FINITE ELEMENT MULTIBODY MODELING OF ROTORCRAFT SYSTEMS

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Abstract

This paper describes an ongoing effort in the area of multibody finite element dynamics for the modeling of rotorcraft systems. The key aspects of the simulation procedure are discussed and selected rotorcraft applications are presented.

Introduction

Multibody dynamics analysis was originally developed as a tool for modeling mechanisms with simple tree-like topologies composed of rigid bodies, but has considerably evolved to the point where it can handle nonlinear flexible systems with arbitrary topologies. It is now widely used as a fundamental design tool in many areas of mechanical engineering. In the automotive industry, for instance, multibody dynamics analysis is routinely used for optimizing vehicle ride qualities, a complex multidisciplinary task that involves the simulation of many different sub-components. Modern multibody codes can deal with complex mechanisms of arbitrary topology including sensors, actuators and controls, are interfaced with CAD solid modeling programs that allow to directly import the problem geometry, and have sophisticated graphics, animation and post-processing features. The success of multibody dynamics analysis tools stems from their flexibility: a given mechanism can be modeled by an idealization process that identifies the mechanism components from within a large library of elements implemented in the code. Each element provides a basic functional building block, for example a rigid or flexible member, a hinge, a motor, etc. Assembling the various elements, it is then possible to construct a mathematical description of the mechanism with the required level of accuracy.

Despite its generality and flexibility, multibody dynamics analysis has not yet gained acceptance in the rotorcraft industry. Historically, the classical approach to rotor dynamics has been to use a modal reduction approach, as pioneered by Houbolt and Brooks [1]. Typical models were limited to a single articulated blade connected to an inertial point, and the control linkages were ignored. The equations of motion were specifically written for a blade in a rotating system, and ordering schemes were used to decrease the number of nonlinear terms. In time, more detailed models of the rotor were developed to improve accuracy and account for various design complexities such as gimbal mounts, swash-plates, or bearingless root retention beams, among many others. The relevant equations of motion were derived for the specific configurations at hand. In fact, the various codes developed in-house by rotorcraft manufacturers are geared towards the modeling of the specific configuration they produce. This approach severely limits the generality and flexibility of the resulting codes. In recent years, a number of new rotorcraft configurations have been proposed: bearingless rotors with redundant load paths, tilt rotors, variable diameter tilt rotors, and quad rotors, to name just a few. Developing a new simulation tool for each novel configuration is a daunting task, and software validation is an even more difficult issue. Furthermore, the requirement for ever more accurate predictions calls for increasingly detailed and comprehensive models. For instance, modeling the interaction of the rotor with a flexible fuselage or with the control linkages must be considered in order to capture specific phenomena or instabilities.

Clearly, a more general and flexible paradigm for modeling rotorcraft systems is needed. It seems that many of the concepts of multibody dynamics analysis would be readily applicable to the rotorcraft dynamics analysis, since a rotorcraft system can be viewed as a complex flexible mechanism. In particular, the ability to model novel configurations of arbitrary topology through the assembly of basic components chosen from an extensive library of elements is highly desirable. In fact, this approach is at the heart of the finite element method which has enjoyed, for this very reason, an explosive growth in the last few decades. This analysis concept leads to new comprehensive simulation software tools that are modular and expandable. Modularity implies that all the basic building blocks can be validated independently, easing the more challenging task of validating complete simulation procedures. Because they are applicable to configurations with arbitrary topologies, including those not yet foreseen, such simulation tools will enjoy a longer life span, a critical requirement for any complex software tool.

This paper describes a multibody dynamics approach to the modeling of rotorcraft system and reviews the key aspects of the simulation procedure. The proposed approach provides the level of generality and flexibility required to solve complex problems.

Element Library

The element library involves structural elements: rigid bodies, composite capable beams and shells, and joint models. Although a large number of joint configurations are possible, most applications can be treated using the well known lower pair joints presented here. More advanced joints, such as sliding joints and backlash elements are briefly described.

Beam, Shell and Rigid Body Models

Rigid body and beam models are the heart of rotorcraft multibody models. Shell models are also useful for dealing with composite flex-beams in bearingless rotors. Rigid bodies, beams and shells are all characterized by the presence of linear and rotational fields. In the proposed formulation, all elements are referred to a single inertial frame, and hence, arbitrarily large displacements and finite rotations must be treated exactly.

Rigid bodies can be used for modeling components whose flexibility can be neglected or for introducing localized masses. For example, in certain applications, the flexibility of the swash-plate may be negligible and hence, a rigid body representation of this component is acceptable; the model consists of two rigid bodies, representing the rotating and the non-rotating components, respectively, properly connected to each other and to the rest of the control linkages.

