HELICOPTER SIMULATION TECHNIQUES FOR FULL MISSION FLIGHT SIMULATION*

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ABSTRACT

The power of simulation as a design and training tool has long been recognized and successfully exploited by the fixed-wing aircraft community. This in turn has begun to influence the helicopter industry which until now used simulation to a much lesser extent. This is evidenced by the emphasis on simulation by the U.S. Army in the procurement of the next generation light helicopters (LHX) and the investments currently made by the helicopter companies on simulation equipment and facilities. The approach to fixed-wing aircraft simulation has become fairly uniform within the industry despite advances in aircraft technology and capabilities. On the other hand, rotorcraft simulation has taken divergent paths. There is a plethora of techniques and more are in the offing. One reason is that the rotor wake, rotor dynamics, and the interaction between the rotor, airframe, engine and drive train are extremely complex and difficult to model, even to achieve a credible offline non-realtime simulation. Consequently, designers of helicopter engineering/training simulations face a bewildering array of techniques for real-time, man-in-the-loop simulation.

This paper surveys the different rotor modeling techniques from a real-time simulation user's perspective. It describes the most commonly used techniques, their underlying assumptions and simplifications, computing requirements, and strengths and weaknesses. It is hoped that the paper will provide a potential designer/user with an understanding of the options available to him and help him choose an approach that will best meet his needs.

INTRODUCTION

As a result of the inherent complexity in modeling helicopter dynamics in general and rotor dynamics in particular, many approaches have been developed. Generally the differences between these models grew out of the need to have a real-time man-in-the-loop simulation capability. This has resulted in varying degrees of physical accuracy each approach attempts to achieve. The degree of accuracy has been primarily driven by the real-time processing requirements and computational limitations.

Though a large number of methods exist, they can actually be classified into four truly unique techniques. They are (in order of increasing computational rigor):

1) Perturbation Models (no rotor representation)
2) Rotor Disc Models (sometimes known as a Bailey model)
3) Rotor Blade Map Models
4) Rotor Blade Element Models

The following sections discuss these techniques in detail. Where possible, references to successful applications of each method are given.

HELICOPTER MODELING CONSIDERATIONS

The major difficulty in developing a representative real-time simulation of helicopter dynamics stems from the complexity of its primary lifting and propulsion system, the main rotor. To further complicate the problem there are interference effects on the aircraft, flight regimes unique to the operation of helicopters, and a number of possible vehicle configurations. These effects are generally coupled and require an exhaustive physical analysis for accurate modeling. While a detailed analysis of each effect is beyond the scope of this paper, some of the physical considerations to be taken into account in modeling are discussed below.

Unlike a fixed wing aircraft, which is generally characterized by a rigid wing with some propulsive system, helicopter flight characteristics are primarily dominated by a number of rotating lifting surfaces. The aerodynamic forces acting on the helicopter are functions of not only vehicle speed and angle of attack, but also blade rotational speed and blade section velocity. The blade section velocity varies with radial distance from the hub and is also dependent upon the current blade azimuth position. This results in a non-uniform velocity distribution (or inflow) over the rotor disc. In order for the helicopter to produce a uniform load distribution over the disc, allowing stable flight, the rotor blades must have their angles of attack varied continuously throughout their rotation through "cyclic pitch" produced by the helicopter control system. In addition, the blades are free to flap, and swing back and forth in the plane of the rotor disc. To further complicate rotor model dynamics, the rotating blades are sufficiently elastic to have structural modes of bending, torsion and twist. A number of aerodynamic phenomena must also be considered. In forward flight, rotor systems are characterized with reverse flow regions on the retreating blades. A vortex ring state exists on the main rotor in settling flight and on the tail rotor in crosswinds and sideward flight. Compressibility effects near the blade tips, and blade stall characteristics are also areas of concern for the rotor modeler. Reference 1 describes in detail all of these characteristics and their relationship with the rotor and vehicle.

