ADVANCED HELICOPTER FLIGHT SIMULATION WITH CONTROLLER IN THE LOOP

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Abstract

In this paper a simulation tool for flexible rotorcraft and its application to helicopter vibration control is presented. An integrated aerodynamic, structural and control simulation environment based on proven engineering tools in computational fluid dynamics, multibody simulation and control design is developed. The simulation tool allows aeroelastic analysis and controller in the loop simulation of flexible rotorcraft. Due to the modular approach the accuracy level of the structural simulation can be adapted to the required analysis task and the aerodynamic model can be choosen according to the aerodynamic phenomena which have to be considered. A model of a BO105 rotor equipped with an individual blade root control system is set up. Results of a fully coupled simulation comprising structure, aerodynamics and control are presented.

1 Introduction

Rotorcraft applications are widely spread in aeronautics nowadays. Their unique abilities in transport, surveillance and air rescue have ensured their great success in modern society. Typical problems regarding passenger comfort and broad acceptance lie in the inherent high vibration and noise level due to the rotating lift producing mechanism. As a result of vibration all structural parts related to the rotating mechanical system have to be inspected and replaced in rather short time intervals. Due to high maintenance cost but also to passenger comfort it is of great interest to further reduce vibration and interior noise. Furthermore stringent restrictions on noise level for flying in densely populated areas require further reduction of emitted sound pressure level.

Much research has been conducted to tackle these problems. Promising new methods in vibration reduction have been introduced by using active control strategies[1] like higher harmonic control (HHC),[2] individual bade control (IBC),[3, 4, 5] the actively controlled trailing edge flap (ACF)[6] and active control of structural response (ACSR).[7] Regarding the noise problem, control studies have been focussing on the helicopter interior noise-field,[8] whereas the area of noise emission research is concentrating on analysis and prediction of sound pressure experienced in the neighbourhood of the rotorcraft.[9]

Through advances in smart structure technology the active control strategies just described become more likely to be put into practice. For assessing the benefit of smart structures in rotorcraft control and aerodynamics very accurate models of the structure-fluid interaction are in demand.

The present work demonstrates the application of a simulation environment comprising structural and aerodynamic models[10] to the field of helicopter vibration simulation and analysis. The accuracy level of both the structural and the aerodynamic model is modularly adaptable as required by the analysis to be performed (e.g. flight simulation or aeroelastic analysis). For the aerodynamics it can be chosen eighter a 'fast' blade element inflow model[11] with aerodynamic coefficients tuned by flight test result,[12] a vortex lattice method (2D discretization)[13] or a 3D Euler method.[15]

The overall simulation model is based on a general purpose multibody code SIMPACK,[17] developed at DLR (German Aerospace Research Center) allowing bodies to be modelled as rigid or flexible. Thus on the structural side there is a choice between a purely rigid body model, elastic beam models for the rotor blades and arbitrary FEM models for both blades and fuselage. Force elements are used to model applied forces and torques such as aerodynamic loads, or interaction between the bodies, resulting from dampers, springs, actuators or contact.

Computer oriented procedures called 'multibody formalisms' are used to generate the equations of motion for the system in a general form. Here, the equations of motion are provided in state space representation, i.e. a minimal set of first order (kinematical and dynamical) nonlinear differential equations, in which the constraint forces have been eliminated.[17]

To integrate the controller, the simulation engine of MATRIXx/SystemBuild is linked via TCP/IP interface. In case of structural modeling based on FEM, the FE model is included in a preprocessing step. Complex aerodynamic models are provided by co-simulation via TCP/IP standard interfaces to CFD codes developed at the Institute of Aerodynamics at University of Stuttgart.[13, 15 and 16]

Other examples of multibody modeling in helicopter simulation can be found in[24–26] with particular focus on rotor dynamics. An application of MBS simulation to the identification of controller design models is reported in *Bertogalli et al.*[27] All these works are mainly based on analytical inflow models as reviewed in,[28] which of course is reasonable and sufficient for real-time simulation purposes. Usage of MBS in aeroelastic analysis with basic aerodynamic wake modeling is introduced by *Mantegazza et al.*[29–31]

In this paper a MBS model of a BO105 helicopter will be developed. The simulation tool is set up to model the BO105 rotor equipped with individual blade root control (IBRC) actuators. Full scale wind tunnel investigations[32] and flight tests[33] have been successfully conducted with this helicopter. In the rotor system the rigid pitch link rods are replaced by hydraulic actuators. This allows an individual control of the pitch angle of each blade superimposed to the conventional control via swashplate.