Beams are typically used for modeling rotor blades, but can also be useful for representing transmissions shafts, pitch links, or wings of a tilt rotor aircraft. In view of the increasing use of composite materials in rotorcraft, the ability to model components made of laminated composite materials is of great importance. Specifically, it must be possible to represent shearing deformation effects, the offset of the center of mass and of the shear center from the beam reference line, and all the elastic couplings that can arise from the use of tailored composite materials. Most multibody codes are unable to deal with such structures with a sufficient level of accuracy. An efficient approach to this problem is based on a two step procedure. At first, the sectional properties of the beam are computed based on a linear, two-dimensional finite element analysis of the beam cross-section. These properties are used to define the physical characteristics of the beams involved in the multibody system. Next, the dynamic response of the multibody system is computed using a nonlinear, finite element procedure. Ref. [2] gives details and examples of application of this process.

Joint Models

A distinguishing feature of multibody systems is the presence of a number of joints that impose constraints on the relative motion of the various bodies of the system. Most joints used for practical applications can be modeled in terms of the so called *lower pairs*: the revolute, prismatic, screw, cylindrical, planar and spherical joints, depicted in fig. 1.

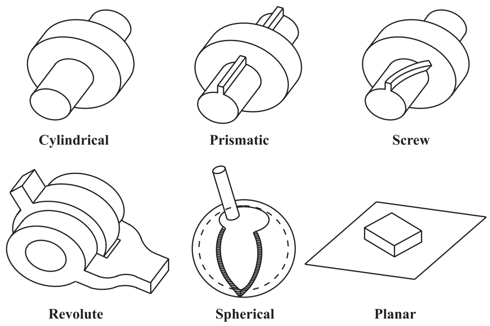

Figure 1: The six lower pairs.

Articulated rotors and their kinematic linkages are easily modeled with the help of lower pair joints. For example, a conventional blade articulation can be modeled with the help of three revolute joints representing pitch, lag and flap hinges. Another example is provided by the pitch-link, which is connected to the pitch-horn by means of a spherical joint, and to the upper swash-plate by a universal joint to eliminate rotation about its own axis.

The explicit definition of the relative displacements and rotations in a joint as additional unknown variables represents an important detail of the implementation. First of all, it allows the introduction of generic spring and/or damper elements in the joints, as usually required for the modeling of realistic configurations. Second, the time histories of joint relative motions can be driven according to suitably specified time functions. For example, in a helicopter rotor, collective and cyclic pitch settings can be obtained by prescribing the time history of the relative rotation at the corresponding joints.

In the classical formulation of prismatic joints for rigid bodies, kinematic constraints are enforced between the kinematic variables of the two bodies. These constraints express the conditions for relative translation of the two bodies along a body fixed axis, and imply the relative sliding of the two bodies which remain in constant contact with each other. However, these kinematic constraints no longer imply relative sliding with contact when one of the bodies is flexible. To remedy this situation, a *sliding joint* [3] was proposed that involves kinematic constraints at the instantaneous point of contact between the sliding bodies. This more sophisticated type of constraint is required for the accurate modeling of specific rotorcraft components. Consider, for instance, the sliding of the swash-plate on the rotor shaft, or the sliding joints involved in the retraction mechanism of the variable diameter tilt rotor [4], as discussed in the applications section.

Backlash behavior can be added to the modeling of revolute joints, as described in ref. [5]. The joint is generally free to rotate, but when the relative rotation reaches a preset value, a unilateral contact condition is activated corresponding to the backlash "stop". The associated contact force is computed according to a suitable contact force model. This element can be used to model the blade droop stops, as shown later on.

Aerodynamic Models

A description of the various aerodynamic solution procedures used for the modeling of rotorcraft is beyond the scope of this paper. Simplified models based on lifting line theory and vortex wake models, or sophisticated computational fluid dynamics codes can be used for this purpose. At each time step of the simulation, the aerodynamic loads acting on the blades and wings must be computed based on the present configuration of the system, and are then used to evaluate the dynamic response.

Robust Integration of Multibody Dynamics Equations

From the description given so far, it is clear that the equations governing nonlinear flexible multibody systems present very specific features. First, they are highly nonlinear. There are several possible sources of nonlinearities: large displacements and finite rotations (geometric nonlinearities), or nonlinear constitutive laws for the deformable components of the system (material nonlinearities). Second, when constraints are modeled via the Lagrange multiplier technique, the resulting equations present a dual differential/algebraic (DAE) nature. Third, the exact solution of the equations of motion implies the preservation of a number of dynamic invariants, such as energy and momenta. Fourth, when the elastic bodies of the system are modeled by means of an appropriate spatial discretization process, such as the finite element method, high frequency modes are introduced in the system. Note that these high frequency modes are artifacts of the discretization process, and bear no physical meaning. In large systems, numerical round-off errors are sufficient to provide significant excitation of these modes, hindering the convergence process for the solution of the nonlinear equations of motion. Furthermore, the nonlinearities of the system provide a mechanism to transfer energy from the low to the high frequency modes. Hence, the presence of high frequency numerical dissipation is an indispensable feature of robust time integrators for multibody systems.

