FIRST-PRINCIPLES FREE-VORTEX WAKE ANALYSIS FOR HELICOPTERS AND TILTROTORS

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ABSTRACT

The development of high-fidelity models of the rotor wake is an issue of continuing, critical importance in the design of new helicopters and tiltrotors, as well as in the understanding of a wide range of problems in rotor aerodynamics, dynamics, and acoustics. This paper outlines a set of interrelated modeling methods developed over the last two decades that have yielded a unified free wake model suitable for the full range of current helicopter and tiltrotor designs. These methods, now embedded in the CHARM comprehensive analysis of rotorcraft aeromechanics, can produce high fidelity predictions of rotor performance, unsteady airloads, and noise as well as accurate predictions of rotor-induced flow fields and airframe loads over a wide range of aircraft configurations. An important feature of the wake modeling described here is that it is a first-principles analysis completely free of user-selected empirical parameters. This allows the model to be used as a design tool for analyzing future rotorcraft concepts as well as in flight simulations where wake characteristics vary with the flight condition. This paper describes the key technical elements of this model and provides numerous examples of its validation against challenging data sets for a wide range of rotorcraft applications. Results include new correlations with Tilt Rotor Aeroacoustics Model (TRAM) airloads measurements establishing that both helicopter and tiltrotor aeromechanics phenomena can be predicted accurately without adjusting the wake model.

INTRODUCTION

It has long been recognized that accurate modeling of the rotor wake is essential for effective aeromechanics analysis. It has also been found that "free wake" methods, those that allow vortex wake elements to convect and distort freely according to the governing physical laws, are necessary for many important applications, (see Ref. 1 for a good discussion). These critical applications include prediction of hover and forward flight performance, (e.g., Refs. 2, 3); blade dynamics, (e.g., Refs. 4-6); flight dynamics, (e.g., Refs. 7, 8); vibratory airloads and noise (e.g., Refs. 9, 10); and interactional aerodynamics, control and stability, (e.g., Refs. 11, 12).

Since the predominant flow physics beyond a region of roughly one chord from the rotor blade is well characterized by potential flow, free-vortex methods have held great promise for providing accurate aeromechanics tools. With this in mind, several researchers began developing free-vortex wake models for helicopter rotors in the 70's and 80's, (e.g., Refs. 3, 13-17), with numerous advancements and improvements incorporated in the subsequent decades, (e.g., Refs. 18-26 to name just a few). A good overview of the overall methodology and modeling issues associated with free-vortex methods can be found in Ref. 27.

Free-vortex wake models typically consist of one or more vortex filaments trailing from each rotor blade freely distorting in a Lagrangian sense based on the local flow velocity. The strength of these vortices is directly proportional to the gradient of bound circulation on the rotor blades. The wake-induced velocity is determined by integrating the Biot-Savart law along the length of each vortex filament. A smoothing core is required to avoid infinite induced velocity on the vortex filaments. This smoothing core – typically parameterized by a "core radius" – in general seeks to mimic the behavior produced by the viscous core that is observed in the physical flow field.

Despite the great promise of free wake approaches, it soon became evident that many important predictions are highly sensitive to the choice of input parameters, most notably the vortex core radius. Standard practice has become assigning this core radius either based on empirical measurements and core properties or as necessary to match a given data set. This approach, (among other factors), has greatly impaired the ability of free wake methods as design tools, since the true core radius in the vicinity of the rotor varies greatly depending on the blade planform, flight condition, and azimuthal variation of blade loads. In hover, performance predictions are extremely sensitive to the

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