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# A 3D analytical model for orthogonal blade-vortex interaction noise

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ABSTRACT

A 3D analytical model of an Orthogonal Blade-Vortex Interaction (OBVI) for Counter-Rotating Open Rotor (CROR) tonal noise is investigated. The specific influence of two parameters taking into account the three-dimensionality of both the vortex velocity and the convection velocity within the rotor-rotor volume is addressed. The first step is to extract the vortex parameters from a recent unsteady Reynolds-Averaged Navier-Stokes computation and validate different vortex models. Lamb-Oseen and Scully vortices reproduce the behavior of the tip-vortex tangential velocity fairly well. Regarding the vortex axial velocity modeling, a Gaussian profile fits well with numerical results. On the one hand, the impact of the stream-tube contraction unbalances the lobes of the unsteady pressure with opposite phases produced by the OBVI event. This effect is larger than that of an equivalent blade sweep. On the other hand, adding the axial velocity deficit to the tangential one also unbalances the pressure lobes. Finally, from an acoustic point of view using Curle's acoustic analogy, both the stream-tube contraction and the axial velocity deficit have the same effect: they turn an acoustically-low efficient quadrupole into a strong dipole making these parameters fundamental for future CROR OBVI investigations.


## 1. Introduction

Because of the weight and space limitations of nacelles for future Ultra High By-Pass Ratio (UHBR) turbofans, Counter-Rotating Open Rotor (*CROR*) design could be a viable alternative to classical turboengines for commercial airplane propulsion. Since the beginning of CROR design with the preliminary work on the UnDucted Fan engine in the nineties [1–5], significant tonal noise reduction for this novel architecture has been achieved. Nowadays, 3D aerodynamic and aeroacoustic optimizations have yielded fully three-dimensional blade shapes and cropped aft rotor that have achieved substantial reductions in tonal noise without efficiency penalties at cruise conditions [6]. Yet, one of the main concerns regarding CROR noise, is to meet the community noise levels standards set by the International Civil Aviation Organization at take-off and approach conditions. At these regimes, it is particularly essential to take into account the three-dimensionality of the flow induced by unbalanced flow conditions within the CROR due to inflow incidence or streamtube contraction between the front and rear rotors. At these flow regimes, cropping the aft rotor might be insufficient to reduce the interaction noise due to the front-rotor tip vortex impingement as was recently shown by Soulat et al. [7]. In a typical uncropped CROR

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## Nomenclature

*Latin symbols*

| | |
|---|---|
| $a$, $b$ | constants in the Lamb-Oseen gust spectrum |
| $a_\nu$ | constant in the turbulent kinematic viscosity |
| $V_z^{max}$ | maximum of the vortex axial velocity |
| $r_0$ | radius of the vortex core |
| $k$ | acoustic wavenumber |
| $b_\varphi$, $\Phi_i$ | coefficients of the helix regression in the azimuthal direction |
| $c$ | chord length |
| $R1(R2)$ | front (aft) - rotor |
| $R_{VI}$ | radius of the OBVI event |
| $C_{chord}(C_{span})$ | amplitude of the projection angle related to the chordwise (spanwise) variable |
| $C_{amp}$ | amplitude of the upwashes spectral density |
| $\tilde{p}$ | aerodynamic surface pressure on the blade |
| $\tilde{l}_{tot}$ | total aerodynamic pressure jump on the blade |
| $\tilde{G}^*$ | upwash spectral density related to the azimuthal velocity of the vortex |
| $\tilde{G}^{z_v}$ | upwash spectral density related to the axial velocity of the vortex |
| $\tilde{G}^{tot}$ | upwash spectral density related to all velocities. |
| $\mathbf{U}_0$ | convection velocity vector |
| $c_\beta$ | vena contracta contraction radius coefficient |
| $S_0$ | source-observer distance corrected by 1D convection velocity |
| $R$ | Observer radius of the microphone $\sqrt{x_{c2}^2 + y_{c2}^2 + z_{c2}^2}$ |
| $V_\theta^{max}$ | maximum of the vortex azimuthal velocity |
| $U_c$ | phase speed of the incoming vortex] |
| w | upwash velocity |
| $(X_v, Y_v, Z_v)$ | coordinates of the vortex core line |
| $r_X$ | viscous vortex radius growth rate |
| $r_i$ | initial viscous vortex radius value |
| $V_X^{max}$ | viscous azimutal-vortex maximum velocity diffusion rate |
| $V_i^{max}$ | initial viscous azimutal-vortex maximum velocity value |
| $p_{atm}$ | standard atmospheric pressure (101325 Pa.) |
| $(u_v, v_v, z_v)$ | vortex velocity in the vortex reference frame |
| $(u_v, v_\beta, z_\beta)$ | vortex velocity in the vortex-vena contracta corrected reference frame |
| $(k_x, k_y, k_z)$ | aerodynamic wavenumbers in the unswept blade reference frame |
| $(r_v, \theta_v, z_v)$ | vortex reference frame in cylindrical coordinates |
| $(x_{c2}, y_{c2}, z_{c2})$ | unswept aft-blade reference frame in Cartesian coordinates |
| $(X, Y, Z)$ | global reference frame in Cartesian coordinates |
| $(X, R^c, \Phi)$ | global reference frame in cylindrical coordinates |
| $(R_{VI}\Phi), R_{VI}, X)$ | unwrapped OBVI reference frame in Cartesian coordinates |