All these features of multibody systems must be carefully considered and specifically taken into consideration when developing robust simulation procedures that are applicable to a wide spectrum of applications. In particular, problems related to the modeling of helicopters put stringent requirements on the accuracy and robustness of integration schemes. Indeed, rotors are characterized by highly nonlinear dynamics, large numbers of constraints, especially when the entire control linkages are modeled, highly flexible members, large number of degrees of freedom, and widely different spatial and temporal scales. On this last issue, consider, for instance, the dramatic difference between the axial and flap-wise bending stiffnesses of a typical rotor blade.

The classical approach to the numerical simulation of flexible multibody systems is generally based on the use of off-the-shelf, general purpose DAE solvers. DAE integrators are specifically designed for effectively dealing with the dual differential/algebraic nature of the equations, but are otherwise unaware of the specific features and characteristics of the equations being solved. Although appealing because of its generality, this approach implies that the special features that were just pointed out will be approximated in various manners.

While this standard procedure performs adequately for a number of simulations, alternate procedures have been developed [6, 7]. Instead of applying a suitable integrator to the equations modeling the dynamics of multibody systems, algorithms are *designed* to satisfy a number of precise *requirements*. These design requirements are carefully chosen in order to convey to the numerical method the most important features of the equations being solved. In particular, the following requirements will be satisfied by the proposed approach: *nonlinear unconditional stability* of the scheme, a *rigorous treatment of all nonlinearities*, the *exact satisfaction of the constraints*, and the presence of *high frequency numerical dissipation*. The proof of nonlinear unconditional stability stems from two physical characteristics of multibody systems that will be reflected in the numerical scheme: the preservation of the total mechanical energy, and the vanishing of the work performed by constraint forces. Numerical dissipation is obtained by letting the solution drift from the constant energy manifold in a controlled manner in such a way that at each time step, energy can be dissipated but not created. Algorithms meeting the above design requirements are described in refs. [8, 9, 10, 11, 12, 13, 14, 15, 6, 7].

Solution Procedures

Once a multibody representation of a rotorcraft system has been defined, several types of analyses can be performed on the model. The main features of the static, dynamic, stability, and trim analyses are briefly discussed in the following sections.

Static Analysis

The static analysis solves the static equations of the problem, *i.e.* the equations resulting from setting all time derivatives equal to zero. The deformed configuration of the system under the applied static loads is then computed. The static loads are of the following type: prescribed static loads, steady aerodynamic loads, and the inertial loads associated with prescribed rigid body motions. In that sense, hover can be viewed as a static analysis.

Once the static solution has been found, the dynamic behavior of small amplitude perturbations about this equilibrium configuration can be studied: this is done by first linearizing the dynamic equations of motion, then extracting the eigenvalues and eigenvectors of the resulting linear system. Due to the presence of gyroscopic effects, the eigenpairs are, in general, complex. For typical rotor blades, the real part of the eigenvalues is negligible, whereas for transmission shafts, this real part is large and provides information about the stability of the system. Finally, static analysis is also useful for providing the initial conditions to a subsequent dynamic analysis.

Dynamic Analysis

The dynamic analysis solves the nonlinear equations of motion for the complete multibody system. The initial condition are taken to be at rest, or those corresponding to a previously determined static or dynamic equilibrium configuration.

Complex multibody systems often involve rapidly varying responses. In such event, the use of a constant time step is computationally inefficient, and crucial phenomena could be overlooked due to insufficient time resolution. Automated time step size adaptivity is therefore an important part of the dynamic analysis solution procedure. All the results presented in this work make use of the error estimator of ref. [13].

Stability Analysis

An important aspect of the aeroelastic response of rotorcraft systems is the potential presence of instabilities which can occur both on the ground and in the air. Typically, Floquet theory is used for this purpose because the system presents periodic coefficients. Application of Floquet theory to rotorcraft problem has been limited to systems with a relatively small number of degrees of freedom. Indeed, as the number of degrees of freedom increases, the computational burden associated with the evaluation of the transition matrix becomes overwhelming. A novel approach has been proposed, the *implicit Floquet analysis* [16], which evaluates the dominant eigenvalues of the transition matrix using the Arnoldi algorithm, without the explicit computation of this matrix. This method is far more computationally efficient than the classical approach and is ideally suited for systems involving a large number of degrees of freedom. The implicit Floquet analysis can be viewed as a post-processing step: all that is required is to predict the response of the system to a number of given initial conditions. Hence, it can be implemented using the proposed multibody dynamics formulation.

