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Rotorcraft comprehensive code assessment for blade–vortex interaction conditions

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A B S T R A C T

The scope of this paper is the presentation of the computational methodologies applied in the comprehensive code for rotorcraft developed in the last years at Roma Tre University, along with the assessment of its prediction capabilities focused on flight conditions characterized by strong blade–vortex interactions. Boundary element method approaches are applied for both potential aerodynamics and aeroacoustics solutions, whereas a harmonic-balance/modal approach is used to integrate the rotor aeroelastic equations. The validation campaign of the comprehensive code has been carried out against the well-known HART II database, which is the outcome of a joint multi-national effort aimed at performing wind tunnel measurements of loads, blade deflection, wake shape and noise concerning a four-bladed model rotor in low-speed descent flight. Comparisons with numerical simulations available in the literature for the same test cases are also presented. It is shown that, with limited computational cost, the results provided by the Roma Tre aero-acousto-elastic solver are in good agreement with the experimental data, with a level of accuracy that is in line with the state-of-the-art predictions. The influence of the vortex core modeling on aerodynamic predictions and the influence of the inclusion of the fuselage shielding effect on aeroacoustic predictions are discussed.

1. Introduction

Comprehensive codes represent a fundamental support for the modern rotorcraft design, often aiming at the development of new concept configurations. Indeed, typically composed of the combination of engineering models for the description of rotor structural dynamics (for instance, through beam-like blade representations) and unsteady aerodynamics (for instance, through coupling two-dimensional section models with wake influence from free-wake approaches), these offer lower-cost, reduced-order computational simulations of rotorcraft with respect to higher-accuracy CFD/CSD solvers, thus allowing a fast determination of the trend of the influence of parameter variations on design and often physical insight, as well [1,2].

The HART II test campaign [3–5] is the best-known experimental campaign on helicopter rotor aerodynamics, aeroelasticity and aeroacoustics, performed at the DNW low-speed wind tunnel by a joint multinational effort of DLR (Germany), AFDD and NASA Langley (USA), Onera (France) and DNW (Netherlands), which provides an extensive database perfectly suited for comprehensive code validation purposes. Such database covers trim, elastic motion, aerodynamic loads, radiated noise, wake shape and flow velocity measurements for a four-bladed model rotor in low-speed descent flight.

It represents a challenging validation test in that this flight condition is difficult to simulate due to the complex interaction between rotor blades and wakes (Blade–Vortex Interaction, BVI) that takes place. The BVI phenomenon consists of the passage of a rotor blade through the vortices released by the other blades of the rotor. The aerodynamic effects produced by BVI are impulsive changes in blade loads that are particularly relevant in the blade span regions where the interaction occurs with the high-strength trailing tip vortices [6]. In turn, these give rise to high vibratory loads and external acoustic annoyance and hence have a great impact on cabin acoustic comfort, fatigue-life of structures, and on environmental and public acceptance of helicopters. For this reason, the availability of reliable tools for the prediction of BVI aerodynamic–aeroelastic–aeroacoustic effects is of paramount importance for new generation helicopter design (strongly aiming at reducing both maintenance costs and noise levels), and hence the development of solvers suited for this task has captured the interest of many rotorcraft researchers.

In the years following the test campaign, several research centers and universities, including those involved in HART II, had been

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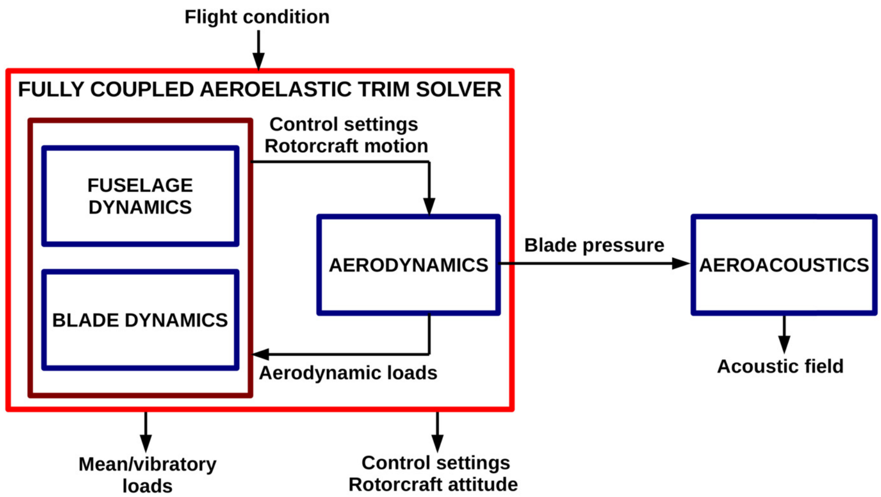

