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Analysis of vibrations of an innovative civil tiltrotor

M. Gennaretti [a,*], M. Molica Colella [a], G. Bernardini [a], C. Monteggia [b], E. Fosco [b], P. Ferro [b]

[a] Department of Engineering, University Roma Tre, Via della Vasca Navale 79, 00146 Rome, Italy
[b] AgustaWestland, Cascina Costa di Samarate, Varese, Italy

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ABSTRACT

This paper presents the assessment of vibratory levels of the tiltrotor ERICA. It is the result of a joint activity of University Roma Tre rotorcraft group and AgustaWestland, within the European Integrated Project NICETRIP. The loads transmitted by the wing to the fuselage are evaluated by a wing–pylon–proprotor aeroelastic model which takes into account the aerodynamic interaction effects dominated by the impact between proprotor wake and wing, as well as the mutual mechanical influence between elastic wing and proprotor blades. The aerodynamic analysis is based upon a boundary integral formulation suited for configurations where strong body–vortex interactions occur, while wing and blades structural dynamics is described through nonlinear beam-like models. A detailed FE model of the fuselage is used to define the transfer functions relating cabin vibrations to the vibratory loads transmitted by the wing. The numerical investigation will consider airplane- and helicopter-mode flight configurations, also examining some of the aeroelastic phenomena most affecting cabin vibrations.

1. Introduction

The aim of this paper is the analysis of the cabin vibration levels of tiltrotor ERICA in airplane-mode and helicopter-mode flights. It is the result of a collaborative work involving the University Roma Tre rotorcraft group and AgustaWestland, within activities of the European Integrated Project NICETRIP [17]. ERICA is a second generation tiltrotor under preliminary design by NICETRIP partners. Its specific and innovative features are the geometrically and aerodynamically advanced rotors optimized to allow both VTOL and STOL, and the tilting external half wing (tilting independently of the pylon) which significantly improves hovering performance (by decreasing the wake downwash on the wing) and enlarges both the flight envelope and the conversion corridor.

During the last fifty years there has been a continued effort to develop tiltrotor aircraft technology and make it suitable and safe both for military and civil use. The motivation for this durable commitment stays in the great potential that such a hybrid vehicle has: the chance to perform VTOL, high performance in hover flight condition and a helicopter-type maneuverability, together with high cruise speed and altitude in airplane configuration. Especially the civil transport aviation foresaw the environmental and economical benefits due to VTOL capability, which entails a minor need for infrastructures and a major public acceptance in terms of acoustic impact, due to a network based on vertiport stations for peer to peer transport. In order to reach a high diffusion of tiltrotors, the major issue of vibrations cannot be neglected, as it is strictly related to passengers comfort and fatigue life of the structures (and hence to maintenance costs). In addition, vibrations have a negative impact on functionality of onboard instruments, also making their reading difficult. Indeed, the development of reliable aeroelastic tools for the design of new generation tiltrotors is one of the goals towards which the rotorcraft community has focused much of its research activity (see, for instance, Refs. [11–13,16,18]). They need the application of accurate structural and aerodynamic models able to take into account the mechanical mutual influence between elastic wing and rotor blades, along with the aerodynamic interaction effects that are dominated by the interference between proprotor wake and wing. These requirements become critical in the analysis of tiltrotor ERICA, in that it is characterized by geometrically advanced, curved-axis, rotor blades and a complex three-element wing structure composed of a torque tube, an inner fixed wing and an outer movable wing.

Here, a two-step procedure for the evaluation of ERICA cabin vibrations is applied: first, the loads transmitted by the wing to the fuselage are predicted through the wing–pylon–proprotor aeroelastic model developed by University Roma Tre (UniRomaTre), and then the corresponding cabin vibrations are obtained by transfer functions derived by means of a detailed fuselage FE model developed by AgustaWestland.