Trim Analysis

The problem of rotorcraft trim involves both the search for a periodic solution to the nonlinear rotor equations and the determination of the correct control settings that satisfy some desired flight conditions. The determination of control settings is an important aspect of rotorcraft analysis as these settings are known to deeply affect the entire solution as well as stability boundaries. The auto-pilot and discrete auto-pilot methods [17] are well suited for the solution of the trim configuration when the problem has been formulated using the proposed finite element based multibody dynamics analysis. The auto-pilot method modifies the controls so that the system converges to a trimmed configuration. Additional differential equations are introduced for computing the required control settings. The discrete auto-pilot approach modifies the control settings at each revolution only.

Applications

The following applications are presented in this section: the conversion from hover to forward flight mode for a variable diameter tilt-rotor and the aeroelastic analysis of the shipboard engage operations of a H-46 helicopter.

Modeling a Variable Diameter Tilt-Rotor

The example deals with the modeling of a variable diameter tilt-rotor (VDTR) aircraft. Tilt-rotors are machines ideally suited to accomplish vertical take-off and landing missions characterized by high speed and long range. They operate either as a helicopter or as a propeller driven aircraft. The transition from one mode of operation to the other is achieved by tilting the engine nacelles. VDTR's further refine the tilt-rotor concept by introducing variable span blades to obtain optimum aerodynamic performance in both hover and cruise configurations. A general description of current VDTR technology is given in ref. [4], and fig. 2 schematically shows the proposed design.

Fig. 3 presents Sikorsky telescoping blade design. Fig. 4 depicts a schematic view of the multibody model of a typical VDTR configuration where a sin-

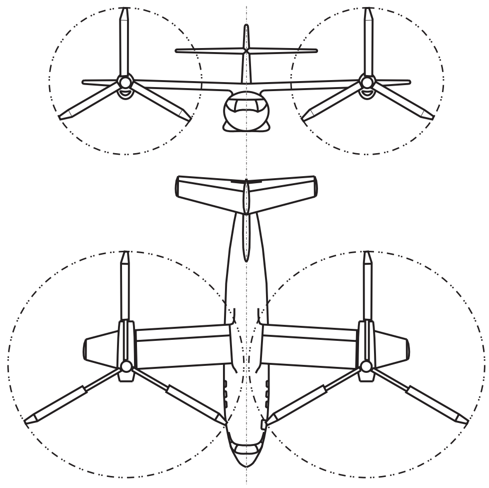

Figure 2: VDTR design schematic. Top figure: cruise configuration; bottom figure: hover configuration.

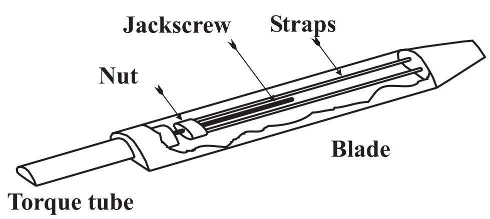

Figure 3: The Sikorsky telescoping blade design.

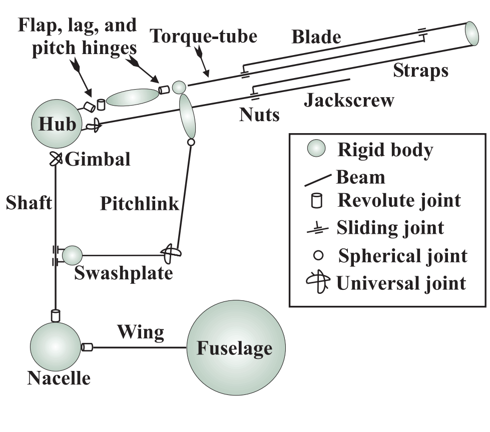

Figure 4: Configuration of the VDTR. For clarity, a single blade only is shown.

gle blade only is shown, for clarity. A sliding joint and a sliding screw joint connect the swash-plate and the shaft. The motion of the swash-plate along the shaft controls the blade pitch through the pitch linkages. Prescribing the relative translation of the sliding joint, *i.e.* the translation of the swash-plate with respect to the shaft, controls the pitch setting, effectively transferring the pilot's command in the stationary system to the blade in the rotating system. The presence of a screw joint forces the swash-plate to rotate with the shaft while sliding along it. This is usually accomplished in a real system with a scissors-like mechanism that connects swash-plate and shaft. This level of detail in the model, although possible using beams and/or rigid bodies and revolute joints, was not considered to be necessary for the present analysis. A sliding screw joint models the nut-jackscrew assembly. The motion of the nuts along the jackscrew allows to vary the blade span in a continuous manner. By prescribing the relative translation at the joint, the blade can then be deployed or retracted according to a suitable function of the nacelle tilt. Finally, sliding screw joints are used to model the sliding contact between the torque tube and the outboard blade. Note that a sliding screw joint must be used here as the pilot's input is transferred from the linear motion of the swash-plate to twisting of the torque tubes through the pitch links, and finally to twisting of the outboard blade. Appropriate springs and dampers are provided at the gimbal, while springs are present at the flap and lag revolute joints in order to correctly represent the characteristics of the system.