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In addition to problems that arise from modeling the rotor, the helicopter is also characterized by a variety of flight regimes. Along with the normal maneuvering flight envelope, the helicopter routinely takes off vertically, hovers, translates forward, sideward and rearward and can autorotate. There are also a number of interference effects arising from the downwash of the rotor impinging on the fuselage, horizontal tail, vertical tail, external stores and the tail rotor. Also, ground interference effects occur during take off, landing and operations near the ground. These and other second order effects are not well understood and are usually empirically modeled with varying degrees of success.

Currently there are many vehicle and rotor configurations which present unique and challenging problems for helicopter modelers. Historically, teetering, articulating and tandem rotor systems were the norm. With the advent of advanced technologies, hinge-less rotors, coaxial counter rotating rotors, tilt rotors and the X-wing rotor are all being developed. Tail rotor (or anti-torque devices) technology has not been left behind in these advances. No tail rotor (NOTAR) and shrouded rotors are also being developed.

Ideally a simulation model would take into account all the above considerations. However, any reasonable analysis must rest on a multitude of simplifying assumptions of which there is a great variety in the literature. The following paragraphs will introduce some of the most common methods of analyzing rotor dynamics and attempt to identify these assumptions and differences.

PERTURBATION MODEL

Perhaps the simplest and the earliest technique was the development of the perturbation model. This model is generally comprised of constant, linear derivatives, which define the total aircraft performance about a trim point and is therefore, limited to small perturbations about the chosen trim point. The model contains no separate rotor representation, however, rotor effects are lumped into the derivatives corresponding to the six rigid-body degrees of freedom of the vehicle.

To accurately model a rotorcraft, the classical set of six rigid-body degrees of freedom must be augmented with three more eqations representing the coning, longitudinal flapping angle, and lateral flapping angle of the rotor. However the time constant of a conventional rotor system is on the order of 1/4 to 1/2 of a rotor revolution. This rapid response gives way to a quasi-static assumption, which results in the elimination of blade motion as a separate degree of freedom by replacing the rotor with a black box at the top of the mast. This essentially produces forces and moments instantaneously in response to changes in flight conditions or control inputs. The resulting six equations of motion are consequentially similar to those used for fixed wing simulation. A detailed analysis of this technique has been developed in chapter 9 of reference 2. This technique has been used successfully on a number of design and evaluation programs, ranging from the control law analysis of the three axis flight director (ref. 3), to the investigation of VTOL automatic landing technologies (ref. 4).

A variation of this technique is currently being evaluated by McDonnell Douglas Helicopter company (MDHC). The approach relies upon the perturbed response of a quasi-static rotor map model with dynamic inflow. An n^{th} order polynominal expression will be developed by performing a regression analysis on the perturbed response. The eventual outcome will be an n^{th} order polynominal which will be representative of the rotor dynamic response throughout the flight envelop of interest. It is expected this approach will yield a simplified rotor model easily supported in real-time by a micro computer and easily tunable with variation of the polynominal coefficients. The main application of this effort is for use in low cost helicopter trainers. The primary advantage of the approach will be a simplified model which has been derived from a more sophisticated technique run in an offline environment.

These methods have provided a satisfactory approach to real-time dynamics simulation about the trim points of interest. However, they are not valid when the simulated flight regime is far from the trim points used to develop the coefficient model or polynominal expression. The computational requirement of this method is easily supported by a mini computer or even a micro-computer system, making this technique particularly desirable for part-task training simulations or simulations with a limited flight envelop.

ROTOR DISC MODELING

Rotor disc modeling, as the name implies, is founded upon the idealization of the rotor as a uniform disc which is articulated about its hub. This method, some times called a Bailey model, was originally developed by F.J. Bailey in the early 1940's (ref. 5). As a result of its simplicity, this technique or derivatives of it have been used extensively in real-time simulation studies (references 5, 6, 7, 8, 9, 10, and 11). Generally these models are quasi-static in nature and do not explicitly account for dynamic rotor effects, such as rotor blade flapping or coning.

