

Teaching Graduate Rotorcraft Design Based on Twenty Years of Experience

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Introduction

Rotorcraft is a general term for rotary-wing aircraft and includes all aircraft that include any rotary-wing device for generating lift or propulsion for a portion of the aircraft's flight envelope. Therefore, rotorcraft includes helicopters, autogyros, tilt-rotor aircraft, and compound helicopters (which include both wings and auxiliary propulsion devices). Rotorcraft are typically low disk loading vehicles operating below 50 lbs/ft², where disk loading is defined as the ratio of the gross weight to rotor disk area. The author has personally been involved with rotorcraft, since learning to fly Army helicopters in the late 1960s which included a tour as an Army helicopter pilot and commander in combat in Southeast Asia. Involvement in rotorcraft design and development commenced with an assignment as an aeroelasticity and dynamics engineer with the U.S. Army Aviation Systems Command in 1974, following receiving a M.S. degree in Aerospace Engineering at Georgia Tech. Participation in the development and transition to production of today's fleet of Army helicopters: the UH-60 Black Hawk, the AH-64 Apache, the CH-47 Chinook, and the OH-58D Kiowa Warrior, led to some unique insights and experience related to these complex and unique, but wonderful machines. Leading the development of the next generation of rotorcraft, the LHX-RAH-66 Comanche, in the early 1980s provided an understanding of the role of technology, as well as its fickleness. Teaching rotorcraft design at Georgia Tech since 1984 as the Rotorcraft Design Professor and leading the Center of Excellence in Rotorcraft Technology (CERT) as its Director since 1986 has led to an understanding and appreciation of the role of interdisciplinary basic research for the advancement of complex systems, such as rotorcraft. This paper will attempt to provide some lessons learned from twenty years experience in teaching rotorcraft design.

Understanding Rotorcraft

Rotorcraft are extremely complex machines due to the interdisciplinary interactions that take place throughout their flight regimes. The helicopter schematic provided in Figure 1 provides some brief descriptions of some of the physical phenomena that rotorcraft encounter. The easiest way to explain this environment is to cite that in forward flight at a single cruise flight speed of approximately 140 knots the airspeed from the retreating blade tip to the advancing blade tip crosses the entire subsonic speed range from Mach number zero to almost one. This results in Dynamic Stall on the retreating blade to Transonic Flow (Shock Waves) on the advancing blade. In addition, the time varying aerodynamics at each section of the rotor blades and the limberness

of the long, high aspect ratio blades result in Aeroelastic Response. The interaction of the Vortex Wake shed by the blades, especially at the tips, result in Unsteady Aerodynamics which not only interact with the following blades, but also with the tail rotor and other lifting surfaces. These interactions cause Dynamic Loads which impact the Structural Dynamics of the airframe.