Since actual data for this configuration was not available, the model used for this example has telescoping blades as in fig. 3, but the structural and aerodynamic characteristics are those of the XV-15 aircraft [18, 19]. Fig. 5 gives the variation of the thrust coefficient C_T in hover as function of the power coefficient C_P; good correlation with the experimental data is observed.

The VDTR rotor is initially in the hover configuration, with the nacelles tilted upwards and the blades fully deployed. The rotor angular velocity is 20 rad/sec. The shaft rotational speed and blade pitch setting are kept constant while the nacelle is tilted forward to reach the cruise configuration. At the same time, the blades are retracted to avoid impact between the blade tips and

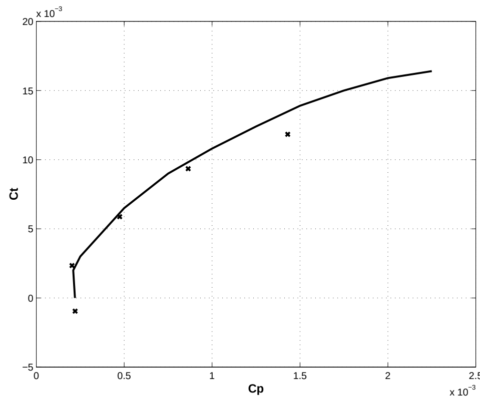

Figure 5: Thrust coefficient C_T versus power coefficient C_P for varying collective angle, for the VDTR model with XV-15 data.

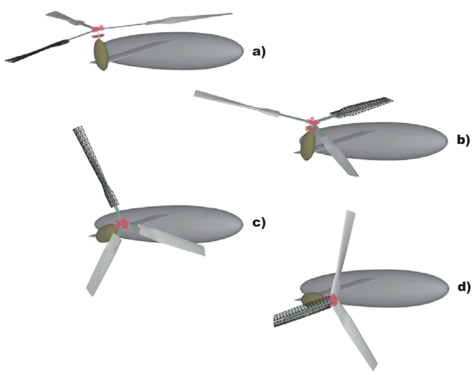

Figure 6: Snapshots of the VDTR multibody model during the conversion process.

the fuselage, and to optimize aerodynamic performance. The maneuver is completed in 20 sec, corresponding to about 64 revolutions of the rotor. The time history of the relative prescribed rotation at the wing-nacelle revolute joint is given as $\varphi = 0.25\,\pi\,(1 - \sin\,(2\,\pi(t/40 + 0.25))$, while the prescribed displacement at the nut-jackscrew sliding joint is linear in time. The retracted rotor diameter for cruise mode is 66% of that in hover. This simulation was conducted in a vacuum, *i.e.* without aerodynamics forces acting on the blades.

Fig. 6 gives a three dimensional view of the VDTR multibody model at four different time instants throughout the maneuver. This view is de-

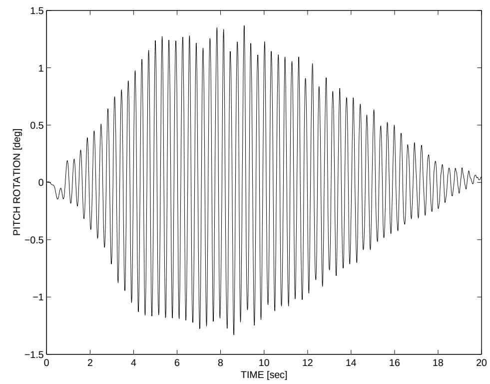

Figure 7: Time history of the relative rotations at the pitch hinge.

ceptively simple. In fact, the tilting of the nacelle involves a complex tilting motion of the gimbal with respect to the shaft. In turn, flapping, lagging and pitching motions of the blades are excited. As the nacelle begins its motion, gimbal rotations are excited and sharply increase during the first half of the conversion process. Then, the dampers present in the universal joint progressively decrease the amplitude of this motion. Fig. 7 shows the time history of the blade pitch. This pitching is entirely due to the gimbal tilting, since the swash-plate location along the shaft was fixed, which would imply a constant value of pitch for a rigid system.

Fig. 8 shows the time history of the force at the jackscrew-nut sliding joint during the blade retraction. Note that the jackscrew carries the entire centrifugal force. Indeed, the blade is free to slide with respect to the torque tube, and hence, no axial load is transmitted to this member. As a result, the variable span blade is subjected to compression during operation, a radical departure from classical designs in which blades operate in tension. As expected, fig. 8 shows that the axial load in the jackscrew decreases as the rotor diameter is reduced. The high frequency oscillating components of the signal are once again due to the flapping, lagging and tilting motions of blades and gimbal discussed above.