Results of a rotor dynamics simulation comprising structure, aerodynamics and control from the MATRIXx/SystemBuild environment are presented.

2 Coupled Simulation Environment based on Multibody Simulation Code

2.1 Multibody Simulation

Multibody systems (MBS) are models of technical systems consisting of rigid or deformable bodies. The bodies contain mass, inertia and geometrical properties. They are connected to each other or to the environment by means of joints and force interaction. The environment may be an arbitrary moving reference frame or just inertial fixed. Joints denote the restriction of each body to move with atmost 6 degrees of freedom to each other depending on restrictions defined by neighbouring bodies. Force interaction denotes the force interference of such bodies or the environment, e.g. gravity or aerodynamic drag. A general multibody system, as considered here, is shown in figure 1. A method to provide differential equations to describe the MBS behaviour is called a multibody formalism.

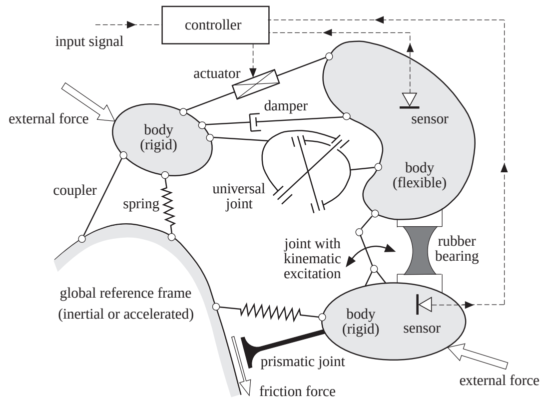

Figure 1: General Multibody System

Multibody formalisms are computer algorithms to generate automatically the equations of motion for systems of the general form shown in figure 1. These are based on data, which describe the system elements and system topology, i.e. the way the nodes on the system bodies are connected by force elements and joints. Two groups of formalisms may be distinguished resulting in basically different types of equations of motion. The first group yields the Lagrangian equations of type 1, which contain the unknown generalized constraint forces in terms of Lagrangian multipliers. These differential equations are accompanied by a set of algebraic constraint equations. The resulting representation of the system motion is sometimes called the descriptor form of the equations of motion. It is simple to generate, but it requires the numerical solution of differential-algebraic equations.[18] By contrast, the second group of formalisms provides the state space representation of motion, i.e. a minimal set of first order (kinematical and dynamical) differential equations, in which the constraint forces have been eliminated. Numerical methods for solving these equations are often considered to be more mature with respect to computational efficiency. The starting point for the development of both types of formalisms are the equations describing the motion of a representative system body i, acted upon by the applied external and internal forces and torques due to the force elements and the unknown internal joint forces and torques between the system bodies.

2.2 Kinematics and Kinetics

The motion of an arbitrary body is described by its position ($\mathbf{x_I}$) and its velocity ($\mathbf{x_{II}}$) vector:

$$\mathbf{x_I} = \begin{bmatrix} \mathbf{r} \\ \alpha \\ \mathbf{q} \end{bmatrix} \qquad \mathbf{x_{II}} = \begin{bmatrix} \mathbf{v} \\ \omega \\ \dot{\mathbf{q}} \end{bmatrix} \tag{1}$$

These vectors satisfy the kinematic equations of motion

$$\dot{\mathbf{x}}_\mathbf{I} = \mathbf{X}(\mathbf{x_I}) \cdot \mathbf{x_{II}} \ , \quad \mathbf{X}(\mathbf{x_I}) = \begin{bmatrix} \mathbf{E} & \tilde{\mathbf{r}} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{ang} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & \mathbf{E} \end{bmatrix} \tag{2}$$

which exhibit the linear dependency of the derivatives of the position variables with respect to time on the velocity variables.

The general intend of formulating equations of motion in computational dynamics is not to find nicely problem-adopted equations, moreover it is aimed to formulate the algorithm in a way to scope with a broad variety of model classes in regard to computational efficiency.