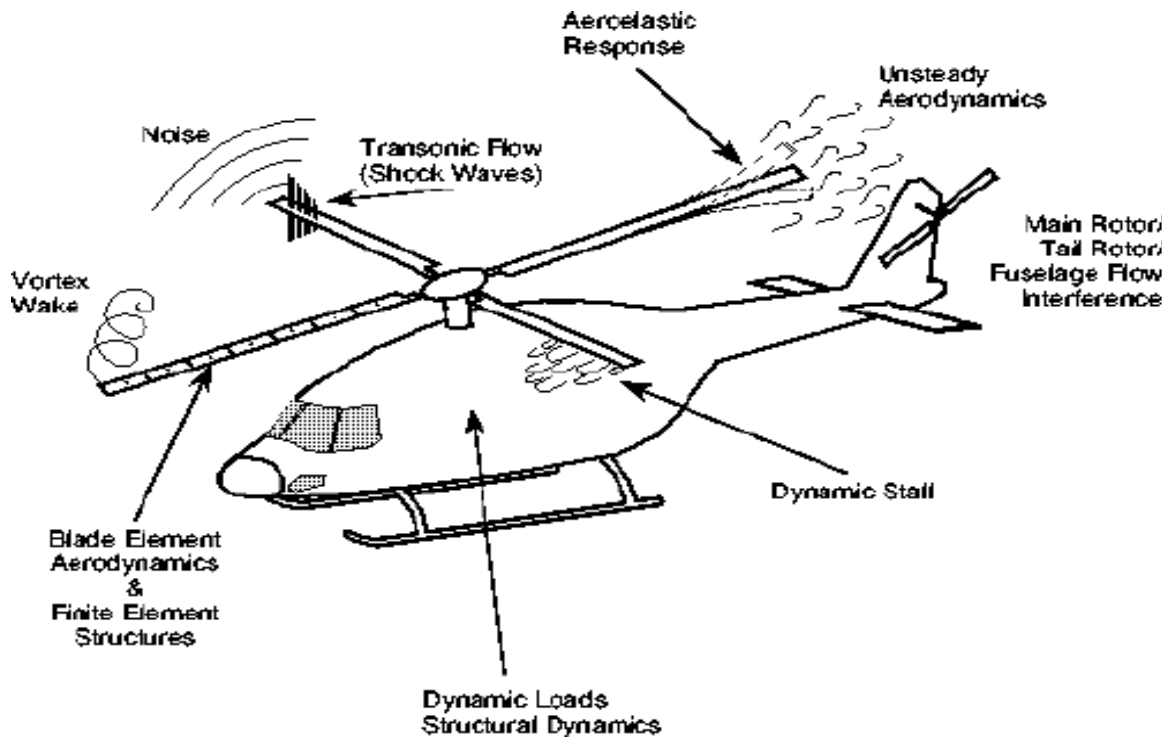


Figure 1. Interdisciplinary Phenomena found on Rotorcraft

The easiest way to explain the interdisciplinary nature of rotorcraft is to look at the number of feed-forward and feedback loops encountered in a typical flight condition. These loops are illustrated in Figure 2.

The feed-forward loop starts with the Pilot trimming the aircraft and providing Blade Control inputs to the main rotor and tail rotor systems. A Stability and Control Augmentation System (SCAS) is usually required to assist the pilot in performing these functions. The Blade Control inputs change the angle of attack of the blades which provides vertical lift through Collective Pitch control if all the blade angles of attack are changed the same. If the blade pitch is different for the various blades, through Cyclic Pitch control, the rotor thrust vector is tilted and provides both lift and propulsion forces. The Blade Airfoil Angle of Attack changes results in two feedback loops, the Circulation and the Airloads. The Circulation combines with the Fuselage Wake to create the Flow Field which results in Wake Impingement on other parts of the air vehicle in the fixed system. The Airloads interact with the Blade Structural Dynamics in an

aeroelastic way and then combine to result in the Hub Loads that excite the rest of the air vehicle. The Hub Loads interact with the Powerplant/Drivetrain and excite the Airframe Dynamics. The output of this interaction between the Hub Loads and the Airframe Dynamics are the Fuselage Vibrations. Also there is feedback of the Quasi-Steady Rigid Body Motions which affects the Pilot's Trim condition.