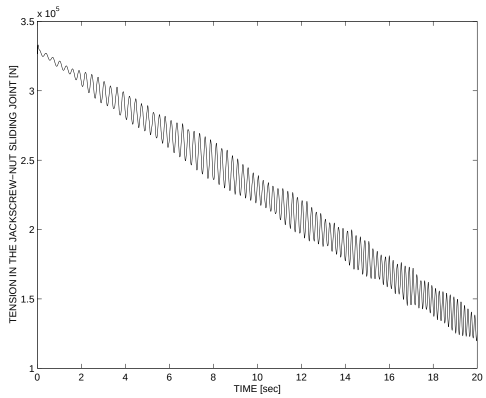

Figure 8: Time history of the force at jackscrew-nut sliding joint during blade retraction.

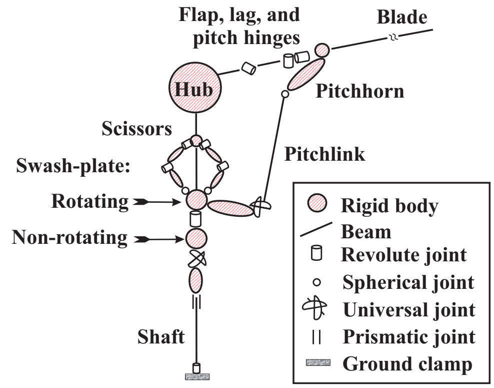

Figure 9: Multibody model of the rotor.

Aeroelastic Analysis of Shipboard Engage Operations

When operating in high wind conditions or from a ship-based platform, rotorcraft blades spinning at low velocity during engage and disengage operations can flap excessively. During these large flapping motions, the blades hit the droop and flap stops. The droop stop is a mechanism that supports the blade weight at rest and at low speeds. Excessive upward motion of the blade is restrained by a second stop, called the flap stop. Impacts with the droop and flap stops can cause significant bending of the blades, to the point of striking the fuselage.

The H-46 helicopter was modeled here. First, the model was validated based on the available data. Next, the transient response of the system during engage operations was simulated. Complete details on this problem can be found in ref. [20]. In this effort, the aerodynamic model was based on unsteady, two-dimensional thin airfoil theory [21], and the dynamic inflow formulation developed by Peters [22].

H-46 Model Validation

The H-46 is a three-bladed tandem helicopter. The structural and aerodynamic properties of the rotor can be found in ref. [23] and references therein. Fig. 9 depicts the multibody model of the control linkages that was used for this study. The rotating and non-rotating components of the swash-plate are modeled with rigid bodies, connected by a revolute joint. The lower swash-plate is connected to a third rigid body through a universal joint. Driving the relative rotations of the universal joint allows the swash-plate to tilt in order to achieve the required values of longitudinal and lateral cyclic controls. The collective setting is achieved by prescribing the motion of this rigid body along the shaft by means of a prismatic joint. The upper swash-plate is then connected to the rotor shaft through a scissors-like mechanism, and controls the blade pitching motions through pitch-links. Each pitch-link is represented by beam elements, in order to model the control system flexibility. It is connected to the corresponding pitch-horn through a spherical joint and to the upper swash-plate through a universal joint to prevent pitch-link rotations about its own axis. Finally, the shaft is modeled using beam elements. The location of the pitch-horn is taken from actual H-46 drawings, while the dimensions and topology of the other control linkages are based on reasonable estimates. Fig. 10 gives a graphical representation of the control linkages, as obtained through the visualization module. Only one blade is shown, for clarity.

During the engage simulation, the control inputs were set to the following values, termed standard control inputs: collective $\theta_0 = 3$ deg., longitudinal cyclic $\theta_s = 2.5$ deg., lateral cyclic $\theta_c = 0.0693$ deg. These values of the controls were obtained with the proper actuations of the universal and prismatic joints that connect to the lower swash-plate.

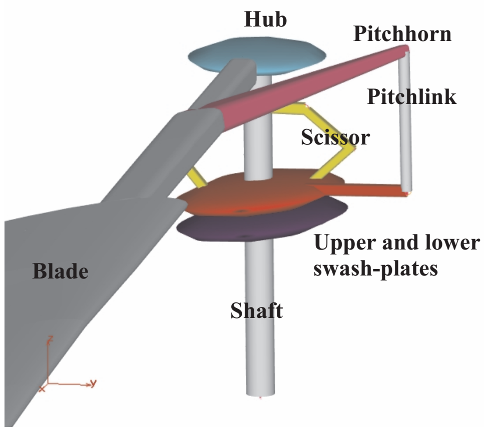

Figure 10: Graphical representation of the multibody model of the control linkages. One single blade shown for clarity.