Based on Hamilton's principle one yields:

$$\mathbf{M}\dot{\mathbf{x}}_{II} = \mathbf{h_a} + \mathbf{h_c} \tag{3}$$

The matrices $\mathbf{M}$, $\mathbf{h_a}$ and $\mathbf{h_c}$ denote the generalized mass matrix, the applied and constraint forces respectively. The applied force may be separated into:

$$\mathbf{h_a} = \mathbf{h}_\omega + \mathbf{h_g} + \mathbf{h_e} + \mathbf{h_p} + \mathbf{h_f} \tag{4}$$

In this expression $\mathbf{h}_\omega$ are generalized inertia forces due to angular velocity ω of the body reference frame motion. They are as well as the gravitational forces $\mathbf{h_g}$ distributed over the body volume V_0. The generalized internal forces $\mathbf{h_e}$ result from elastic body deformation whereas $\mathbf{h_p}$ is due to external surface forces. The last term $\mathbf{h_f}$ represents the forces and moments applied by force elements attached to the body, they are known functions of the system states and possibly additional quantities as shown in figure 1. Forces arising from joints are unknown, they yield the constraint forces. The generalized mass matrix M can be partitioned according to the $6 + n_e$ velocity variables $\mathbf{x_{II}}$:

$$\mathbf{M}(\mathbf{x_I}) = \begin{bmatrix} m\mathbf{E} & \dots & {\scriptstyle sym.} \\ m\tilde{\mathbf{c}} & \mathbf{I} & \dots \\ \mathbf{M}_{et} & \mathbf{M}_{er} & \mathbf{M}_{ee} \end{bmatrix} \tag{5}$$

The scalar m represents the body mass, matrices c and I stand for the distance vector of centre of mass from body reference frame and the inertia tensor of the deformed body respectively. The sub-matrix $\mathbf{M_{ee}}$ contains the generalized masses with respect to the modal coordinates q, arising from Ritz approximation accounting for elastic bodies. The matrices $\mathbf{M_{et}}$ and $\mathbf{M_{er}}$ contain the coupling terms of reference motion and deformation, respectively.

The separation of body motion into reference motion and deformation leads to a corresponding separation of linear and angular momentum vector for the body. All of the generalized forces and masses in equation (3) are algebraic expressions, containing the state variables (1) and integrals over the shape functions.[19]

Having derived kinematic and kinetic equations for one body benefit is drawn of the general tree structure of mechanical systems. Thus the equations can be applied to each body coupled by constraint equation restricting relative motion among them. Systems with kinematic loops are transformed to tree structured systems. The loop closing constraints, obtained as algebraic equations, form the Differential Algebraic Equations (DAE). Special adopted solvers are developed to scope these problems.[18]

Application examples as considered here appear to be of tree structure. The implemented recursive equation set up scheme yields the nonlinear equations of motion in explicit form

$$\dot{\mathbf{x}} = f(\mathbf{x}, \mathbf{u}, t) \tag{6}$$

where $\dot{\mathbf{x}}$ are the generalized states (position and velocity) of the system. The vector $\mathbf{u}$ denotes inputs to the system. Note the benefit in computational efficiency of the so called $O(n)$ formalism to generate explicit ODE by avoiding inversion of the overall system mass matrix[20] (processing time increases linear with the number of bodies).

2.3 MBS Interfaces via IPC Coupling

Adressing multi-field problems such as the structure-fluid coupling of elastic aircraft, the underlying MBS code SIMPACK offers the possibility to interfere when creating the equation of motion (6). This can be achieved by means of so called User Routines allowing for coding of user defined functionality. Regarding equation (4), this corresponds to introduce user defined forces $\mathbf{h_f}(\mathbf{x}, \mathbf{u}, \mathbf{t})$ to the system. At the same time the full state vector $\mathbf{x}$ is made available. These are exactly the values needed to match the boundary conditions of each field considered.