The wing–pylon–proprotor aeroelastic model is obtained by coupling the nonlinear, integro-differential equations governing bending and torsion of wing and proprotor blades [8] with an unsteady aerodynamic solver based on the boundary integral formulation for potential flows presented in Ref. [5]. The structural dynamics of wing and proprotor blades is described by

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[*] Corresponding author. Tel.: +39 (06) 57333260; fax: +39 (06) 5593732.
E-mail address: m.gennaretti@uniroma3.it (M. Gennaretti).

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beam-like models valid for curved beam undergoing moderate deflections, with inclusion of wing–proprotor mechanical interaction [8]. The aerodynamic formulation is fully three-dimensional, is suited for capturing the effects of the strong aerodynamic interference between wing and proprotor, and allows the calculation of both wake distortion (free-wake analysis) and pressure field forcing the structure [5]. The Galerkin method, followed by a harmonic balance approach, is applied for the numerical integration of the resulting aeroelastic system [4,6].

A detailed structural model of the ERICA tiltrotor airframe, developed within the NICETRIP program and specifically tailored for dynamic analyses, is used as modal reference for tuning the aeroelastic model, as well as tool for identification of the transfer functions applied in the final cabin vibratory assessment. The employed FE model includes a detailed fuselage structure description, wing components and a first framework of the tail based on a preliminary aeroelastic analysis.

The numerical investigation presented has three main objectives: first, validation of the structural model of the ERICA wing–pylon–proprotor system through comparison with FEM commercial codes, then definition of the aeroelastic model more suited for evaluation of the vibratory loads transmitted by the wing to the fuselage and, finally, cabin vibratory assessment of the ERICA tiltrotor in hovering and airplane configurations.

2. Wing–pylon–proprotor aeroelastic model

The solution tool developed for the evaluation of the wing–pylon–proprotor vibratory loads consists of a dual-step process. First, the aeroelastic deformations of the wing–pylon–proprotor system are determined by a solver that combines the structural dynamics equations with a sectional, quasi-steady aerodynamic model corrected with the wake inflow [6]. The wake inflow is predicted by an unsteady, three-dimensional, boundary element solver for potential flows that is able to capture accurately the effects of the aerodynamic interference between propeller and wing, with inclusion of propeller-wake/wing impacts [5]. Then, once the aeroelastic response is achieved, the same boundary element solver is applied for the accurate evaluation of pressure distributions on proprotor and wing, and hence of the aerodynamic contribution to the unsteady loads transmitted to the fuselage. Note that, the adoption of this dual-step procedure is aimed at obtaining a good trade-off between efficiency of the wing–pylon–proprotor aeroelastic solver and accuracy in predicting the transmitted vibratory loads. It is based on the assumption (from experience) that the prediction of the high-frequency vibratory loads is significantly more affected by the accuracy of the used aerodynamic model than blade deflections. In the following, the aerodynamic and structural models, as well as the solution procedure used to evaluate the periodic response of the aeroelastic system are briefly outlined.

2.1. Aerodynamic boundary element formulation

The aerodynamics of wing–proprotor systems is strongly affected by the interactions occurring between proprotor blades and wing. The periodic blade passages close to the wing are an important source of oscillation in wing and blades pressure fields, but in several flight conditions the unsteady aerodynamic loads over the wing are dominated by the impact with proprotor wake vortices. For instance, this occurs in airplane-mode configurations where the wing portion located behind the propeller is massively impinged by the wake vorticity released by the rotor blades: this generates pressure fluctuations that, in turn, contribute to the vibratory loads transmitted to the airframe.

