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Research paper

# Helicopter nonlinear aerodynamics modelling using VehicleSim

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ABSTRACT

This work describes a model developed to analyze the aerodynamic loads on a helicopter model on conventional configuration implemented with VehicleSim, a multibody software specialized in modelling mechanical systems composed by rigid bodies. The rotors are articulated and the main rotor implementation takes into account flap, lag and feather degrees of freedom for each of the equispaced blades as well as their dynamic couplings. This article presents an aerodynamic model that allows to simulate hover, climb, descent and forward flight as well as trajectories under the action of several aerodynamics loads. The aerodynamic model has been built up using blade element theory. All the dynamics, aerodynamic forces and control action are embedded in a single code, being this an advantage as the compilation time is greatly reduced. The software used in this work, VehicleSim does not need external connection to other software. This new tool may be used to develop robust control methods. The nonlinear equations of the system which can be very complex, are obtained, in particular, this article presents the equations for flap and lag degrees of freedom in hover flight. The control approach used in here consists of PID controllers (proportional, integral, derivative), which allow to use VehicleSim command exclusively to simulate several helicopter flight conditions. The results obtained are shown to agree with the expected behaviour.



## 1. Introduction

Full helicopter behaviour modelling is still a far fetched task as the aerodynamic environment that surrounds a helicopter is highly complex and taking into account the nonlinear dynamics that would represent a realistic and high fidelity helicopter model is a cumbersome task. The availability of simplified aerodynamic models for the response of the rotors aerodynamic loads in the control inputs is very helpful for robust control design.

In helicopter study, experimental data related to several flight conditions are significantly limited due to practical and economical reasons. This difficulty can be overcome using simulations in order to evaluate the applicability of a model identification scheme and to validate the test of robust control systems for the helicopter. The design codes should cover a wide range of rotorcraft configurations and rotor types, as well as dealing with the entire rotorcraft. The code should be flexible to adapt or extend new problems for all operating conditions and all helicopter configurations. The main goal of this paper is to present a first approach to helicopter modelling using VehicleSim, this sets the path to build up a complete rotorcraft model that takes into account the nonlinear dynamics and aerodynamics couplings.

Since the 1990's, several multibody dynamics software have been implemented and developed in the rotorcraft field. The multibody dynamics approach is needed in order to deal with complex mechanisms with great variety of shapes as the mechanisms found in rotors. For example, a simulation program for the dynamics of the main rotor of the AGUSTA A109c helicopter was developed (based on Automatic Dynamic Analysis of Mechanical Systems (ADAMS) general-purpose multibody simulation code). Due to the complexity of the dynamics and aerodynamics of the helicopter rotor, extensive use was made of particular features of this code, such as the possibility to import data from finite elements codes in order to model flexible bodies, and to link user-written subroutines to the main body of the program for the simulation of applied aerodynamic loads and nonmechanical phenomena [1].

Comprehensive Analytical Model of Rotorcraft Aerodynamics and Dynamics (CAMRAD) II was used to research performance enhancements to large rotorcraft. The rotor models were allocated to be as basic as possible to separate the effects of each advanced concept. The rotors contained rigid blades, rigid control systems and they were shaped as isolated rotors in a wind tunnel. The tilt rotor was implemented as a single rotor. The effects of improved airfoils and active controls were studied. Airfoils with higher maximum lift and with reduced drag were also analyzed. The results presented an improvement in the maximum lift capability for the helicopter, however, they showed a large improvement for the tilt rotor [2].

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DYMORE was used to predict the aeroelastic response and stability of the helicopter rotors [3]. However, this software provides a simple two-dimensional unsteady airfoil theory and a finite state dynamic inflow model to calculate the inflow velocity field over the rotor [4,5]. On the other hand, modelling and control of a laboratory helicopter was carried out by Zupancic et al. [6] using Dymola/Modelica environment. The model consisted of three inputs, the corresponding voltages drove to the rotors and the servomotor. The function of the last one, was to position the weight. So, the model displayed a nonlinear multivariable system. Two different areas such as mechanical systems and control systems were combined as a multi-domain approach. The overall scheme of the model consists of the coordinate system definition, the stand model, the helicopter body, the tail and main rotor model and the controller with two reference signals for the pitch and the rotation angle. The control system was designed and optimised using the Matlab/Simulink environment. In Simulink the overall mechanical model was presented with the Dymola block.

In addition to this, MBDyn (MultiBody Dynamics) is a multibody code that provides a framework for integrated simulation of complex multi-physics problems. It has been used in [7] to implement a nonlinear multibody aeroelastic model of the SA330 Puma helicopter. The main rotor was modelled using the multibody approach. The relative motion between rigid bodies were described using kinematically exact constraints, applied by means of Lagrange multipliers, allowing to describe the relative motion between rigid bodies; structural dynamics were dealt with by using a finite element approach, based on an original formulation of Ghiringhelli et al. [8], while inertia was represented by lumping masses at the nodes. A simple inflow model based on momentum theory was used on the blade element (2D) aerodynamics. The results presented the soundness of the co-simulation approach, which could provide a tool to add some frictionless and frictional contact capabilities to multibody formulations, in this manner, it is not necessary the complete reformulation of the dynamics in a nonsmooth dynamics simulation framework.