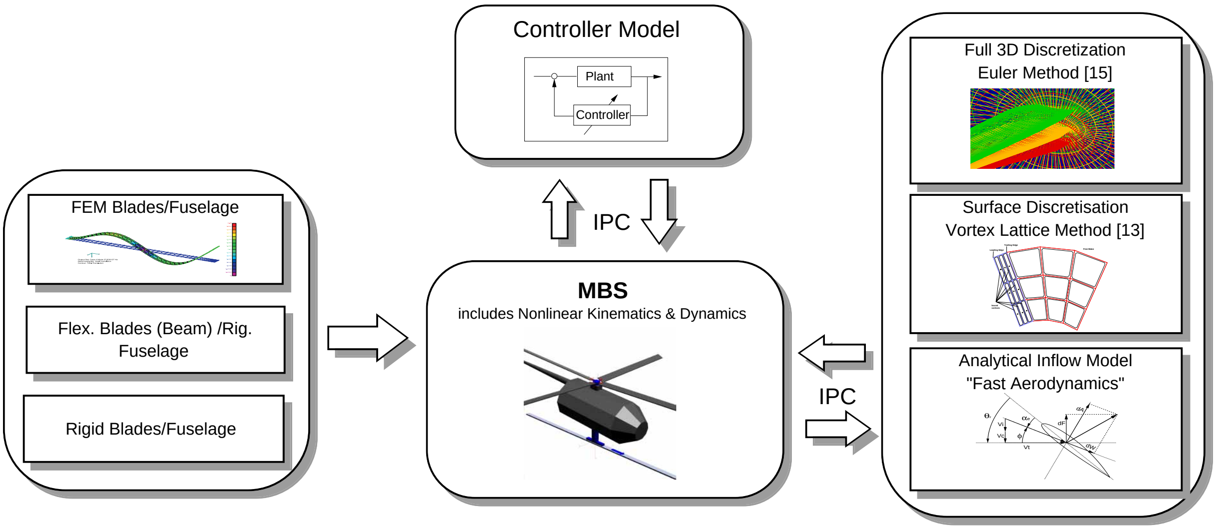

Figure 2: Modular Modeling and IPC Simulation Interfaces

The mechanical system, defined by a set of rigid and flexible bodies is submitted to loads by nodal forces and torques to approximate the continuous distributed fluid forces. The fluid field with its common contact areas to the surface of the bodies has to fulfill the kinematic boundary conditions given by the body surface position and velocities. This requires the choice of fluid-structure contact surfaces (wet surface) for which a nodal discretization has to be done. For these nodes, kinematics are made available to the fluid solver, which calculates the resultant nodal force and torque load.

Considering a typically coupled problem such as an aircraft wing in free flow conditions, the discretization and solving of the fluid grid requires a far larger amount of processor power and memory consumption than the participated structural solver. For this reason, the Panel- and Euler - fluid solvers have to run on high performance multiprocessor computers to guarantee results in reasonable time. The MBS code as the structural solver requires about ten percent of overall simulation time and runs easily on standard Unix or PC workstations. To enable necessary software communication, an Inter Process Communication (IPC) scheme had been developed and set up.[16] It enables platform independent data communication via Internet. Another important interface is the possibility of having linked the MBS code to control system analysis programs. A far simpler case of a coupled multi-field problem is that of controller-MBS interference, some output or state quantities of the mechanical system are measured and feed back by a mostly linear feedback law to generate actuator signals. An important issue is the possible introduction of algebraic loops into the overall simulation by direct-feed-through terms. This has to be accounted for choosing a numerical solver algorithm. For generality and simplicity of the overall simulation scheme, the same interface method via IPC had been used to link control loops established in MATRIXx/SystemBuild.

2.4 Modular structural modeling

Depending on the application example considered different level of complexity are possible (see figure 2). The simplest one is the purly rigid case. All bodies in the helicopter model are selected to be rigid. This might be sufficient for trim calculations and necessary when using the overall simulation for real time simulation purpose. The next stage of complexity is given by selection of flexible blades. Hereby either Euler-Bernoulli beams are available or arbitrary complex beam or shell models for refined FE-modeling of the blades. The flexible bodies are hereby set in a preprocessing step, in case of FE modeling a modal analysis has to be performed. The highest level of model complexity is given by full FE modeling of both the rotor blades and the fuselage. This might be necessary for investigating vibration level inside the cabin at the pilots seat or at locations of sensitive payload.