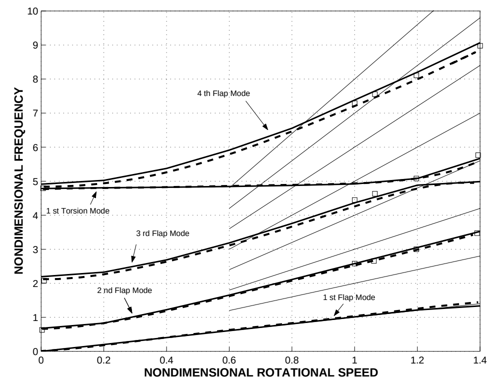

Figure 11: H-46 fan plot. Present solution: solid line; ref. [23]: dashed line; experimental values: □ symbols.

In this work, only the aft rotor system is modeled. The blades were meshed with 5 cubic geometrically exact finite elements, while the droop and flap stops were modeled using the revolute joint with backlash described previously. The stops are of the conditional type, activated by centrifugal forces acting on counterweights. The droop and flap stop angles, once engaged at rotor speed below 50% of the nominal value $\Omega_0 = 27.61$ rad/sec, are -0.54 and 1.5 deg, respectively.

Experimental data available for this rotor configuration include static tip deflections under the blade weight and rotating natural frequencies. This data was used for a partial validation of the structural and inertial characteristics of the model. As expected, static tip deflections are in good agreement with Boeing average test data, within a 2% margin. Fig. 11 shows a fan plot of the first flap-torsion frequencies for the rotor considered in this example, where quantities are nondimensionalized with respect to Ω_0. These modes are in satisfactory agreement with the experimental data, and with those presented in ref. [23].

Transient Analysis of Rotor Engage Operations

Next, a complete rotor engagement was simulated. A uniform gust provides a downward velocity across the rotor disk, in addition to a lateral wind component. The vertical wind velocity component was 10.35 kn, while the lateral one was 38.64 kn, approaching from the starboard side of the aircraft. The situation is typical of a helicopter operating in high wind conditions on a ship flight-deck. The run-up rotor speed profile developed in ref. [24] from experimental data was used in the analysis. The simulation was conducted by first performing a static analysis, where the controls were brought to their nominal values and gravity was applied to the structure. Then, a dynamic simulation was restarted from the converged results of the static analysis.

Fig. 12 shows a three dimensional view of the rotor multibody model at three different time instants throughout the engage operation. Large flapping motions of the blades induced by the gust blowing on the rotor disk are clearly noticeable even in this qualitative picture. Fig. 13 gives the out-of-plane blade tip deflection, positive up, for a complete run-up. During the rotor engage operation, the maximum tip deflections are achieved during the first 6 sec of the simulation. Then, as the rotor gains speed, the deflections decrease under the effect of the inertial forces acting on the blade. Here and in the following figures, the thick broken line shown in the lower part of the plot gives the time intervals when the revolute joint stops are in contact. Because of the large downward gust blowing on the rotor disk, only the droop stop is impacted by the blade, while the flap stop angle is never reached.

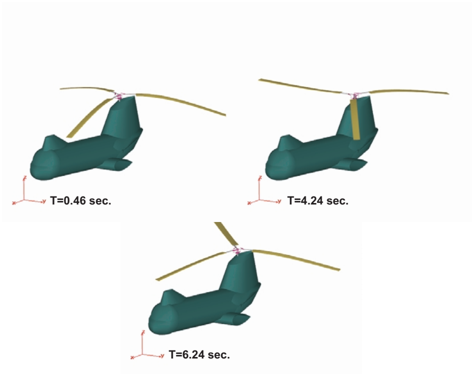

Figure 12: Predicted configuration of the rotor system during an engage operation in a uniform gust.

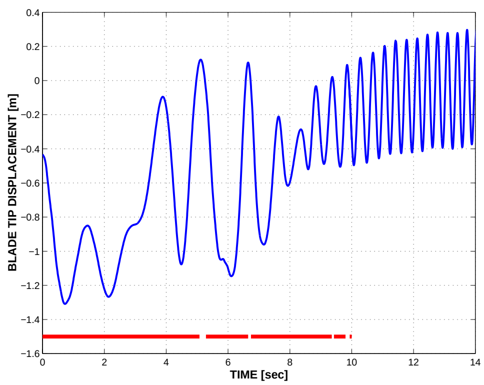

Figure 13: Out-of-plane blade tip response for a rotor engage operation. The thick broken line indicates the extent of the blade-stop contact events.

