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Framework for Multidisciplinary Analysis, Design, and Optimization With High-Fidelity Analysis Tools

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February 2009

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Abstract

A plan is presented for the development of a high fidelity multidisciplinary optimization process for rotorcraft. The plan formulates individual disciplinary design problems, identifies practical high-fidelity tools and processes that can be incorporated in an automated optimization environment, and establishes statements of the multidisciplinary design problem including objectives, constraints, design variables, and cross-disciplinary dependencies. Five key disciplinary areas are selected in the development plan. These are rotor aerodynamics, rotor structures and dynamics, fuselage aerodynamics, fuselage structures, and propulsion / drive system. Flying qualities and noise are included as ancillary areas. Consistency across engineering disciplines is maintained with a central geometry engine that supports all multidisciplinary analysis. The multidisciplinary optimization process targets the preliminary design cycle where gross elements of the helicopter have been defined. These might include number of rotors and rotor configuration (tandem, coaxial, etc.). It is at this stage that sufficient configuration information is defined to perform high-fidelity analysis. At the same time there is enough design freedom to influence a design. The rotorcraft multidisciplinary optimization tool is built and substantiated throughout its development cycle in a staged approach by incorporating disciplines sequentially.

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List of Symbols and Acroynms

AFCS	Active Flight Control System
BIVDS	Boeing Integrated Vehicle Design System
CD	Conceptual Design
CFD	Computational Fluid Dynamics
C_D	Drag Coefficient
CG	Center of Gravity
C_L	Lift Coefficient
C_M	Pitching Moment Coefficient
C_T	Rotor Thrust Coefficient
C_Q	Rotor Torque Coefficient
C81	Helicopter simulation program—industry standard format for airfoil data
DES	Detatched Eddy Simulation
DFM	Design for Manufacturing
DOC	Direct Operating Cost
FEM	Finite Element Model
FM	Figure of Merit
IGES	Initial Graphics Exchange File
IPT	Integrated Prodect Team
LCT	Longitudinal Cyclic Trim
L/D	Lift to Drag Ratio
LES	Large Eddy Simulation
MDA	Multidisciplinary Analysis
MDAO	Multidisciplinary Analysis and Optimization
MDO	Multidisciplinary Optimization
n	number of blades
OASPL	Over All Sound Pressure Level
OEI	One Engine Inoperative
OML	Outer Mold Line
PD	Preliminary Design
RCAS	Rotorcraft Comprehensive Analysis System
RCDA	Rotorcraft Conceptual Design and Analysis
RFP	Request for Proposal
TRL	Technology Readiness Level
URANS	Unsteady Reynolds-Average Navier-Stokes

VABS	Variational Asymetric Beam Section
$\delta 3$	kinematic flap-pitch coupling from control system and flapping hinge geometry
σ	rotor solidity (ratio of blade area to disk area)
μ	advance ratio flight speed to rotor tip speed in hover

Aknowlegments

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1. Introduction

Multidisciplinary optimization (MDO) has demonstrated some practical benefits in conceptual rotorcraft design where simple analyses are brought together in a single program or framework for rotorcraft sizing. Conceptual sizing tools such as HESCOMP [1] use top level engineering analyses to determine first-order aircraft size that will meet mission requirements. More sophisticated MDO processes utilize sizing tools to determine aircraft size for multiple missions or for cost effective solutions to primary missions. Comparing design solutions from sizing results targeted to specific aircraft configurations yields analysis of alternatives to support design decisions and down-selects for further design development.

The extension of MDO processes to advanced stages of design has seen less success in rotorcraft applications. Yet an MDO system at the preliminary design (PD) phase can have large benefits as costly redesign and program delays can be avoided. An MDO system that infuses high-fidelity analyses quickly and consistently across the design space will lead to improved designs because first-time decisions can confidently consider impacts to all relevant engineering disciplines. "Band-aid" design fixes which usually penalize performance and/or weight can be minimized or avoided altogether.

The extension of MDO into the preliminary design stage is the subject of this report and addresses *NASA Research Announcement Subtopic A.3.7.1. High-Fidelity Multidisciplinary Methods*. The goal is to present, and substantiate a plan to establish a framework for high-fidelity multidisciplinary-analysis-optimization (MDAO) tailored to integrated rotorcraft design in the preliminary design context.

Three points of emphasis drawn from the NASA Research Announcement (NRA) established the context for this research. "Multi-disciplinary" suggests exploiting potential tradeoffs between groups and disciplines, which is most effective earlier in design cycle. "Optimization" implies meaningful changes and improvements to a design, which is most fruitful and least limited earlier in the design cycle. "High-fidelity analysis" typically requires a detailed design definition, which is when design begins to be defined at a level of detail where high fidelity tools are used. Currently, optimal design at PD tends to be single-disciplinary, and therefore does not exploit MDAO to balance potential tradeoffs. This project addressed a shortcoming in current design practice in rotorcraft, namely, that the mating of high-fidelity analysis tools in an MDAO framework is not exploited to explore the design space fully or to reduce design cycle time.

In response to the NRA, the Boeing Company proposed a straw man five-year plan that established a progression of activities moving from problem definition, to execution, to evaluation and testing. Objectives for the one year research effort were a high-level subset of the five year plan: Clarify design goals for rotor and fuselage. Determine what types of details are required to move from conceptual design (CD) to preliminary design (PD). Determine individual-discipline design problems. Evaluate effectiveness of high-fidelity analysis tools for use in MDAO. Establish framework for integrated MDAO. Report findings and refine an efficient and effective MDAO framework that could be implemented in a five-year timeframe.

Five key disciplinary areas were selected for the one year substantiation effort: rotor aerodynamics, rotor dynamics and structures, fuselage aerodynamics, fuselage structures, propulsion, and drive system. Flying qualities and noise were included as ancillary areas. These disciplines have clear multidisciplinary involvement through the various subsystems. Others such as control system design could be included;

however, they should only be included if warranted by knowledge of a peculiar connection such as when a control system is designed to stabilize an inherently unstable configuration.

Problem formulation, which formally consists of determining design objectives, constraints, variables, and fixed problem parameters, is essential in MDAO. Establishing the design problem within a design timeline context allows development of consistent levels of detail and approximation. Problem formulation should be constructed without undo bias toward a particular MDAO approach, retaining the unique nature of rotorcraft design.

1.1. Technical Approach

A straw man five year plan was presented; the one year effort is designed to consider the plan critically and either substantiate or modify it. Research centered on preliminary evaluation of several parts of this plan. The approach to the research herein was to address systematically the following questions—applicable to MDAO in general:

What are the design objectives?

Program Management typically has three metrics to judge any engineered system: cost, schedule, and quality (performance). Adherence to schedule and budget should be improved by the automation and integration of an MDAO approach to design; so design objectives can target technical performance and cost. Efficient MDAO would allow a design team leader to trade off weight minimization, performance maximization, vibration reduction, and cost minimization. Weight and performance are traditionally used as design objectives for optimization. Cost as an objective is to some extent implicitly embedded in weight and performance, so weight can be used as a surrogate objective that encompasses others. Vibration reduction is important to passenger acceptance and to reduction of the weight of vibration treatment. Weight, performance, cost, and so forth could be folded into one high-level objective, but more insight may be gained by performing trade-offs among the objectives.

Design objectives may or may not change moving from conceptual design to preliminary design. In conceptual design, objectives relate to sizing a configuration to meet mission requirements, or to life cycle and fleet costs. Conceptual design should produce a configuration that meets requirements; preliminary design should maintain or improve the performance established in the conceptual design. Retention of design objectives from conceptual design to preliminary design should be reviewed.

How are high-fidelity analyses and optimization currently used?

Designers and disciplinary experts are joined in the Integrated Product Team (IPT) structure where their contributions are considered from outside their area of expertise. This is where interdisciplinary interactions and constraints are managed. While ad hoc optimization procedures are being replaced by formal procedures coupled with high-fidelity analysis, multidisciplinary considerations are not significantly exploited within optimization at present. Progress in rotorcraft MDAO requires an examination of single-disciplinary optimal design as currently practiced; this will contribute to a better understanding of how to formulate an MDAO problem.

Another area of current practice that must be documented is how to make the step from an optimized conceptual design to preliminary design where high-fidelity tools are used. Various disciplines may operate at relatively different levels of detail at the same phase of design. Furthermore, high-fidelity analysis generally is used for high-resolution problems where information that defines the configuration might initially be insufficient. For example, a conceptual design airframe has little or no information about where to put frames and stringers. Robust optimal design techniques may be required to address uncertainty inherent at this level of design.

A key consideration is the performance of high-fidelity tools, especially validation and run time. Validation of high-fidelity tools is ongoing as development continues. MDAO research efforts should proceed on the assumption that accuracy will continue to improve; therefore tools will not be extensively validated in this research, but the current status of validation will be reviewed. High-fidelity generally implies long computer run time, which becomes increasingly problematic when optimization is considered. MDAO cannot improve design cycle time unless large numbers of designs can be evaluated efficiently. Current analyses should be assessed for use in an MDAO design framework, not just for accuracy but for their ability to discriminate or contribute to high-level objectives efficiently.

The inclusion of high fidelity analysis tools raises an issue of maintaining appropriate levels of approximation across various engineering disciplines. It may or may not be appropriate to accept a low level of fidelity in one area while working high-fidelity in another. For example, it may be sufficient to use C81 airfoil tables for rotor loads and dynamics and engine performance maps for propulsion, while using exact airfoil geometry in CFD for aerodynamic performance.

Initially, the expectation is to use high-fidelity analyses that are generally available: NASTRAN for fuselage structural and dynamic analysis, OVERFLOW for airframe and airfoil aerodynamic analysis, RCAS for rotor dynamics and loads, CHARM for rotor aerodynamics and VABS for detailed blade cross section properties and stress recovery. Boeing currently employs these tools in design. These particular tools are widely used in the rotorcraft industry and there are equivalents that can be effectively substituted. Modern integration frameworks such as ModelCenter™ from Phoenix Integration Inc. are available to assist not only with the integration and automation of the MDAO process but also with the use of high performance computing. That is, work can be farmed out to clusters of computers to reduce clock time.

How are disciplines connected?

Multidisciplinary optimization involves managing the ways in which disciplines are interconnected. Research must focus on to what extent disciplines are connected and to what extent various disciplines can affect high-level objectives and constraints. Decomposition-based MDAO techniques generally require an understanding of system or disciplinary connectivity to support a rational and effective parsing of the problem. This aspect of problem definition is essential for developing a meaningful design framework, but is not at present well understood in the rotorcraft design problem beyond experience and intuition.

A systematic map of design variables from various subsystems or disciplines should be constructed. This map will establish the relative strength of interactions and should portray them graphically. Statistical methods can be applied; a design space survey, random or otherwise, can be used to support this effort. Information flow diagrams and optimal scheduling of tasks can also be employed not just to assist development of an MDO problem but also to manage updates as design progresses.

How can MDO be applied?

Decomposition schemes often attempt to parse subsets of the MDO problem to disciplinary experts while managing global multidisciplinary interactions. Example methods include Collaborative Optimization, Concurrent Subspace Optimization, Analytic Target Cascading, and Bi-Level integrated Synthesis System. The goal is to exploit the full potential that could be gained by considering all aspects of the design at the same time while solving the design problem in manageable portions. Any such scheme must be designed (or selected) to fit the problem at hand. For this reason most of the early effort of the five year plan and the one year effort is focused on understanding and formalizing the MDO rotorcraft design problem.

Managing multiple objectives also requires some consideration. At present, the chief engineer (or IPT/AIT leadership) balances multiple objectives using experience and intuition. This decision process can be formalized in “Design by Shopping” [2], where the Pareto optimal set is portrayed graphically so tradeoff sensitivities can be seen by inspection. Many other approaches to multi-criteria optimal design can be evaluated.

What restricts MDAO in rotorcraft design?

The biggest obstacle to implementing MDO technology in rotorcraft design, especially preliminary design, is establishing a coherent and consistent MDO problem. Once established, other technical challenges to implementation of an MDO strategy will be clearer.

Most obvious is integration of large-scale codes, which is complicated by complex input/output. A framework for managing data flow is imperative to establishing consistency for the MDO problem and could be a significant challenge in the design environment. This includes managing data consistently at different levels of fidelity for different disciplinary considerations, which points to a significant investment in infrastructure.

Run time of high fidelity analyses can be prohibitive. Use of quick-running surrogate models has been considered in rotorcraft optimal design. Application of surrogate models to rotorcraft optimization traditionally has had mixed results because of inaccuracy, depending on the nature of the design problem. Emergent techniques mitigate this by updating surrogate models as needed [3].

Stochastic searches are expected to find a true global optimum more reliably than gradient-based searches; however, stochastic searches usually require many more function evaluations. Gradient-based search can fail in the multi-modal design space of rotor blade design [4]. These issues can be explored in the one year effort but can only be thoroughly tested within the five year plan.

An additional challenge is code reliability. Convergence problems can be common when changing design variables change the system dynamics (particularly with rotor dynamics codes); therefore an MDAO framework should address this problem.

Ideally, any proposed methodology should be tested against the current design paradigm. Such a test is unlikely because of the prohibitive level of resources required. However, some level of analysis and validation is necessary to test a new system for design. The proposed methodology should be efficient and effective, but solution of the MDAO problem using a new scheme can be expected to have difficulties; therefore at least one year should be reserved for this task. Furthermore, the proposed solution procedure should be implemented with increasing complexity and problem dimensionality.

1.2. Project Overview

This one year substantiation plan addressed subsets of the above questions and five year plan to the extent applicable to a one year effort. While key questions may of necessity be considered only on a high-level, this technical approach will provide the assessment needed to substantiate and refine the five year plan. In particular:

- Establish formal design objectives for rotor and fuselage
- Generate baseline conceptual design; use it to determine what types of details are required to move from conceptual design to preliminary design
- Construct formal statements of individual-discipline design problems
- Evaluate effectiveness of high-fidelity analysis tools for use in MDAO
- Merge individual-discipline design problems; establish framework for integrated MDAO
- Write a report that proposes an efficient and effective MDAO framework as supported by determinations from the previous tasks

The scope of the substantiation effort was directed toward substantiation rather than execution. Therefore the investigations were comprehensive but not necessarily exhaustive. While this project undertook key aspects of the proposed five-year plan, the level of refinement and depth of coverage was not as extensive as required for implementing design optimization. Nonetheless, considerable attention was given to defining the optimal design problem for a tandem rotor helicopter, evaluating the suitability of analysis codes for use in optimization, and understanding how the various disciplines and subsystems interact, both physically and analytically.

2. Rotorcraft Design

2.1. Design Cycle

One goal for this project was to frame a system for optimization that considered the current design process. The three main phases of a typical design cycle are often cited as conceptual, preliminary, and detailed. Transitions from one to the next are usually marked by milestones in the form of key decisions or design reviews after a prescribed level of design maturity has been reached. Design begins with requirements specification generated by customers either explicitly as in a request for proposal (RFP) or by inference. Conceptual design explores high level concepts from which a choice is made. Detailed design generates component drawings or equivalents that can be sent to the shop for production. Preliminary design is a transition that starts from the chosen concept and ends with a certain level of completeness that has drawings for components, but drawings do not contain a definition for every feature that the component will eventually need. The level of completeness or definition is sometimes prescribed to define when preliminary design is complete, but is still somewhat arbitrary.

Additional product research and testing phases appear throughout the duration of the design cycle (Figure 1): exploratory research and testing. Exploratory research usually begins before the inception of the formal design cycles but is adapted and matured for specific application to the design during conceptual, preliminary, or detailed design. In the rotorcraft world exploratory research includes manufacturing processes, innovative rotor blade shapes, new materials, flight control concepts, and so forth. Successful exploratory research leads to concepts of components with relatively low technology readiness levels (TRL) until a certain amount of testing can be done. On occasion, the testing is folded into the design cycles; at other times, testing is done off-line for application beyond a specific rotorcraft design.

Currently, most rotorcraft MDO occurs at the conceptual level where candidate vehicles can be grossly defined and sized for specific mission requirements using relatively simple analysis. At this stage, design details are not well defined, easily allowing MDO to shape the design. Simple analysis can introduce risk in an MDO particularly for innovative concepts that might stretch the analysis tool beyond its calibrated limits. However as more design details become available, it becomes possible to incorporate high-fidelity tools. Though as the design matures, it becomes more difficult to change. Therefore incorporating high fidelity tools early in the design process mitigates risk from low order analyses while the design is still sufficiently fluidic. Developing a high fidelity MDO from an existing conceptual level MDO allows high fidelity tools to be used where it makes sense and early in the design once the definition becomes available. Boeing’s Rotorcraft Conceptual Design and Analysis (RCDA) system is a typical conceptual level MDO environment from which a high fidelity system can spawn.

2.2. Rotorcraft Concept Design and Analysis System (RCDA)

Sizing is an essential function in conceptual design to support configuration selection and refinement, and sizing tools have been developed over several decades to support conceptual sizing efforts by using elementary analysis methods to evaluate performance and trend data to estimate weights for aircraft systems. Over time performance methods were enhanced to reflect distinct capabilities by use of rotor maps, which provide power required versus propulsive force, airspeed, and thrust. These maps could be based on detailed analysis, test data, or both. Similarly weight trends were enhanced while keeping a

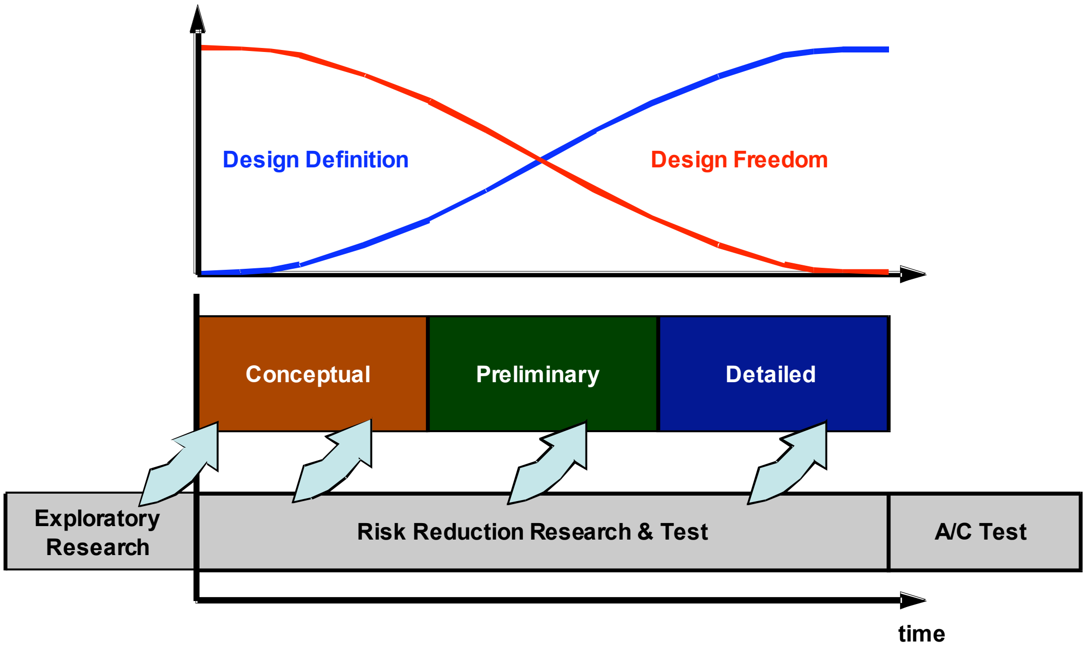


Figure 1. Phases of a typical design cycle

quick-running and simple approach to sizing with technology factors that are based on research or actual samples. Basic sizing codes, however, need to be augmented for a more complete evaluation of a design to include things such as handling qualities and trim, and cost analysis. Integrating modules for conceptual design tasks was the subject of the Boeing Integrated Vehicle Design Program (BIVDS). Under BIVDS Boeing developed tools and processes for conceptual and preliminary design of a wide range of vehicle types including specialized analysis, geometry, and optimization methods [5] – [10].

RDCA [5] is an outgrowth of this effort specialized for rotorcraft. Modules and analyses are integrated within ModelCenter™ from Phoenix Integration, Inc. ModelCenter is commercial off-the-shelf software for integrating multiple analyses, exploring the design space with visual aids, and optimization. Figure 2 shows a screen shot of RCDA as viewed in ModelCenter.

RCDA was originally developed for military transport helicopters; sizing a civilian transport required four minor updates to the RCDA system. Weight trends were modified to reflect the Model 360. This ensured that optimized designs reflected the technology and mission of the baseline civil transport. Sponsons were removed from the geometry engine to reflect the Model 360 lines. A civil cost model replaced the military model. Finally, a noise module was integrated. This module provided a relative assessment of overall sound pressure level for a forward observer as a function of blade thickness and advancing tip Mach number.

The rotorcraft industry has matured conceptual design processes, like RCDA, to include optimization of select configurations. The core process is a sizing code like HESCOMP, which uses low-fidelity analysis methods and trend data for weights and costs, which are based on high-fidelity analysis or actual aircraft data. The main advantage is the fast computational speed that allows thousands of designs to be examined. One disadvantage is that trend data may not be accurate or applicable if the design under study

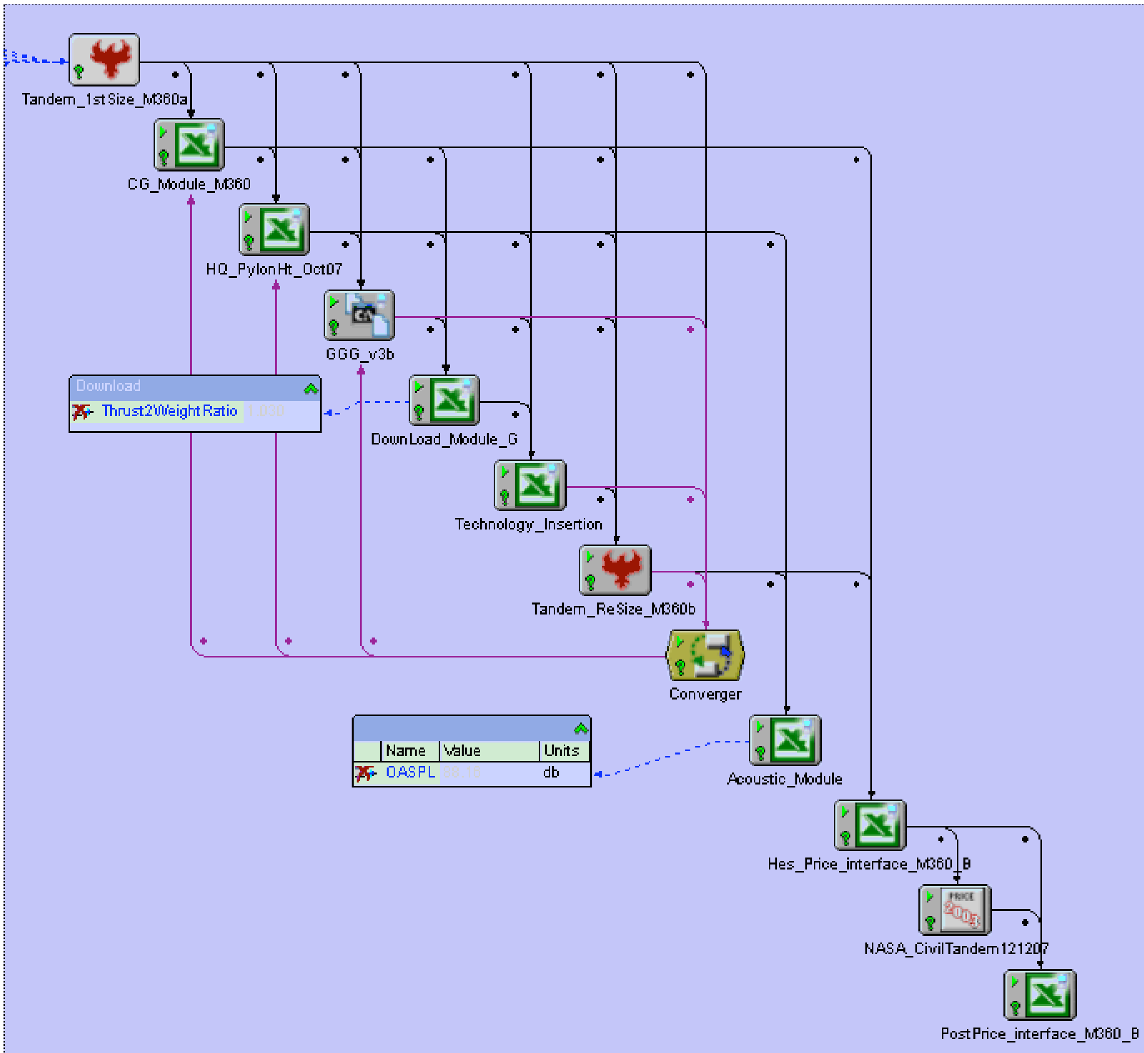


Figure 2. RCDA screen

is too different from the designs on which trends were based. This potential shortcoming is mitigated by re-examining the trends with new data or new analysis.

2.3. Context for High Fidelity MDAO

For an integrated optimization system, design variables, objectives, and constraints should be those that would be considered at the same time in the design cycle. It would not make sense, for example, to size a lag damper lug at the same time as choosing the number of blades. The latter decision is made early in the design cycle, the former is made in detailed design. Determination of a context for optimization was part of this study.

Moving high-fidelity analyses into conceptual design is an emerging trend. Use of high-fidelity methods earlier in the design cycle is an attempt to mitigate uncertainty in the technical performance of a particular design and more completely fathom the design before downselecting from among configurations. Ideally, decision making would have the information available from a fully-developed design. The following example of fuselage aerodynamics shows how high-fidelity analysis can be injected into the current sizing system and how the lines between conceptual and preliminary design are blurred:

At the conclusion of a conceptual helicopter sizing, outer mold line (OML) definitions do not exist beyond broad parameters like length, width and height. Aerodynamic data used in sizing is therefore based on historical information or on simplistic relationships involving gross geometric parameters. Greater aerodynamic fidelity in conceptual sizing could have a significant impact on the outcome. A refined aerodynamic analysis, though, requires greater geometric definition. In the framework of Boeing's RCDA process, an OML is produced that can be utilized for high fidelity engineering analysis, Figure 3. With the OML, aerodynamic analyses can impact conceptual sizing by improving the fuselage drag and download estimates. The aft fuselage shape plays a major role in determining the fuselage drag. Tailoring the shape for aerodynamic efficiency will improve the fidelity of the RCDA sizing and also produce initial geometry for preliminary design. This example is illustrative only; note that aft fuselage tailoring is currently not an element of conceptual sizing.