Methods of modeling flexible bodies in a multibody system have been reviewed in Shabana.[21] Here the floating frame of reference formulation will be used. In this methodology the motion of a flexible body is subdivided into a reference motion and a deformation. The former may be described as the motion of a body reference frame, whereas deformation is the motion of the points of the body with respect to its reference frame. Introducing a Ritz approximation, one obtains a representation of the body deformation by a reduced set of modal variables.[22]

The deformations are assumed to be small which holds for many applications. Simplifications due to linearization can be applied to increase computational efficiency. In case of high acceleration, e.g. due to high rotational velocity (helicopter application), high inertial forces act upon the body. If the stiffness in direction of inertia load is high, the system deformation remains small. However, in this case additional terms in the linearised equations have to be considered, so called 'geometric stiffness terms'[19,23] which are accounted for in the MBS code.

2.5 Modular aerodynamic modeling

For the coupled aeroelastic and flight mechanics simulation different stages of accuracy (and also processing speed) of aerodynamic models can be chosen (figure 2).

For trim and 6 dof flight simulation an analytical blade element theory is available. The lift coefficients are either given from tables or might be adjusted (tuned) by simulation with aerodynamic models of higher level of accuracy. The data for drag are estimated from profile data. The basic task using an analytical approach lies in the determination of the local induced velocity. The method applied here is the calculation of a mean induced velocity for the rotor disk fulfilling mass, energy and momentum conservation for the rotor as an entity (momentum theory). This results in a radial constant mean induced velocity. The combination of momentum and blade element theory gives a radial distribution of induced velocity and allows the consideration of local geometrical and aerodynamical parameters. By means of user defined force elements, this method has been directly implemented in the MBS code.[11] Further work is in progress to include dynamic inflow models[28] to improve this fast method.

The next level of accuracy is defined using a panel method, the 'Rotor Free Wake Vortex Lattice Method' (ROVLM).[13] This panel code follows linear velocity potential theory. The doublet strength of each new spanwise wake row at the end of each time step is obtained from the blade trailing edge panels of each spanwise section. The ROVLM code had to be modified to use the common IPC interface data for kinematics of the 'wet surface' nodes as well for the rigid body motion of rotor and fuselage of the MBS. Thus the actual rotor geometry and its full velocity state is generated from the kinematic data. Having resolved pressure from velocity distribution, local force vectors for each blade panel can be calculated. These are transfered back to the MBS coupling nodes to apply aerodynamic load. Basics of the method and its modification can be found in the literature.[13,14]

The highest level of accuracy available is coupling the MBS model to a finite-volume Euler method called INROT.[15,16] The physical laws of conservation of mass, momentum and energy constitute the founding equation for all aerodynamic equation. Applying these equations to an infinite small control volumina, one yields a system of nonlinear partial differential equations, which are well known as the Navier Stokes Equations. Its solution for practical problems is quite difficult in terms of processing time and memory requirement. Neglecting effects such as friction and heat transfer the equation simplify to the Euler equations. Regard to parallel processing, INROT uses the so called Chimera technique to discretisize the 3D fluid field. This technique allows computational efficient discretization of the field in case of relative motion among different aerodynamic bodies. In case of the helicopter application there are individual grids around each blade and the fuselage. All individual body grids move in a base grid which covers the entire computational domain. In contact regions of the grids the boundary conditions are fulfilled. Reference simulations have been conducted,[16] aeroelastic investigations on rotary and fixed wing applications are in progress.

3 Multibody model of BO105 helicopter

In the following an application example will be presented. The helicopter considered is a four bladed Eurocopter BO105 helicopter. A topology map of the system with one representative blade is shown in figure 3.

The MBS model set up consist of four ridid and four flexible bodies forming a typical chain-like structure of the MBS. The first rigid body is a dummy body which is driven in translational x-direction by a kinematic excitation function to maintain constant forward velocity. On this body the rigid fuselage is attached via a zero dof joint. The joint inbetween is used to preset fuselage pitch angle in forward flight condition. On top, a rigid rotormast continues the body tree of the MBS connecting the rotating rotor body to the fuselage. A constant angular velocity of 44,4 rad/sec is ensured using another kinematic excitation joint. By an axis offset of 0.25 m four flexible blades are attached to the rotor. The con-

