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ANALYTICAL INVESTIGATION OF ROTOR-STRUT POTENTIAL INTERACTION NOISE

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ABSTRACT

This paper presents a methodology to predict the tonal noise radiated by a propeller-strut configuration by modeling the potential inflow distortion induced by the strut. The approach combines a theoretical description of the potential flow around a circular cylinder with the force distribution and induced velocity computed using an unsteady panel method. The analytical results show satisfactory agreement with measurements from previous studies, demonstrating the suitability of the proposed methodology as a fast and effective prediction tool.

Keywords: *Propeller noise, potential interaction noise, noise prediction, urban air mobility.*

1. INTRODUCTION

A significant part of the aerodynamic noise radiating from an unmanned aerial vehicle (UAV) arises from the interaction between the turbulent wake and the acoustic field produced by the rotors and the supporting strut located downstream. The intensity of such interaction depends on the proximity between these components and encompasses several noise generation mechanisms, including the sound emitted by the rotor operating in the potential distortion of the strut. Clarifying these mechanisms can offer guidelines for the future design of quieter UAVs and foster the development of analytical noise prediction tools to exploit in the early design stage, where the detailed geometry of the propulsion systems is still unknown.

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Several studies in the literature have focused on the analytical modeling of propeller-strut potential interaction noise [1–6]. However, most of these relied on measurement data or high-fidelity numerical simulations to provide input to the prediction models, particularly for the propeller-induced velocity. Low-fidelity methods, such as blade element momentum theory (BEMT), have been regarded as subject to significant uncertainties [4]. In this study, we propose an alternative approach, making use of a fast mid-fidelity simulation framework coupled for the estimation of the aerodynamic data required by the model.

2. METHODOLOGY

2.1 Experimental setup

The analytical results presented in this study are intended to reproduce the measurements performed by Gallo *et al.* [3] in the JAFAAR anechoic room of the von Karman Institute for Fluid Dynamics. Acoustic measurements were performed using a 7-microphone directivity arc (with radiation angles ranging from $0°$ to $90°$ relative to the propeller axis) to investigate the noise emitted by a propeller operating upstream of a cylindrical rod (see Figure 1). A two-bladed Mejzlik 13"x4.2 propeller, driven by a T-motor AT 2814 KV1050 and controlled by a Scorpion Tribunus II 12-80 A, was tested for different rod diameters and propeller-strut distances. For comparison with noise prediction results, the case with the propeller operating at $6000\,\mathrm{RPM}$ and with a strut radius of $a_c = 0.02\,\mathrm{m}$ located at $d = 0.01\,\mathrm{m}$ from the rotor plane is selected.

2.2 Analytical model

The analytical flow-distortion model used in this paper is based on the classical incompressible solution for the flow past a circle. The two-dimensional nature of the model of-

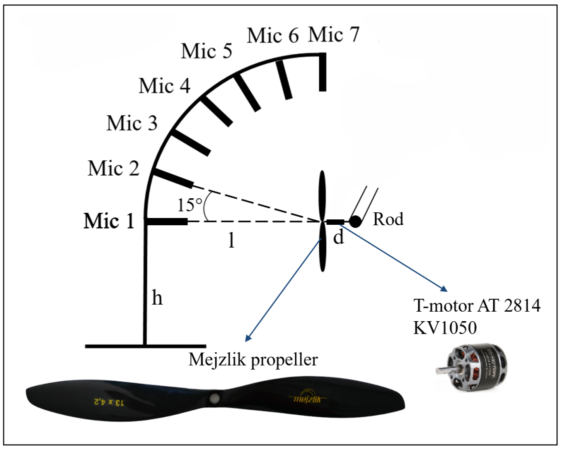

Figure 1. Propeller-strut experimental setup [3].

fers an advantage when dealing with struts of non-uniform cross-section, as it allows the structure to be divided into segments in accordance with a strip-theory approach for rotor noise prediction. Following Roger *et al.* [7], the expression for the upwash velocity w in the direction normal to the blade chord in the polar coordinates (r, ϕ) along the mean circle of the considered blade strip reads

$$\frac{w(r,\phi)}{U_z(r)\,a_c^2} = \sin\alpha\sin\alpha_0\,C_d(r,\phi) - \sin\alpha\cos\alpha_0\,D_d(r,\phi) + \cos\alpha\cos\alpha_0\,A_d(r,\phi) + \cos\alpha\sin\alpha_0\,B_d(r,\phi), \quad (1)$$

where

$$A_d(r,\phi) = \frac{(d^2 - r^2\sin^2\phi)}{(d^2 + r^2\sin^2\phi)^2};\, B_d(r,\phi) = \frac{2d\,r\sin\phi}{(d^2 + r^2\sin^2\phi)^2}$$
$$C_d(r,\phi) = \frac{\cos\phi(d^2 - r^2\sin^2\phi)}{(d^2 + r^2\sin^2\phi)^2};\, D_d(r,\phi) = \frac{d\,r\sin 2\phi}{(d^2 + r^2\sin^2\phi)^2}.$$

Here, α, and α_0 are the blade pitch angle and the flow swirl angle with respect to the rotor axis, respectively, while U_z is the propeller induced velocity. Since the strut only extends on half of the rotor disk plane, w is set equal to zero for $\phi \in [3\pi/2; \pi/2]$ [6]. Although w is stationary, the blade experiences periodic distortion in its reference frame, whose k-th harmonic can be computed through a Fourier series:

$$w_k(r) = \frac{1}{2\pi}\int_0^{2\pi} w(r,\phi)e^{ik\phi}d\phi, \quad k \geq 1. \quad (2)$$