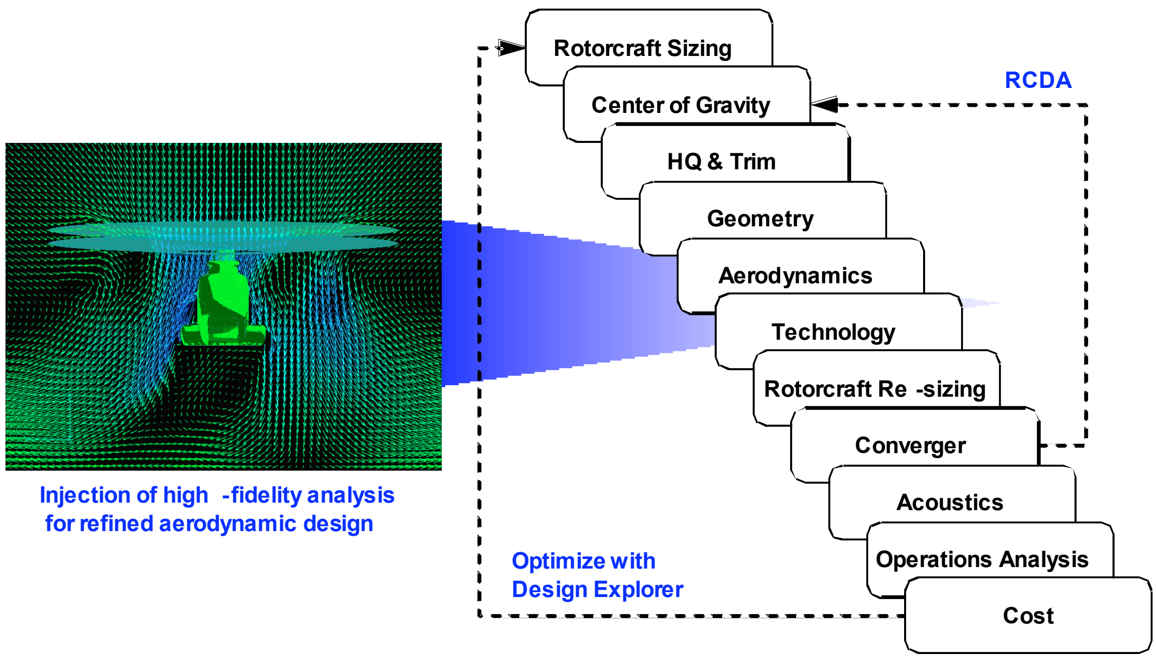


Figure 3. The Boeing RCDA Process using High-Fidelity Analysis to Support Sizing

High fidelity analyses are used throughout all design phases. Exploratory research employs high-fidelity analysis and/or testing as appropriate to validate new concepts for use in future designs. Conceptual design can and should move from time to time into what could be called "high-fidelity", both in terms of the level of definition of the design and the level of analysis. That is, certain aspects of a design need to be probed carefully for decision making. This can be thought of as better substantiation for concept selection and refinement, which is the product of conceptual design. The previous example indicates an isolated move into preliminary design for a key subsystem for verification of the concept, but not preliminary design of the entire aircraft. Preliminary design employs high-fidelity analysis to provide performance and loads estimates, as well as stresses, natural frequencies, stability, and others. In detailed design high-fidelity analysis is used to verify the design, especially detailed component stresses. High-fidelity analysis is also used to support testing with pre-test predictions and post-test investigation and to support research for validating new technology in exploratory research.

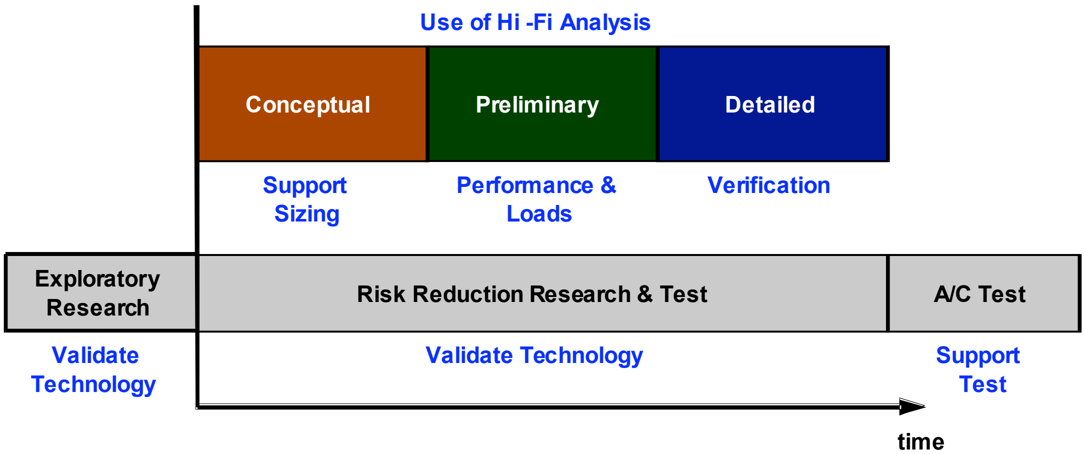


Figure 4. High-fidelity analyses in the design cycle

Three aspects of the design process are considered together to set the context for a framework for MDAO with high-fidelity analysis: First, optimization requires design freedom, which is higher in conceptual design and lower in detailed design. Early stages of Preliminary Design retain sufficient design freedom to warrant continued use of optimization. Second, high-fidelity analysis is usually associated with an advanced design stage, where the level of definition is also very high. Third, early stages of design are multi-disciplinary by necessity, and later stages are more segregated. Early PD is when multi-disciplinary optimization with high-fidelity analysis can benefit design and needs to be developed for the rotorcraft industry. Optimization should be targeted toward an early phase of design, when the majority of life cycle cost is determined.

Key decisions and process deliverables also place the context. Figure 5 shows the design timeline with placement of the proposed “Framework for Multidisciplinary Analysis, Design, and Optimization with High-Fidelity Analysis Tools” in early PD. Key decisions and process deliverables that precede and follow the framework are also shown.

The largest portion of determined cost, which is locked in by the intrinsic nature of the design, is set in the earliest phases of design, Figure 6. Because of this, conceptual design is where techniques for robust design can be most fruitful. Conceptual design involves an inherently multi-disciplinary exploration of the design space (optimization); however, while high-fidelity analyses support conceptual design, high fidelity methods are not used as design exploration tools, but rather as verification of a design point. The framework for MDAO that is the subject of this research can potentially be pulled into conceptual design to support the concept decision making process if warranted, but this does not change the boundary points for the framework, namely: start with a refined definition, and end with an optimally-sized or optimally-shaped version of that refined concept.

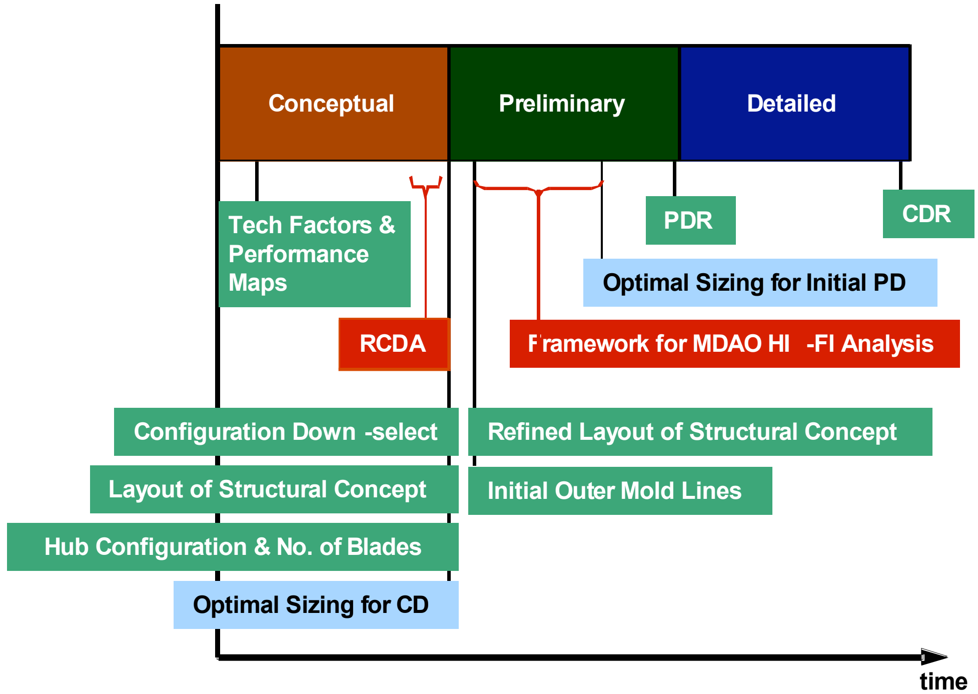


Figure 5. Context for MDAO framework

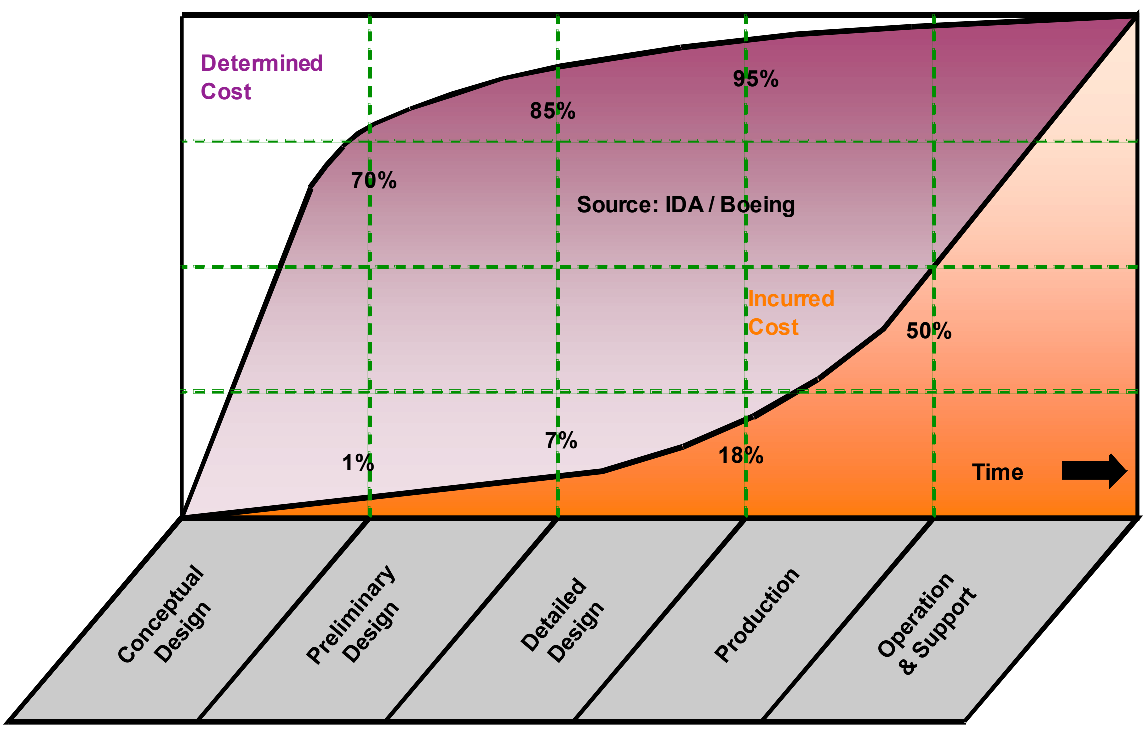


Figure 6. Cost in the aircraft life cycle

Decisions related to hub and number of blades are critical to defining a concept and must therefore be determined in CD. Hub type defines control power and basic stability characteristics as well as fundamental aeromechanical behavior. Hub design also contains drivers for cost and maintenance such as inspection intervals and bearing maintenance. For the tandem configuration, hub design is important for setting limits on rotor overlap to maintain blade clearance. Blade count is driven by cost, maintenance, hub packaging, noise, and aerodynamic performance. Like hub design, blade count is important for setting rotor overlap limits, and must therefore be determined with aircraft configuration and sizing optimization.

2.4. Design for Manufacturing, Cost, and Requiements

Design for manufacturing (DFM) entails consideration of a number of aspects of the design; some are more applicable to preliminary design and some more applicable to detailed design (e.g. mistake-proof design and ease of assembly). Simplification and standardization are essential elements that may drive a reduction in the number of design variables. An example is airframe stringers that are the same everywhere, even though they may be oversized in most regions. Design for ease of fabrication may also provide guidance that effectively constrains the design space. For example, a square blade is easiest to build, followed by a constant chord with a tapered tip; swept tips are more difficult. Spur gears are easier than helical gears. Selection or limitation of tip shape, gear shape, and so forth provide an inherent management of cost or manufacturability. Cost as an objective includes many aspects of DFM. Cost and design for manufacturing are probably most effectively implemented within a preliminary design optimization context by providing guidance to constrain the design space, limit choices of material selection, and bound the geometry where certain shapes might be too extreme.

Experience is essential, especially knowledge of company practices and processes. Exploratory research contributes to the experience base and is most valuable for new concepts. This is an example where research provides a "going in" approach to design so that design for cost and manufacturing are inherent in whatever design is being optimized.

It is well understood that any design is shaped fundamentally by requirements. Requirements have three main sources: customer needs, regulations, and internal design standards. Customer requirements are sometimes soft as in a performance capability that would be nice to have but are not essential to meet. Requirements are manifested in the design process, especially in optimization, by defining the so-called "ground rules", which really means the design objectives and constraints.

Many requirements are built into the conceptual design process. Most obvious are payload and range, and block speed. Customer concerns about cost drive direct operating costs (DOC) and acquisition cost. Consideration of these is built into the conceptual design and sizing process either explicitly by a direct computation or implicitly through design rules of thumb (stall boundary and one engine inoperative (OEI) performance are examples). Other requirements are more relevant to preliminary design. Safety factors are directly included in strength and life computations, and these are typical constraints for preliminary design.

For the purposes of this report, concepts for manufacturability and cost, and the architecture for managing requirements are embedded into the process of design problem formulation and will not be otherwise specifically addressed.

3. Generation and Optimization of Baseline Design

Project plans called for establishment of a baseline aircraft to be used to define the context of Preliminary Design as compared to Conceptual Design. Generally no clear distinction exists to mark the transition from one phase of design to the next; however, to frame the PD problem and provide a context for this study, the transition point was established as the final result of conceptual sizing from the RCDA system. Thus the baseline provided a realistic and tangible conceptual design to be held in view while considering how to frame the continued problem in Preliminary Design.

The Model 360 civil transport, Figure 7, was selected as a baseline aircraft [11]. Configured for 30 passengers, the 36,000 pound gross weight helicopter is designed to a range of 315 nautical miles at a maximum cruise speed of 200 knots. To explore the effect on design sizing a noise reduction requirement was added to the design mission.

Figure 7. The Model 360 civil transport aircraft

3.1. Concept Optimization

Implementation of formal optimization requires selection of optimization criteria and constraints that can be computed by analysis from a set of specific fixed and variable design parameters. Decision makers may vary the design problem as requirements are better understood or as changes are more difficult to make, especially moving from concept selection and refinement into PD. The essential aspect of formulating an optimal design problem is to choose an objective to minimize (or maximize). Multiple objectives are usually considered by decision makers simultaneously yet independently so that trade offs can be understood. Attempts to consolidate objective functions into one do not allow decision makers to discern the trade space. Aircraft performance metrics for optimization can be chosen from among such things as range, cruise speed, or payload; the product of speed and payloads are part of a combined metric called productivity. An aircraft that exceeds baseline performance goals can potentially increase its value but quantification of the value cannot be easily defined.

Weight is a popular design objective in subsystem design. Decreased system weights can improve aircraft performance. Furthermore, weight can be a surrogate for cost, given a fixed state of technology to achieve the design. Operators of fixed wing civil transports typically attempt to minimize seat-mile costs. The metric is simple and relevant to a civil transport rotorcraft though does not reflect the relatively high purchase cost of rotary wing aircraft. Development cost is critical both to military and civilian aircraft and is passed on in acquisition cost.

Two objective functions were employed for sizing the 30 passenger civil transport rotorcraft: cash direct operating costs (DOC), and acquisition cost. They were chosen because they reflect key elements of life cycle costs relevant to operators. They were retained as separate objectives to see the trade space. Ultimately, choice of an objective function for optimization should be made to reflect goals and desires of the customer. Development of disciplinary design problems described in Section 4 discusses continued development of objective functions in disciplinary PD.

Sizing optimization also included certain constraints, most of which were derived from the capability and performance of the Model 360 civil transport as described above: payload equal to 30 passengers, range equal to or greater than 315 nautical miles, max cruise speed equal to 200 knots. A noise constraint was added to a second optimization case to see the impact of a modest noise reduction below the optimized baseline: overall sound pressure level (OASPL) 3 dB less than the optimized baseline. The mission for sizing with RCDA is outlined graphically in Figure 8.

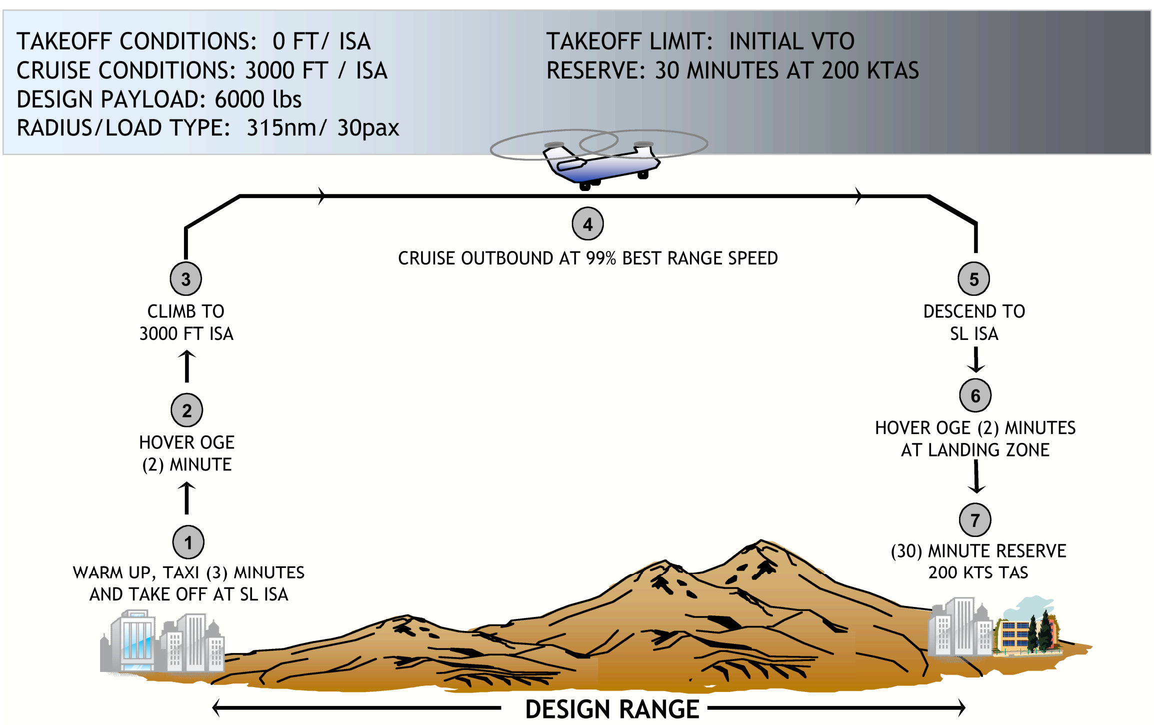


Figure 8. Mission for concept sizing

Within the refinement of a selected configuration are a few key sizing variables to optimize the configuration for the given mission. They often include (as in this example), but are not limited to, rotor radius, rotor tip speed, and number of blades. Parametric optimization using the first two was performed to examine optimal design without and then with the constraint on noise. One key constraint was imbedded implicitly: overlap of the rotors is a fixed ratio to the rotor radius, 30 percent for a four-bladed rotor.

Design of experiments provides response surfaces that can be used to explore the design space. Response surfaces are surface fits that are generated from select choices of design variables called response surface designs, which provide the best sampling of the design space to minimize the error of the response surface. As surface fits, they are relatively quick to interrogate, which makes it easy to generate contour plots.

Contour plots from the baseline design scenario are shown in Figure 9 and Figure 10. Shaded regions represent designs that are infeasible, first in minimum cabin length to accommodate 30 passengers, next in maximum noise with 3dB reduction from the baseline. The green contour line shows cabin length, blue contours show direct operating costs as a ratio relative to the baseline design, black contours show acquisition cost as a ratio relative to the baseline, and red contours show overall sound pressure level. The figures also have a mark in the center, 49.7 ft diameter and 700 feet per second tip speed, showing the original design based on the Model 360 passenger transport marked Baseline.

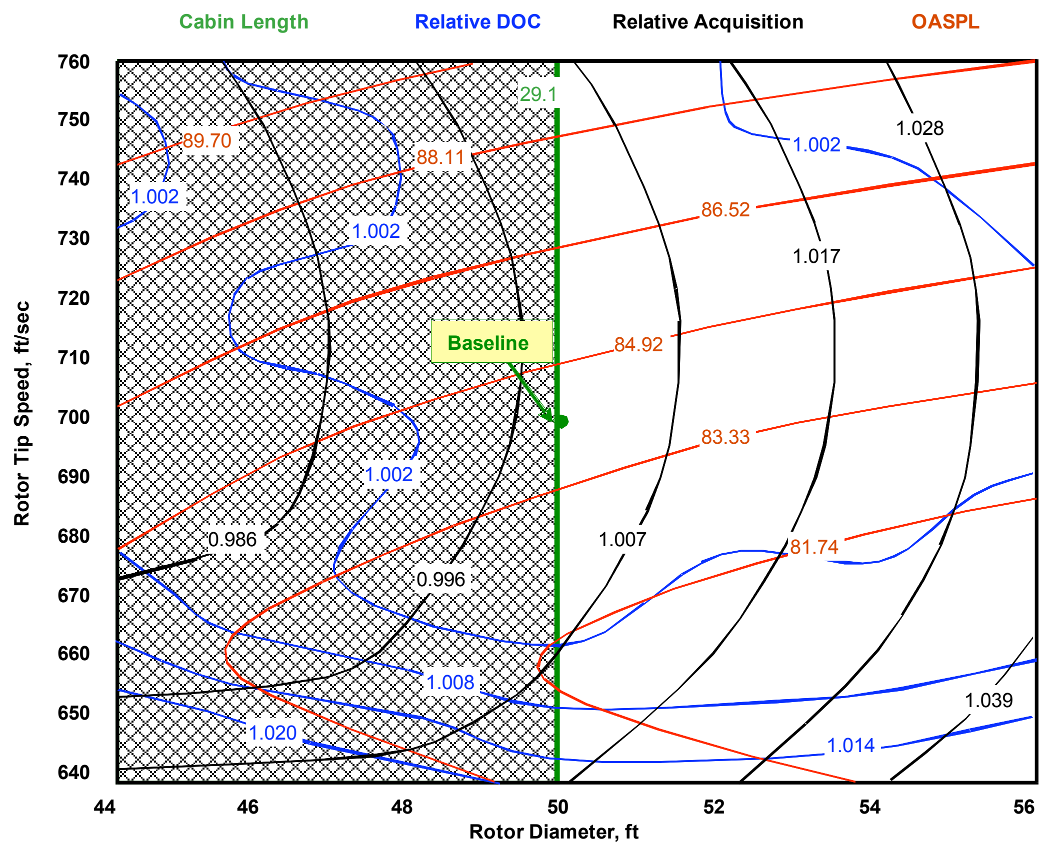


Figure 9. Tandem rotor design contours without noise constraint.

Acquisition contours show a predictable trend with increasing cost versus rotor diameter, which is equivalent to fuselage length through the fixed rotor overlap ratio. DOC contours near the Model 360 baseline are fairly shallow, which accounts for their irregular shape as generated from a response surface. They become much steeper at low tip speeds, which is inline with common trends of increase fuel consumption with lower tip speed. Noise contours also show a predictable general trend of lower noise with lower tip speed. This trend is complicated by the fact that lower tip speeds require higher solidity, which drives up blade thickness and thereby noise.

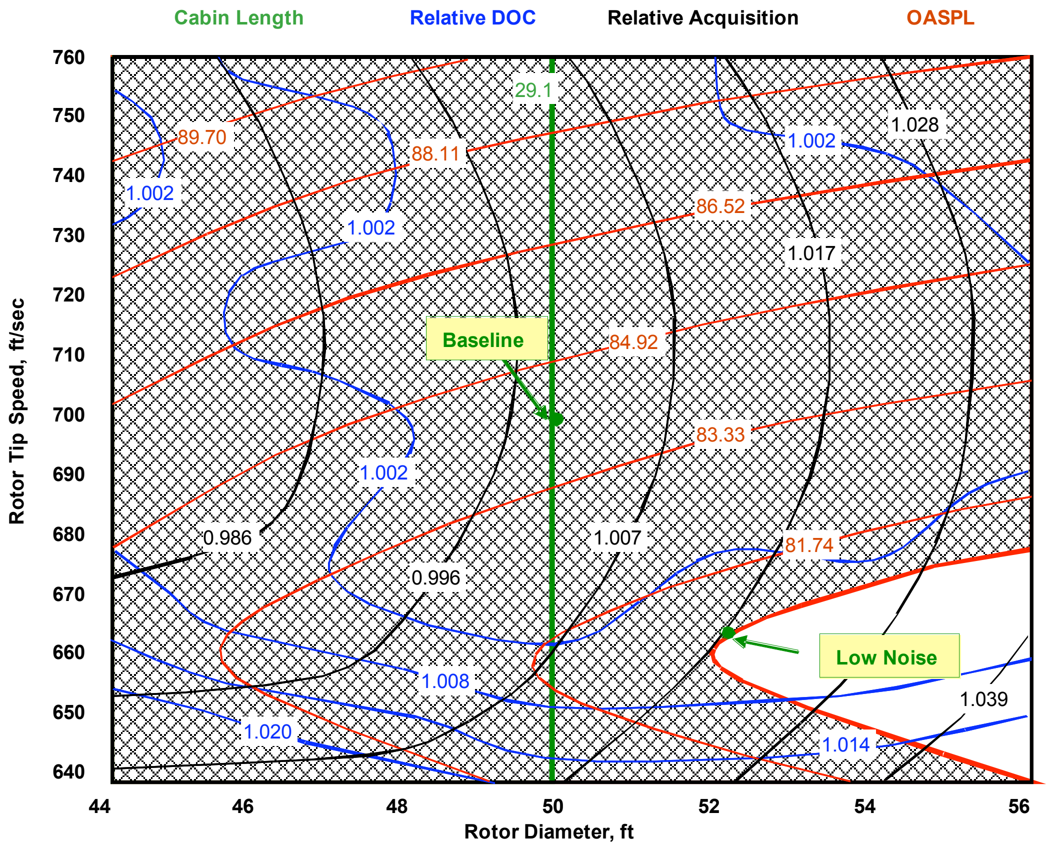


Figure 10. Tandem rotor design contours with noise constraint.

A comparison of key attributes of the baseline and low-noise designs is show in Table 1. Increases to empty and gross weights are about 1,000 lb. Relative costs are slightly higher for the low-noise design which reflects the modest goal of 3 dB reduction, which is just perceivable.

Table 1. Comparison of baseline and low-noise designs

	Baseline	Low-Noise
Rotor Diameter, ft	49.7	52
Tip Speed, fps	700	666
Gross Weight, lb	36,300	37,500
Empty Weight, lb	23,000	24,000
Solidity	0.109	0.113
Disk Loading, psf	9.37	8.81
Installed Hp	8,030	8,358
Fuel, lb	6,310	6,470
OASPL, dB	84.15	81.15
Relative Acquisition Cost	1.000	1.017
Relative Cash DOC	1.000	1.004

3.2. Moving From Conceptual Design to Preliminary Design

While phases of design can be defined by certain milestones, transitions are typically blurred as the design moves toward an increasingly high level of definition. For the purpose of this research, CD ends with a selected configuration that has been optimally sized by a system like RCDA with a commensurate level of definition. This definition includes the following: number of blades, rotor diameter, fuselage dimensions, tip speed, engine (number and type), gross engine placement, fuel tank placement, technology insertions (structures, rotor, flight controls, etc.), drive system macro-level placement, and gross structural concepts. Several key physical parameters that define the conceptual design are shown in Figure 11. High-fidelity MDAO problems that are framed in ensuing sections are based on a step increase in the level of definition above this—at least an order of magnitude. Additional assumptions to bridge this gap are described in this section.

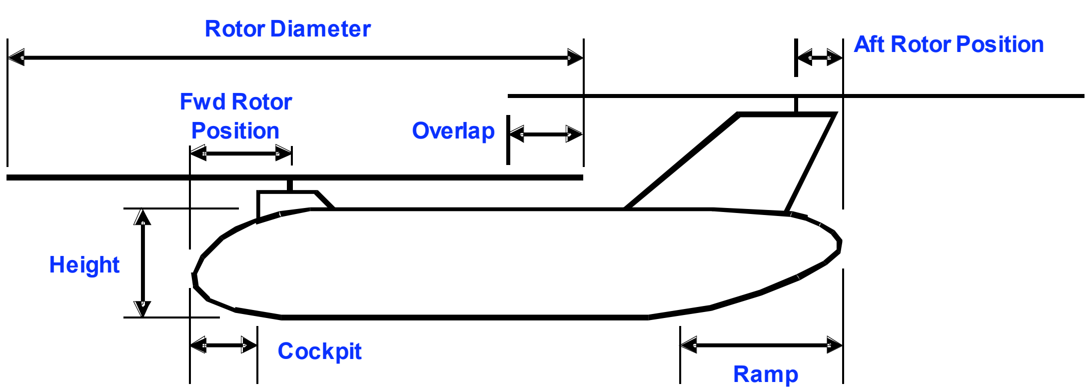


Figure 11. Key parameters from conceptual design

Some conceptual design parameters may be implicit. For example rotor maps might imply certain technology, tip shape, twist distributions, and so forth. Technology factors often imply specific concepts, for example active flow control. An engine cycle deck (black box engine performance program) may likewise imply a very specific engine. Weight and cost allocations are parameters that also contribute to the definition of a conceptual design, but have no direct physical meaning. Preliminary design begins with the addition of a substantial amount of detail above what comes from the CD process.