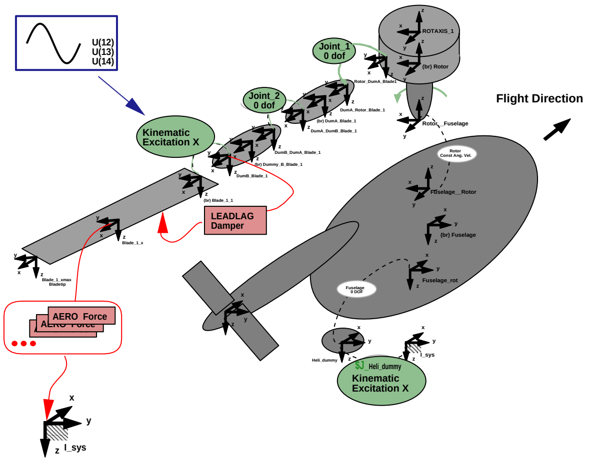

Figure 3: Topology map of MBS helicopter

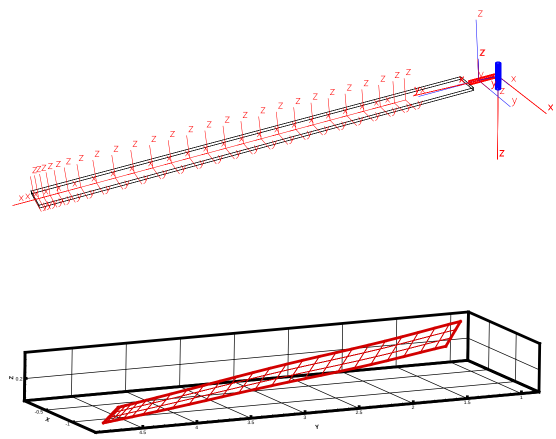

Figure 4: Aerodynamic Discretization of the blade

necting joints of the dummy bodies inbetween are chosen to be zero dof accounting for the model of a hingeless rotor. The build-in orientation of the blade attachment points for the particular rotor are rotated by 2,5 degrees to set a build-in precone angle. Each blade is attached by means of a one dof kinematic excitation joint imposing the blade pitch angle. The blade flapping and lead-lag motion is accounted for in the flexibility distribution of the euler-bernoulli beam used. Each blade is discretisized in two ways. Firstly the structural discretization into seven beam sections defining spanwise stiffness and mass distribution. The second discretization means the aerodynamic coupling nodes defining the aerodynamic center line of the blade. Figure 4 shows these 26 marker points and their representation as panel grid points in the vortex lattice code. A constant linear blade twist of -8 degrees is accounted for in the panel code.

4 Investigation of Vibration based on Coupled Simulation

For helicopter vibration control a measurement of some or all of the following quantities is needed: Forces and moments at the rotor hub, accelerations at specific points of the fuselage respectively in the cabin and/or accelerations at the rotor blades themselves. Based on these measurements appropriate commands for the actuators are derived by a controller and are fed back to the IBC inputs. Thereby the pitch angles and consequently the blade loads are changed in order to achive the aim of vibration reduction.

To be used in helicopter vibration control, a simulation tool must provide the required measurements and accept the necessary inputs for the actuators. Here appropriate interfaces are realised as non-linear user code blocks (UCBs) in the MATRIXx/SystemBuild environment.

In the process of designing a vibration controller, the responses of actuation have to be determined. Thus the transfer function from actuator input to system output in terms of vibrational responses at the rotor hub is of interest.

To demonstrate the capabilities of the presented simulation tool for helicopter vibration control, an appropriate open loop control simulation has been performed. For that purpose signal generators have been set up in the MATRIXx/SystemBuild environment to generate the desired IBC inputs. The resulting outputs are saved. For closed loop vibration control the signal generators are replaced by the controller which calculates the IBC inputs from the measured quantities.