*Greek symbols*

| | |
|---|---|
| $a_\beta$, $R_i$ | coefficients of the helix regression in the radial direction |
| $\Gamma$ | total circulation of the vortex |
| $\varphi$ | helicity angle of the vortex trajectory |
| $\gamma_1(\gamma_2)$ | front (aft) rotor stagger angle at the OBVI location |
| $\beta$ | Vena contracta angle |
| $\beta_1(\beta_2)$ | compressibility coefficient in the chordwise (spanwise) direction |
| $\kappa$ | Helmholtz parameter |
| $\alpha$ | Lamb-Oseen maximum velocity location coefficient |
| $\Phi'$ | dimensionless velocity potential |
| $\nu(\nu_t)$ | Laminar (turbulent) kinematic viscosity |
| $\rho_0$ | density of the flow at rest |

*Subscripts/Superscripts*

| | |
|---|---|
| $(.)^{LO}$ | variable related to the Lamb-Oseen vortex model |
| $(.)^{Sc}$ | variable related to the Scully vortex model |
| $(.)^{Va}$ | variable related to the Vatistas vortex model |
| $(.)_{LE}$ | variable related to the first iteration of the Amiet-Schwarzschild method |
| $(.)_{TE}$ | variable related to the second iteration of the Amiet-Schwarzschild method |
| $(.)'$ | variable in the cartesian swept coordinate system |
| $(.)^*$ | Dimensionless coordinate |
| $(\tilde{.}), (\hat{.})$ | variable in the Fourier space |

configuration computed at cruise and take-off conditions, Peters and Spakovszky [8] showed numerically that the tip contribution caused by the Orthogonal Blade-Vortex Interaction (OBVI) can be as large as the front rotor-wake impact for specific interaction frequencies. It is then essential to assess tonal noise for this case with accurate but quick model of the OBVI noise mechanism. An analytical procedure was recently proposed by Roger et al. [9] to predict OBVI tonal noise for CROR preliminary designs. The present work extends the aforementioned model by introducing two new features.

The first one takes into account the fact that the streamtube for an open-rotor at approach contracts inwardly. This effect, called stream-tube contraction, is seen both in numerical simulations [10,11] and experiments [12]. The contraction is taken into account using an additional angle thereafter called $\beta$. A single angle is used because Computational Fluid Dynamics (CFD) results exhibit such variations when tracking the vorticity maximum in the tip region between the two rotors (Fig. 1 in [13]). For CROR designs, a linear approach is more realistic than the rational-linear regression based on single rotor experiments [12].

The second feature is to provide a truly 3D vortex model by adding an axial velocity on top of the tangential velocity used

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