At CD, the rotor is defined primarily by radius and solidity. In preliminary design the aerodynamic configuration of the blade is defined by span-wise distributions of chord, twist, and airfoil shapes. Structural design is defined by spar shapes, including transitions, ply lay-ups including material selection, ply angles, ply drop-offs or ply additions, tuning weight placement, balance weights and retention, blade-hub interface, and so forth. A typical blade definition can require several hundred parameters at a mature stage, and at least fifty for early assessments.

Weight trends for CD are based on analysis of actual aircraft with appropriate adjustments for the configuration under consideration. Weight targets for individual subsystems need to be replaced with something more tangible: a drawing. The drawing at the PD level shows how large parts and payloads will be integrated into the airframe. Major load paths will also be shown, but not sized. This drawing demonstrates that the sizing produces a design that can work and can fit what it needs to onboard. An example of the transition from geometry to design is shown in Figure 12.

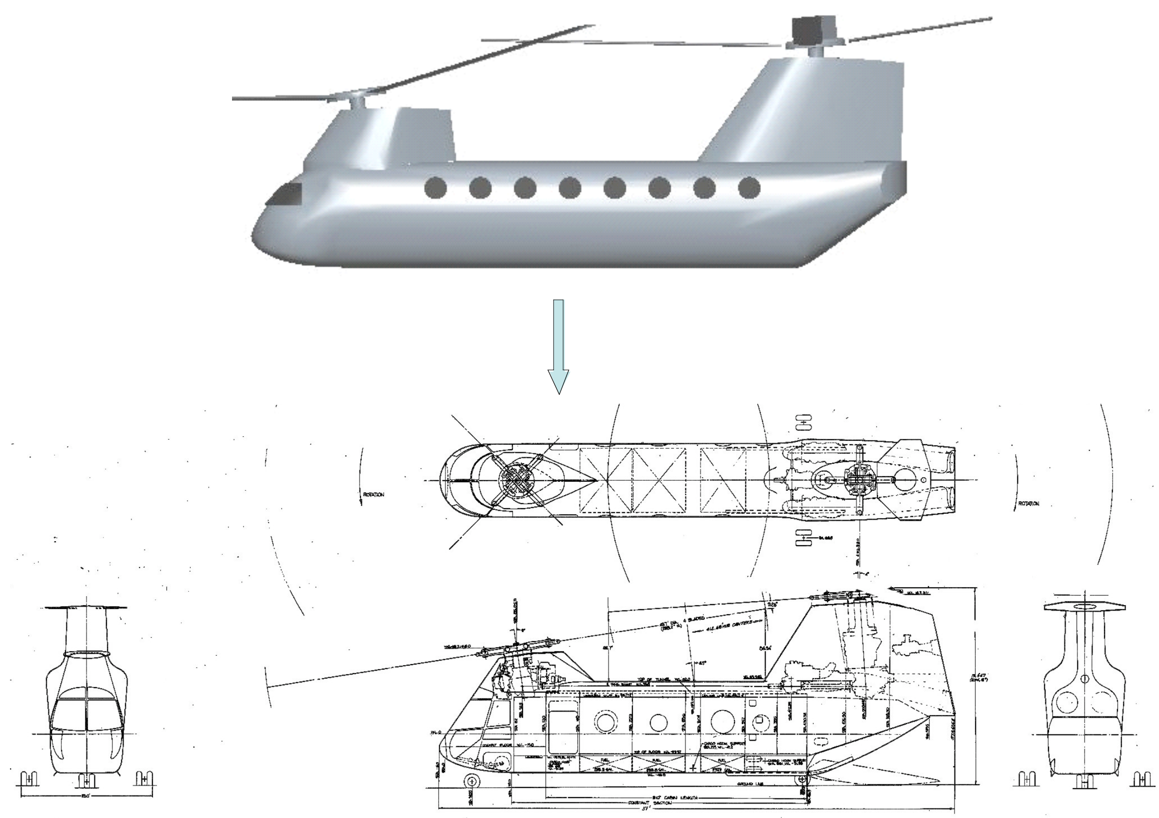


Figure 12. Conversion of geometry to design

One of the biggest steps moving from CD to PD is the concept for arrangement of structure, especially for the fuselage. Major frames for transmissions, landing gear, engines, payload, fuel, and so forth must be added. Minor frames must also be added, as well as, stringers, doors, and windows. Arrangement of these items must be conceived and drawn by an expert designer who has knowledge of integration and load paths. This process begins early in conceptual design and leads to an increasingly refined version of design layout. It is necessary not just to show structural layout but to show layout of all key components: transmissions, engines, rotor blades, payloads, and so forth. Topological optimization can be applied to this process.

4. Individual-Discipline Design Problems

Understanding the MDAO problem first requires a clear view of the disciplines involved. Several disciplinary experts were solicited for their view of what an optimal design problem would be if isolated from cross-discipline or multiple subsystem considerations. Each prepared a statement of an optimal design problem from their view, initially without regard to how to execute or how to integrate the design problem with other disciplines or subsystems. Problem statements included the following: objectives to be minimized or maximized, design variables (parameters that an optimization would change), constraints, and fixed design parameters. Emphasis was placed on forward-thinking extension of current practice, especially regarding inclusion of design variables that are not traditionally under the purview of the expert's functional area. This extension forced consideration of interdisciplinary aspects of design that may have been overlooked with a single-discipline approach. The process produced individual discipline design problems that exhibited rich multi-disciplinary couplings.

Five core disciplines were given primary consideration: aerodynamics, dynamics, airframe, propulsion, and drive system. Ancillary consideration was given to noise and flying qualities, especially with regard to how noise and flying qualities design metrics are most directly coupled to the project's core disciplines.

High-fidelity analysis is fundamental to preliminary design in most disciplinary areas. Design decisions that come from CD can and should be further refined in PD because high-fidelity analysis that is incorporated into an integrated optimal design system should yield additional improvements to the aircraft. CD should, however, refine the design so that additional changes are small.

The following subsections take each disciplinary area and lay out rationale for individual discipline design problems followed by a simple statement of an optimal design problem for that discipline. Even though individual discipline problems were solicited, they are not fully segregated, which reflects attention to the true multidisciplinary nature of rotorcraft design. Full integration of these design problem statements will follow in subsequent sections. These design problem formulations are not exhaustive, but represent a comprehensive view of the scope of a rotorcraft MDO. The objective of this section is to make a comprehensive summary of the scope of the individual design problems so that appropriate optimization strategies can be determined. The key factors are the number of objective functions (single vs. multi-objective) and constraints, the approximate number of design variables (problem size), and the types of design variables (continuous, integer, discrete, and categorical).

Problem formulations presented herein include various design objects and constraints, all of which are derived from the computed output of analysis codes. They also include design variables, which are either inputs to analysis codes or are transformed into inputs. Of particular note are shape variables that are used in shape optimization. Shape optimization is a natural complement to design using analytical methods. Shape optimization employs a number of control points and geometric parameters about which a smooth and well-defined shape can be fit. Generally, a larger number of parameters can produce more general shapes. In optimization a larger number of parameters equals a larger problem size, so the choice of defining parameters must be chosen for the smallest count that retains the ability to generate geometric shapes with the needed generality. Additional requirements for parameterization will be discussed in the section on analysis.

4.1. Rotor Aerodynamics

Though aerodynamic interactions exist between the rotor and airframe, aerodynamic design of the airframe and rotor systems are largely decoupled. (A distinction is made here between aeromechanical phenomena versus factors that would influence the design to be one way rather than another. For example, rotor wake impingement on the airframe would not drive a decision on blade twist distribution, but pylon height may be increased to alleviate rotor-body aerodynamic interference. This will be expounded in Section 6). Aerodynamic design of a rotor is a formidable task by itself because of the diverse and complicated flow field. The rotor must perform well in environments including retreating and advancing blade in forward flight at various advance ratios and in hover. Often it is possible to simplify the rotor design process by taking advantage of the nearly two dimensional flow over a majority of the blade. This is convenient for airfoil shape design. For establishing the twist distribution or designing blade tip shapes, a three-dimensional approach is appropriate.

Optimization goals for rotor aerodynamic performance depend on the mission. Blade design can easily favor forward flight at the expense of hover performance and visa versa. Vertical lift is essential for helicopters, but hover may or may not be the most important mission segment. The difference between power available and rotor power required must allow both vertical flight and forward flight. Optimization could favor minimizing hover power, or minimizing cruise power. Alternatively they could be equally weighted. Hover and cruise power therefore can be viewed as multiple performance objectives, or as one performance objective and a performance constraint.

The rotor must perform well as a system and therefore it is ideal to optimize the elements of the rotor simultaneously. In other words, twist, chord, sweep, taper, anhedral and airfoil shape, when optimized together, should produce an optimal rotor. The large dimension design space, multi-objective nature of rotor performance, and long run times hinder aerodynamic optimization.

Rotor Airfoil

Airfoil optimization is traditionally handled in the exploratory research phase, which means that airfoil research will yield new designs from which to choose for any new development. This type of optimization is limited by its two dimensional nature, which does not account for actual three dimensional flow fields on a rotor. Suitability for use in a particular design requires analytical evaluation and/or testing of the application to a particular blade, which is a preliminary design effort. Analytical methods are attractive because of reduced reliance on wind tunnel testing and the ability to explore a larger design space though shape variables. This allows airfoil selection to move beyond discrete choices to multi-disciplinary optimization in preliminary design.

The rotor experiences two-dimensional flow over a large portion of the blade; therefore it is possible to decouple airfoil shape from the other parameters that make up the spanwise characteristics of the blade. (Note that blade structural design may necessitate a thicker airfoil for structural efficiency. This does not, however, dictate details of the airfoil shape.) This approach has some advantages, namely:

- The target performance of an airfoil is generally well-understood
- High-fidelity airfoil analysis runs relatively quickly.
- Many flight conditions can be considered simultaneously.

- Experimental verification of airfoil performance can be done cheaply before three-dimensional blade design is initiated.

- Tables of airfoil performance are a large part of many rotorcraft analysis processes.

Airfoil optimization has competing aerodynamic requirements stemming from various operating conditions. These have been documented by Dadone [12]. Among the key criteria are:

$$\text{Maximize } C_{l\max} \text{ at } M_\infty = 0.4$$

$$\text{Maximize } M_{DD} \text{ at } C_L = 0.0$$

$$\text{Maximize } L/D_{\max} \text{ at } M_\infty = 0.6$$

The first two are forward flight requirements for the retreating and advancing blade respectively. The third is a hover requirement. Constraints on the airfoil section can include the magnitude of the pitching moment, a minimum thickness, location of the aerodynamic center, and radius of the leading edge. Other less quantitative requirements exist such as ensuring the blade stalls from the trailing edge first. Airfoil sections that have these good characteristics are appropriate for the "working" section of the blade, between 70% and 90% of the rotor radius.

Candidate sections that have large pitching moments will adversely affect pitch link loads. Pitch link loads include all aerodynamic and dynamic loads integrated down the blade and reacted by the control system. Therefore adverse pitching moments at one particular blade section can be compensated by favorable pitching moment elsewhere. The pitching moment constraint can be somewhat relaxed during an airfoil optimization at one section provided an optimization for a different working section can make compensation. (An integrated aeroelastic design has the potential to mitigate adverse loads from pitching moments.)

Table 2. Rotor airfoil objectives

Objective	Notes
Maximize $C_{l\max}$ at $M_\infty = 0.4$	Retreating blade performance metric
Maximize M_{DD} at $C_L = 0.0$	Advancing blade performance metric
Maximize $L/D_{\max}$ at $M_\infty = 0.6$	Hover performance metric

Table 3. Rotor airfoil design variables

Constraint	Number of design variables	Type of design variables	Notes
Shape control parameters	10-20	Continuous	
Estimated total	10-20		For each airfoil

Table 4. Rotor airfoil design constraints

Constraint	Number of constraints	Notes
Airfoil thickness	1-2	Driven by spar thickness requirements
Pitching moment	1	To reduce pitch link loads
Location of aerodynamic center	1	
Trailing edge stall	1	Produces more benign stall as compared to abrupt leading edge stall
Leading edge radius	1	Driven my material properties
Estimated total	5-6	For each airfoil

Rotor Blade

Design of a blade planform involves finding optimal spanswise arrangements and distributions of built-in twist, chord, sweep, anhedral, and airfoil selection. Ideal twist and ideal chord distributions can be computed using basic aerodynamic principles for a hovering rotor, but these computations use simplifying assumptions that may not apply. Furthermore, design for forward flight and maneuver brings additional requirements that change the definition of optimum. Airfoil design was discussed in the previous section. It was noted that with reliable computational methods airfoil design could be brought into the preliminary design level. This subsection will assume a fixed set of airfoils chosen for their favorable properties.

Twist, chord, sweep, and anhedral are often parameterized in some simple way. Design of the V-22 blade used a weighted balance between ideal twist for cruise and ideal twist for hover, which is a single, parameter approach. Figure 13 demonstrates anhedral parameterization using the control points of a spline. A slightly more sophisticated approach for sweep is also shown in Figure 13. Blade tip design is especially critical because of high dynamic pressure, three dimensional flow, and compressibility effects at the rotor tip. It is especially true here, as it is for all parameterization, that the goal is to provide the necessary generality with the fewest parameters.

A design that has been optimized in one flight condition may be inferior in another. Robust aerodynamic design is considered by analyzing off design conditions. This principle is illustrated by an advanced tip example in Figure 14. It is clearly seen that the design has a higher peak figure of merit than the straight blade; however the advanced shape quickly stalls after its peak. Conclusions as to the value of tip would be different depending on which C_T/σ was analyzed. The performance of the blade must also be characterized for other atmospheric conditions (i.e. cold weather) and for different advance ratios of forward flight.

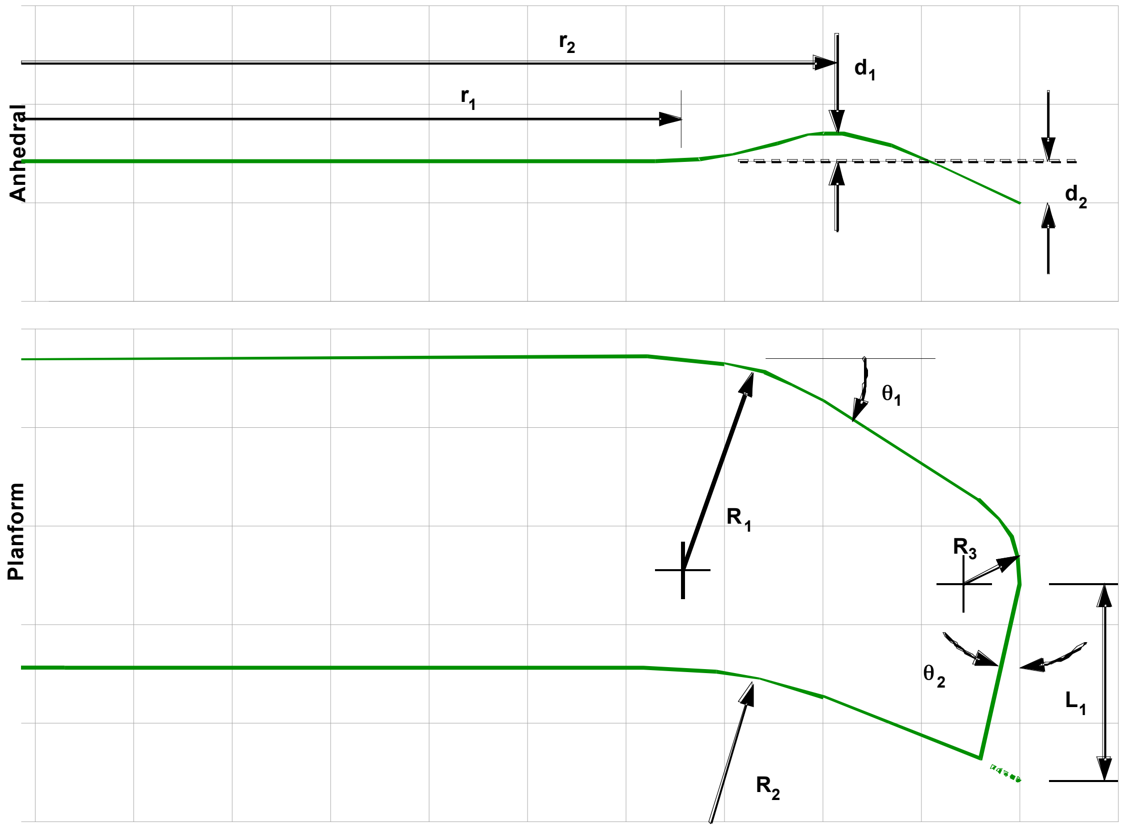


Figure 13. Typical parameterization schemes for anhedral and sweep

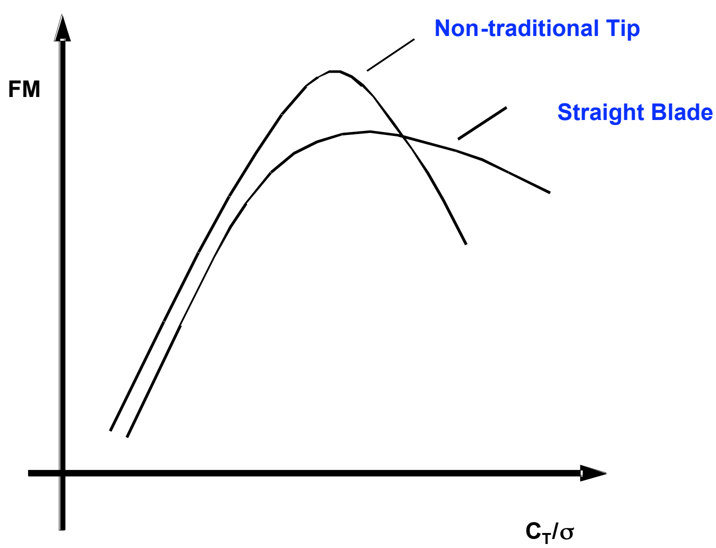


Figure 14. Hover performance of an advanced tip versus traditional tip blades

Table 5. Rotor blade objectives

Objective	Notes
Minimze cruise power	Multiple airspeeds
Minimze hover power	Multiple points

Table 6. Rotor blade design variables

Design Variable	Number of design variables	Type of design variables	Notes
Twist distribution control parameters	1-10	Continuous	
Chord distribution control parameters	1-10	Continuous	
Sweep distribution control parameters	1-10	Continuous	
Anhedral distribution control parameters	1-10	Continuous	
Airfoil spanwise placemnt	2-3	Continuous	Depends on number of different airfoils
Estimated total	1-45		For each airfoil

Table 7. Rotor blade constraints

Constraint		Notes
Cruise power	1-3	Alternative to use as objective
Hover power	1-3	Alternative to use as objective
Blade area or solidity	1	Maneuver limit

4.2. Airframe Aerodynamics

Fuselage Download

In the current optimization environment of RCDA, download for a tandem helicopter is approximated by assuming a two-dimensional drag coefficient for the fuselage cross section, which varies between candidate designs based on differences in fuselage width and length. The assumed drag coefficient is fixed among the candidates, which improperly implies a conservative download assessment for a clean fuselage or an aggressive download assessment for a poorly designed fuselage cross sectional shape.

An alternative to this approach is to introduce high-fidelity aerodynamic methods to define an optimal fuselage cross section by reducing the effective drag coefficient under downwash. The drag coefficient assessment requires a sophisticated aerodynamic evaluation that can effectively distinguish the merits of one shape over another. Because the drag coefficient is a strong function of where the flow separates,

Figure 15, the analysis must incorporate the effects of viscosity and, specifically, model the boundary layer properly, as well as the large separated region under the fuselage.

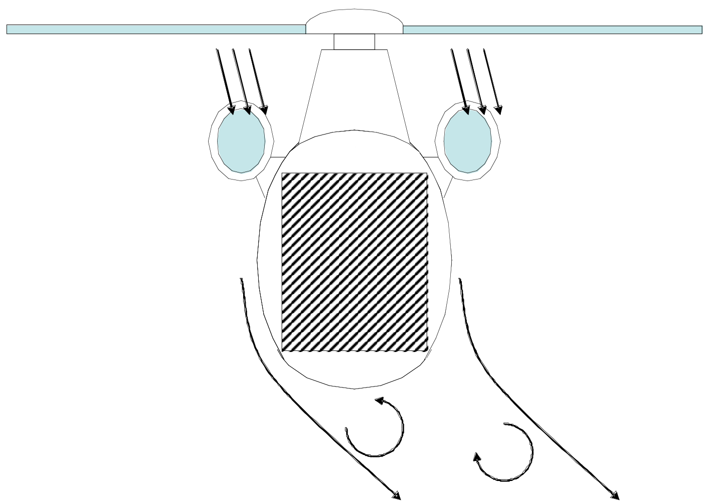


Figure 15. Separated region under a helicopter fuselage

The objective of the optimization problem is to minimize the vertical force directed in the downward direction. The vertical force can be minimized by changing the cross sectional shape. Design variables are the set (or subset) of parameters that define the shape. There are many ways to parameterize the cross section; coordinates of the control points of a NURBS curve is one, Figure 16. There are a few requirements that the parameterization should maintain, namely: small changes in the value of the parameters should produce small changes to the shape; changes in the value of the parameters should lead to expected changes to the geometry; the parameters should produce smooth shapes with ideal curvature continuity.

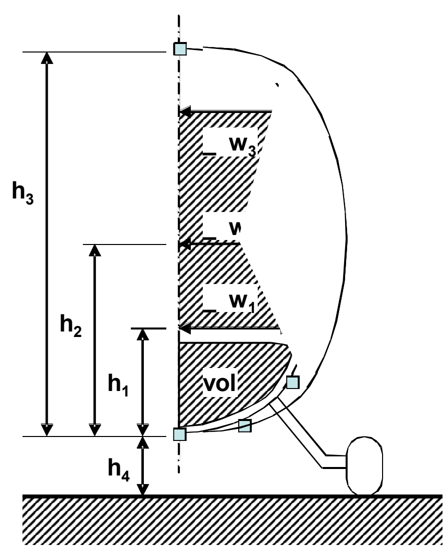


Figure 16. Design variables and constraints of a cross sectional optimization

Also shown in Figure 16 are examples of practical configuration constraints that the fuselage cross section area must accommodate. The most obvious is that the fuselage must encompass interior cabin dimensions. In addition to cabin dimensions, there might also be a volume requirement to stow luggage, fuel, retractable landing gear, avionics, and so forth. Landing gear design and crashworthiness requirements might also dictate a minimum height above the ground that the fuselage must maintain with a compressed landing gear.

Table 8 Fuselage download system objectives

Objective	Notes
Minimize veritcal force coefficient	Multiple fuselage stations

Table 9 Fuselage download design variables

Design Variable	Number of design variables	Type	Notes
Cross section shape control parameters	5-15	Continuous	One set for each fuselage station
Estimated total	5-75		1-5 fuselage stations

Table 10 Fuselage download design constraints

Description	Number of constraints	Notes
Width at various waterlines	2-5	Internal volume, one for fuselage station
Height above ground	1	Ground clearance, one for fuselage station
Cross section area for fuel volume	1	Internal volume, one for fuselage station

Fuselage Drag

Drag of the fuselage in forward flight strongly influences helicopter sizing. In conceptual sizing, the zero-lift drag of a fuselage is estimated based on the wetted area. In RCDA, the wetted area is accurately predicted from geometry that is produced after the initial sizing; subsequent iterations converge the sizing and geometry. Being based on wetted area rather than flow analysis, fuselage drag is still a first order estimate.

Fuselage drag can be minimized by properly shaping the aft section to minimize or eliminate regions of separated flow and reduce the strength of vortices along the ramp. The aerodynamic objective is to minimize drag over a small range of angles of attack where the aircraft is expected to cruise. Considering more angles of attack will produce a robust design to changes in operating conditions, however practical computing requirements might limit the number of terms to one or two:

$$\min \frac{D(\alpha_1)}{q_\infty} + \frac{D(\alpha_2)}{q_\infty} + \ldots + \frac{D(\alpha_n)}{q_\infty}$$

Possible variations to the aft fuselage section are shown in Figure 17. Shape control variables are used to alter the shape of the aft section (and sponsons, if equipped). Note that the length of the aft fuselage section is a parameter determined for payload integration and therefore remains fixed during this aerodynamic optimization.

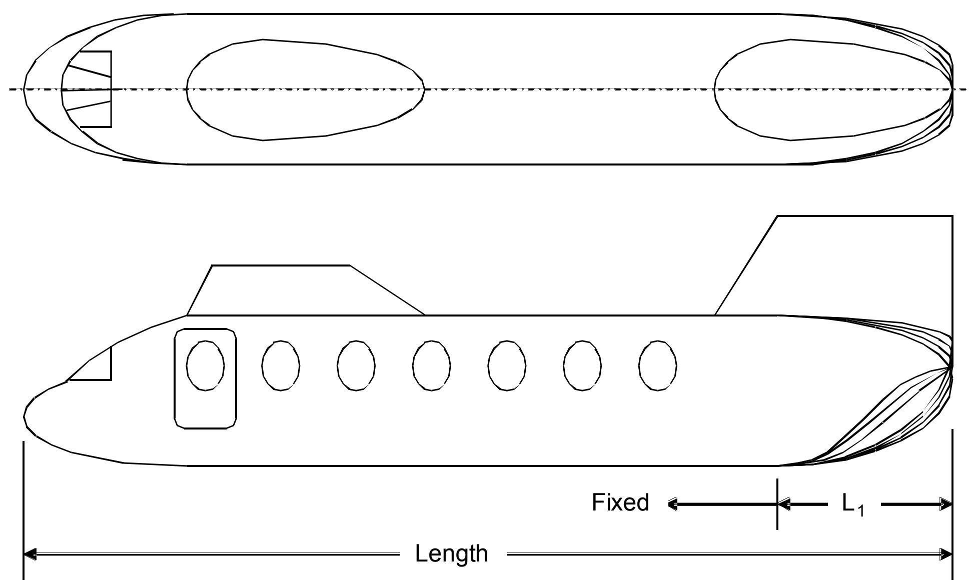


Figure 17. Aft section reshaping for improved fuselage drag

Table 11 Fuselage drag objectives

Objective	Notes
Minimize drag force coefficient	Multiple angle of attack

Table 12 Fuselage drag design variables

Design Variable	Number of design variables	Type	Notes
Aft body shape control parameters	5-15	Continuous	
Estimated total	5-55		

Table 13 Fuselage drag design constraints

Description	Number of constraints	Notes
Shape contraints for integration of subsystems	1-10	Integration of ramp door, straight hinge lines for landing gear doors, etc.

4.3. Rotor Dynamics

Design for vibration reduction is most effectively addressed at the main source of vibratory loads: the rotor. While aerodynamic loads from blade passage near the airframe contribute to vibration, rotor hub loads are the primary forcing function of fuselage vibration for most configurations. Rotor loads are the sum of loads at the root of each blade, so controlling the dynamic response of the blade is essential to controlling vibratory loads on the hub.

Certain aspects of rotor design that effect vibration are typically chosen at the conceptual design phase where cost and performance trade off studies are used to evaluate the overall design; most important are number of blades and type of hub (articulated, rigid, gimbaled, etc.). These choices are also made to influence control power and low-frequency dynamic properties related to aircraft flying qualities. Traditionally, these choices are considered parameters (i.e. fixed) in the rotor dynamics PD problem. Design aspects of the blade itself that affect vibration, a higher frequency phenomenon, are considered as design variables.

Because rotor loads are transmitted to the fuselage at multiples of the rotor frequency times the number of blades, blade design can target frequency placement to avoid resonant dynamic amplification. The typical design guideline for frequency separation is 0.2 to 0.5 per-rev from critical frequencies, which depend not just on the number of blades but also on the type of blade mode. Early application of formal optimization for vibration reduction was to change blade beam structural properties to achieve the required frequency separation [13]. Weller demonstrated that this approach is flawed because it does not consider modal hub shear [14].