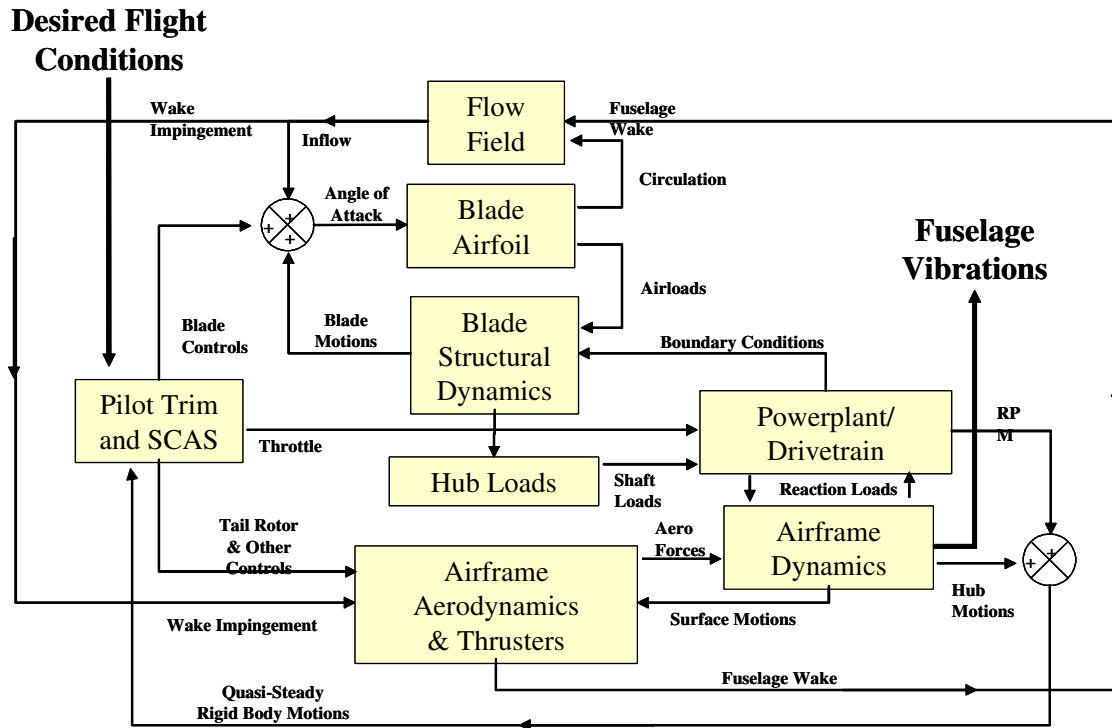


Figure 2. The Interdisciplinary Nature of Rotorcraft

While different kinds of rotorcraft have slightly different interactions than those discussed above for the helicopter, they still are substantial for all types of rotorcraft.

Rotorcraft Conceptual and Preliminary Design Considerations

Obviously the environment illustrated in Figure 1 and described in Figure 2 requires a very complex simulation and modeling environment. While the rotorcraft community has had on-going efforts for at least the past forty years to develop comprehensive rotorcraft analysis tools that can represent most of the interactions illustrated in Figure 2, no single tool exists today to reliably predict Airframe Vibrations. Instead, a series of analysis tools are usually loosely coupled with geometry to provide the prediction capability. However, even these approaches are not sufficient and reliance on trial and error testing is usually still required.

Georgia Tech Integrated Product and Process Development (IPPD) Environment for Rotorcraft Conceptual and Preliminary Design

Over the years Georgia Tech has developed an IPPD methodology that has been the foundation of its graduate program in Aerospace Systems Design. Although initiated in the 1980s for rotorcraft, the Aerospace Systems Design program has grown by leaps and bounds and today cuts across the entire spectrum of aerospace systems. For the past few years the Rotorcraft

Conceptual and Preliminary Design IPPD Environment has followed the flow illustrated in Figure 3. Both Product and Process Development are illustrated as it is the integration of these two that are the key for product success.

Under Product Development, Requirements Analysis is conducted on a Request For Proposal (RFP), usually initiated by the American Helicopter Society (AHS) and one of the major rotorcraft companies on a rotating basis. Students in the graduate course in Aerospace Systems Engineering are taught the fundamentals of IPPD and apply them to a number of complex system formulation projects. One of these projects is usually based on the AHS rotorcraft student design competition RFP and the results end up in a Baseline Model Selection. The first course in Rotorcraft Design, taught in parallel with the Aerospace Systems Engineering course, concentrates on using Vehicle Sizing and Performance methods to conduct conceptual design and parametric analysis of potential solutions.

