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Uncertainty quantification for the aeroacoustics of rotating blades in the time domain

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ABSTRACT

Aeroacoustics has received great attention in the past decade, owing to the ever stricter noise regulations. Despite the stochastic nature of most aeroacoustic systems, non-deterministic investigations in regards to computational aeroacoustics (CAA) are limited. In this paper, uncertainty quantification has been achieved for the noise propagation stage of hybrid CAA, and also on the noise prediction of a non-lifting helicopter rotor in hover. Analytical and computational fluid dynamics test cases have been analyzed, with uncertainties propagated through these systems using non-intrusive polynomial chaos methods. It is shown here that the source of the uncertainty in the noise is dominated by the major characteristic properties of the simulations, such as the mean flow Mach number and blade tip Mach number. Only at a low tip Mach number uncertainties in the blade thickness may contribute significantly to the noise uncertainty. Apart from this, it is seen to be unlikely that small uncertainties in the geometry, ambient conditions and observer properties will contribute significantly to the noise uncertainty. A peak pressure uncertainty of up to 20% is seen in the hovering helicopter test case, from small, realistic uncertainties. This highlights the importance of considering uncertainties in CAA investigations.

1. Introduction

Aeroacoustics refers to the sound generated from turbulent fluids, or aerodynamic forces interacting with surfaces, such as an airfoil. One approach to analyzing an aeroacoustic system is referred to as computational aeroacoustics (CAA). Hybrid CAA is a common and efficient approach that couples a computational fluid dynamics (CFD) solver with an acoustic prediction module (APM). The CFD solver identifies the noise sources, whereas the APM propagates the noise to the desired observers. Typically, deterministic inputs are utilized in both the identification and propagation of noise, despite the stochastic nature of the inputs, with few exceptions known to the author [1–5]. In contrast, non-deterministic CFD investigations have received significant interest in recent years [6–8].

Aeroacoustic performance of turbomachinery and aircrafts is now an essential component in design procedures, owing to the onset of strict noise regulations and requirements. With increasingly strict noise guidelines, the natural progression in the field is to move towards non-deterministic analyses of aeroacoustic systems. A non-deterministic approach to analyzing aeroacoustic systems aims to reduce the risk of obtaining performance levels lower than predicted. This is achieved by accounting for uncertainties present in realistic operating conditions, such as geometrical uncertainties from manufacturing tolerances, and uncertain physical model parameters. The opportunity to contribute to establishing a robust design framework for CAA provides the motivation for the present investigation.

The available literature in the field of UQ in CAA focuses on quite specific applications. Namely, there have been investigations regarding.

- a geometrical uncertainty in the rod-airfoil benchmark test case [1],
- inlet velocity profile uncertainties for the trailing-edge noise of a controlled-diffusion airfoil [2,5],
- uncertainty quantification on the self-noise prediction of a low-subsonic axial fan, including rotational speed and volume flow-rate uncertainties [3,5], and
- geometrical uncertainties in a coaxial contrarotating rotor [4].

The aim of this investigation is to generalize the uncertainties to focus on uncertainties present in most hybrid CAA investigations. Subsequently, the findings will be analyzed in a new application.

Due to the limited resources mentioned in the literature, the focus of this investigation is on one of the fundamental components of CAA. Namely, the first aim of this investigation is to analyze the sensitivities and uncertainties present in the noise propagation stage of CAA. [9]

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Here, the noise propagation is described by the Ffowcs Williams-Hawkings (FW-H) equation [10], which is one of the most commonly used approaches in the literature. The formulations utilized here were developed by Ghorbaniasl and Lacor [11], and can be interpreted as an extension of the solution of the FW-H equation of Farassat [12]. The uncertainty statistics and variable sensitivities are calculated using non-intrusive polynomial chaos expansion.

The investigation will include three test cases, consisting of two analytical noise sources, and one CFD-based test case. These test cases will be separated into two categories, representing two different commonly utilized configurations. The first configuration utilizes a stationary data surface (and source), and is considered in order to determine the uncertainties in noise that may be present simply due to uncertainties in the noise propagation region. The second configuration utilizes a moving data surface (and source), and is considered in order to determine the influence of uncertainties in a typical rotorcraft simulation regarding aeroacoustics.

First, an analytical noise source utilizing a stationary acoustic data surface will be considered. This test case represents a wind tunnel configuration, with a stationary source and a moving medium. Using a simple source will allow a focus on uncertainties only in the noise propagation region, which may be relevant for a wide variety of realistic test cases.

The second configuration of a moving data surface (and source) will be analysed through a CFD test case and an analytical test case. The CFD test case considered here is the uncertainties present in the aeroacoustics of a hovering helicopter rotor. This test case is chosen as the aeroacoustics of rotors has been studied extensively for the past decade [13], however it has not been considered in the context of UQ. Thus, this investigation will add a new application of UQ for CAA to the limited available literature. Furthermore, an analytical test case that represents a helicopter rotor in forward flight is considered. Here, the analytical results will be compared to the CFD results in order to analyze any similarities and differences, as well as further uncertain parameters are considered.

The layout of this paper is as follows. In Section 2, details of the acoustic propagation formulations and the UQ methodology are outlined. The test cases are presented in two separate sections; in Section 3 the stationary data surface test case is presented, followed by the moving data surface test cases in Section 4. Concluding remarks are given in Section 5.