Alternately, hub loads can be computed and minimized directly using comprehensive rotor analysis codes. As hub loads are the primary forcing function to fuselage vibration, reducing hub loads should lower fuselage response. This approach has been systematically examined and shown to work for design of a low vibration rotor. The objective function is the sum of hub loads times weighting factors that represents the relative strength or importance of the fuselage responses to each load. This approach has been refined, matured, and demonstrated in the work of Tarzanin and Young [15].

Direct estimation of fuselage vibration using coupled rotor and airframe models is anticipated to become increasingly reliable so that the metric for vibration reduction in rotor design can be the computed vibratory response of the fuselage. The rotor is typically analyzed as an isolated system that is grounded at the hub center. Dynamic interaction with the fuselage is assumed to be small and not to affect the dynamics of the rotor with any significance. Analyzing the rotor and airframe coupled systems is the ideal because it eliminates this assumption, but has many challenges from the larger number of degrees of freedom, finding aircraft trim, and converging a system that has rotating and non-rotating elements.

NASTRAN fuselage models can now be coupled to rotor models inside comprehensive codes allowing analysis of the total system and a direct computation of airframe vibratory response. This is one of the primary minimization goals for design of both the rotor and the airframe; however, use of a vibration metric requires a reliable NASTRAN model that is usually not available at early preliminary design.

Rotor blades are modeled as elastic beams with additional elements such as springs for pitch links, dampers, and hinges. Simplified lifting-line aerodynamics with vortex wake modeling provides external forcing for the structural elements. As elastic beams they are defined by their bending and torsion stiffness, neutral axis and shear center location, and inertial properties. As such, these beam properties are often the primary design variables; however, these parameters that define elastic beam elements cannot be arbitrarily changed. As an aerodynamic surface rotor blades are thin and wide. External dimensions are specified by optimal aerodynamic performance; that shape limits how far a designer can go to adjust the elastic blade properties. Furthermore, the various beam properties are not actually independent. For example, without changing structural material, a move to increase stiffness will generally increase weight. Similarly, additional material to increase bending stiffness will probably increase torsion stiffness. Composite tailoring provides additional design freedom that allows the beam properties to be more de-coupled.

Selection of critical flight conditions as design cases is difficult. Cruise flight is always a design condition because that is the longest mission segment, but vibration must be acceptable at all normal steady flight conditions. Vibration tends to increase with speed, and the increase can become quite steep as the rotor moves into dynamic stall and high ranges of μ and high C_T/σ. Airloads at these flight conditions are difficult to predict, which makes vibration prediction difficult. Low-speed transition is often a high-vibration flight regime because of the proximity of the rotor wake to the rotor; however, it is also a low-time flight condition where high vibration can be accepted. A rotor designed for low vibration at high-speed is often suitable for low speed. Vibration minimization at two flight conditions helps to insure a robust solution: normal cruise and either low-speed transition or combination of high μ and high C_T/σ.

Rotor-rotor aerodynamic interference can increase the strength of vibratory loads on the aft rotor thereby increasing vibration. This can be mitigated by increasing the vertical spacing of the pylons and rotor-rotor separation in trim, Figure 18. Parameters that effect aircraft trim are primarily under the purview of Flying Qualities but are noted here as potential design variables for the vibration problem.

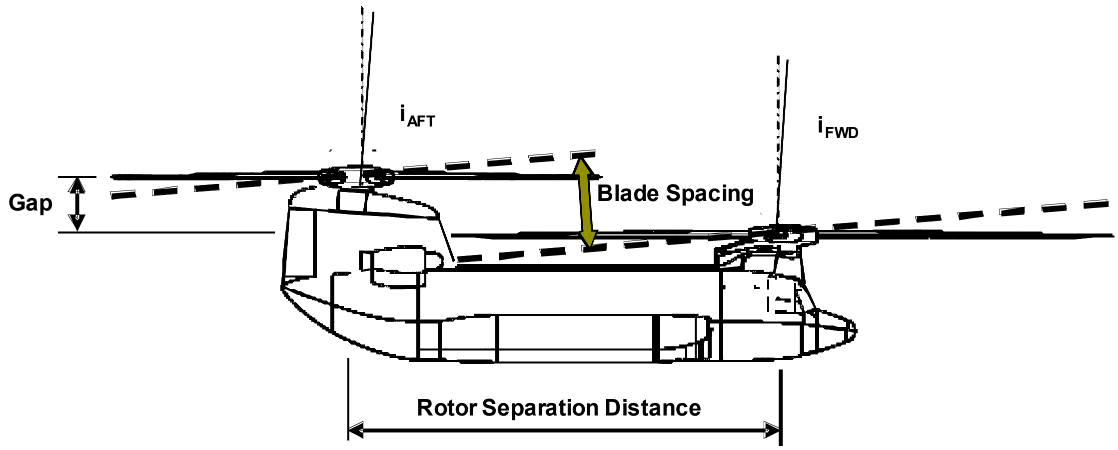


Figure 18. Tandem rotor blade spacing design variables

Table 14. Rotor dynamics objectives

Objective	Notes
Weighted sum of hub forces and moments at n/rev and 2n/rev at two critical flight conditions	Typical objective
Weighted sum of vibration responses at two critical flight conditions	Alternate objective

Table 15. Rotor dynamics design variables

Design Variable	Number of design variables	Type	Notes
Section masses	5-20	Continuous	
Section chord-wise center of gravity	5-20	Continuous	
Section flap-wise bending stiffness	5-20	Continuous	
Section chord-wise bending stiffness	5-20	Continuous	
Section torsion stiffness	5-20	Continuous	
Aft pylon height	1	Continuous	
Longitudinal cyclic trim			
Shaft angles	2	Continuous	
Blade sweep and droop angles	2	Continuous	
Built-in twist distribution	3-5	Continuous	
Airfoil selection	2-5	Catagorical	
Control system stiffness	1	Continuous	
Estimated total	36-116		

Table 16. Rotor dynamics design constraints

Constraint	Number of constraints	Notes
Autorotation inertia	1	
Flutter stability	1	
Rotor stability	1	
Total rotor mass	1	
Srain	10-40	
Inter-relation among beam elastic properties	5-20	

4.4. Rotor Structure

From a structural standpoint, a rotor blade is a simple beam that must be designed to withstand a given static and fatigue loading spectrum. Additional design considerations include damage tolerance, lightning protection, moisture intrusion, erosion protection, and track weight fittings. Blade design and hub design are integrated not just through the design of the blade-hub attachment interface, but through loads, which might be higher or lower depending on the blade's dynamic response. Strength must include consideration of high-cycle fatigue in level flight and maneuvers; low-cycle fatigue from alternating startup, flight, and shutdown; and limit loads from peak maneuvers and ground conditions.

A dynamic design that is specified in terms of beam properties can be handed off to the blade designer to match. The blade designer, however, is constrained by choice of a structural concept. Modern blades are all very similar: a D-shaped spar with a solid nose block that may contain balance weights, an aft fairing supported by honeycomb, an outer skin, and others, as seen in Figure 19. This structural configuration is relatively easy to manufacture. The designer has choice of material, ply angles, and numbers of plies in different areas to use as design variables within a given structural concept. Multi-spar or other structural concepts add additional complexity that must be justified, perhaps by strength, damage tolerance, or dynamics requirements. In a coordinated design effort the blade designer can propose cross section configurations to provide desired dynamic properties; and this can be provided in the form of side constraints on beam properties or constraining functional relationships among properties.

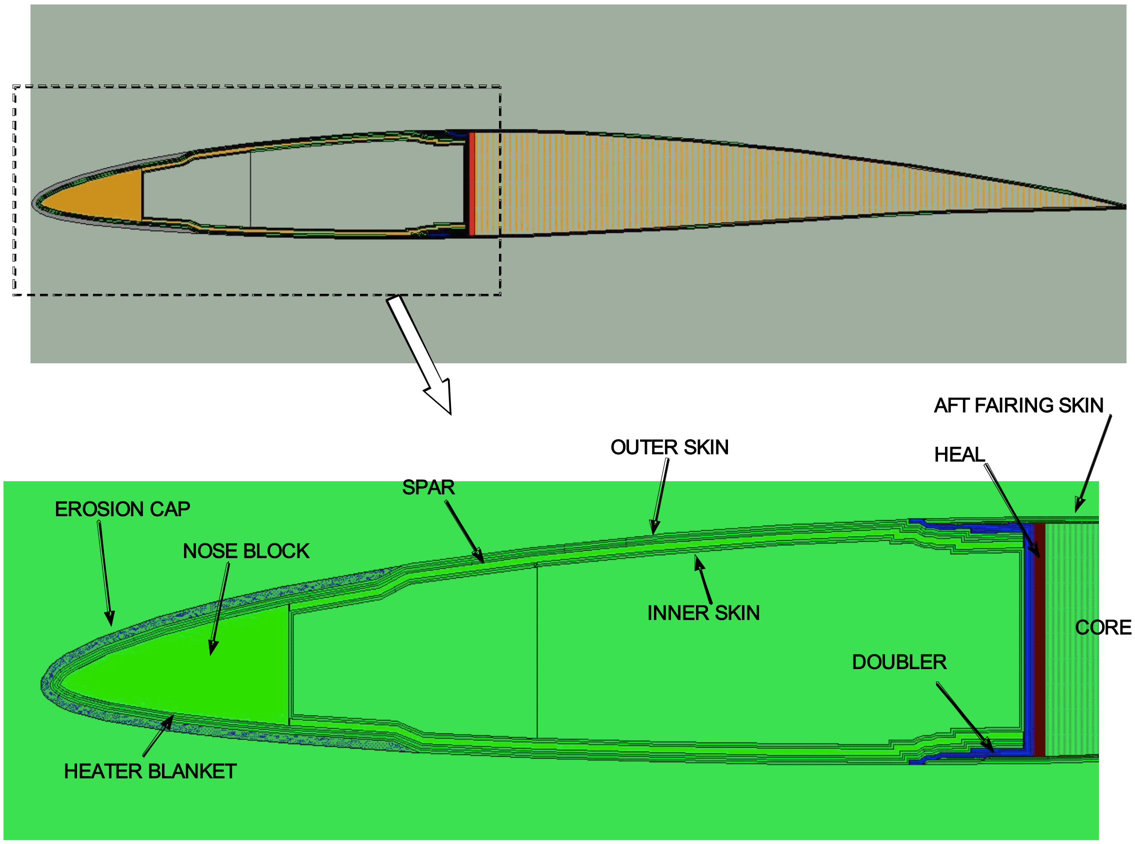


Figure 19. Typical blade cross section

Blade layout is typically a series of 20 to 50 two-dimensional slices at various blade span-wise stations where changes occur. Design by cross sections works well with structural dynamics and loads models that represent blades as beams. Given the large number of plies that exist in a typical blade cross section, on the order of one hundred, the definition of a cross section may contains several hundred pieces of information pertaining to ply location, ply material, and ply angle. Exploration of the design space at the early PD level is effective with 5 to 20 cross sections. While cross sections vary along the span, they are linked along the span by two key aspects of the design. First is internal configuration, which generally will not change from section to section until the root transitions to the blade attachment. Second is ply choices. Many plies will appear as a continuous material for the entire length of the blade, so each cross section may have the same ply thickness, ply material, and ply angle for many of the plies. These two aspects link the cross sections potentially to reduce the number of impendent design variables. Otherwise, a designer may create a span-wise variation of cross sections by build-up or drop-off of plies. In this case, assumptions must be made for design purposes as to what happens between cross section slices and how one cross section transitions to the next.

Certain features of the hub design are established in conceptual design, especially hub configuration, hinge locations, damper attachment, blade attachment, and pitch control arrangement. Alterations to the blade structure and aerodynamic design can have a strong impact on loads that feed into the hub, so additional hub sizing should be a part of blade design, especially bearing sizes and lugs.

Table 17. Rotor structure objectives

Objective	Notes
Blade weight	
Hub Weight	

Table 18. Rotor structure design variables (most simple)

Design Variable	Number of design variables	Type	Notes
Outer skin material	1	Discrete	
Outer skin ply count	# sections	Integer	10-20 sections
Outer skin ply angle	1	Continuous or Discrete	
Spar material	1	Discrete	
Spar ply count	# sections	Integer	10-20 sections
Spar ply angle	1	Continuous or Discrete	
Inner skin material	1	Discrete	
Inner skin ply count	# sections	Integer	10-20 sections
Inner skin ply angle	1	Continuous or Discrete	
Heal material	1	Discrete	
Heal ply count	# sections	Integer	10-20 sections
Heal ply angle	1	Continuous or Discrete	
Doubler material	1	Discrete	
Doubler ply count	# sections	Integer	10-20 sections
Doubler ply angle	1	Continuous or Discrete	
Aft farining material	1	Discrete	
Aft farining ply count	# sections	Integer	10-20 sections
Aft farining ply angle	1	Continuous or Discrete	
Hub sizing	4	Continuous	
Estimated total	72-132 approx.		Spanwise unification can reduce this count

Table 19. Rotor structure design variables (more general)

Design Variable	Number of design variables	Type	Notes
Outer skin material	# plies	Discrete	2-8 plies
Outer skin ply count	# sections	Integer	10-20 sections
Outer skin ply angle	# plies	Continuous or Discrete	2-8 plies
Spar material	# plies	Discrete	10-40 plies
Spar ply count	# sections	Integer	10-20 sections
Spar ply angle	# plies	Continuous or Discrete	10-40 plies
Inner skin material	# plies	Discrete	2-8 plies
Inner skin ply count	# sections	Integer	10-20 sections
Inner skin ply angle	# plies	Continuous or Discrete	2-8 plies
Heal material	# plies	Discrete	10-40 plies
Heal ply count	# sections	Integer	10-20 sections
Heal ply angle	# plies	Continuous or Discrete	10-40 plies
Doubler material	# plies	Discrete	5-10 plies
Doubler ply count	# sections	Integer	10-20 sections
Doubler ply angle	# plies	Continuous or Discrete	5-10 plies
Aft farining material	# plies	Discrete	2-8 plies
Aft farining ply count	# sections	Integer	10-20 sections
Aft farining ply angle	# plies	Continuous or Discrete	2-8 plies
Hub sizing	4	Continuous	
Estimated total	122-348 approx.		Spanwise unification can reduce this count

Table 20. Rotor structure design constraints

Constraint	Number of constraints	Notes
Static strength		
Fatigue strength		
Autorotation inertia		
Fairing buckling		
Spar wall buckling		
Track and balance		
Stability		

4.5. Fuselage Structure

Traditionally, limited information for the airframe structure is input to the conceptual design process; trend data is relied upon heavily. Preliminary design is where the airframe starts to take shape. The conceptual design process provides critical information leading into preliminary design. An OML loft has been defined including fuselage length, width, and height. Gross weights and the fuselage weight allocation have been established from trend data. Maneuver and ultimate load factors have been decided. Considering all of this conceptual design information, the OML loft is the variable most closely coupled to the sizing of the structural airframe and the least understood without high fidelity analysis. Aerodynamics would optimize to a small fuselage for download and drag reduction; Airframe Design would like a large fuselage to react bending. The ideal trade-off is found, ideally, in an optimization process that considers all variables that affect the OML loft.

The Airframe group attempts to adhere to conceptual weight trend data. It is their job to provide a path forward for manufacturing a fuselage that meets these weight expectations. Cost is also an important criterion that affects the overall business case. Both the weight and cost targets flow down from the conceptual design. Given a structural concept, cost is assumed to be a subset of the parametric weight, and that weight can be assigned a cost in dollars per pound. Therefore, airframe weight is the objective to be minimized for the high fidelity airframe optimization problem. Airframe weight is defined as the weight of all primary loaded structure necessary to carry flight and useful loading. Airframe weight is a function of sizing variables and material density, and is driven by external loading.

Typical production design includes 1000's of load cases. Approximately 150 external loading conditions should be evaluated to determine the 50 most critical to be applied to optimization. These envelop the entire gross weight range as well as the aircraft center of gravity range. They are a combination of Federal Aviation Regulations Part 29 and manufacturer's design standards. Loads cases include steady and maneuvering flight, forwards, sideways, landing at various attitudes, taxiing and ground handling, crash and ditching, and so forth. Load cases must generally be recomputed as the design evolves, that is, as weights and sizes change.

Topological optimization can be employed to gain insight to the optimum structural arrangement or configuration. Topological optimization will migrate structure to the optimal location for the given loading; however, this often produces an unorthodox structural arrangement, which should be evaluated against a traditional arrangement of skin stringer systems supported by hoop frames. At the very least, insight to an optimal structural layout will be gained with topological optimization. An excellent example is found in [16].

Once a structural arrangement has been decided, it can now be refined with sizing design variables. The primary structure can usually be broken down into the following groups: skins, stringers, longerons, frames, and bulkheads. Design variables for optimization are a subset of the definition of the loads model. Sizing variables typically have lower limits at minimum gage for the material and manufacturing condition and an upper bound that is within bounds of the structural allowable. Airframe designers can decide how to proceed considering the topology and traditional design approaches for the best practical path forward.

Geometric spacing variables, such as stringer and longeron spacing, frame and bulkhead spacing or location, frame height, and stringer/longeron height, are considered for design. Cross sectional shape, thickness, area, and inertia for each individual part are all part of the design space. There are also design variables for the material. The specific design variables that are needed can be dictated (or limited) by a manufacturing strategy as well as the flexibility to tailor the design for weight savings. For example, one extreme is to unify skin thickness as a design variable throughout the entire airframe, and the opposite extreme is to retain separate thickness design variables in each structural bay. The simplest approach generates a smaller optimal design problem and can be used in initial studies to find stress hot spots. The most likely balance is skin thickness variables in regions that are selected with the aid of the simpler approach. While the approach with the largest set of design variables has the most flexibility to improve weight it is also the most complex from a manufacturing standpoint. Note also that thickness variables can be discrete if there is a need to limit selections to standard thicknesses. These are, however, generally treated as continuous variables.

Another example is stringer design. Stringer design variables can be unified through the entire airframe or in regions. Furthermore, stringers can be sized with a smaller or larger set of parameters. Figure 20 shows stringer sizing parameters for a hat-shaped stringer. Thickness alone provides one variable, but height and widths provide more. Most similar structural parts can be optimized like this, with an increasing level of generality moving from part thickness to details of the shape. A manufacturing approach or cost study may assist in selecting the balance between design freedom and simplicity.

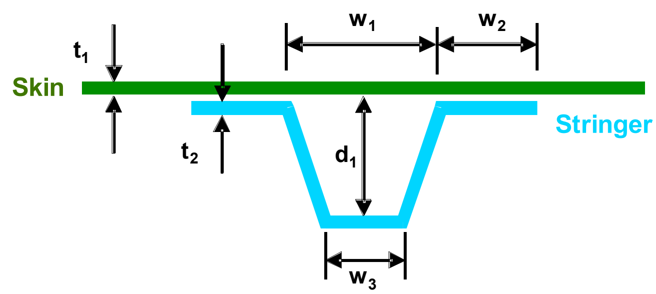


Figure 20. Hat-shaped stringer sizing

Airframe design has several constraints. Most obvious are that each part shall not exceed ultimate strength and local stability criterion. Sometimes it is necessary to constrain displacements at certain locations, especially rotor hubs. For airframe global stability at the vehicle level, no eigenvalue can go below 1.0 plus a 10 percent margin. The airframe must also be able to withstand a useful fatigue life for high cycle and low cycle loading. Also, if infinite life is not economical the damage tolerance for critical components must be identified and inspections defined.

Airframe design is also part of the aircraft strategy for low vibration by keeping airframe natural frequencies away from key forcing frequencies. Modal frequencies should be separated 10% from the n/rev natural frequencies for the entire weight envelope. A lower bound to all frequencies is often added so that modal frequencies do not contribute to ground resonance or control system coupling – typically around 1 to 2 Hz. Notional avoid bands are portrayed in Figure 21. Note that the avoid regions become larger at higher frequencies. This is because of increasing uncertainty in frequency prediction at higher frequencies. Frequency separation may become unachievable; therefore judgment may be required to supersede these rigid constraints. Two favorable phenomena come in to play at higher frequencies: Rotor loads that force airframe vibration typically become smaller, and modes become more localized and can be de-tuned locally. Vibrations at discrete locations should be constrained to an upper limit if not minimized directly. Direct minimization of vibration has not been employed in design as yet because of underdeveloped and unreliable analytical prediction methods.

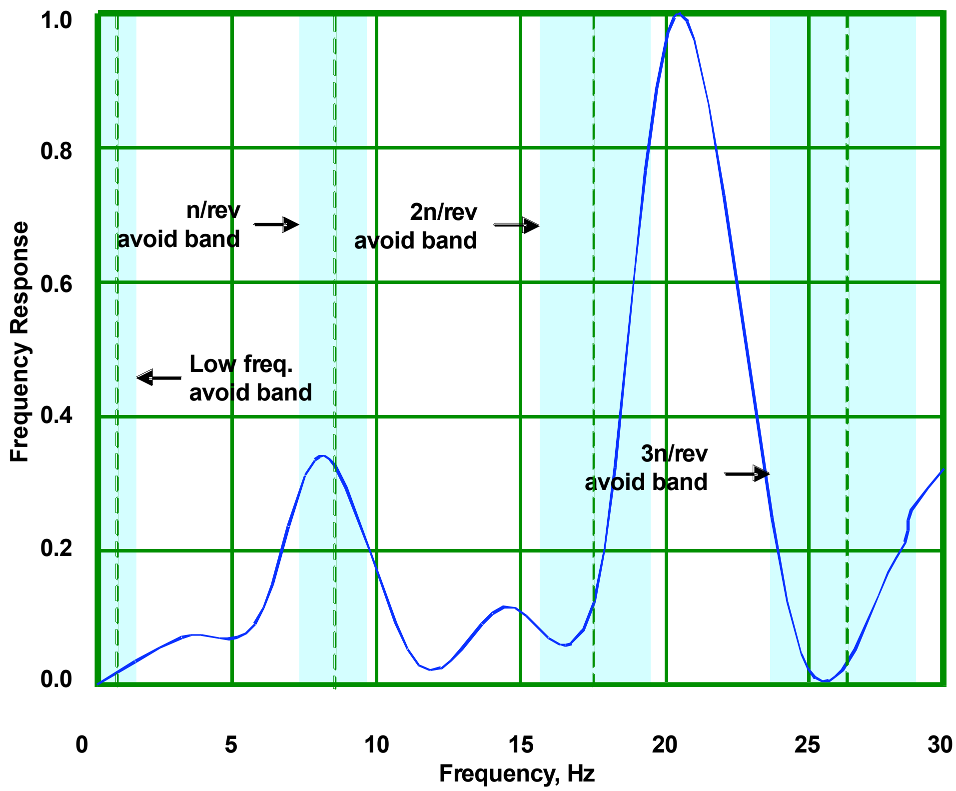


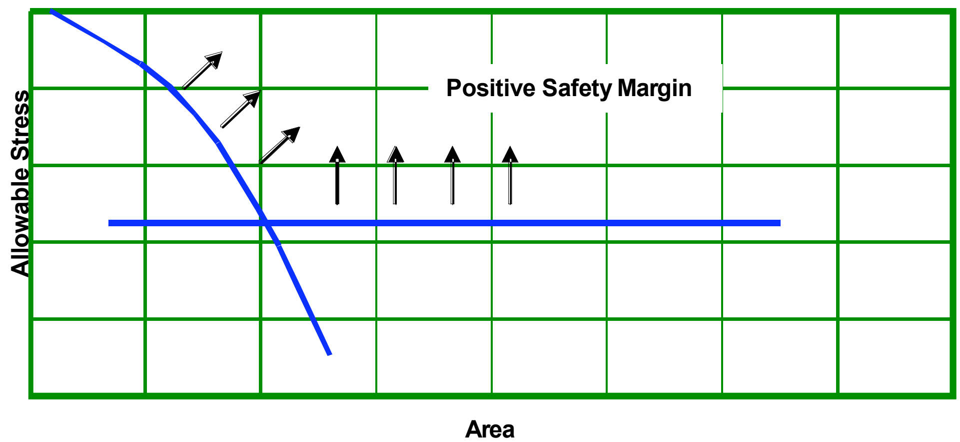
Figure 21. Avoid bands for fuselage frequency tuning

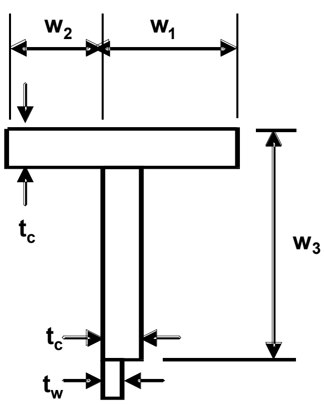
For impact events such as crash landing and bird strike, the airframe must meet certain energy absorption characteristics, internal volume restrictions, and resist material failure. Energy absorption concepts are developed in the exploratory research phase, accounted for in weight sizing trends, and implemented into design at the preliminary design level. The airframe must absorb residual energy from high impact landings that is not absorbed by the landing gear. While deformation is allowed in this circumstance, 90 percent of the original internal volume must remain. Retention of high-mass items such as engines may dictate limit strengths of the material or may become an additional load case for design or these critical areas.

The tandem configuration does not have lifting surfaces such as wings or stabilizers. Fixed surface flutter for small aerodynamic surfaces may be required for landing gear doors or other small surfaces, but need not be considered within the MDO problem. This would not be the case for a tiltrotor, where wing design would be an integral part of the MDO problem.

Given the large-scale nature of fuselage structural optimization, it is necessary to find a suitable tradeoff between problem size and model fidelity. Design variables for parts like stringers can be reduced to one cross section area; however, as the area becomes small, failure modes may include localized effects that cannot be captured only by the axial stress of the area. The design curve was developed at Boeing and refined by Hunter [17] to capture dozens of failure modes in a single process that creates allowable stress as a function of area for a particular family of cross section shape. Classical analysis is used to generate point designs that represent positive safety margin by manipulating the structural parameters. Typical output from this is the lumped area of the cross section and the allowable stress at the threshold of positive safety margin. This process facilitates a reduction in design variables without loosing the effects that the shape has on strength.

Figure 22 shows an example of frame chord area versus allowable stress for a T-shaped cross section. The non-linear curve towards the left represents the buckling critical region and the flat horizontal curve represents the strength critical region. The optimizer will work to find the optimal area that satisfies the applied stress in the model to the allowable stress of this design curve; the resulting area has implicit meaning to the higher fidelity design definition with the dimensions shown in the table. The benefit of a single functional response is fewer sensitivities and quicker runtime.





Area	t_c	w_1	w_2	w_3
0.1164	0.06	1	1	1
0.1536	0.06	1	1	1
0.1900	0.10	1	1	1
0.2256	0.12	1	1	1
0.2604	0.14	1	1	1
0.3276	0.18	1	1	1
0.3600	0.20	1	1	1
0.4224	0.24	1	1	1

Figure 22. Design curve example

Table 21 Fuselage structure objectives

Objective	Notes
System weight	

Table 22 Fuselage structure design variables

Design Variable	Number of design variables	Type	Notes
Skin thickness	1 per region	Continuous or discrete	50-100 regions
Stringer/longeron sizing	1-5 per region	Continuous	50-100 regions
Frame sizing	1-5 per region	Continuous	50-100 regions
Material	1-3	Catagorical	
Stringer/longeron spacing	1 per region	Continuous	10-30 regions
Frame spacing	1 per region	Continuous	3-5 regions
Bulkhead spacing			
Estimated total	164-1138		

Table 23 Fuselage structure design constraints

Description	Number of constraints	Notes
Ultimate compression strength	# stress locations	
Ultimate tensile strength	# stress locations	
Fatigue strength	# stress locations	
Deflection limit	2-5	Key ariframe locations
Global eigenvalue	1	> 1.1
Energy absorption high-energy impact	1	Residual energy not absorbed by landing gear
Internal volume retention high-energy impact	1	90 %
Natural frequency lower limit	1	All modes
Natural frequency separation	# Modes	10% of n/rev 2n/rev, etc

4.6. Drive System

Delivery of torque from the engines to the rotors requires a system of transmissions and shafts with several direction changes to conform the geometry of the drive system to the available space inside the airframe. The drive system is the interface between the rotor and the engines, so a large speed reduction is required, starting with typical engine speeds of 15,000 to 20,000 rpm, moving to rotor speed of 200 to 400 rpm for large to medium helicopters. Rotorcraft use relatively high power compared to other vehicles of the same weight. Design of a low-weight transmission that meets the rigorous demands for a safe flight vehicle is a very difficult challenge.