Georgia Tech Rotorcraft IPPD Design Methodology

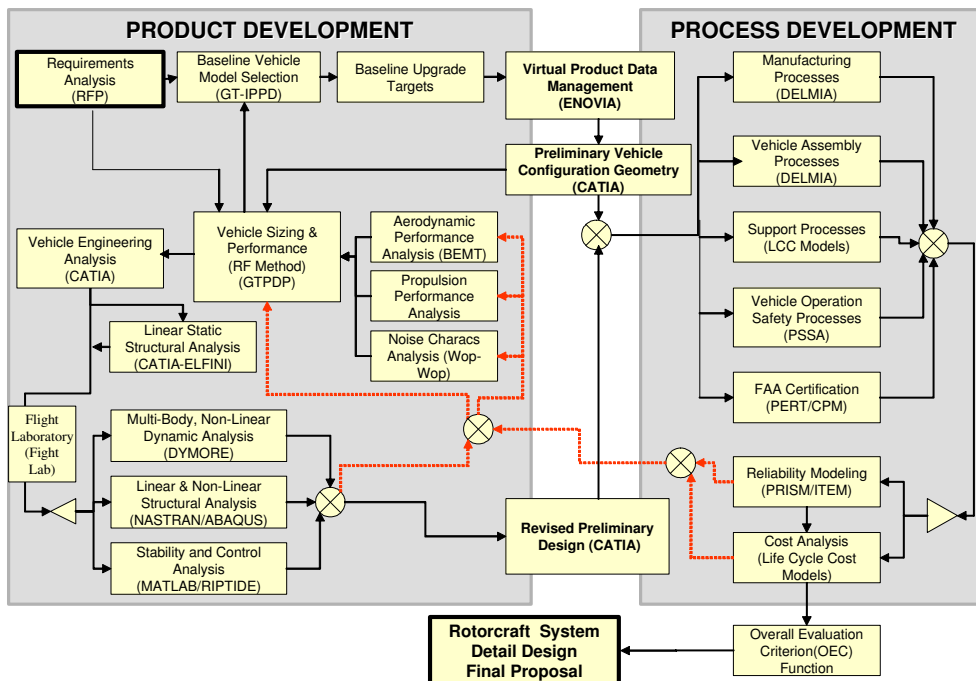


Figure 3. Georgia Tech Rotorcraft Conceptual and Preliminary Design IPPD Environment

The R_F Fuel Balance Method is used to teach the students the essential elements of vehicle sizing, both individually and in a team project. The R_F Fuel Balance Method is illustrated in Figure 4. It starts with the Requirements on the left and consists of both Mission and Performance inputs. The Mission inputs are fed into Fuel Ratio Required and Available models which lead to the determination of the Vehicle Gross Weight. In a similar approach the Performance inputs are fed into Available Power and Required Power models which are used to identify the critical Vehicle Power Loading. The balance of the critical Vehicle Power Loading with the Vehicle Gross Weight results in the Installed Power and a viable configuration solution. An optimum design

can be obtained by varying the disk loading to obtain a minimum gross weight solution, as illustrated in Figure 5. The geometric description of the viable configuration solution completes the conceptual design cycle, as illustrated for a light commercial helicopter in Figure 6.