2. Mathematical background

2.1. Noise propagation formulations

The acoustic propagation formulations utilised here have been proposed by Ghorbaniasl and Lacor [11]. The formulations can be interpreted as an extension of formulation 1 and 1A of Farassat [12], that are solutions to the FW-H equation [10]. The applicability of Farassat's formulations, and consequently the present formulations, for the prediction of aerodynamic noise of rotors has been discussed in [14]. The formulations are in the time domain, and suitable for the prediction of the sound field radiated by moving bodies in a uniform steady flow with arbitrary orientation.

The advantage of the hybrid CAA method lies in these equations; the equations are computationally efficient and accurate in propagating noise through a stationary or steady and uniform moving medium. In the propagation region between the noise sources and observers, a fine mesh in the CFD simulation is not required. This non-requirement affords great computational savings to the hybrid CAA method.

Here, only the final formulations utilised for the noise propagation stage of this study will be presented. For the full derivation of the formulations, one can refer to the publication of Ghorbaniasl and Lacor [11]. The basis of the noise propagation is the FW-H equation, which can be written in a form applicable to a moving medium solution as

$$\left[\frac{1}{c_0^2}\frac{D^2}{Dt^2}-\nabla^2\right]\{p'(\boldsymbol{x},t)H(f)\} = -\frac{\partial}{\partial x_i}[L_i\delta(f)] + \frac{D}{Dt}[Q\delta(f)] + \frac{\partial^2}{\partial x_i \partial x_j}[T_{ij}H(f)] \tag{1}$$

with the loading noise source term given by

$$L_i = \rho u_i[u_n-(v_n-U_{\infty n})] + P_{ij}\hat{n}_j \tag{2}$$

the thickness noise source term given by

$$Q = \rho[u_n-(v_n-U_{\infty n})] + \rho_0(v_n-U_{\infty n}) \tag{3}$$

and the Lighthill stress tensor (quadrupole noise source term) given by

$$T_{ij} = \rho u_i u_j + [(p-p_0)-c_0^2(\rho-\rho_0)]\delta_{ij}-\sigma_{ij} \tag{4}$$

Here, c_0 is the speed of sound, the time derivative is obtained as $D/Dt = \delta/\delta t + U_{\infty i}\delta/\delta x_i$ where $U_{\infty i}$ is the ith component of the mean flow velocity, and the pressure fluctuation p' is given at Cartesian coordinates $\boldsymbol{x}$ and time t. $H(f)$ is the Heaviside function (indicating a volume distribution of sources) and $\delta(f)$ is the Dirac delta function (indicating a surface distribution of sources). $f(\boldsymbol{x},t) = 0$ denotes a data surface that encloses the source region, where the surface may be coincident with a body (impermeable surface) or a permeable surface away from the body. $\hat{n}_i$ is a unit normal on the data surface pointing outward with respect to the source region ($f > 0$). Furthermore, u_i denotes the fluid velocity, P_{ij} is the compressive stress tensor, σ_{ij} is the viscous stress tensor, a subscript 0 indicates a fluid property at rest, and a subscript n denotes the local normal term of the data surface. Repeated indices follow Einstein's summation notation.

In order to reduce the computational requirements of the noise propagation methodology, the computationally expensive quadrupole noise source term is neglected. However, for an accurate prediction of transonic rotor noise that will be encountered, the contribution of the non-linear volume term is required. Hence, a permeable data surface that encloses the rotor blade, as well as the transonic fluid region, can be utilized. Consequently, the noise contribution from the quadrupole source term is represented by the remaining terms in the formulations.

The solution to Eq. (1) has been derived by Ghorbaniasl and Lacor [11], and is presented here in the most general form. This being a moving medium formulation that is valid for arbitrary body motion and geometry in a steady uniform flow with arbitrary orientation. The overall acoustic pressure is given by

$$p'(\boldsymbol{x},t,\boldsymbol{M}_\infty) = p_L'(\boldsymbol{x},t,\boldsymbol{M}_\infty) + p_T'(\boldsymbol{x},t,\boldsymbol{M}_\infty) \tag{5}$$

with the loading type noise contribution given by

$$\begin{aligned}4\pi p_L'(\boldsymbol{x},t,\boldsymbol{M}_\infty) = \frac{1}{c_0}\int_S\left[\frac{\dot{L}_R}{R^*(1-M_R)^2}\right]_e \mathrm{d}S \\ + \int_S\left[\frac{L_{R^*}-L_M}{R^{*2}(1-M_R)^2}\right]_e \mathrm{d}S + \frac{1}{c_0}\int_S\left[L_R\frac{R^*\dot{M}_R + c_0(M_{R^*}-M^2)}{R^{*2}(1-M_R)^3}\right]_e \mathrm{d}S \\ - \int_S\left[L_R\frac{M_{R^*}M_R + \gamma^2(M_{\infty M}^2-M_{R^*}^2)}{R^{*2}(1-M_R)^3}\right]_e \mathrm{d}S \\ - \int_S\left[\frac{L_{R^*}M_R + \gamma^2(M_{\infty M}M_{\infty L}-L_{R^*}M_{R^*})}{R^{*2}(1-M_R)^2}\right]_e \mathrm{d}S\end{aligned} \tag{6}$$