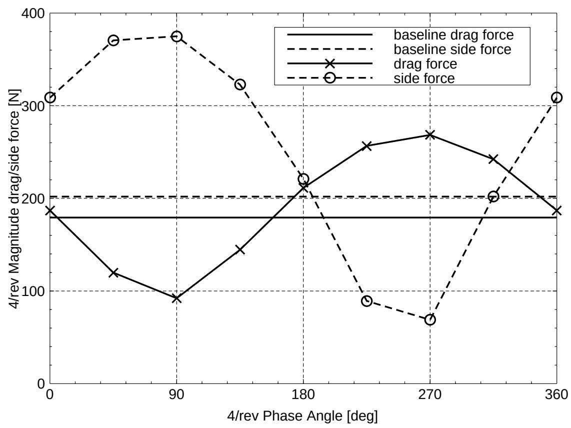

Figure 5: 4/rev drag and side force at rotor hub vs. IBC phase angle for single harmonic 4/rev collective control with amplitude 0.2 deg, μ = 0.26

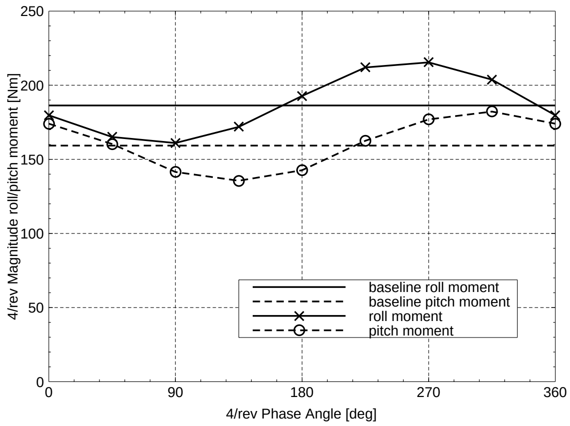

Figure 6: 4/rev roll and pitch moment at rotor hub vs. IBC phase angle for single harmonic 4/rev collective control with amplitude 0.2 deg, $\mu = 0.26$

Figures 5 and 6 exemplarily show the 4/rev magnitudes of the vibrational forces and moments at the rotor hub as responses to single harmonic 4/rev control input dependent on the IBC phase angle in comparison with the vibrations with IBC off (baseline case). The calculations are done for the helicopter trimmed in forward flight with $\mu = 0.26$ and a collective 4/rev IBC input with an amplitude of 0.2 deg.

The simulation shows that the IBC inputs have a considerable effect on drag and side force vibrations whereas the amplitude of 0.2 deg appears to be too small to allow a significant vibration reduction in the roll and pitch moments at the rotor hub.

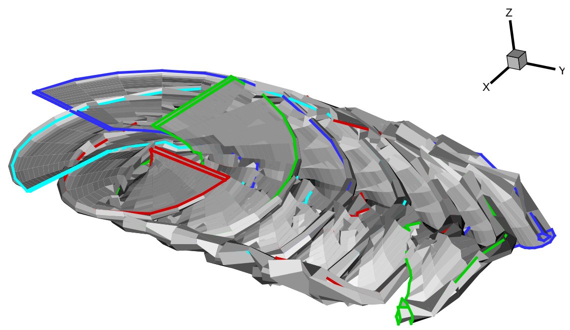

Figure 7: Flow field from coupled simulation after four revolutions, $\mu = 0.26$

The aerodynamics are calculated by a vortex lattice method (ROVLM), the flow field after four revolution is shown in figure 7. At the outer boundaries of the flow field the panels can be observed to roll up to build the rotor wake vortex.

5 Summary and Conclusions

Needs for controller design and verification but also for basic studies of physical phenomena in helicopter vibration control led to the further development of simulation and modeling capabilities. This paper presents the application of a simulation environment for flexible rotorcraft to the field of vibration control. The tool is a modular ensemble of proven software tools, each of them highly specialized in its own engineering discipline. The center link to all modules is a general purpose multibody code. Depending on the issue to be investigated, the structural model can be refined and extended by finite element models of certain bodies. The aerodynamic model can be choosen according to the aerodynamic phenomena which have to be considered.

Having reviewed the basic ideas of multibody simulation the modular concept of model refinement on both the structural and the aerodynamic part were presented. In the sense of aerodynamics and controller link the modular concept is realized on the level of data exchange via inter process communication. In the MATRIXx/SystemBuild environment the interfaces are realised as non-linear user code blocks and thus allow maximum freedom in the choice of controller testing and implementation. Remarkable advantages of the modular concept are decentralized calculation, maintainance and development of the participated software tools.

The application to individual blade control of rotors shows the capability of the presented simulation tool to be used in helicopter vibration control research. This establishes a basis for validating vibration reduction controllers in a very accurate simulation, which typically have been designed based on lower order, less accurate models.

Acknowledgement

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