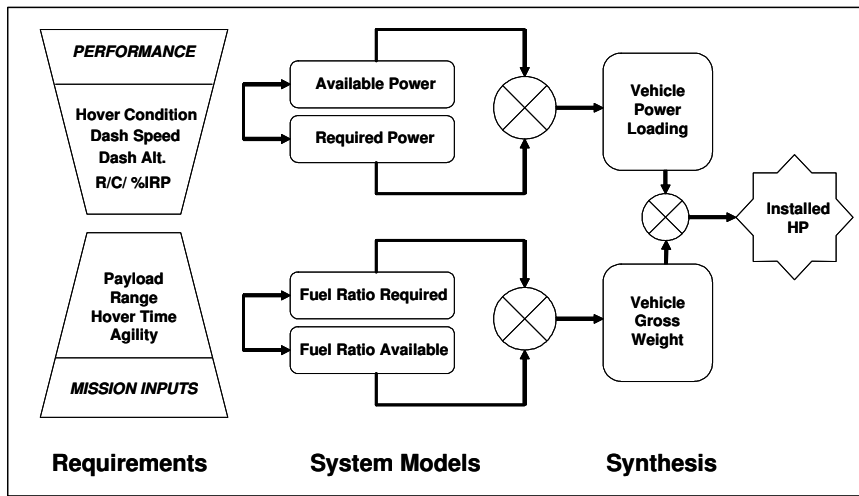


Figure 4. The R_F Fuel Balance Vehicle Sizing Method

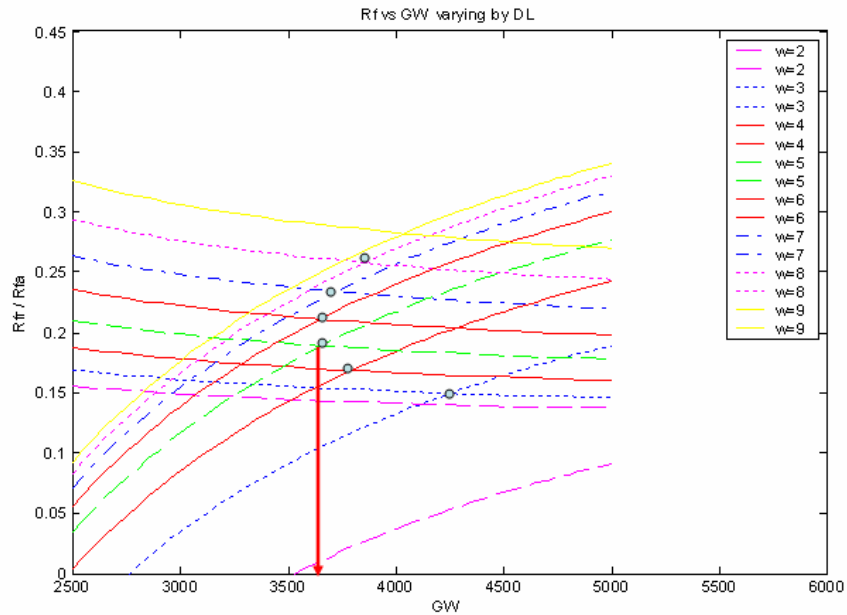


Figure 5. Variation of Disk Loading (w) to Obtain Minimum Weight Solution

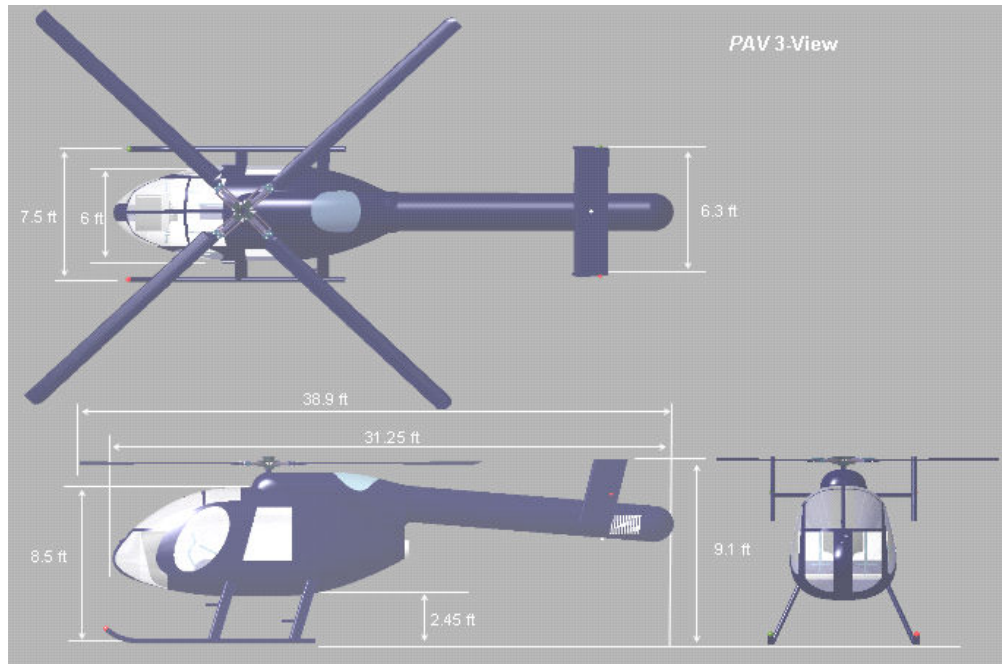


Figure 6. Three View Geometric Solution for Light Commercial Helicopter

Rotorcraft Preliminary Design

With preliminary vehicle geometry identified, the second iteration of design, the *preliminary design cycle*, can begin. Once again, Vehicle Sizing and Performance is utilized. This time a more substantial approach in the form of the Georgia Tech Preliminary Design Program (GTPDP) is utilized. While GTPDP has been revised to size and evaluate performance for a variety of rotary wing vehicle concepts, it is not comprehensive enough for analyzing most of the interdisciplinary interactions illustrated in Figure 2. The purpose of conceptual sizing and performance computer codes are to be able to evaluate a number of vehicle concepts quickly using first order aerodynamics and propulsion analyses. Therefore, more sophisticated disciplinary analysis tools are often used to provide inputs to the sizing and performance computer codes. This is illustrated in Figure 3 by the three boxes providing input to GTPDP. Aerodynamic Performance Analysis, Propulsion Performance Analysis, and Rotor Noise/Vibration Analysis.

Once the initial preliminary design vehicle is sized, a higher definition vehicle geometric model (CATIAV5) can be generated for engineering analysis, as illustrated in Figure 3. Initial structural static analysis can be accomplished in CATIA V5; however, a comprehensive rotorcraft analysis is required for predicting air loads and flight dynamics. This is illustrated in Figure 3 by the box labeled Flight Laboratory (FlightLab). FlightLab is comprehensive rotorcraft analysis tool developed by ART, Inc based on an object-oriented, selective fidelity modeling approach⁶. The FlightLab selective fidelity modeling approach is illustrated in Figure 7. As can be seen, a variety of options are available for modeling the complex environment illustrated in Figure 2.