The primary interfaces for the drive system are the input from the engine and the output to the rotors; both speeds and torques are usually prescribed. Torque is proportional to power and is inversely proportional to shaft speed, so a high-speed shaft transmits power with low torque, which makes supercritical shafts an attractive option though with risk. A supercritical shaft has structural frequencies that are lower than the rotating frequency; therefore a shaft resonance occurs during rotor run-up, which may require dampers to avoid damaging deflections when passing though the resonance. This removes some of the weight advantage. Current helicopter shafts are usually sub-critical.

Speed reduction stages are also part of the design balance. It is desirable to have a speed reduction wherever there is a gearbox for direction changes; this can reduce the total number of gears. In general, designers try to find a combination of gear reduction stages and shaft sizes for a low-risk and light weight solution to transmit the rated power.

Transmission layout is established during conceptual design so that weights and aircraft internal arrangements can be checked. The next step is to design reduction stages within each gear box. It is usually best to use the minimum number of gear boxes so that no unnecessary weight is added. Figure 23 shows a tandem rotor drive system in schematic form with key components and their corresponding input/output speeds. Engine and rotor speeds are specified to the drive system design as fixed parameters. Torques and steady maneuver loads (hub loads) are also external inputs to transmission design.

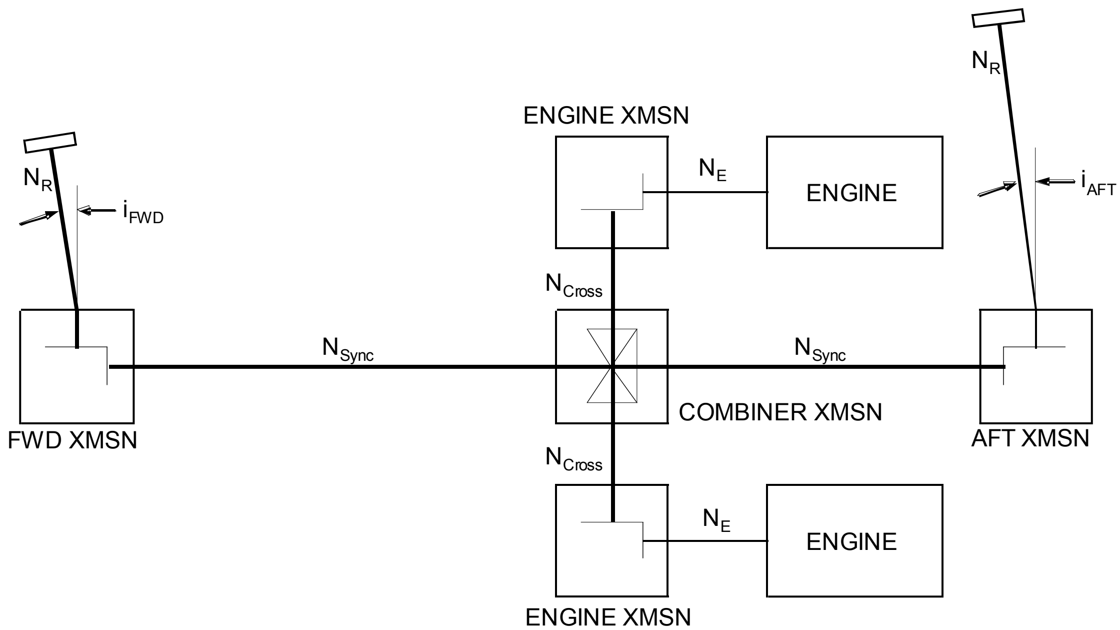


Figure 23. Drive system schematic for preliminary design

Each gear box usually has at least one stage for speed reduction. The largest reductions are usually in the rotor transmissions so that torque is low elsewhere in the system. Multiple speed reductions can be designed into each transmission, which brings extra gearing with associated weight. Designs are optimized from a weight standpoint by balancing loads and the number of gear stages and reduction ratios of each. From the standpoint of cost and maintenance, fewer gear boxes and reduction stages are usually least costly, given technical limitations for speed reduction per stage.

Power losses are important because even a fractional improvement can lower operating costs in the long term. Power losses are minimized by tooth form, low friction bearings, coatings, gear type, and so forth. Windage losses are also very important but difficult to predict. Control of windage losses is reserved for the detailed design stage.

Transmission housings transmit reaction loads from bearings to the airframe. Detailed finite element models are used to minimize housing weight during the detailed design stage, but housing geometry is sized during preliminary design using simple methods. At this point the concept for attaching the transmission to the airframe has been designed but needs to be sized. This may be lugs on the housing that bolt onto the airframe, and simple stress methods provide a check on sizing.

Table 24 Drive system objectives

Objective	Notes
System weight	
Power losses	

Table 25 Drive system design variables

Design Variable	Number of design variables	Type	Notes
Number reduction stages	1	Integer	
Gear ratios	# stages	Continuous	
Gear type	# stages	Discrete	
Gear geometry	# gears	Continuous	
Bearing type	# bearings	Discrete	
Bearing geometry	# bearings	Continuous	
Housing geometry	# transmissions	Continuous	Sizing of key load-bearing locations
Shaft type	# shafts	Catagorical	Composite, metal, etc.
Shaft diameter	# shafts	Continuous	
Estimated total	20-50		

Table 26 Drive system design constraints

Description	Number of constraints	Notes
Gear ratios	# stages	Maximum speed reduction
Gear contact sresses	# gears	
Gear bending stresses	# gears	
Housing stresses	# transmissions	
Shaft stress	# stages	
Shaft frequencies	# stages	
Deflections	# stages	
Gear resonance freqnecies	# gears	
Rotor-rotor frequencies	1	
Lubication flash temperature	# transmissions	
Heat rejection	# transmissions	
Fabrication	# transmissions	

4.7. Propulsion System Integration

The sophisticated and challenging design requirements of modern helicopters encourage the tight coupling between propulsion and airframe system design. Coupling between propulsion and other engineering disciplines is unique in that a major component of the propulsion system, the engine, is traditionally designed separately from the airframe. Coupling engine design and airframe design in a multidisciplinary optimization is complicated by the fact that subject matter experts usually reside in separate companies. In helicopter design, engine performance is typically addressed with a black box, usually a cycle performance program, commonly referred to as decks, supplied by the engine company. In conceptual design, the deck is often “rubberized” to allow engine growth with helicopter gross weight.

At the conclusion of conceptual design an estimate of rotor power and auxiliary system requirements is known with sufficient certainty that when combined with a technology readiness requirement (usually driven by non-engineering considerations like cost and schedule) results in a list of candidate engines, i.e. the approximate size and number of engines are known. High level decisions are made concerning whether the engine is an existing production engine, a lightly modified existing engine, a heavily modified existing engine, or a new design requiring testing and certification. The list of candidate engines may also be scrubbed with other operational requirements such as the level of icing certification. A candidate engine, or list of candidate engines, becomes a fixed design parameter in helicopter MDO at the preliminary design level.

Once an engine is down-selected, helicopter designs have little or no influence on the *uninstalled* engine performance. Still, a tightly integrated MDO with propulsion considerations is warranted because the propulsion system, that is the engine’s installed performance, strongly influences a number of key design objectives: Hover and take-off performance objectives are limited by total installed power. Fuel volume and therefore take-off gross weight is driven by installed engine specific fuel consumption. Handling quality and configuration layout objectives are influenced by the location of the engine. Maintenance access requirements are influenced by the location and shape of the engine cowling. Architecture and allocations of the fuel inserting system, environmental control system, electrical power system, transmission efficiency, and hydraulic system must be designed for the candidate engines selected during the conceptual phase.

The engine supplier guarantees minimum performance of an uninstalled engine. The airframe designers apply ambient conditions, flight speed, recovery curves, customer bleed schedules, power extraction, inlet pressure losses, and exhaust pressure losses to obtain the installed engine performance. Thus at the conclusion of conceptual design and throughout preliminary design, propulsion system optimization targets inlet losses, exhaust losses, accessory power extraction, transmission losses, and bleed flow.

For propulsion systems especially, cost is comprised of non-recurring engineering, certification, recurring, reliability & maintainability, fuel, and number of engines. Schedule is driven by development, certification, and production. Major performance metrics for the propulsion system include installed engine specific fuel consumption, installed propulsion system weight, and installed power available. By preliminary design, the size and number of engines has already been determined and therefore many of the decisions that greatly effect cost and schedule have been made. Therefore propulsion system optimization is centered on performance.

Figure 24 illustrates major performance goals and how they are interrelated within the propulsion system. The ultimate system metrics are highlighted in ovals and are strongly influenced by the elements directly beneath them and connected by solid lines. Elements in the hexagon shapes are associated with the engine and cannot be changed without modifying the engine. Airframe designers have some influence over major performance goals by influencing elements in the circles. Dashed lines show a weaker dependency.

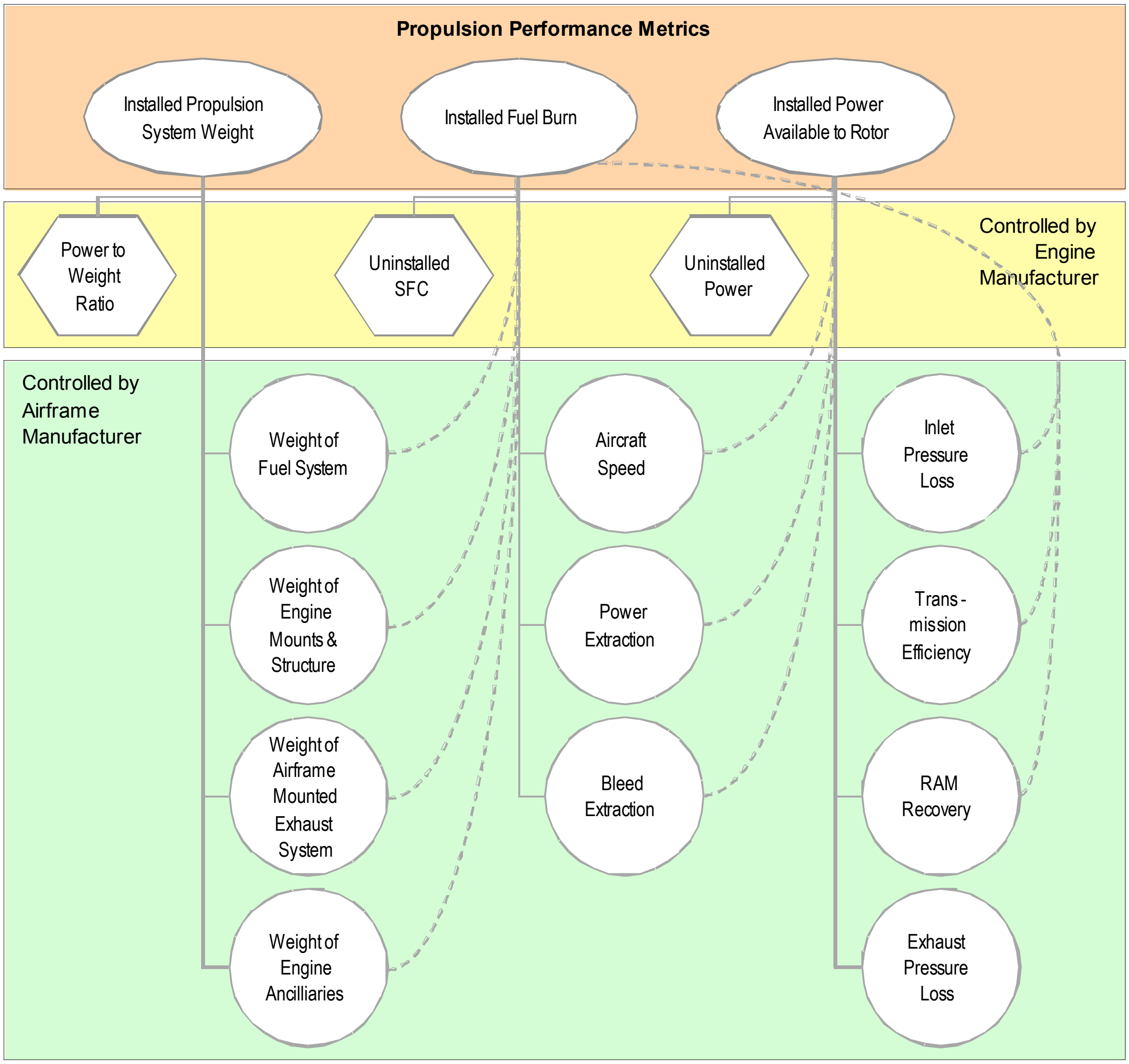


Figure 24. Propulsion performance metrics

Some of the propulsion goals can be met by designing a uniform pressure and steady flow across the face of the inlet. One approach to achieving this goal is to tailor the flow field in front of the inlet by modifying upstream geometry (Figure 25) or angling the placement of the engine. High fidelity computational fluid dynamic analysis is ideal for verifying inlet flow quality. Tied to an optimization scheme that modifies influential geometry, CFD can improve inlet flow quality. Similarly to the fuselage aerodynamics problem, shape parameters would be design variables, which makes the specific variables highly configuration dependant. Inclusion of the rotor flow field to this design problem has been increasingly feasible with the use of CFD. This development may lead to prediction of flow problems that cause engine surge such as ingestion of hot exhaust gas, and unsteady rotor or bluff body wake in various flight conditions.

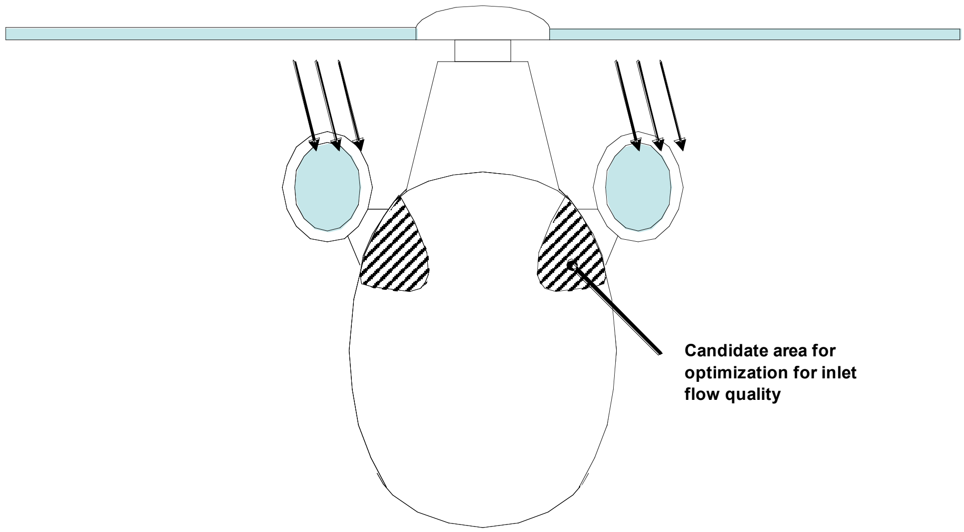


Figure 25. Regions of influence for improving engine installation

Table 27 Propulsion system objectives

Objective	Notes
Minimize Installed power losses	Improves A/C performance
Minimize Mission fuel burn	Ties in to *sfc* target
Minimize Propulsion System weight	Ties in to weight allocation

Table 28 Propulsion system design variables

Design Variable	Number of design variables	Type	Notes
Engine bleed & power extraction	2	Discrete or continuous	Trade-off for energy requirements for accessories
Inlet shape & inlet separator design	6-20	Continuous	Control inlet recovery and flow quality
Exhaust geometry: tail pipe or ejector length and area	2-6	Continuous	Control exhaust losses and temperature
Estimated total	10-28 approx		

Table 29 Propulsion system design constraints

Description	Number of constraints	
Surge margin	1	Ensure engine installation doesn't adversely affect surge margin.
Install power	1	Power requirements from aero performance
Installed *sfc*	1	Minimum sfc required for valid performance assumptions

4.8. Flying Qualities

In a very general sense, aircraft flight characteristics should be natural to the pilot and free of instabilities or low damped oscillations that require tedious attention. Control power should be sufficient to exercise proper control of the aircraft without being overly responsive. These qualities can be formulated more specifically in terms of rates, attitude angles, control deflections, frequency and damping, and so forth, as in ADS-33 [18]. Design for flight characteristics is multidisciplinary, especially involving airframe aerodynamics, configuration, weight properties, low-frequency rotor dynamics, flight control hardware, and flight control laws. It is often desirable to require flight control design to provide required handling quality characteristics that would be more difficult to achieve by airframe design; control laws weigh essentially nothing. To achieve desired handling qualities, a reliable approach that is appropriate for preliminary design is to start with satisfactory characteristics designed into the un-augmented aircraft. Augmentation with control laws can then be tailored separately to give the aircraft the desired flight characteristics. This approach de-couples airframe and rotor design from flight control and control law design to a large extent, but it requires a definition of key un-augmented stability characteristics.

Directional stability of the un-augmented aircraft is important for any configuration but is more difficult to achieve for a tandem configuration. The aft pylon is one of the biggest contributors to directional stability, but its effect is offset by the forward pylon. Aerodynamic shape of the forward pylon can mitigate this by spoiling side-ways lift without generating excess drag. While a tall aft pylon acts as a stabilizing tail, it does so at greater structural expense because of bending moments generated by rotor side forces plus extra structure. Overall aircraft height might also be constrained.

Level trim pitch attitude is preferred not only for passenger comfort but for aerodynamic drag; near-level trim presents the smallest frontal area. Pitch trim depends primarily on rotor shaft angles and Longitudinal Cyclic Trim (LCT), which is scheduled versus airspeed. Hover trim should be below a maximum nose up angle and high-speed forward flight should be below a maximum nose down angle. Changing shaft angles and cyclic trim schedules alters trim flapping, which may lead to design conditions for hub flap, pitch, and lag bearings. One bearing may become more critical depending on trim pitch and flapping.

A rotor responds to an upward vertical gust with a sequence of flapping and thrust changes, both of which produce nose up moments that tend to destabilize the aircraft. Negative pitch-flap coupling, usually built in to the rotor control and hinge kinematics, is often used to control flapping response and thereby limits the destabilizing influence from the rotor. Most helicopters use horizontal tails to achieve longitudinal stability. For the tandem configuration, negative pitch-flap coupling can be applied just to the forward rotor and lower pitch moment changes by lowering thrust changes far in front of the aircraft center of gravity. While pitch flap coupling lowers the flapping response, it also changes the phase, which can introduce additional challenges to the control design. The ability to control large differential thrust is an advantage here, but the only way to exploit this advantage is through control law design. Airspeed stability is likewise affected by flapping response, though beneficially in this case. Slightly negative aircraft-level speed stability is usually negative for the tandem configuration; the automatic flight control system (AFCS) can adequately provide speed stability.

Two types of rotor/body modes that can be affected by the design of the AFCS should have minimum inherent damping. First is the regressing lag mode, which can interact with the body, especially through flexibility in the pylon. This generates a criterion for lag damper sizing. Flexibility in the drive system creates the potential for a rotor-rotor mode, which can make the design unacceptable from a flying qualities perspective. Low rotor-rotor damping can drive requirements on design of the lag damper and can limit design of the AFCS. Pitch-lag coupled may be employed to improve lag mode damping It should be noted that any configuration has the potential to exhibit damping or stability problems with rotor/body or rotor/drive system modes.

Table 30 Flying Qualities objectives

Objective	Notes
Trim pitch attitudes – cruise	Could be constraint
Trim pitch attitudes – hover	Could be constraint

Table 31 Flying Qualities design variables

Design Variable	Number of design variables	Type
Shaft tilt angles	2	Continuous
Longitudinal cyclic trim schedule	2-5	Continuous
Pylon Heights	2	Continuous
Pitch/flap coupling	1-2	Continuous
Pitch/lag coupling	1-2	Continuous
Estimated total	8-13	

Table 32 Flying Qualities constraints

Description	Number of constraints
Steady hub moments	
Control power	
Un-augmented stability derivatives	

4.9. Noise

The dominant source of noise that propagates forward is thickness noise. Thickness noise is the result of the pressure wave generated by a rotating blade as the air is displaced around the blade in a periodic manner. This noise is proportional to the thickness of the blade and the speed (Mach number) at which the air is displaced above and below the blade section. The noise forward of the rotor also experiences Doppler amplification in forward flight. The noise that gets amplified is generated primarily on the advancing side of the rotor and, therefore, the advancing tip Mach number is a very important design criterion for thickness noise. Thickness noise is typically the lowest frequency contributor to the total noise signature and therefore, experiences the least atmospheric attenuation. Design choices that influence thickness noise are the airfoil thickness, number of blades, and operational Mach number. These design choices are basic elements of conceptual sizing. Aside from fundamentally different low-noise technology insertions, rotor noise is navigated primarily in conceptual design. Nonetheless, preliminary design may still consider noise as on objective or constraint using airfoil thickness as a key design variable.

One aspect of the noise problem that requires treatment with high-fidelity methods is rotor-rotor interference. Longitudinal cyclic trim is scheduled such that both rotors flap aft in forward flight which results in lower noise from rotor-to-rotor interference. Blade loads and vibration are also expected to be lowered by increased blade spacing. This also produces a smaller pitch range giving greater pitch bearing life, but this is traded against larger flapping motions. The analysis required to compute noise from rotor-to-rotor interference is beyond the level of fidelity of the sizing codes. High-fidelity methods are required, so it is appropriate to handle this multi-disciplinary consideration in preliminary design.

Table 33 Noise objectives

Objective	Notes
Overall sound pressure level	Could be constraint

Table 34 Noise design variables

Design Variable	Number of design variables	Type
Shaft tilt angles	2	Continuous
Longitudinal cyclic trim schedule	2-5	Continuous
Pylon Heights	2	Continuous
Airfoils thickness	1-5	Discrete or Continuous
Estimated total	8-15	

4.10. Geometry and a Common Database

As high fidelity tools become more prevalent in rotorcraft MDO, the need to manage a consistent database becomes increasingly more important. Naturally, high fidelity engineering analysis requires more information than was previously required in conceptual design. The growing pieces of information describing the design must be consistent across the engineering disciplines if there is any hope of getting various tools to work in harmony. Establishing a consistent database is non trivial. For example, rotor dynamics analysis is dependent on several design parameters, twist along the blade is one. A CFD model to establish rotor aerodynamic performance does not directly depend on twist, but instead uses a grid which presumably has the twist built in. If the CFD grid does not model the twist schedule accurately there will be an inconsistency between the rotor dynamics analysis and the aerodynamic performance analysis.

A geometry engine is one mechanism to facilitate the generation of a consistent database for various design and analysis, Figure 26. The geometry engine will use a set of relevant conceptual level design variables (fuselage length, width, etc.), and supplemental parameters required to use high fidelity analysis (i.e. surface curvature) to produce a vehicle definition [19]. Ideally the geometry engine is sufficiently sophisticated to associate properties such as materials to geometry locations. All engineering disciplines can use either the design variables going in to the geometry engine or the output and be assured of using a consistent geometric database. The geometry engine must meet certain requirements to be useful for MDO.

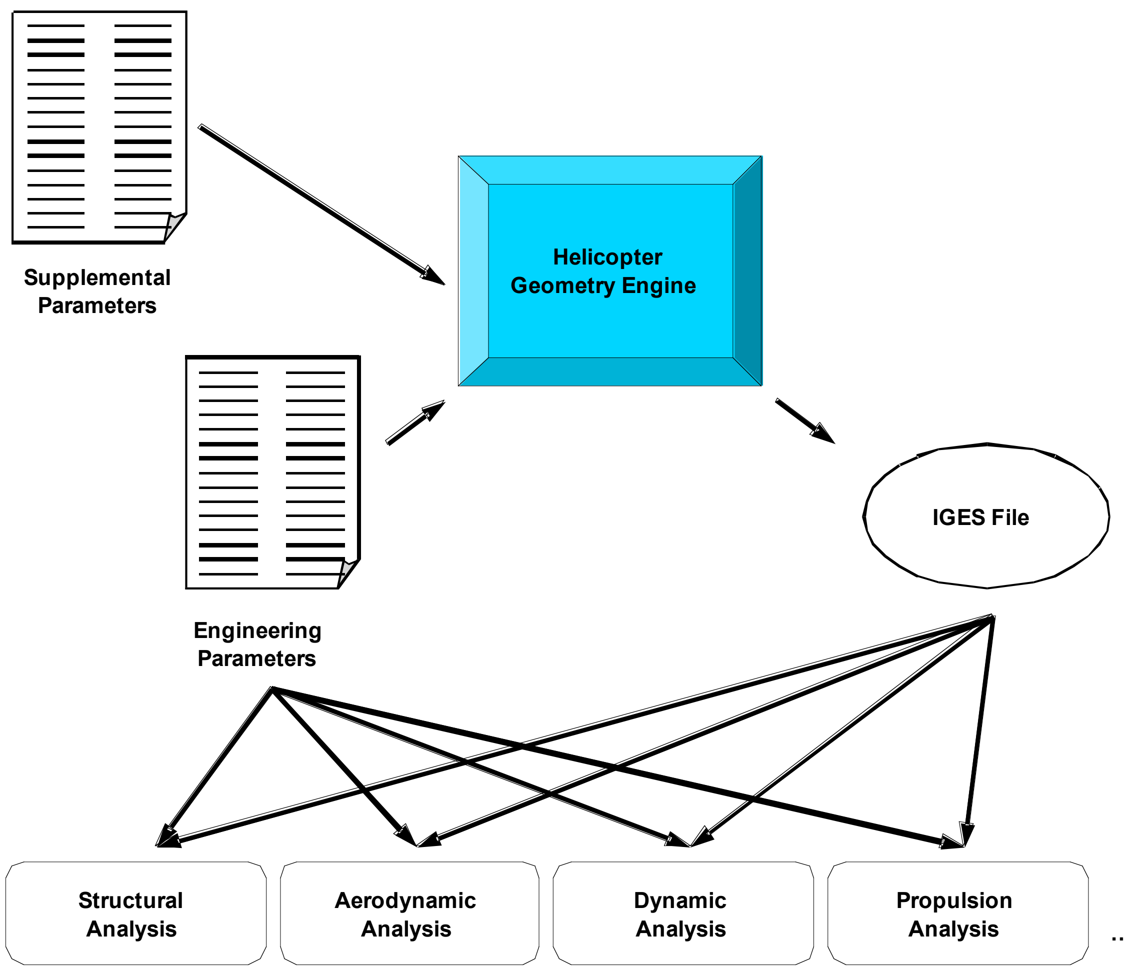


Figure 26. Role of the geometry engine in an MDO process

- The geometry engine must produce geometry that is physically meaningful and analyzable. Airfoil shapes with the lower surface trailing edge above the upper surface are not acceptable.

- The geometry engine must support multiple engineering views. For example, a distinction between the inner mold line (IML) and the outer mold line (OML) is necessary to couple structures and aerodynamics.

- Known engineering requirements and geometric shape constraints should be satisfied though sometimes these can be relaxed within the context of an MDO provided the optimization is properly constrained.

- Optimization requires a well-behaved parameterization. In other words, changes to input variables should produce expected changes to the geometry. Furthermore, small changes to input parameters should generate correspondingly small changes to the output.

- Successful optimizations are most likely to occur with few design parameters so it is highly desirable for the geometry engine to create complex shapes with few design variables.

- The geometry engine must integrate with upstream and downstream design processes. Consistent input parameters with conceptual level analysis greatly simplify the implementation of high fidelity tools. Likewise follow-on designs at the late preliminary or detailed design stage can begin seamlessly if the geometry can be easily ported to a computer aided design (CAD) system.

One example of a geometry engine that satisfies many of these requirements for MDO is the rotor model used for conceptual design exploration of a light attack helicopter. The rotor is defined by a twist and airfoil schedule as well as a handful of parameters to define the tip shape including variables that introduce sweep, taper, and anhedral. Figure 27 shows some of the parameters that define the shape. The geometry engine produces an Initial Graphics Exchange File (IGES) that defines the shape with sufficient detail to produce a three-dimensional CFD grid. Alternatively, structural response analysis codes can directly use the twist schedule.

