c = 0.99$ on the suction side at various z/D locations: (a) upper rotor and (b) lower rotor.

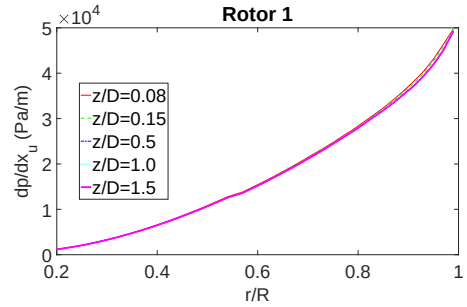


(a)

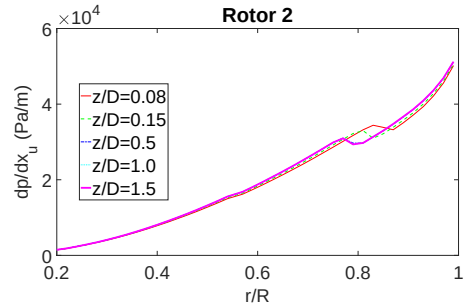


(b)

Fig. 13. Angle of attack as a function of the blade radius at various z/D locations: (a) upper rotor and (b) lower rotor.



(a)



(b)

Fig. 15. Pressure gradient (dp/dx) as a function of the blade radius at $x/c = 0.99$ on the suction side at various z/D locations: (a) upper rotor and (b) lower rotor.

CONCLUSIONS

Trailing-edge noise of a coaxial rotor in hover has been investigated in this paper. An iterative BEMT was used to calculate the blade aerodynamics on both rotors as a function of the axial separation distance. The performance of a small-scale rotor was validated against experimental data. Based on the velocity magnitude and angle of attack from BEMT, boundary-layer flow data including the boundary-layer thickness, pressure gradient, skin friction coefficient, etc., were obtained from XFOIL near the trailing edge along the blade sections for both rotors. Then, the Amiet theory was used to predict trailing-edge noise. The noise predictions were validated in airfoil and single rotor cases. A small-scale untwisted rotor was used to analyze coaxial rotor noise. It was found that the blade aerodynamic change as a function of the separation distance is small. The upper rotor noise remains the same for various separation distances. However, the lower rotor increases noise levels as the separation distance increases. Considering the minor changes in the flow data, this increase in noise levels is attributed to the geometrical distance change. Even though the trend of noise change is expected with changing the geometric distance, it is important to realize that the lower rotor contributes more to the total noise levels at large separation distance. It should be noted that this paper did not cover rotor wake or tip vortex interactions with the blades. It only covers rotor trailing-edge noise. It would be recommended to investigate the problem further for twisted rotors and various operating conditions, and with high-fidelity computational tools.

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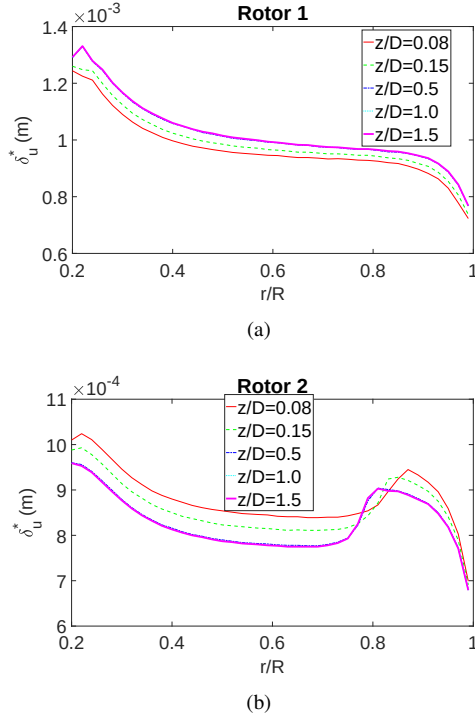


Fig. 16. Boundary-layer displacement thickness (δ^*) as a function of the blade radius at $x/c = 0.99$ on the suction side at various z/D locations: (a) upper rotor and (b) lower rotor.

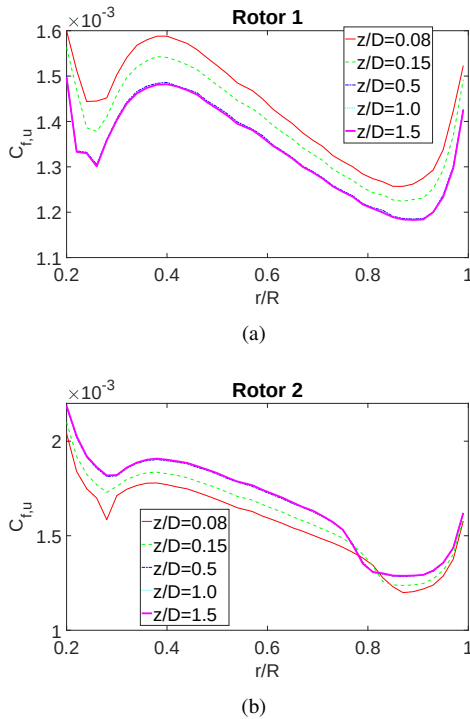


Fig. 17. Skin friction coefficient (C_f) as a function of the blade radius at $x/c = 0.99$ on the suction side at various z/D locations: (a) upper rotor and (b) lower rotor.

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