The analysis of aerodynamic problems involving the strong interaction between vortices and bodies is a complex task that requires the application of suited solvers. In this work, the unsteady wing–proprotor aerodynamics is analyzed through the boundary integral formulation for potential flows introduced in Ref. [5], and successfully applied and validated for the aerodynamic/aeroelastic/aeroacoustic analysis of helicopter rotor configurations experiencing strong blade/wake interactions [1], as well as for the vibratory loads and aeroelastic analysis of tiltrotors [8,15]. It is based on a decomposition of the potential, φ, into an incident potential, φ_I, and a scattered one, φ_S, such that $\varphi = \varphi_I + \varphi_S$. The scattered potential is generated by sources and doublets over the body surfaces, S_B, and by doublets over portions of the wakes that are very close to the trailing edges from which they emanated (near wakes, S_W^N). The incident potential is generated by doublets over the complementary wake regions that compose the far wakes, S_W^F (see Fig. 1). These are the wake portions that may come in contact with other body surfaces. The scattered potential is discontinuous across S_W^N, whereas the incident potential is discontinuous across S_W^F. As demonstrated in Ref. [5], the scattered potential is given by

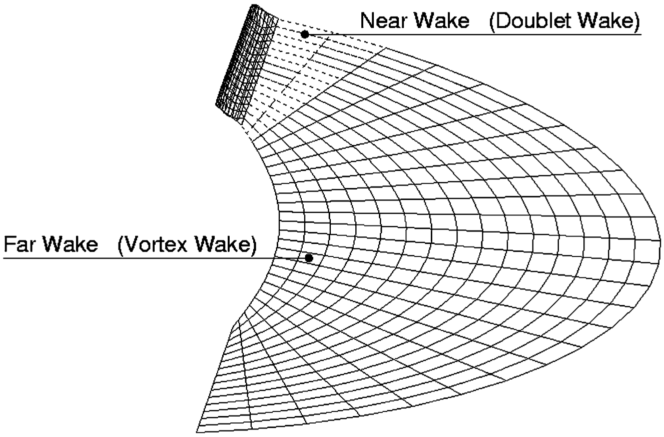

Fig. 1. Wake surface decomposition into near-wake and far-wake portions.

$$\varphi_S(\mathbf{x},t) = \int_{S_B} \left[G(\chi - \chi_I) - \varphi_S \frac{\partial G}{\partial n} \right] \mathrm{d}S(\mathbf{y}) - \int_{S_W^N} \Delta\varphi_S \frac{\partial G}{\partial n} \, \mathrm{d}S(\mathbf{y}) \tag{1}$$

where $G = -1/(4\pi \|\mathbf{y} - \mathbf{x}\|)$ is the unit source solution of the 3D Laplace equation, whereas $\Delta\varphi_S$ is the potential jump across the wake surface. The latter is known through application of the Kutta–Joukowski condition followed by convection of the trailing edge potential discontinuity, that yield $\Delta\varphi_S(\mathbf{y}_W, t) = \Delta\varphi_S(\mathbf{y}_W^{TE}, t - \tau)$, with $t - \tau$ denoting the instant when the wake material point currently in $\mathbf{y}_W \in S_W^N \cup S_W^F$ emanated from the trailing edge point $\mathbf{y}_W^{TE}$ [7]. In addition, $\chi = \mathbf{v} \cdot \mathbf{n}$ and $\chi_I = \mathbf{u}_I \cdot \mathbf{n}$, where $\mathbf{v}$ denotes the body velocity due to rigid and elastic motion, $\mathbf{u}_I$ denotes the velocity induced by the far wake, while $\mathbf{n}$ represents the outward surface unit normal vector.

Eq. (1) is solved numerically by a zeroth order, boundary element method: S_B and S_W^N are divided into quadrilateral panels, φ_S, χ, χ_I and $\Delta\varphi_S$ are assumed to be piecewise constant and the equation is imposed to be satisfied at the center of each body element (collocation method). Similarly, in order to evaluate the induced velocity field, $\mathbf{u}_I$, also the far wake surface is discretized into M quadrilateral panels with piecewise constant potential jump. Indeed, recalling the vortex-doublet equivalence, it yields [5]

$$\mathbf{u}_I(\mathbf{x},t) \approx -\sum_{m=1}^{M} \Delta\varphi_S\big(\mathbf{y}_{W_m}^{TE}, t - \tau_m\big) \int_{C_m} \nabla_{\mathbf{x}} G \times \mathrm{d}\mathbf{y} \tag{2}$$