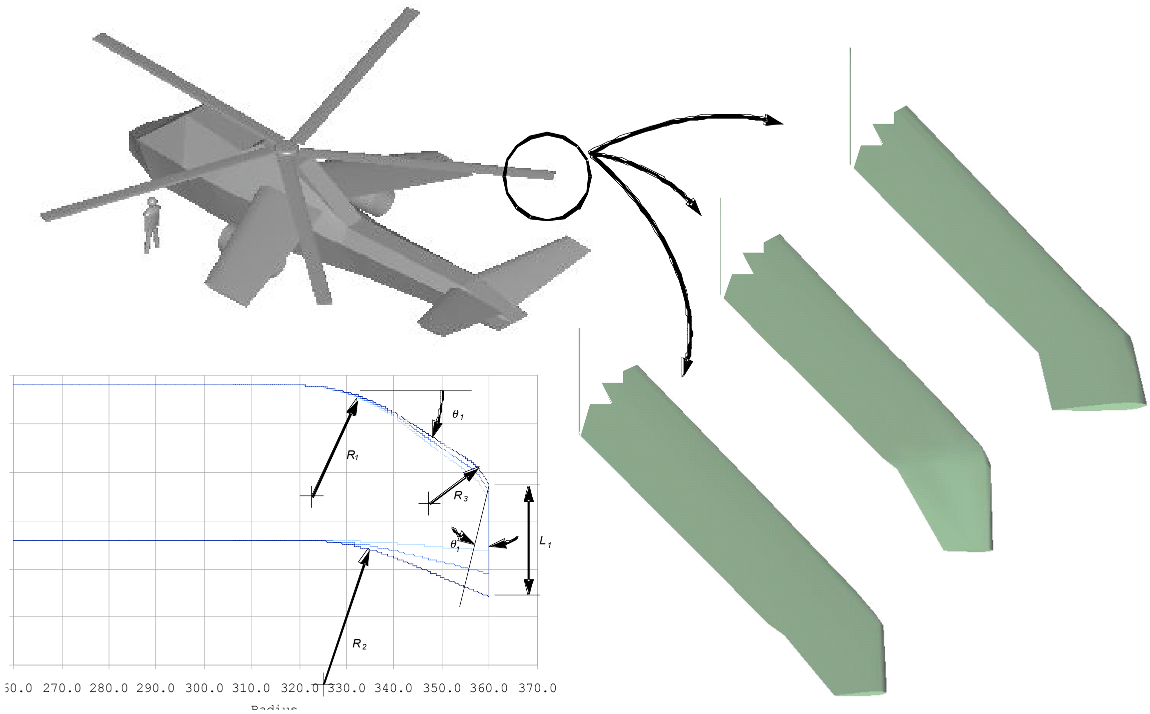


Figure 27. Example of a suitable geometry engine for MDO

Modern CAD programs potentially can provide a basis for managing structural geometry, particularly when the design is defined parametrically at a high level. With a high-level definition, changes in one aircraft-level feature are automatically flowed down to several parts. For example, frames can be designed to fit within the outer mold line minus the skin thickness. A change to the OML or skin thickness can automatically re-size the frames. This requires an up-front commitment as well as foresight.

These methods of managing geometry, aerodynamic and structural, are in development and are not at present mature and reliable for use in an optimization framework. Note also that in current applications of rotorcraft optimization, geometry definitions are self-contained and not tied to a master geometry definition. For example, fuselage structural optimization currently employs a NASTRAN solution. Results are optimally-sized airframe components, but not dimensioned features of a CAD model. Considering the design problems as posed, a likely start to geometry control would be a combination of aerodynamics designing the outer mold line, or loft, by controlling parametric dimensions and outputting an IGES file, then structures sizing the airframe structural components within those dimensions using a NASTRAN-style solution, and then both combined within CAD to form the design.

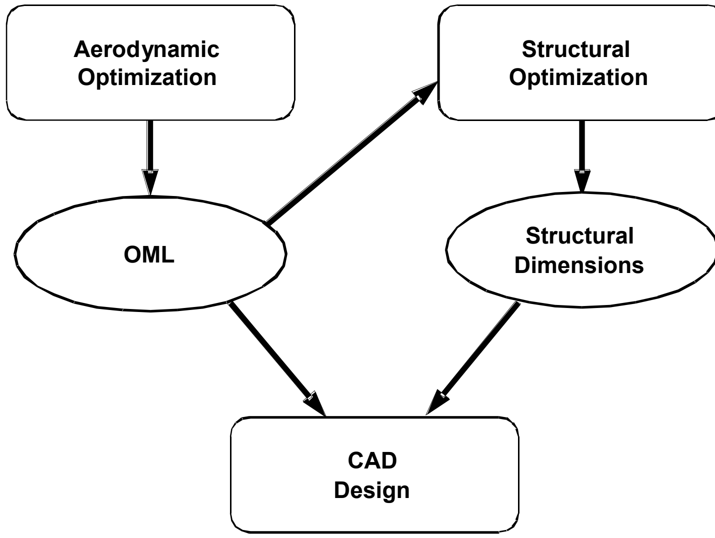


Figure 28. Fuselage geometry

5. High-Fidelity Analysis in Optimization

High-fidelity tools are most effective in multidisciplinary optimization if they produce useful and easy to manage output from easy to manage input. They should be computationally efficient for fast cycle time and robust so that they reliably produce converged solutions. High fidelity tools should be accurate in predicting proper trends of relevant design parameters. This section examines high-fidelity analysis that could be applied to optimal design. Run time and accuracy are the most important questions for this examination followed by sensitivity and complexity both of input/output and integration into computer-driven optimization framework.

Low fidelity methods are often well understood and accurate when calibrated and used accordingly. However, these methods are subject to risk when applied beyond the range of modeling assumptions and calibrated experience. Unfortunately, optimization often moves to areas where analyses become unreliable. The expectation is that high-fidelity analyses provide a better foundation for optimization because "high-fidelity" implies greater accuracy over a larger design space. However, this is not necessarily the case. High-fidelity generally requires more detailed design definition, and inaccurate sensitivity to these parameters can limit the effectiveness of an optimization in a similar manner as with low fidelity analysis. Although absolute accuracy may not be as important as obtaining the correct sensitivity to design variables, inaccurate absolute performance parameters may be an indication that some physical elements are missing.

Various levels of modeling fidelity are in concurrent use during design. An example is in blade design where rotor loads are generated using lifting-line aerodynamics and aerodynamic performance is computed with lifting surface or CFD aerodynamics. Many excellent analysis methods are based on modeling relevant phenomena rather than using computational solutions of the equations of the physics. Modern comprehensive codes are the premier example in rotorcraft analysis. One-dimensional beam models are used to represent a three dimensional body: the rotor blade. This works because simplifying assumptions on kinematics and stress and strain hold true for typical designs. Likewise for lifting-line aerodynamics, wake models, unsteady aerodynamic models, and so forth that are found in comprehensive codes. At the same time, drive system analysis uses relatively simple stress methods rather than FEM, and the fuselage is analyzed primarily using FEM. While use of high-fidelity analyses earlier in the design cycle should be pursued, the right level of fidelity for design optimization may not always be the highest fidelity available.

This section examines key attributes for suitability of an analysis for use in optimization. The most important attributes are: appropriate level of accuracy, quick run time, reliable sensitivity to input parameters, reliable convergence, and ease of integration with an optimizer engine. The last is a matter of software development, such as ModelCenter, that is highly flexible for integration and automatic execution of computer programs.

Because optimizers see computer programs as black boxes, it is important that the program run reliably so that it returns an answer. This is not absolutely necessary, but desirable. Generally, techniques for reliable solution convergence are a matter of experimentation; once found, optimization is facilitated by more reliable and quicker solution time.

Accuracy and run time are generally well known by the subject matter experts who run their computer programs. The typical approach is to model with the highest fidelity and quality that can be tolerated by schedule, so that the increased speed from newer computers is offset by the desire to improve the quality of the results. This trade off between run time and accuracy is a matter of judgment on the part of the disciplinary expert. As for accuracy, if analysts are comfortable with a certain analysis system and would use it to make design decisions, then it should be used in optimization. As for run time and sensitivities, one criterion for suitability is a history of effective use in optimization, which can be used to infer that an analysis is suitable for use in optimization.

5.1. Fuselage Stuctural and Dynamic Optimization

The analysis method of choice for high fidelity structural and dynamic optimization in preliminary design is the vehicle level internal loads finite element model. This is a relatively coarse model that accurately depicts primary load paths and stiffness. Finite element types need to be selected wisely to ensure that the stiffness and all load paths are modeled with the correct intent. The elements must be assigned physical properties and materials. External loads and mass must also be applied to the model so that gross weights and CG ranges are accounted for. Airframe weight should be separated from fixed weights to allow real time optimization and weight/stiffness interaction updates. By using the loads model directly, stiffness will always be up to date during design/optimization.

Not only will a high fidelity airframe optimization provide a "sized" fuselage with positive safety margins, but stiffness will also be defined. This stiffness has a direct impact to significant helicopter design implications such as natural frequency, vibration, and global stability. Only a high fidelity analysis in preliminary design can provide the necessary stiffness information to accurately analyze these early in the design process.

Natural frequency prediction is essential to design for low vibration. Frequencies can be predicted accurately; however, this is usually after the design has matured. Early finite element models must capture key details to avoid the danger of overlooking potentially problematic areas. This is exemplified by Gabel and Lang [20], in Figure 29. This shows that an earlier version of the NASTRAN model, noted as "Ref. 2", lacked sufficient details of the cockpit structure to capture a local mode near 6 per-rev. This was picked up nicely in an updated version with the "Approximate Cockpit Model".

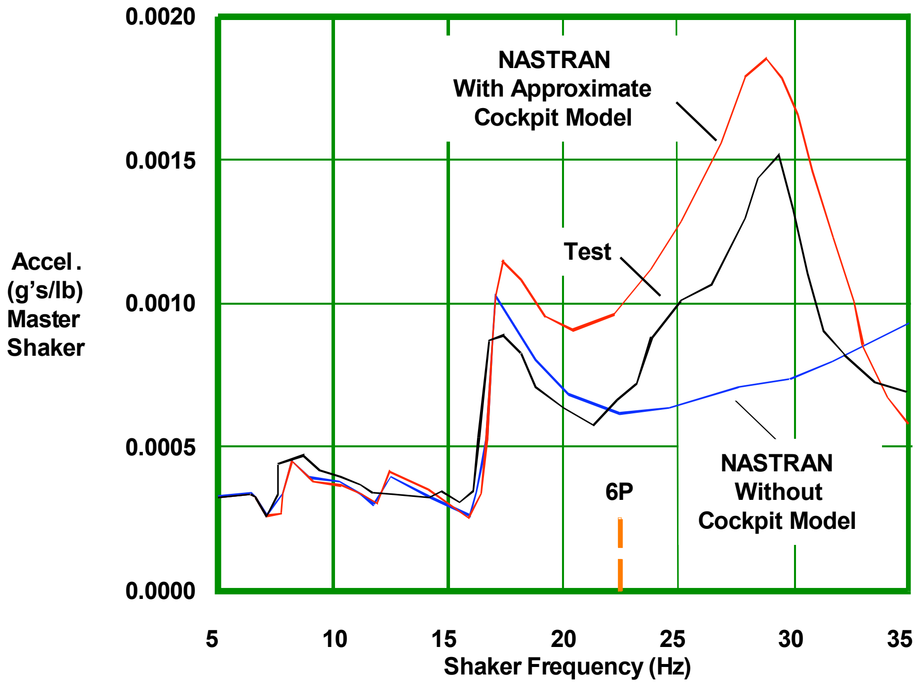


Figure 29. CH-47 Cockpit floor vertical response from vertical forward hub shake, from Gabel and Lang, 1995

The previous example shows that NASTRAN predictions of fuselage natural frequencies can be quite good once the structure is understood and modeled correctly. Figure 30 shows the potential quality of correlation with test data that can be achieved with a more advanced understanding of the airframe, that is, shake test data. Preliminary design does not benefit from shake test data except where experience from previous correlation refines the modeling processes. Therefore there is a danger of missing or miscalculating critical modes.

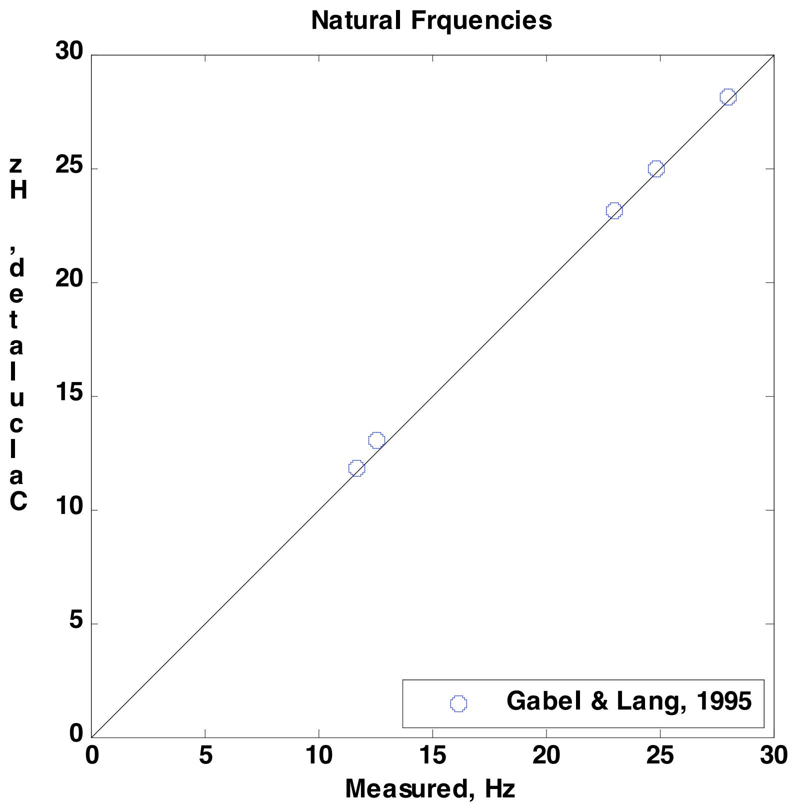


Figure 30. Natural frequency correlation

Table 35. Airframe internal loads and dynamics codes FEM

Analysis	Outputs	Accuracy	Run-time (Linux-PC, 2.99GHz)
Airframe internal loads	Internal stress/strain/force		
Airframe global stability			
Airframe structural dynamics	Natural frequencies	0.1Hz -	20-40 minutes
	Forced response	0.002-0.005 g/lbf	20-40 minutes additional after natural frequency
	Lifting surface flutter	Accuracy unkown	20-40 minutes additional after natural frequency

Internal loads and strength require different modeling assumptions from frequency analysis. This is primarily because strength analysis employs conservative assumptions on the load paths and frequency analysis requires a careful accounting of weight and stiffness. A crash analysis model may be altogether different as well, especially because of the need for nonlinear modeling. This highlights the need for a common geometry database to manage different models. Crashworthiness is often handled separately by focusing on the design of crashworthy features, but a more integrated structural optimization should benefit the design by making use of both basic structure and crashworthy features.

Hunter [17] demonstrated successful use of NASTRAN solution 200 for structural optimization of the Boeing Advanced Tandem Rotor Helicopter (ATRH) airframe. This solution is a self-contained application of optimization within an analysis code. Most beneficial is the capability to achieve the structural goal of weight minimization with frequency separation and strength constraints.

5.2. CFD Methods in Optimization

CFD has a variety of applications within rotorcraft MDO. The challenges of using CFD are often application specific so this section is divided into four broad categories: download optimization, airframe optimization, airfoil optimization, and blade optimization

Download Optimization

For a tandem helicopter, the fuselage has a constant cross section for a majority of the region under the rotors. Therefore, it is appropriate to consider a two-dimensional section for download optimization. Flow solutions of the Navier-Stokes equations, if computed correctly, can accurately predict the aerodynamic efficiency of fuselage cross sectional shapes. Unfortunately, this usually requires large eddy simulations (LES) that are computationally prohibitive in a design environment. However it is not necessary to predict the absolute level of download; it is sufficient to distinguish relative merits among candidate designs as it relates to download. It may therefore be possible with today's computer resources to shape fuselage cross sections with detached eddy simulations (DES), unsteady Reynolds-averaged Navier-Stokes (URANS), or even steady. Reynolds-averaged Navier-Stokes (RANS).

The download optimization process might follow the schematic shown in Figure 31. A guess to the local design variables initializes the process and the cross sectional shape is constructed and evaluated for download and for possible violations of constraints. A sensitivity analysis of the design to local design variables will indicate if an optimum is reached. If so, the aerodynamic design is finished. Otherwise new local variables are derived and another pass-through of the optimization loop occurs. The product of aerodynamic optimization for download is a refined assessment of the download and a cross sectional shape with good download characteristics that also satisfies configuration requirements.

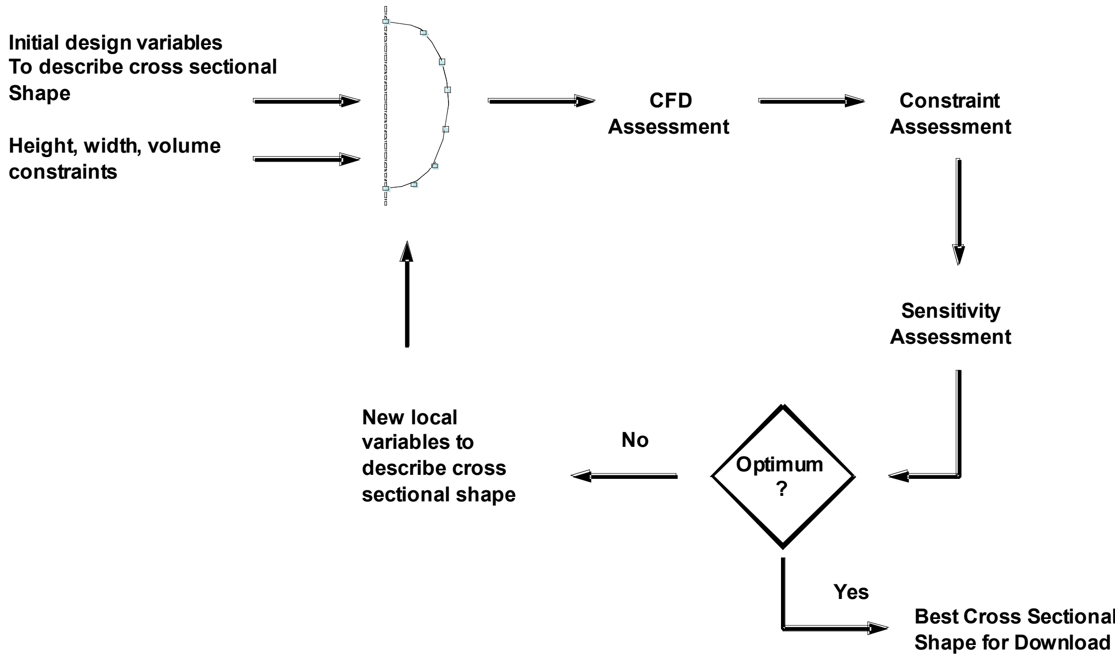


Figure 31. A possible scheme for optimizing fuselage cross sectional shape for minimum download

The quality of the optimization is strongly dependent on the flexibility of the design space to capture many diverse shapes and the accuracy of design sensitivities. Greater sophistication in analysis method requires greater computer resources and therefore may limit the extent to the design space that can be explored. There is a decision made prior to optimization regarding the importance of investigating many diverse designs with degraded accuracy or just a few designs with greater confidence. Figure 32 shows the results of sensitivity calculations made for two candidate fuselage sections using CFD methods of varying fidelity. In this case grid density is used to vary the analysis fidelity. A solution computed on a coarse grid produces a sensitivity 10 percent larger than that computed from a solution on a finer grid.

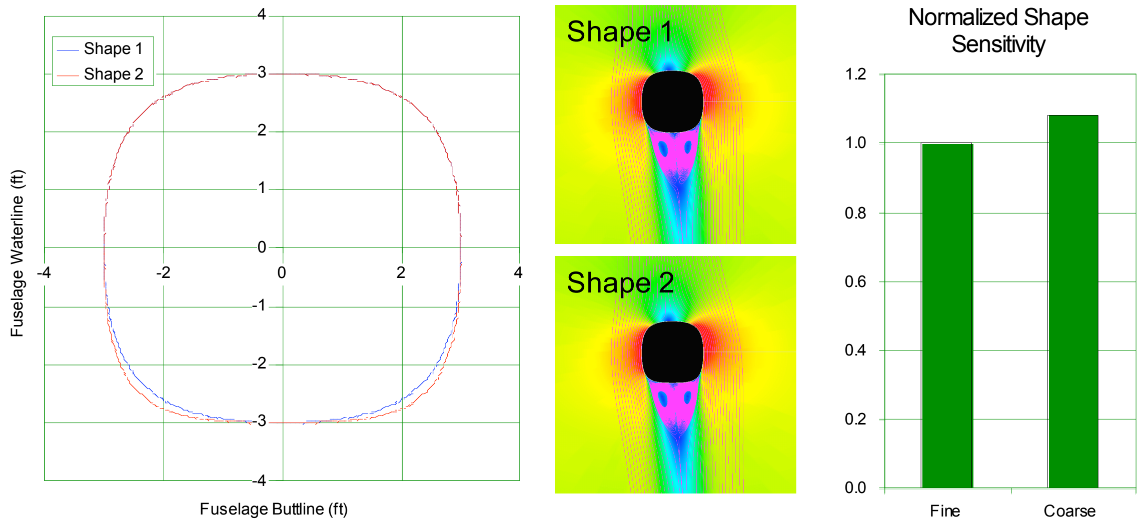


Figure 32. Effect of analysis fidelity on shape sensitivity

Airframe Optimization

Aerodynamic optimization of the airframe generally focuses on drag, but could also address other considerations such as improved stability characteristics or reduced adverse interference effects. Regardless of the objective, the nature of the flow field behind the fuselage dictates the use of a Navier-Stokes solver for helicopter airframe drag reduction optimization. One challenge in using CFD for this application is meeting the requirement to rapidly grid the airframe. Without an automated grid generator, too much time would be spent with hands-on CFD set up to make optimization practical. Capturing the boundary layer in the grid adds a level of complexity over potential flow or Euler grids. Nevertheless, it may be possible to create an automated grid generation process with scriptable software provided large topographical configuration changes do not occur. With structured grids, successful airframe optimization of the High Speed Civil Transport was accomplished using a grid perturbation approach [21]. This required hands-on grid generation of a baseline configuration; subsequent configurations were obtained using CSCMDO, a tool that automatically perturbs the baseline grid to reflect changes in the geometry. However as the optimization proceeds, eventually the geometry changes too far from the baseline and CSCMDO produces grids of degraded quality.

Scriptable grid generation is possible in many packages, for example Chimera Grid Tools, Gridgen, and MADCAP. This approach, in contrast to grid perturbation, may be harder to implement, particularly for structured grids, but once implemented will generally produce grids of higher quality. An example of unstructured grids produced from a script using MADCAP is shown in Figure 33. The geometry was produced by the General Geometry Generator, a Boeing software package for producing parametric variations in geometry for aircraft. The geometry is represented in IGES. MADCAP follows a set of instructions recorded in a script file that reads the IGES and outputs an unstructured grid. A portion of the grid created for a variation in the aft fuselage is shown in the figure.

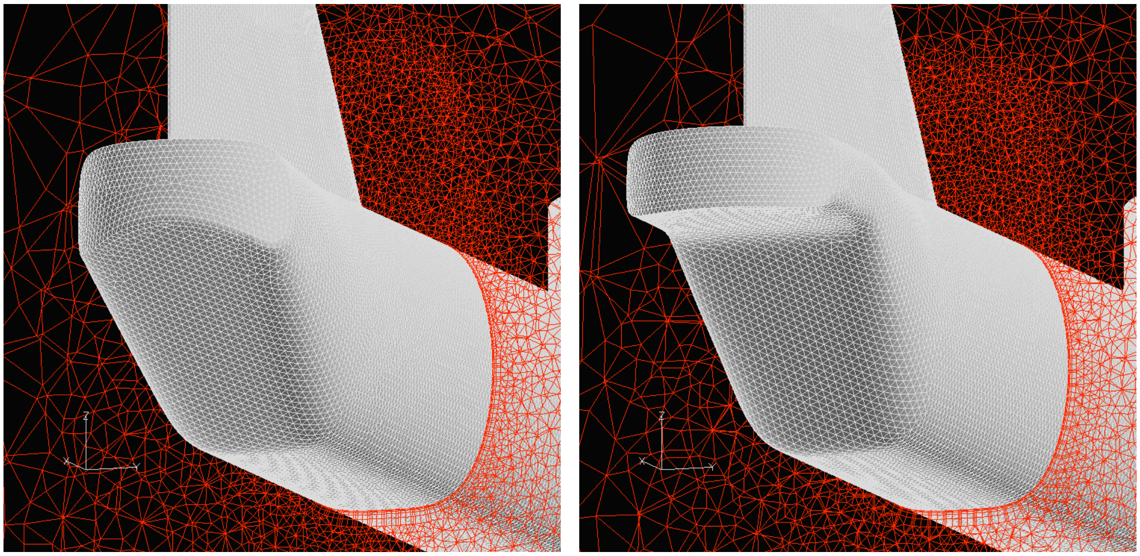


Figure 33. Result of an unstructured automatic grid generation process

Grid generation is a hurdle for CFD-based optimization, but there are others including long run times and noise convergence histories that can lead to inaccurate sensitivities. These challenges are present in blade optimization to an even greater degree and are addressed in that section.

Airfoil Optimization

Airfoil optimization will fail unless the performance is adequately represented. The nature of the high lift objectives and, to a lesser extent, the M_{DD} requirement, dictates an analysis that can capture viscous effects, particularly separation. Reynolds Averaged Navier-Stokes (RANS) methods generally capture complex flow regimes provided the flow separation is not too severe. Implementation of Navier-Stokes based analysis in optimization is complex, requiring grid generation and powerful computers.

Much has been written on the implementation of CFD-based optimization of airfoils. The simplicity of the shape and the relatively quick turn-around time of analysis make airfoil optimization a fairly well-studied topic. Critical to successful shape optimization is the parameterization of the shape. Few design variables describing a large variation is desirable and many good approaches are available, for example [22] and [23].

Optimization of airfoil shape can follow many approaches including gradient-based [24] and genetic algorithms [25]. What makes rotor airfoil optimization unique and what may drive the selection of the optimization method are the many operating conditions of the airfoil and the many performance evaluation criteria. The design metrics of rotor airfoils (section 4.1) complicate the optimization process because these metrics cannot be determined from a single CFD simulation. For example, $C_{l\max}$ for an airfoil is determined by a sweep in angle of attack; zero-lift drag divergence Mach number requires the evaluation of drag at zero-lift over a range of Mach numbers.

One approach to solving the rotor airfoil optimization problem is the design of experiments / response surface approach. With this approach, the design space is strategically interrogated using design of experiments to generate data for a surface fit to relevant airfoil performance parameters. The surface fit or response surface is quick to evaluate and acts as a surrogate to CFD analysis. In this way, several optimizations can be run with various weighting put on each of the competing design objectives. A Pareto front of optimal designs can be defined to determine a good compromise among competing objectives.

A challenge of this approach is the large amount of data required to build and update response surfaces, particularly when the number of variables is large. This problem is mitigated somewhat because good response-model-based methods for both single and multiple-objectives limit their requests for fidelity-improving data to promising regions in the design space [26] – [28].

The following is an airfoil shape optimization using the above mentioned approach to demonstrate its strengths and weaknesses. In this case, six design variables are used to perturb the upper surface of the VR-12 airfoil. The optimization is designed to improve $C_{l\max}$ at Mach 0.4, $L/D_{\max}$ at Mach 0.6, and MDD at zero lift by relaxing the stringent pitching moment that was imposed during the design of the VR-12. Data for the surface fit are obtained by analyzing 125 airfoils throughout the design space. The airfoils were selected via a design of experiment method. Analysis was performed with CFL3D.