The disc modeling techniques found in the literature all vary in level of complexity and detail. However, they do share many commonalities. Basically the modeling technique first assumes a uniform inflow velocity over the rotor disc and by application of momentum theory a local velocity distribution over the disc is determined. Blade forces are then derived by analytically integrating over the radius of the rotor disc. Total forces and moments are then determined by analytically summing the contributions of each blade as an analytical function of the azimuth. This procedure then yields analytical expressions of rotor thrust, hub drag force, hub sideforce, and torque as functions of disc attitude and blade pitch. The disc attitude, or tip path plane orientation, with respect to the swash plate axis is generally represented by values of longitudinal and lateral flapping angles. Blade pitch is generally defined by the longitudinal and lateral cyclic and collective settings.

Different analytical solutions to these equations are possible with different assumptions or simplifications. Some of the most significant and common assumptions associated with this technique are:

1. Rotor blades are rigid in all bending axes.
2. Flapping angles and inflow angles are assumed to be small.
3. Reverse flow region is ignored.
4. Compressibility and stall effects are negligible.
5. Inflow is assumed to be uniform with no dynamics.
6. Tip-loss factor is assumed to be 1.

An attractive feature of this model is its application for tail rotor simulation. Rotor disc models are particularly useful for tail rotor simulation, because most tail rotors can be treated as a teetering rotor system without cyclic pitch. Since tail rotor flapping frequency is high, the tip path plane dynamics can be ignored. This assumption results in a very simple tail rotor model which performs quite well.

Computationally this technique is simple, requiring only the implementation of four equations to describe the rotor thrust, hub drag force, hub sideforce, and rotor torque. However, most rotor disc implementations result in an iterative solution for the values of inflow and thrust. The convergence of this iteration is, of course, a primary computational consideration of the technique. For most applications, however, a rotor disc model can be easily supported in a real-time environment by most real-time processing mini computers.

ROTOR MAP MODELING

The key feature in rotor map modeling is that the performance of the modeled rotor is dependent upon a stored data base. The data base is comprised of six three-dimensional arrays. These arrays contain the steady state coefficent values of rotor thrust, drag, sideforce, torque, and flapping angle for the entire flight regime. Dynamic and aerodynamic effects of transients are dealt with analytically, using closed form analytical procedures. Further, the data base is generated with a well defined blade element model (described in the next section) running in a non-real time environment. The performance of this model, therefore, depends directly upon the fidelity and accuracy of the offline blade element model used in defining the map. With a judicious selection of the proper axis system (i.e. the control axis (ref. 2)), the independent parameters are simplified to axial inflow ratio, advance ratio, and collective pitch. A particular advantage of this methodology is the ability to adjust the data base to assure compliance with static performance criteria over a specific envelop or validation with flight test data.

Unfortunately, the available literature describing mapping techniques is limited in content and distribution. Singer Link (ref 12) and McDonnell Douglas Helicopter Company (ref 13) are the two primary users of Rotor Map modeling. Both companies have had good success in developing a representative real-time simulation with this technique.

The computational complexity of this technique results from a number of axis transformations and three-dimensional table look-ups. Also, and as was the case for the disc modeling technique, an iteration to obtain inflow and thrust is usually required. Further, a significant memory allocation is required for storage of the rotor maps. The real-time processing requirements for this technique becomes consequently more significant than the two methods previously discussed. Generally this technique has been implemented on super-mini computers.

BLADE ELEMENT MODEL

A rotating blade element model is the most computationally accurate analysis of helicopter aerodynamics applicable for real time simulation since it deals with the detailed flow and loading of each blade. Blade element modeling has been widely considered throughout the helicopter community as the best approach for accurate engineering simulation and rotor analysis. This technique has been used mostly in non-real time simulation applications. Until recently, the computational facility needed to support the real-time implementation of such a model has been out of reach for most users. With the availablity of high speed computers at modest prices, blade element modeling technique for real-time simulation has become a realistic possibility.