Fig. 1. Sketch of the aero-acousto-elastic tool.

using the outcomes of the project for the validation of numerical codes dedicated to helicopter rotor analysis. The available literature includes a large number of works concerning assessments based on the correlation with HART II data of both comprehensive rotor codes (see, for instance Refs. [1,2]) and CFD/CSD simulation approaches (see, for instance Refs. [7,8]). In particular, Refs. [1,2] provide also an overview of the methodologies used for the comprehensive codes developed by some international research centers and universities like, among the others, the U.S. Army Aeroflightdynamics Directorate (AFDD) and NASA team, Onera, DLR and the University of Maryland.

For instance, for the correlations presented in Refs. [1,2], the AFDD and NASA team have used the CAMRAD II code [9], with the structural dynamics described through nonlinear finite beam elements, and the aerodynamic loads derived by combining the modified Onera ELDIN theory for unsteady aerodynamics [9] with C81 standard lookup table. A free-wake model with multiple trailers is applied.

A five-step computational method has been applied by Onera, composed of rotor trim, wake prediction, wake roll-up model, blade pressure computation, and finally noise radiation. The HOST comprehensive code [10] provided the aeroelastic blade response, with the structural model based on rigid beam elements with lumped elastic properties, and the aerodynamic loads derived from a lifting line theory which combines 2-D airfoil tables with the Theodorsen theory for unsteady aerodynamics. Firstly, a prescribed-helical-wake code is used to find trim condition and blade deformations, and then a full span free wake model is applied to evaluate blade pressure.

The researchers of the German Aerospace Centre (DLR) have used the comprehensive code S4, whose structural model consists of a finite element method based on the Houbolt and Brooks linear formulation for (flapwise and chordwise) bending and torsion of nonuniform rotor blades [11]. A semi-empirical analytic formulation for the airfoil coefficients, based on the Leiss method [12] for unsteady motion with enhancements suited for BVI problems, is used for modeling aerodynamics. Fuselage effects are introduced by an analytical formulation based on potential flow theory. The Mangler and Squire wake model is used to evaluate performance and vibrations, while an extension of the Beddoes prescribed wake [13] is used for noise evaluation.

The UMARC comprehensive code [14] has been used by the University of Maryland. The aeroelastic solver consists of a finite element method based on a non-linear, second-order, isotropic, Euler–Bernoulli beam model of the blade, loosely coupled with a lifting-line aerodynamic formulation and a free-wake solver.

All these teams have evaluated radiated noise through integration of the Ffwocs Williams and Hawkings equation [15] provided by Farassat's formulation 1A [16].

This paper presents an outline of the computational methodologies implemented in the comprehensive code for aero-acousto-elastic analysis of helicopter rotors developed at Roma Tre University in the last twenty years, as well as the assessment of the quality of its predictions through comparison with HART II data. The Roma Tre University comprehensive code is based on a harmonic-balance/modal approach [17] for the integration of the rotor aeroelastic equations obtained by coupling a beam-like model for the structural dynamics of slender, nonuniform, twisted blades, undergoing moderate displacement (inspired to that introduced in Ref. [18]) with the aerodynamic loads given by a boundary element method (BEM) solver for the solution of potential flows with free-wake modeling [19,20]. The Farassat 1A integral formulation is applied for noise radiation.

In the next sections, first, the aeroelastic formulation (aerodynamics included) and the aeroacoustic formulation implemented in the computational tool are outlined, and then the corresponding aerodynamic outcomes, aeroelastic response and radiated noise are correlated with HART II measurements. These concern the tested four-bladed model rotor in low-speed, descent flight, for three different operating conditions: the baseline, in which only collective and cyclic trim controls are applied, and minimum-noise/minimum-vibration conditions obtained through application of suited 3/rev higher-harmonic controls (HHC).

2. The aero-acousto-elastic comprehensive code

The Roma Tre University comprehensive code includes the detailed aeroelastic response analysis of the blade within the trim procedure: the three-dimensional, potential-flow, rotor aerodynamics solver is fully coupled with a bending-torsion beam model of blade structural dynamics.

Hence, for a prescribed flight condition, the aeroelastic trim module provides pitch control settings and vehicle attitude, blade elastic response, mean and vibratory hub loads, as well as the pressure distributions required to define the noise sources in the aeroacoustic module (see the functional scheme of the code in Fig. 1).

The main solution modules combined in the comprehensive code are briefly outlined in the following.

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