The results of the analysis and the Pareto front of optimal designs obtained by evaluating the response surface are shown in Figure 34. The Pareto front of optimal designs is the locus of points such that an improvement in one merit can only come at the expense of another. A clear knee is present in the $C_{l\max}$ versus $L/D_{\max}$ plot indicating that improvement in $L/D_{\max}$ beyond a certain value can only be obtained at a large expense in $C_{l\max}$. Likewise a $C_{l\max}$ beyond a certain value can only be achieved at a large expense in $L/D_{\max}$.

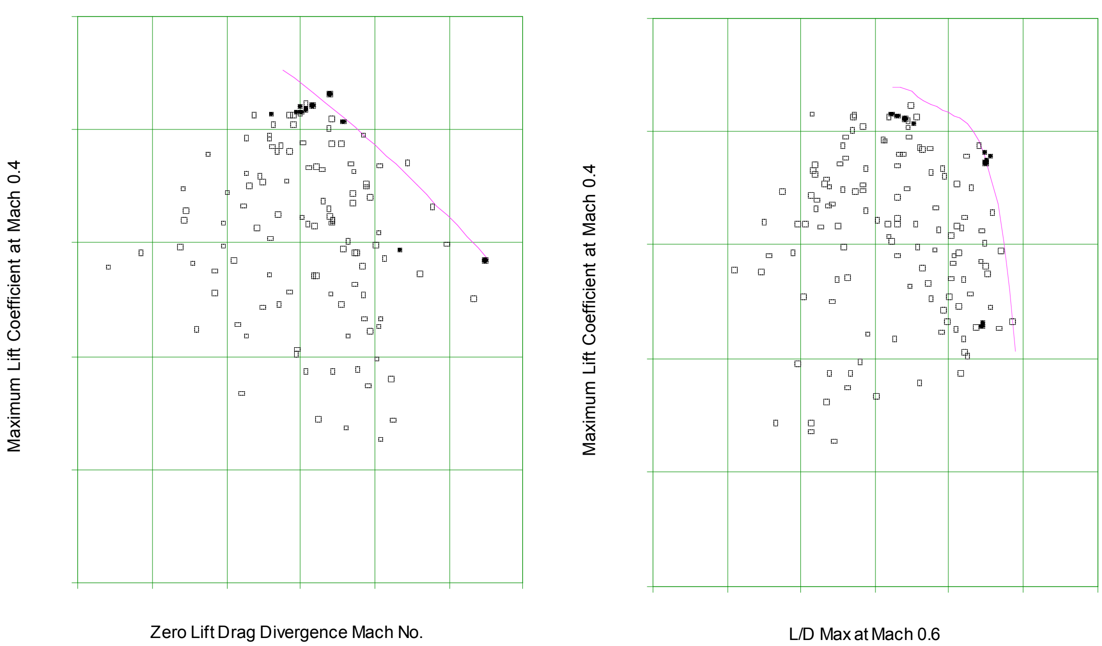


Figure 34. Pareto front and airfoil analysis of a DOE

The airfoils along the Pareto front were analyzed with CFD and plotted in Figure 34 as solid circles. The fact that the solid circles do not fall on the Pareto curve is an indication that the fidelity of the response surface could be improved [28].

Blade Optimization

Airfoil shape optimization is a key element in designing a rotor blade. Beyond this however, is the twist schedule, placement of airfoil sections along the radius, and blade planform definition. High fidelity aerodynamic analysis can have a large beneficial impact to blade design because of the inability of simpler analysis tools to capture the complexity and non-linear aerodynamic nature of the flow field. Today's CFD tools for rotor analysis are much improved over what was available even as recently as five years ago [29– 33], however analysis run time is still on the order of tens of hours. In an optimization environment this requires special treatment [34].

As with fuselage optimization, there is great advantage to automating the grid generation process. At least for a blade this is relatively simple because even most geometrically advanced blades are topographically similar. In other words, the gridding strategy would not change regardless of whether the blade has sweep, taper, or anhedral. This conclusion could break down for extremely creative designs, for example for rotors with leading edge slats, but generally a simple recipe for blade grid generation is straight-forward. One example for blade twist, taper, sweep, and anhedral is shown in Figure 35. The process uses a script that ties together Chimera Grid Tools and ultimately leads to a volume grid for OVERFLOW analysis. This particular approach applies design variables directly to an existing CFD surface grid in contrast to operating on a surface file generated by a geometry engine. The advantage is that the CFD surface grid is available to generate the volume. Operating on an IGES file instead requires the additional step to create a surface mesh that in some cases can be difficult to automate particularly for structured CFD solvers. Unfortunately, the approach in Figure 35 is not conducive to optimization in non-aerodynamic disciplines that would not typically use a CFD surface definition.

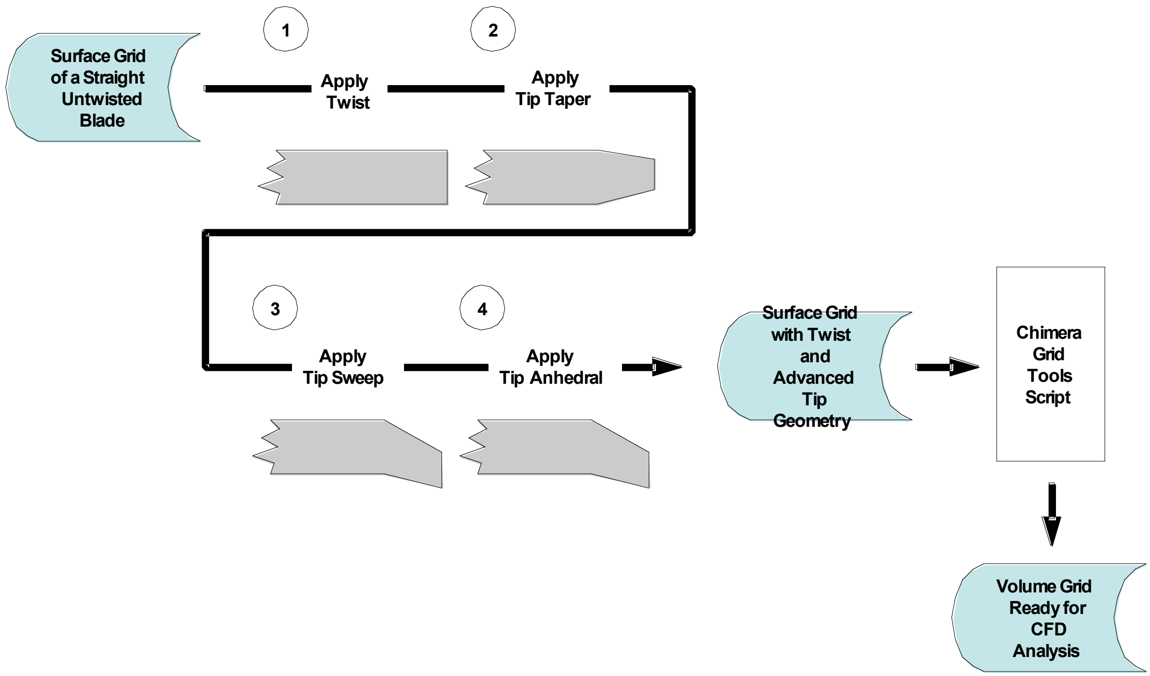


Figure 35: Automatic grid generation process for CFD analysis of an isolated blade.

The evaluation of blade tips in hover is computationally intensive; however the computational cost can be reduced by analyzing one blade of the rotor and imposing periodic boundary conditions as in the domain shown in Figure 36 for a three-bladed rotor. This approach produces steady-state, isolated hover performance parameters such as thrust and torque to compare one design against another; it also generates distributed loads and off-body flow fields which as important in understanding the physics behind the performance. The run time and typical output is summarized in Table 36.

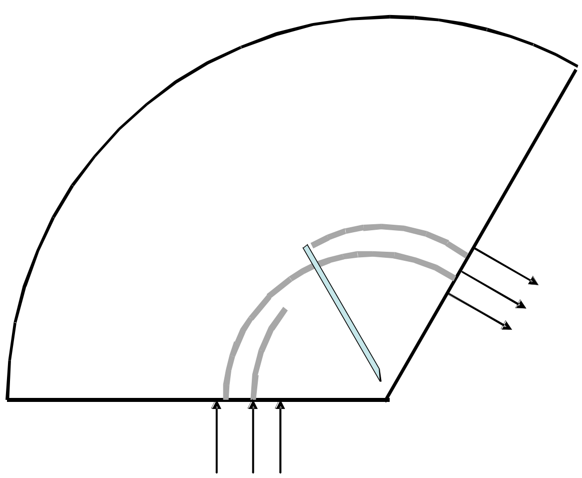


Figure 36. Computational domain for CFD hover analysis.

Table 36. CFD analysis for rotors in hover

Analysis	Outputs	Accuracy	Run-time (Linux-PC Cluster, 2.99GHz, 64 cores)
Rotor in Hover	C_T, C_Q, FM, distributed loads, Surface and off-body flow features	Unknown	24 hours per collective

CFD is under development for forward flight performance. The expectation is that, because of the ability to predict three-dimensional tip effects, advancing blade shock, non-linear unsteady phenomena, and so forth, CFD will be the method of choice for forward flight performance, especially for designs that stretch the modeling assumptions of current methods. At present, however, this approach has not developed as a reliable design tool for aerodynamic performance.

5.3. Comprehensive Codes

The goal of comprehensive codes is to combine advanced analytical technologies that traditionally ran in separate computer codes and were controlled by separate disciplinary experts. The two key areas that have been combined are structural dynamics codes that originally used highly simplified aerodynamics and momentum inflow models with aerodynamic codes that used vortex wake inflow models. These were combined with the ability to trim the rotor. Comprehensive analysis has grown to include interaction of the rotor with the body as in flexible shafts or rigid body motion as well as a drive system. Aerodynamic interactions are also included.

The promise of comprehensive codes is to capture important aircraft subsystems into one analysis so that multi-body and interaction effects can be simulated accurately. Furthermore, the hope is to have a single model that can simulate a variety of aeromechanics phenomena thereby providing analysis output for multiple users in different flight disciplines. The approach tends to rely heavily on modeling rather than physics-based simulation, e.g Leishman unsteady aerodynamic model, and one-dimensional beam model. As such, comprehensive codes tend to work well within the established bounds of the modeling technology, but tend to be less reliable for unconventional designs.

Comprehensive codes, such as RCAS, are used routinely to compute blade loads in steady level flight up to moderately high speeds. For design vibratory loads they are considered reliable. Transition points, such as hinges, cause loads to change quickly. In these regions the load predictions become less reliable. Typical blade loads correlation and error are shown in Figure 37 and Figure 38.

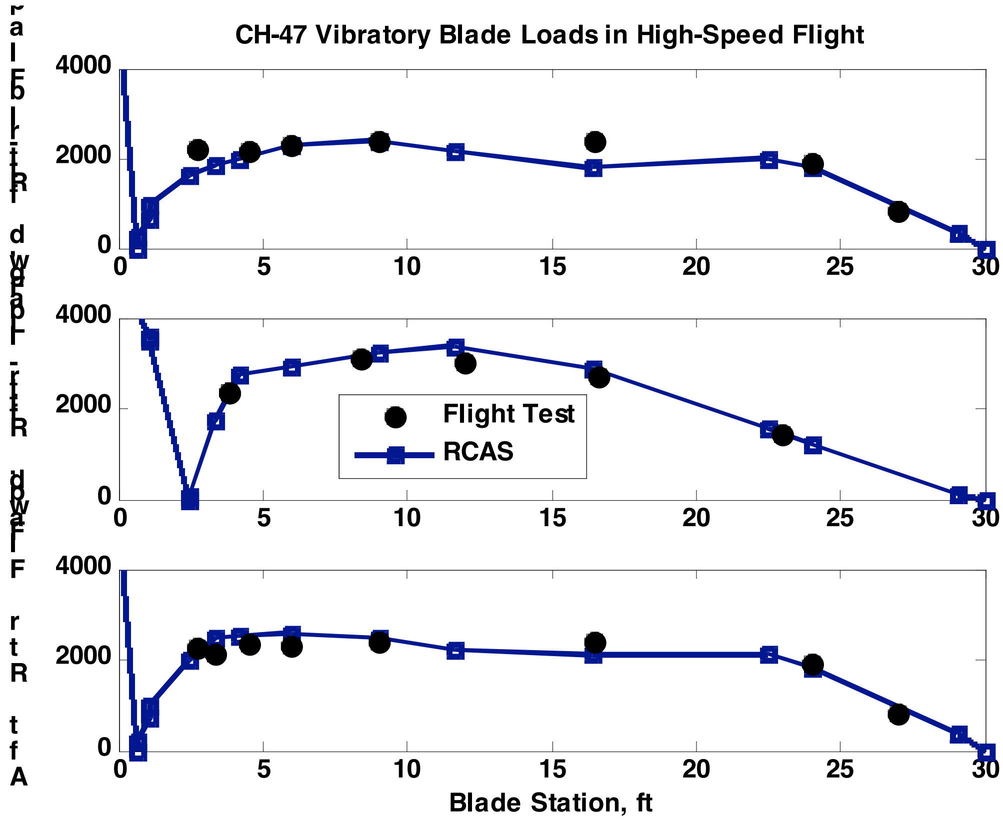


Figure 37. RCAS predicted blade loads

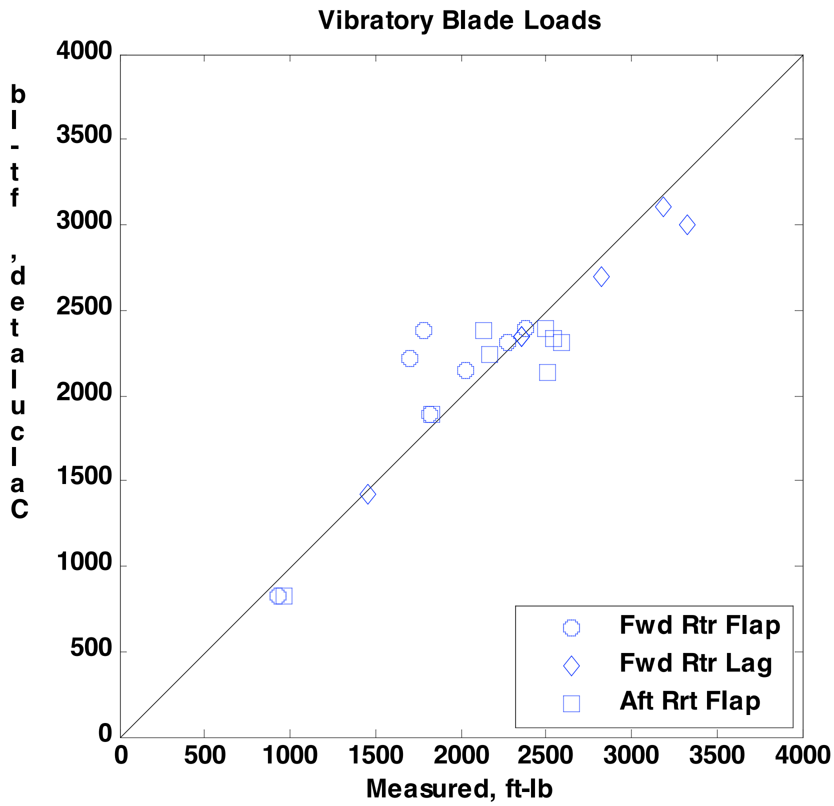


Figure 38. RCAS blade loads prediction error

Maneuver loads for the rotor system are not reliably predicted within the current state of the art. This shortcoming drives designers to develop maneuver loads from a combination of previous data, which may be scaled based on a similar design, and analysis, up to the load factor and speed combination at which they are reliable. A recent study applied CFD to a maneuver of a UH-60, and showed remarkably improved pitch link loads over lifting line methods [35]. Intensive computer memory and CPU resources make the approach impractical except for one-time loads verification (such as detailed design). They did, however, demonstrate similar improvements using a quasi-steady analysis that captures the airflow kinematics and body rotation dynamics of a maneuver. This approach is promising but still un-developed for use for optimal design in PD.

While vibration predictions using comprehensive analysis with lifting-line aerodynamics is generally poor; they are still evaluated as the models and understanding of the design mature. Typical vibration correlation and errors are shown in Figure 39 and Figure 40. Vibration minimization strategy will probably continue to employ a combination of hub loads minimization and fuselage dynamic tuning.

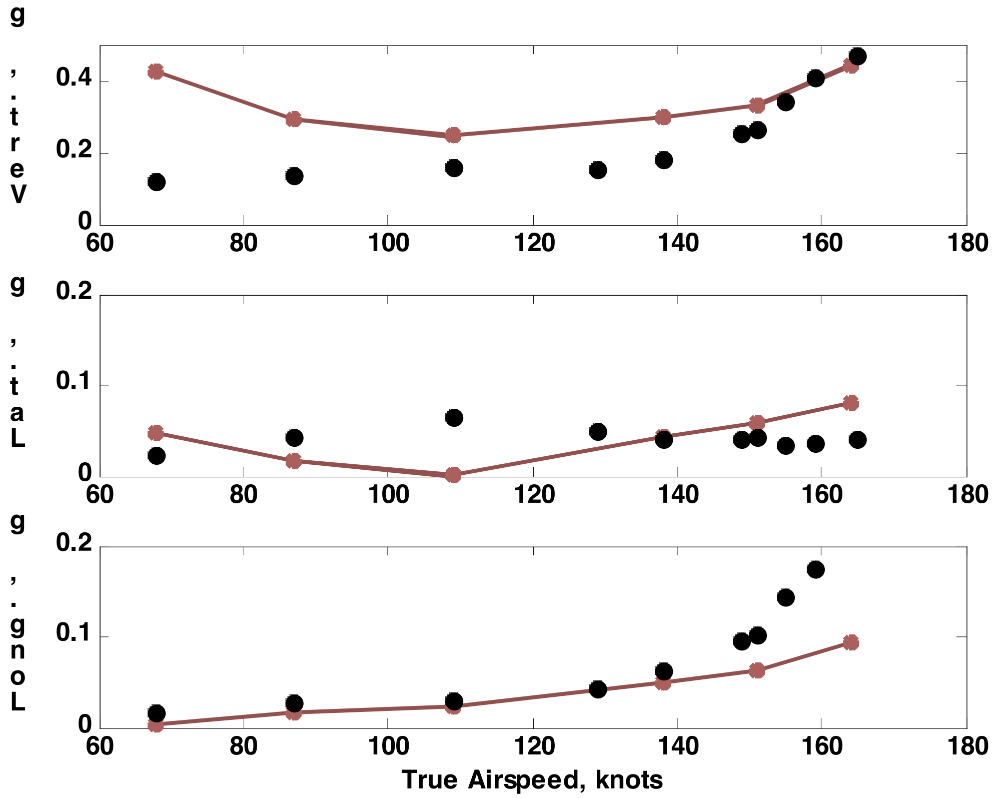


Figure 39. Vibration predictions

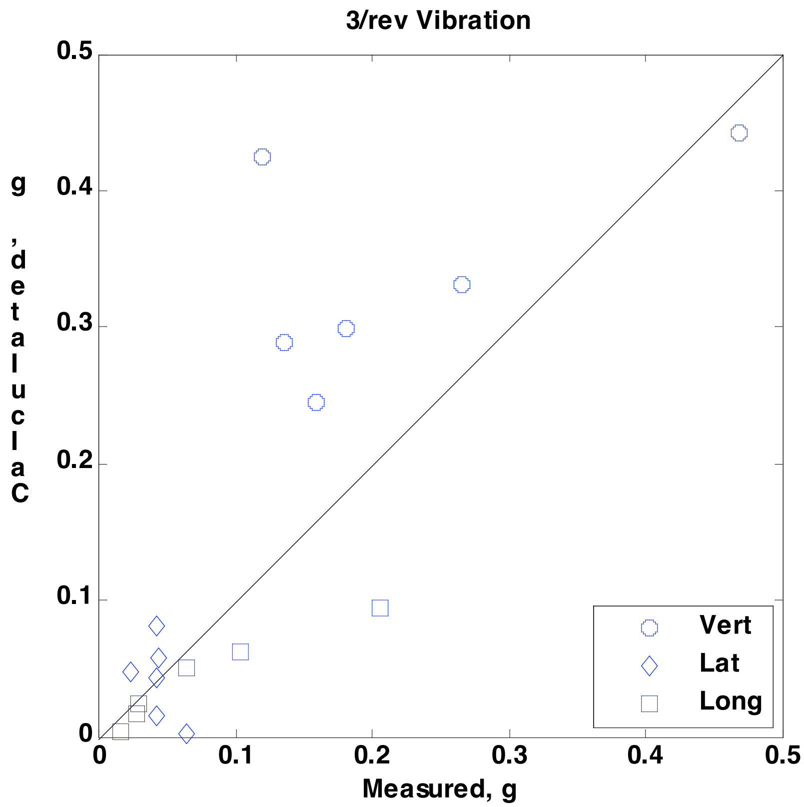


Figure 40. Vibration prediction error

Aircraft trim can also be computed with comprehensive codes. Trim has traditionally been computed with dedicated flying qualities codes that use simplifying assumptions, low-order rotor dynamics, and simple inflow models. Use of the comprehensive code for trim may is sometimes considered too much sophistication for the job; however, with comprehensive the trimmed solution can provide aerodynamic performance as well as blade load predictions. Comprehensive codes are difficult to use for analysis of maneuvering flight. Solution convergence and run time are the primary difficulties.

Table 37. Comprehensive codes (lifting-line aerodynamics)

Analysis	Outputs	Accuracy	Run-time (Linux-PC, 2.99GHz)
Single isolated rotor in forward flight	Blade and control vibratory loads,	10% - 20%	5-30 minutes per case
	Hub loads	50%	
	Power	2% - 5%	
Single rotor in hover	Blade flutter and isolated rotor damping	Accuracy not determined	10 minutes per rpm sweep, ½ minute per rpm
Full aircraft trim with rigid fuselage, AFCS, drive system	Blade and control vibratory loads,	10% - 20%	30-240 minutes per airspeed/condition
	Hub loads	50%	
	power	2% - 5%	
	air resonance and rotor/body/drive stability	Captures air resonance tends, damping ratio error 0.01-0.02	
Full aircraft trim with flexible fuselage	Blade and control vibratory loads,	10% - 20%	60-480 minutes per airspeed/condition
	Hub loads	50%	
	vibration	0.05g - 0.15g average error	

5.4. Rotor Structural Analysis

Rotor structural analysis is an essential part of comprehensive codes. Beam theory provides the elastic model, which is used primarily for the flexible blade. Beam theory also relates cross section design to elastic properties for the beam model and provides stresses. Technical performance of the comprehensive code, described above, depends on the elastic beam model. This section focuses on beam analysis as a pre-processing operation (beam cross section properties) and as a post processing operation (stress/strain).

Properties for cross sections can be generated by simple elastic integrals, but modern nonlinear composite beam theory is not only more accurate, but simplifying assumptions are reduced. Cross section analysis not only provides properties for beam theory, but also converts beam loads into stress and strain. VAB is a finite element-based system based on composite beam theory, and has evolved into an effective tool to support blade design and analysis. It was developed over the last 30 years and described by Hodges [36].

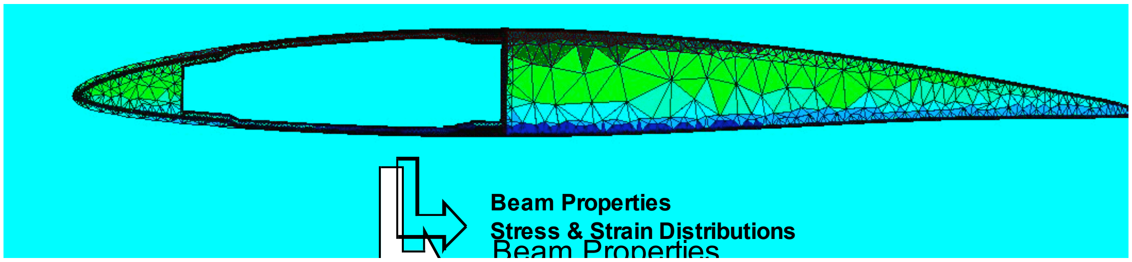


Figure 41. VABS mesh with output and stress contours

The basic stiffness analysis has been validated through the years in the on-going development of VABS. Comparison of a box-beam against other beam theories as well is three-dimensional finite element analysis is found in Reference [37], which validated not only the cross section analysis but also the composite beam theory used in comprehensive codes. Boeing tested the method using static tests of a normal, un-coupled CH-47 blade section and a modification for bending-twist coupling. Figure 42 shows the twist deflection due to applied bending load for the baseline and modified blades. The RCAS composite beam captures the coupling effects. Figure 43 shows the error trend.

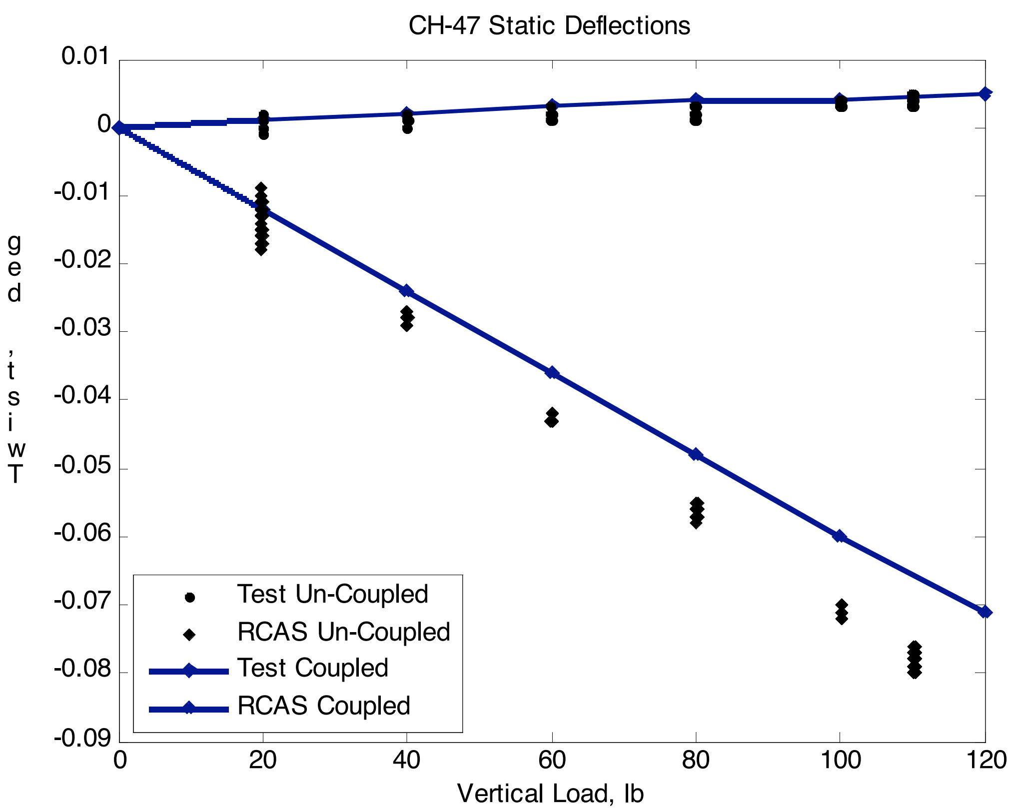


Figure 42. Static deflection correlation: twist due to vertical load (baseline & modified)

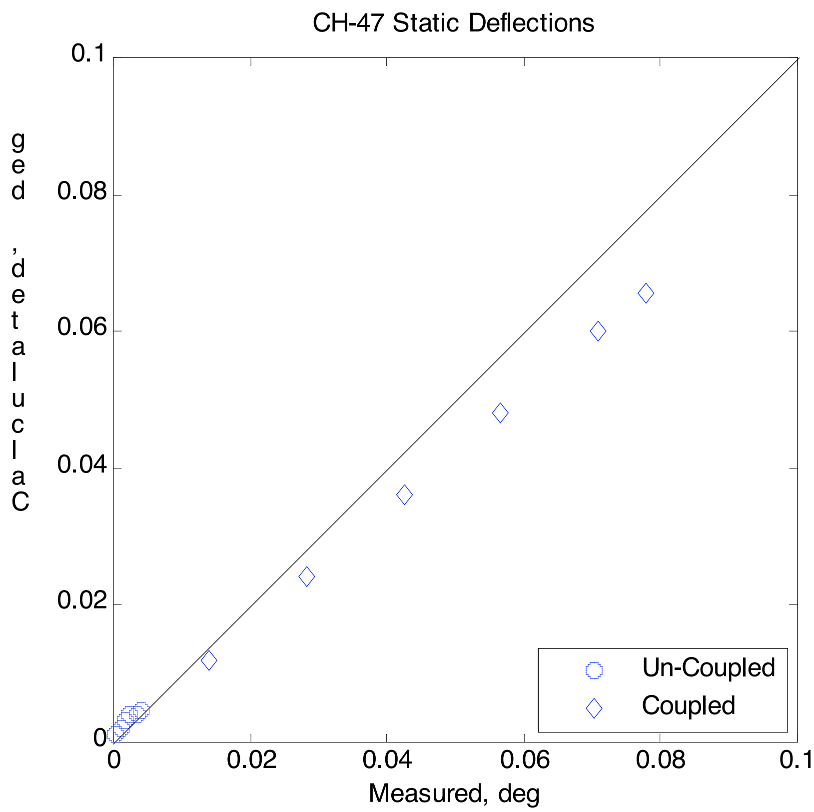


Figure 43. Static deflection error

Because of limited experience using VABS in optimization, a test was performed using a CH-47 blade section—a one percent increase thickness in the thickness of one ply. This particular ply represents about 5.6% of the blade chord-wise stiffness, so the impact of a 1% change on that ply should be about 0.056% of blade stiffness. The VABS model calculated a change of 0.065% of total blade stiffness, which closely reflects the expected change.