The harmonics of lift per unit span can be subsequently derived from the coefficients w_k by means of Sears' theory [8], according to

$$L_k(r) = \pi\rho_0 c U_r w_k(r) \times \left[C(\sigma)(J_0(\mu) - iJ_1(\mu)) + \frac{i\sigma}{\mu}J_1(\mu)\right]^*, \quad (3)$$

with

$$\sigma = \frac{k\Omega c}{2U_r}; \quad \mu = \frac{ikc}{2r}e^{-i\gamma},$$

where U_r is the velocity at the blade section, C is the Theodorsen function, Ω is the rotational speed, c is the chord of the blade section, γ is the blade stagger angle, and * denotes the complex conjugate. L_k can now be decomposed into an axial and tangential force distribution and used in Hanson's model [9] to calculate the tonal far-field noise radiated at the m-th harmonic of the blade passing frequency (BPF). It is important to specify that the formulation of Hanson's model implemented in this paper is valid for acoustically compact cases, which limits the investigation presented here up to the 5th BPF harmonic.

2.3 Unsteady panel method

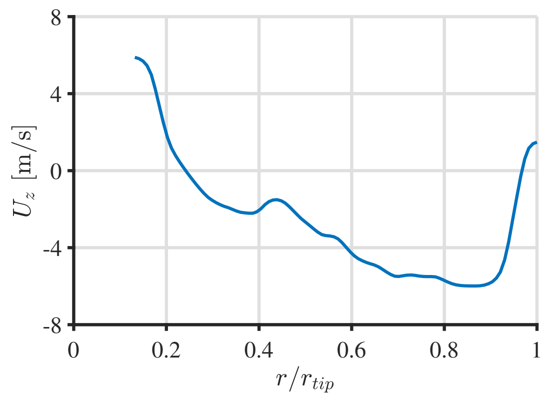

Figure 2. Induced velocity of the isolated propeller extracted 0.01 m from the rotor disk.

The model presented in Section 2.2 relies on the distributions of force per unit span along the propeller blade and the rotor-induced velocity, as well as the flow swirl angle. In the present study, these quantities are computed using the commercial unsteady panel method software FlightStream, which employs a surface vorticity approach augmented with a Prandtl–Glauert correction to account for compressibility effects and a viscous correction that couples the potential flow solution with a numerical boundary layer. The simulation comprises 2568 surface elements, with a mesh resolution of $2.1\,\mathrm{mm}$ at the blade tip and along the leading and trailing edges, and $4.2\,\mathrm{mm}$ elsewhere. The numerical calculation is performed for the isolated propeller spinning at $6000\,\mathrm{RPM}$, and the data are averaged over 8 propeller revolutions. An example of an induced velocity profile extracted downstream of the propeller is shown in Fig. 2, whereas an overview of the inflow distortion induced by the strut and experienced by the blades is illustrated in Fig. 3.

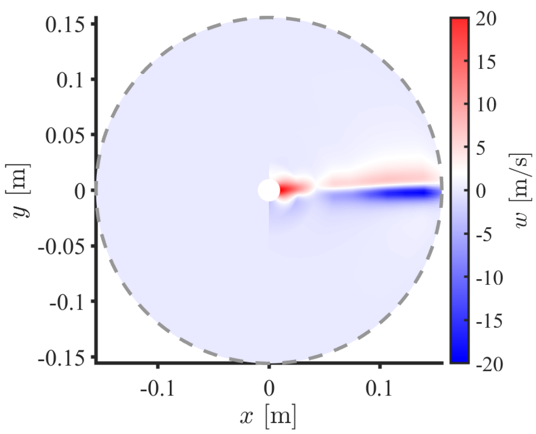

Figure 3. Upwash velocity distortion induced by the strut on the rotor disk.

3. RESULTS AND DISCUSSION

The analytical prediction of the potential interaction noise radiated by the propeller up to a frequency of $5 \times$ BPF is compared to the experimental results of Gallo *et al.* [3] in Fig. 4. The data refer to a radiation angle of $0°$ (see Fig. 1).

In general, the prediction results agree satisfactorily with the measurements for the considered tonal

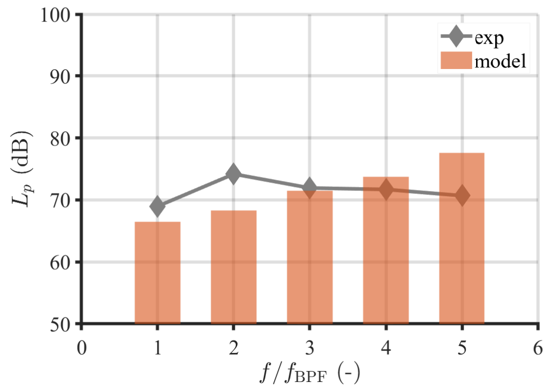

Figure 4. Analytical and experimental sound pressure levels computed with a reference pressure of $20\,\mu\mathrm{Pa}$ and referred to the main BPF and its harmonics.

peaks. The model successfully captures the increase in unsteady loading noise due to the inflow distortion, although the first harmonic is under-predicted. This effect may be due to the diffraction of rotor noise by the strut, which is not taken into account in the analytical model and has been shown to play a significant role at low frequencies [4, 5].

These results confirm that a reasonable potential interaction noise prediction can be achieved without relying on experiments or high-fidelity simulations. In particular, the use of an unsteady panel method, such as FlightStream, provides the input data required for the analytical model with sufficient accuracy and little computational effort, making it an attractive tool for the early-design and optimization stages of UAVs. Further developments of this research will involve the inclusion of sound diffraction effects in the noise prediction model, as well as the potential interaction noise that arises from the unsteady loading of the strut due to the passage of the blade [2].

4. ACKNOWLEDGMENTS

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