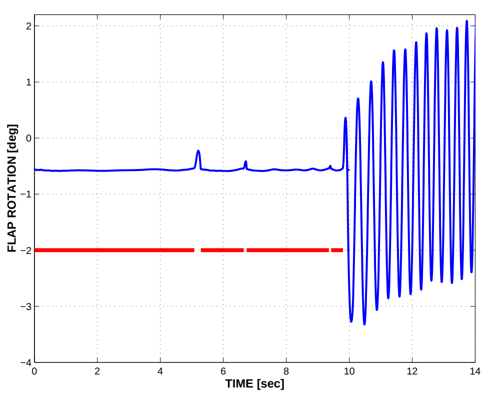

Figure 14: Flap hinge rotation for a rotor engage operation in a uniform gust.

Fig. 14 gives the time history of the flap hinge rotations. Multiple droop stop impacts take place at the lowest rotor speeds, causing significant blade deflections and transfers from kinetic to strain energy. Furthermore, the intensity of the uniform vertical gust component on the rotor disk causes large negative tip deflections even from the very beginning of the analysis, when the blade angular velocity and resulting stiffening effect are still small. After about 10 sec through the simulation, the droop stop is retracted and the blade tip time history exhibits a smoother behavior. In order to simulate the conditional nature of the particular droop stop mechanism used by this helicopter, the stop retraction was modeled by changing the backlash angles of the flap revolute joint at the first time instant of separation between the blade and its stops passed the activation rotor speed (50% of Ω_0).

The results are in reasonable agreement with the simulations of refs. [23]. In particular, the maximum negative tip deflections, that determine whether the blade will strike the fuselage or not, are very similar, as well as the results at the higher speeds. Discrepancies at the lower speeds might be due to the different aerodynamic models employed.

The repeated contacts with the droop stops cause large bending of the blades. Blade deflections can become excessive, to the point of striking the fuselage. For less severe cases where such striking does not occur, significant over-loading of the control linkages could still take place. The multibody formulation used in this work readily allows the modeling of all control linkages, and the evaluation of the transient stress they are subjected to during rotor engage. In view of the multiple violent impacts and subsequent large blade deflections observed, the loads experienced by the various components of the system during an engage operation in high winds could be significantly larger than during nominal flight conditions.

Pitch-link loads were computed during the run-up sequence discussed earlier. Furthermore, the same engage operation was simulated for the case of vanishing wind velocity, in order to provide “nominal” conditions for comparison. For the case of vanishing wind velocity, all other analysis parameters were identical to those used in the previous simulations.

Fig. 15 shows the axial forces at the pitch-link mid-point during a time window between 2 and 10

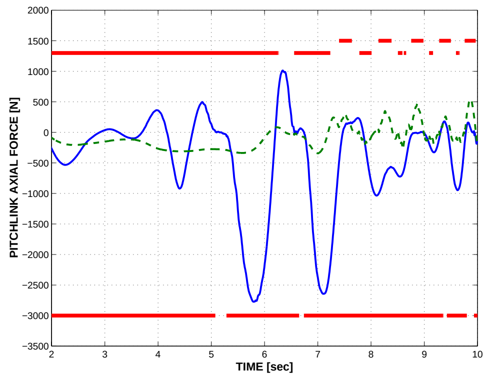

Figure 15: Mid-point axial forces in the pitch-link for a rotor engage operation. Uniform gust velocity: solid line; no gust velocity: dashed line.

sec of the run-up sequence, for which the most violent blade tip oscillations where observed in the previous analysis. The solid line corresponds to the uniform gust velocity case, while the dashed line gives the "nominal", vanishing wind velocity case. The thick broken lines in the lower and upper parts of the plot indicate the contact events with droop and flap stops. The pitch-link loads are far greater than those observed at full rotor speed, due to the large blade flapping motions and repeated impacts with the stops. The vanishing gust velocity analysis predicts blade impacts with both droop and flap stops. However, the uniform gust velocity case is far more severe due to the large blade deflections and resulting compressive loads in the pitch-links.

Conclusions

This paper has described a multibody dynamics approach to the modeling of rotorcraft systems. This approach allows the modeling of complex configurations of arbitrary topology through the assembly of basic components chosen from an extensive library of elements that includes rigid and deformable bodies as well as joint elements.

A key element of the formulation is the development of robust and efficient time integration algorithms for dealing with the large scale, nonlinear, differential/algebraic equations resulting from the proposed formulation. Static, dynamic, stability, and trim analyses can be performed on the models. Furthermore, efficient post-processing and visualization tools are available to obtain physical insight into the dynamic response of the system that can be obscured by the massive amounts of data generated by multibody simulations.

Multibody formulations are now well established and can deal with complex rotorcraft configurations of arbitrary topology. This new approach to rotorcraft dynamic analysis seems to be very promising since it enjoys all the characteristics that made the finite element method the most widely used and trusted simulation tool in many different engineering disciplines and areas. This new paradigm for rotorcraft analysis is expected to gain popularity and become an industry standard in the years to come.

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