The Blade Element Model calculates the forces on each blade element due to its motion through the air, and hence the performance of the entire rotor. It is assumed that each blade element acts as a two-dimensional airfoil section producing aerodynamic forces which are then numerically integrated along the blade span. The influence of the rotor wake and inflow characteristics are accounted for by the induced angle of attack and Mach number at the element section. The solution thus requires an estimate of the wake-induced velocity at the rotor disc, which is provided by either momentum theory, vortex theory, or non-uniform inflow calculations. This technique allows for the inclusion of the combined contributions of aerodynamic effects, leading and lagging degrees of freedom, blade mass properties and inertial loads acting on each simulated blade. The most significant assumption made with Blade Element Models is that the rotor blades are rigid. A complete theory of the Rotating Blade Element modeling technique is developed in Reference 1.

Sikorsky together with NASA has developed a real-time blade element simulation of the UH-60A Black Hawk. Reference 14 describes in detail the development and implementation of this model. Flight Safety has developed a real time blade element model which runs on an AD-10 special purpose computer. Also MDHC is currently developing a generalized real-time Blade Element Model for use on an AD-100 computer. It is anticipated this facility will be capable of processing real-time rotor dynamics at hundreds of Hertz.

A shortcoming to the Blade Element Modeling technique is that it does not readily meet static performance criteria over the entire flight regime. This shortcoming is a result of the two dimensional lift and drag coefficient definition of the blade airfoil section operating in a three dimensional enviroment. Often this definition does not offer sufficient flexibility to satisfy the aircraft performance over the entire flight envelop. Also the technique is inherently computationally intensive which complicates its use in real-time simulation. There have been a number of studies which have investigated the degradation of this modeling technique as functions of number of elements and number of azimuth integration stations (reference 15, 16).

Modified Blade Element Approach (MBE)

A variation to the Blade Element Modeling approach is the Modified Blade Element (MBE) model. The modified blade element approach is characterized by the computation of forces at incremental points on a blade which is fixed at several azimuth station, whereas the rotating blade approach continuously computes the forces ating on a blade as it is rotated through its azimuth. A physical conception of this method can be achieved by regarding the method as a strobing of the blade performance as it passes the fixed azimuth stations. A detailed analysis of the method has been developed in reference 17. This technique has proved to give good static performance and matches with flight trajectories have been obtained with this method (ref. 11). One reason for this success is that the local blade coefficents are estimated in the least-squares sense to give the best fit to rotor static performance directly from flight data. Reference 18 compares the performance of the Blade element model with that of the MBE model. Surprisingly, little degradation in the performance of the MBE was found.

Performance Driven Blade Element (PDBEM)

Reference 19 attempts to combine the good static performance behavior of the rotor map technique with the dynamic characteristics of the Blade Element modeling techniques. The intent of this effort is a model which maximizes the relative strengths of the two primary techniques and minimizes their weaknesses. This is the basis of the "Performance Driven Blade Element Method."

The "Performance Driven Blade Element Method (PDBEM)" was developed to satisfy two major criteria. The first criterion is to meet steady state performance standards over the entire envelop. The second is to provide satisfactory dynamic performance. The manner in which this is accomplished is to employ an off-line model to automatically compute the rotor performance at each required point and then to use an optimization algorithm to systematically adjust the blade element functional coefficient data until the performance criterion is satisfied. Then, the resulting coefficient data are stored in tables to be used by a blade element model in real time to compute the rotor forces and moments.

However, this technique has not been validated in an actual application to determine whether the expected advantages actually materialize.

CONCLUDING REMARKS

This paper has briefly discussed the most common approaches to real time helicopter rotor simulation. Experience indicates that the linearized pertubation model and rotor disc model are quite acceptable for part-task trainers or simulations with limited flight and visual simulation capability. For engineering simulators and full mission simulators the rotor blade map method or the rotor blade element model is desirable. Rotor mapping is preferable when considerable model tuning is required to match simulation specifications or flight data. When a new helicopter or rotor design is analyzed then the blade element modeling offers more flexibility and better dynamic characteristics. This also avoids the need to regenerate the rotor maps offline with every design change.

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