Multibody software packages can be used for control purposes, in fact, Masarati [9] used the general multibody solver MBDyn, to present an algorithm for the real time solution of inverse kinematics and inverse dynamics of redundant manipulators formulated in redundant coordinates. In order to show the capability of the approach, three inverse kinematics problems were displayed such as three link arm, feedforward control of a PA10 like robot, feedforward and feedback control of a bioinspired robot. They allowed to estimate positions, velocities, and accelerations. Furthermore, an inverse dynamics problem that calculates feedforward generalized driving forces was also considered. Shen et al. [10] showed the development and validation of a stiff-inplane tiltrotor model using two multibody helicopter codes, the two dynamics codes used DYMORE and MBDyn. The dynamics models included the gimballed hub, rotor blades, feather links, swashplate, conversion actuators which were linked to the pylon, and the elastic wing. The rotating system was implemented with a clamped blade model. It consisted of a clamped beam. This clamped blade model was connected to the gimbal hub through a flexbeam, torque tube and control system (feather link, feather horn and swashplate), allowing to build the single blade model. The experimental data derived, in the wind tunnel and in the ground vibration tests, were used to validate the models. In addition to this, these models were used to obtain the whirl-flutter stability boundary. The results provided good agreement with the experimental measurements.

In [11], the author derived a helicopter mathematical model consisting of main and tail rotors, with six nonlinear equations. Some simulations were carried out under specific flight conditions and each induced velocities were also used according to these. Perturbations such as wind crossing or vibration engine were considered in order to build up a robust model. Simulations of lateral and ascend flight could be found using the model. This approach was suitable to simulate and to control a helicopter, as a result the model could be used to control autonomous radio helicopter or automatic helicopter pilot as well as to build a flying computer training program. Nowadays, the industry of miniaturized is focused in low power embedded systems as they provide accelerated 3D graphics that allow complex visualization for embedded applications. Frantis et al. [12] dealt with development of a simple flight model suitable to be implemented as a C++ algorithm for real time usage. The model was used for embedded flight simulator in a synthetic vision system. Siva et al. [13] studied the effect of uncertainties on performance predictions of a helicopter. They considered uncertain variables, the main rotor angular velocity, main rotor radius, air density, blade chord and blade profile drag coefficient. The propagation of these uncertainties in the performance parameters such as thrust coefficient, induced velocity amongst others, were studied. In this work, different flight regimes and their aerodynamic environment were considered.

Blade element theory is commonly used in helicopter flight simulation models. The theory consists on dividing a blade into various blade elements orientated in the chord wise direction; each element is aerodynamically independent from the neighbouring elements. This allows the use of 2D aerofoil characteristics in order to determine the forces and moments produced on the blade [14]. Other approaches can also be considered such as Brown's Vorticity Transport Model (VTM) [15] that allows to analyse aerodynamic and dynamic performance on several rotor helicopter configurations under both steady and manoeuvring flight conditions. The aerodynamical module uses a computational solution of the Navier-Stokes equations. It is expressed in vorticity velocity form in order to simulate the evolution of the wake of a helicopter rotor. The key to the method is the use of a Computational Fluid Dynamics (CFD) type vorticity conserving algorithm to evolve the governing equations through time. Standard CFD methods that rely on a primitive variable formulation of the Navier-Stokes equations, that is, in terms of velocity and pressure, are susceptible to excessive numerical dissipation of vorticity [16]. CFD is an extensive method of research, this approaches can solve issues such as rotor wake prediction, compressible aerodynamics, interaction problems, amongst others [17,18].

The aerodynamic helicopter model presented in this paper, is a new implementation that aims to connect the necessity of a stable rotorcraft able to operate in several flight conditions to the robust control community. This allows to test the approach presented by Carrillo-Ahumada et al. [19], in this work the authors improved the performance of a helicopter with two degrees of freedom by using the tuning of Pareto-optimal robust controllers. The tuning procedure was established on the simultaneous minimization of the integral of square sum of errors and the integral of square sum of control action. Thus, the helicopter model presented in this article, provides a new platform to validate the tuning procedure as a reliable tool. On the other hand, a controller based on eigenstructure assignment could be applied to this model [20] too, this approach was applied to an unmanned helicopter and the flexibility of eigenstructure assignment should improve the rotorcraft response if a recurrent algorithm was used to select new eigenvalues and/or eigenvectors for decoupling purposes. This technique proved its efficiency for that type of system.

This work simulates the nonlinear dynamics coupling and the rotors' aerodynamic loads in a single code, being an advantage with respect to the work presented by Bertogalli et al. [1], Zupancic et al. [6]. In addition, it allows some additional advantages such as the reduction of the compilation time and portability. Furthermore, this work goes in the line of Frantis et al. [12], being this an alternative to embedded codes in the aeronautical field.