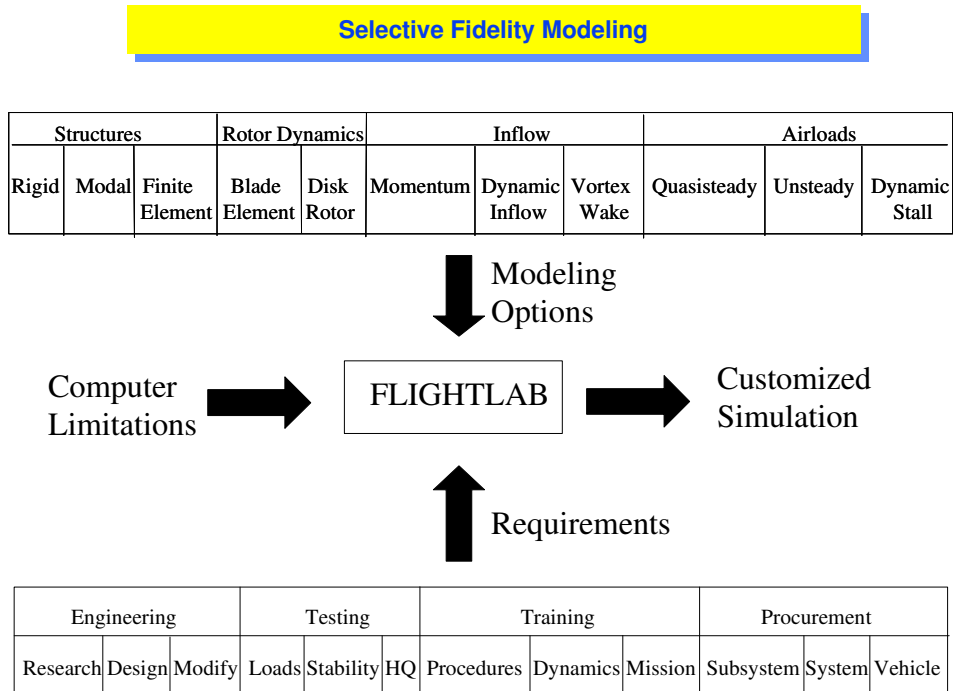


Figure 7. Selective Fidelity Modeling Available in FlightLab

While FlightLab can be used as a comprehensive rotorcraft model for generating airloads and flight dynamics, more specific applicable engineering analysis tools can also be utilized. These are illustrated by the boxes taking the outputs from FlightLab:

- multi-body, nonlinear, finite element dynamic analysis, such as included in the Georgia Tech developed DYMORE modeling approach⁷
- linear and nonlinear structural analysis, such as included in NASTRAN V5i or ABAQUS
- stability and control analysis and design, such as included in MATLAB/LMS Virtual Lab/CATIA V5

Outputs from these analyses are used to complete the product preliminary design cycle and update the GTPDP model. In addition, the revised preliminary design information is included in the CATIA model as illustrated.

With this description of the product design approach completed, the almost parallel process design on the right half side of Figure 3 will now be described.

Process development includes consideration of all the cost/time activities that occur throughout the life cycle of the system and are necessary to achieve the key product characteristics . These are manufacturing and support processes, as well as certification and safety processes. Information and modeling of these processes are difficult in preliminary design, but are essential if engineered complex systems, such as aerospace vehicles, are to result in robust solutions.

A very useful product life cycle tool for evaluating manufacturing and assembly processes is DELMIA. Support processes can be evaluated through Life Cycle Cost (LCC) models. Vehicle operational safety processes can be evaluated through a Preliminary System Safety Analysis (PSSA) utilizing the methods and tools identified in SAE ARP 4761.⁸

The FAA certification process can be evaluated by identifying the appropriate FAR requirements and determining a certification schedule by using such tools as Program Evaluation Review Techniques (PERT)⁹ and Critical Path Methods (CPM).

Two critical analyses that must be conducted using the inputs from the processes described above are a system reliability analysis and a LCC analysis. System reliability can be evaluated through tools such as PRISM¹⁰ or ITEM¹¹.

The results of the Process Development assessment are fed back to update the synthesis model in GTPDP, as well as the vehicle preliminary design definition in CATIA. It is also used for evaluation of the Overall Evaluation Criterion (OEC), which becomes the criterion function that is tracked in the next detail design iteration.

Lessons Learned

A number of lessons have been learned based on twenty years of teaching realistic rotorcraft design. Five substantial ones are:

1. Both conceptual and preliminary design courses are required for realistic complex systems, such as rotorcraft
2. In today's environment both product and process design and development are required; thus realistic teaching requires introducing both
3. A complex system formulation course done as a prerequisite or parallel course to conceptual rotorcraft design is desired
4. If possible the final iteration of rotorcraft preliminary design should include a preliminary system safety assessment and development of a certification schedule
5. Rotorcraft potential will only be fulfilled by innovative rotorcraft designers who appreciate the complexity, but also the uniqueness of rotorcraft

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Biographical Information

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Dr. Schrage is a Professor in the School of Aerospace Engineering at Georgia Tech. He directs the Center of Excellence for Rotorcraft Technology (CERT) and the Center for Aerospace Systems Analysis (CASA). Prior to coming to Georgia Tech in 1984 he was a Senior Executive Servant as the Director for Advanced Systems for the Army Aviation Systems Command. He also is a former Army Aviator with combat experience in Southeast Asia. He has a B.S. in General Engineering, USMA, West Point, NY and has the following advanced degrees: M.S. in Aerospace Engineering, Georgia Tech, M.A. in Business Administration, Webster U., and a D.Sc. in Mechanical Engineering, Washington U. (St. Louis).