Table 38. Rotor structural analysis

Analysis	Outputs	Accuracy	Run-time (Linux-PC, 2.99GHz)
Blade elasticity	Cross section properties, deflections	1%–5% direct deflections, 10%–20% coupling deflections	45 seconds per cross section
Blade elasticity	Stress/strain		45 seconds per cross section

5.5. Rotor Structural and Dyanamic Optimization

Rotor structural and dynamic designs are very closely linked. The disciplinary design problems in Sections 4.3 and 4.4 show ambivalence in how to perform rotor structural/dynamic optimization. Two different types of design variables can be used: high-level beam properties like bending stiffness, and low-level structural properties like ply counts. Both have been used, sometimes in combination. Note that use of high-level properties effectively operates on the analytical model and not the physical definition of the design.

When high-level properties are used, there must be a starting point and bounds on these properties that represent a physically realizable yet undetermined design. It has also been mentioned that high-level properties are not really independent, so some interrelationship must be included. This approach has an advantage because it is not constrained by a particular concept for the cross section design. It allows the optimization to explore a broad design space so that the possibilities for improvement can be investigated. Another advantage is that fewer design variables are used, although design with aeroelastic coupling introduces "off-diagonal" terms in the stiffness matrix, which can magnify problem size. The disadvantage is that you don't know whether the design can actually be achieved, again, unless there are proper bounds on the properties.

When low-level details are used, a structural concept must be assigned. While the topology of the structural concept can change somewhat, as in chordwise spar placement, the variability is limited and therefore so is the amount of improvement in the optimal design.

A multi-level approach is one that combines application of high-level and low-level design variables. The advantage to this approach is found when there are many more design variables at the low-level than the high level. Each high-level cross section is parsed out to a low-level optimizer that finds a feasible match to the high-level target properties. A coordination parameter is used to assess at the high-level how close to a feasible match the low-level optimization was able to get. Each low-level optimization can be assigned to separate processors, so the scheme is scalable. Sequential and multi-level optimization schemes are compared in Figure 44. The selection of one or another approach must be made for each application. Introduction of elastically coupled blades to the design problem would not add significantly to the low-level design variable count, but would substantially increase the design variable count at the high level.

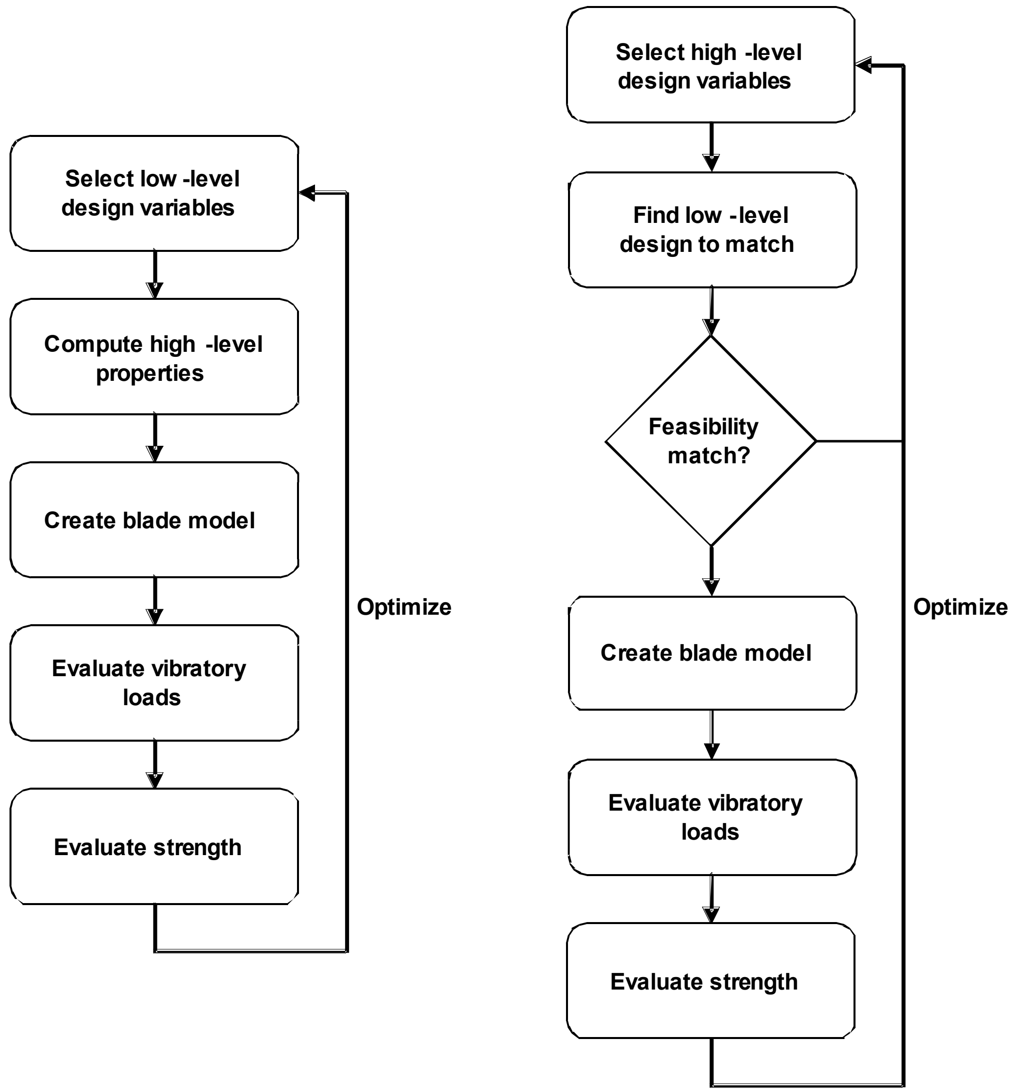


Figure 44. Sequential and multi-level blade structural optimization schemes

5.6. Lifting-Surface Aerodynamics

Lifting-surface analyses augmented with airfoil table lookup for viscous drag effects are standard practice for assessing rotor performance. These analyses utilize geometry parameters that can easily describe the complete geometry with a small number of inputs (e.g. taper, twist, sweep). Lifting-surface analyses are often run over the entire anticipated range of operating conditions in order to identify the robustness of each geometry choice.

Hover predictions are obtained for a range of atmospheric conditions and collective angles. The measure of effectiveness for hover is peak efficiency or figure of merit. The analyses used for both hover and forward flight depend on airfoil tables that have been established through test or a separate airfoil analysis. Hover analyses based on lifting-line or lifting-surface methods can be accurate to within 5%. One difficulty associated with hover performance predictions is the modeling of an aerodynamically unstable flight condition.

Forward flight predictions can be substantially better than hover predictions since the flight conditions are stable. Inaccuracies arise, however, when analyses attempt to predict performance near the limits of the rotor. Stall and compressibility play substantial roles at high speeds and high gross weights. Performance in near-stall conditions is poorly predicted and often poorly understood. Nonetheless, the bulk of the usable flight envelope is well-predicted using lifting-surface aerodynamic analyses.

A recent and fairly complete assessment has been performed by Continuum Dynamics, Inc. [38], authors of the aerodynamic performance code CHARM, which can analyze isolated rotors as well as interactional aerodynamics, particularly rotor-fuselage, multiple rotors, and ground effect. CHARM predictions are generally excellent. Figure of merit is typically better than 0.01 (one "count")

Table 39. Lifting-surface aerodynamics

Analysis	Outputs	Accuracy	Run-time (Linux-PC, 2.99GHz)
Single rotor in hover	Power	1%–2% FM	15-30 minutes per collective/condition
Single rotor in forward flight	Power	2%–5% C_P/σ	5-15 minutes per airspeed/condition

5.7. Drive System Methods

As in most design areas, information about the drive system is incomplete in the preliminary design stage. For drive system design, detailed finite elements models are used in advanced stages to check critical areas. As design progresses, increasing numbers of critical areas are checked. The most critical parts receive detailed attention first; these are often the largest gears, where re-sizing for additional strength or dynamic resonance would cause the biggest disruption to the design as a whole.

At the early stages, empirical methods are used for gearbox weight [39]. This method uses trend data for drive system components in a similar manner as weight trends in conceptual design sizing. These techniques are relatively straightforward compared to CFD or FEM and can be coded in dedicated computer programs or even spreadsheets. Gear strength is implicit in the sizing method. The weakness is that the method is tuned for spur gears, and may not accurately reflect other gear types.

Analysis of the actual gears employs ANSI/AGMA methods that are implemented in computer programs. Standards contain various gear types (spur, helical, spiral-bevel, etc.) These programs compute gear tooth contact and bending stresses and compare against allowable stresses. Lubrication flash temperatures are also computed. Run-time is very fast. Later design stages will use detailed FEM-type analysis, but for this phase of design, accuracy is reliable.

At a mature stage of design the transmission housing will undergo thorough analysis with a detailed FEM model. During design, key features will be checked with hand calculations, especially bearing supports and lugs for attachment to the airframe. Stress concentration factors are essential to a reliable hand calculation; a local FEM can provide these if the geometry is outside of the experience base.

AMGA gear analysis methods have been successfully demonstrated in optimization by Saribay et al. [40], where an intermeshing drive system was optimized for a Kaman K-Max intermeshing helicopter.

5.8. Acoustics

Assessment of acoustic properties has two key components: high-resolution airloads and noise computation. The former is the input to the latter in the form of pressures. The former is also the weak link in the design optimization as proposed. Accurate prediction of airloads relies on accurate prediction of the wake position. Vortex wake methods that are common to comprehensive codes provide sufficient accuracy for certain aeromechanic computations such as power and vibratory blade loads, but are not accurate for noise. This is especially true for rotor-rotor wake interactions where, even with a free wake model, tracking of the wake placement is not precise and the methodology is uncertain. CFD methods are developing as an alternative. Their use for noise computations are subject to limitations as described above, namely long run-time and complexity. They are also subject to vorticity diffusion, which is critical to capturing impulsive loading when a vortex passes near a blade.

Noise computation is exemplified by WOPWOP and its various versions and refinements. Accuracy is considered good, as far as there are accurate pressures from the airloads computations. Run time is also relatively short. While acoustic noise prediction is currently marginally reliable for the proposed design problem, ongoing research is underway that could bring CFD-based noise methodology into practical use in design optimization [41].

5.9. Managing Optimization Run times

The multi-objective nature of rotorcraft design problem drives the optimization procedure towards a procedure that can rapidly produce a Pareto front of optimal designs to understand the trade between one objective and another. Utilizing any analysis that has long run time, especially RANS based CFD, is an issue when generating the Pareto front because of the many analyses involved. A popular alternative to reduce overall run time is the response surface that can be used as a surrogate for the computationally intensive analyses during optimization, especially for producing the Pareto fronts. Additionally, ongoing advances in high-performance computing should make optimization with high-fidelity methods more feasible.

5.10. Managing Optimization In the Presence of Uncertainty

Helicopters can and have been designed with uncertain knowledge about many aspects of the design. Risk, from uncertainty especially from vibration and loads, is evaluated and mitigated with wind tunnel testing, prototypes, and so forth. Inaccuracy in analytical capability is part of risk management in design. One way to mitigate risk is to incorporate robustness into the design optimization problem. The goal of the analyst is to bring the best tools and have knowledge of their strengths and weaknesses; then do the best he can.

For many of the analyses that are used to support the design of a rotorcraft the fundamental question to be asked is, can you trust it for use in optimization?

The backup plan is part risk reduction. For example, vibration prediction is notoriously elusive. A design can contain provisions for vibration treatment such as active vibration suppression with the hope that it will not be needed. Another example is transmission design, where room for growth in bearings and gears can be retained in at least one dimension without intruding into other areas.

6. Interdisciplinary Design Map and Collaborative Design

The promise of large-scale integrated multi-disciplinary optimization is systematic design space exploration and optimal design where design tradeoffs are part of a structured system, which should lead to superior design. While the IPT structure provides a venue for interdisciplinary considerations to be discussed in a team environment, it does not provide a systematic approach where mathematical programming techniques can be employed in a multi-disciplinary way toward common high-level objectives. This section examines how the previously-described disciplinary design problems are interconnected. Understanding the extent and nature of these interconnections assists in the formulation of an execution strategy.

As a combined optimal design problem, what has been presented is large-scale, and probably requires a decomposition strategy. Actual design employs decomposition even without a formal optimization architecture. Rational for decomposition must consider the nature and complexity of interactions between subsystems or disciplines that may be highly problem dependant. The evaluations contained in this section are based on subject matter expert experience with regard to the tandem helicopter configuration of the baseline design—expectations on the impact of something from one area on the optimal design in another are based on experienced judgment, and may be problem dependant.

The interdisciplinary map shows various areas of stronger and weaker coupling but does not constitute a complete strategy for MDAO. A design paradigm is also presented that focuses on optimization as a tool to support decision making in design. This method is one among many that may be applied, but it has the key element of providing insight into the design space to the decision maker. This is essential because decision makers need more than just the "optimized" design.

6.1. Subsytem Design with Loads and Design Exchange Cycles

Design progression traditionally includes period updates called "loads drops", at which time the current configuration is frozen and all external loads are re-computed. External loads include potentially thousands of cases: steady flight, maneuver flight, landing and taxiing, gust, crash, ditching, start-up and shut down, static ground, and so forth. These external loads are fixed until the next loads drop, which means that actual loads lag behind efforts to reduce weight. High level design information is periodically exchanged with a similar rhythm, Figure 45. This paradigm might not be ideal in a multi-disciplinary sense, but it reflects the practical reality of the design of a complex system such a rotorcraft where ground rules are constantly changing and many people are involved.

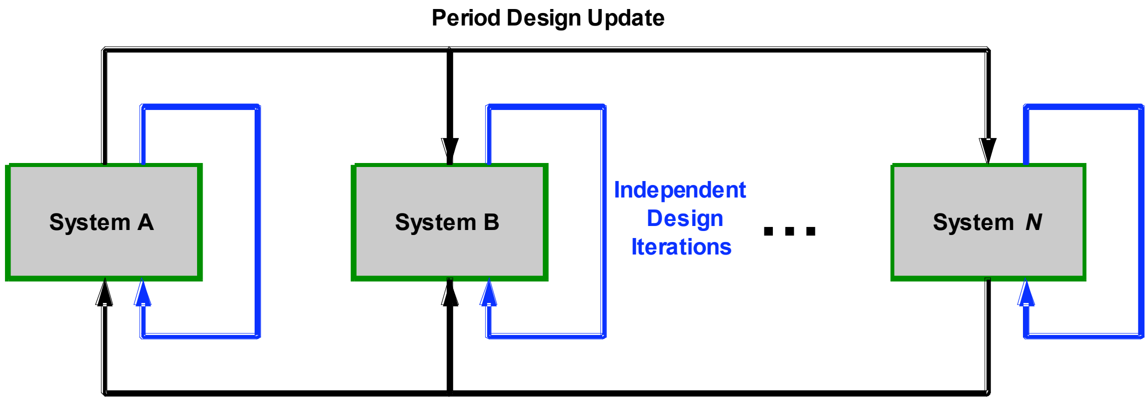


Figure 45. Design rhythm with period updates

Improved software and process technology should allow more frequent loads updates, especially within optimization. Considering the loads drop in fuselage structural optimization as an example, design entails sizing elements for minimum system weight, and much of the external loading spectrum is loads that are proportional to weight, especially landing, ground handling, and steady rotor forces. Therefore a weight reduction should produce a corresponding loads reduction, but loads are not updated within optimization but rather after optimization. A system to update loads within fuselage optimal sizing could be considered as an alternative; both systems are compared in Figure 46.

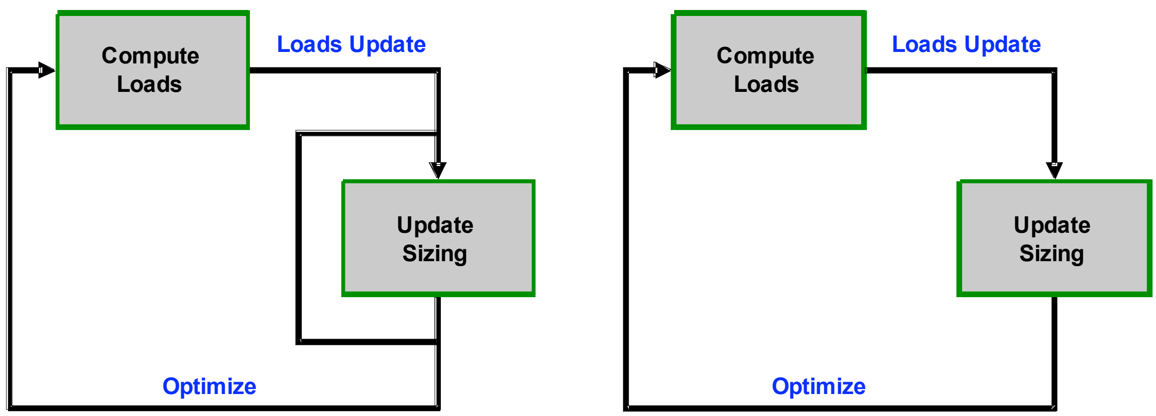


Figure 46. Loads drop versus loads update systems

6.2. Criteria for Determining Multidisciplinary Coupling

Considering that decomposition is expected the question is how loosely or tightly coupled are the various subsystems and disciplines? If the design in system B is highly sensitive to the update from system A then they are tightly coupled. Where little experience exists in rotorcraft design, statistical methods such as analysis of variance (ANOVA) can be used to evaluate these interaction strengths. This requires an infrastructure for computing responses from a sampling of design variables, which might not be available early in the design. Experience is critical. Note that there is a distinction between whether *analysis* in one subsystem is affected by another and whether the *design* of one subsystem is affected by another. For example, fuselage and propulsion system aerodynamics are strongly affected by the rotor downwash, but the design of the fuselage shape would not be influenced by details of the blade design such as chord or twist; likewise blade chord and twist would not be influenced by the shape of the fuselage.

If subsystems are tightly coupled, another consideration is how many design variables must be shared to decompose the problem. If there are only a few common variables, then decomposition may be more practical.

6.3. Interdisciplinary Design

Design analysis is a complex web of information flow. Outputs from one analysis are often inputs to another. The individual discipline design problems in Chapter 4 were examined for their inter-connectivity, using a high-level approach based closely on an organization structure for simplicity. The initial investigation used a process flow diagram that arranged design variables and responses according to disciplinary groupings: fuselage aerodynamics, and propulsion, fuselage structure and dynamics, flying qualities, drive system, rotor aerodynamics and noise, and rotor structure and dynamics. In structural design the analytical model is used in multiple ways: internal loads analysis, frequency analysis, and weights. Because of this, structural model building elements were added to simplify the process flows.

In Figure 47 design definition blocks represent groupings of design variables as posed by the individual disciplines. Exceptions are found where two or more disciplines claim ownership of common design variables. Airframe aerodynamic and propulsion system integration both primarily involve shaping the loft to improve airflow conditions; therefore they are grouped together. Likewise rotor aerodynamic performance and noise are closely linked by high-resolution airloads. Airframe structural design closely integrates airframe strength margins and the tuning of fuselage frequencies. While multiple claims of ownership do exist in practice, here they were assigned to one owner for the purpose of developing the interdisciplinary map.

Process elements were arranged diagonally and then connected according to simple reasoning: considering the disciplinary design problems that have been developed, what information is needed for that element? Information flow is clockwise so that feed-forward is in the upper right side of the diagonal and feed-backward is in the lower left. The high-level version of the diagram, Figure 47, is shown in more detail in Figure 48. (This figure is shown enlarged in the Appendix, along with a sequenced version that shows how the analyses can be performed sequentially from a given design definition. That is, it is not necessary to iterate on the analysis to evaluate a design for this multidisciplinary design problem.)

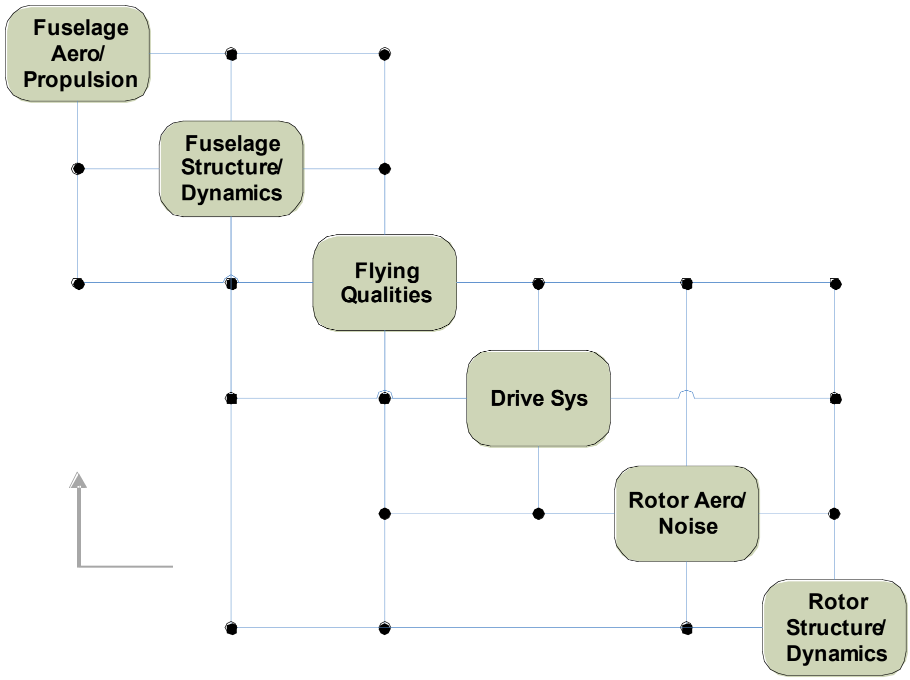


Figure 47. High level process

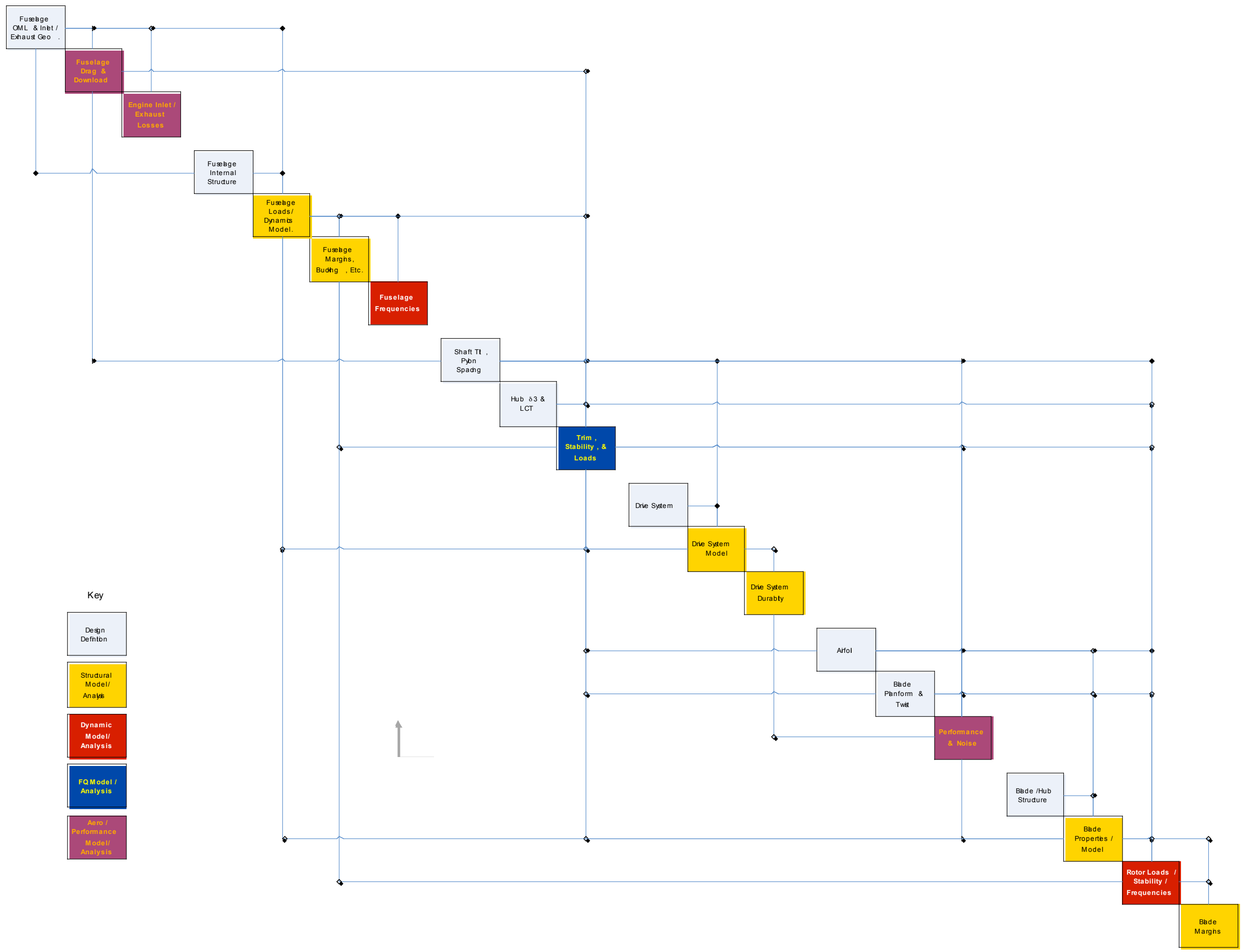


Figure 48. High level process with details

In each grouping the design definition feeds into an analysis or a model; additionally each grouping requires information from at least one other grouping. This information takes the form of design information, or a model that provides subsystem or aircraft-level weights, or additional modeling information (e.g. rotor model for flying qualities aircraft-level trim and stability), or loads for the computation of strength margins or component life. The multi-disciplinary nature of the proposed design problems is clearly seen. In what follows, the stage is set for decomposition in to multi-level design by examining the inputs and outputs of three major design groupings; airframe, flying qualities and drive system, and rotor system.

A more detailed view of airframe design is portrayed in Figure 49 with descriptions of key inputs and outputs. Body forces, especially drag and download are required for trim as are airframe weights; these are outputs from Airframe Design. Note that weight information is collected as input from the drive system and blade/hub models and assembled in the loads model. Inputs also include shaft tilt and pylon vertical spacing, which are defined primarily for optimizing trim attitudes and secondarily to improve spacing between rotors for noise and dynamic loads. Fuselage drag optimization as posed in Section 4 suggests analysis at several pitch angles for a robust optimum; therefore trim information is not required. Finally, external vibratory and steady loads are needed by the loads model. Information inputs and outputs involving airframe design elements tend in practice to be slow moving in that updates are periodic while design progresses. Furthermore, optimal designs are not likely to be strongly impacted by subsequent updates to the inputs. Therefore the airframe design can be considered loosely coupled to the other design elements.

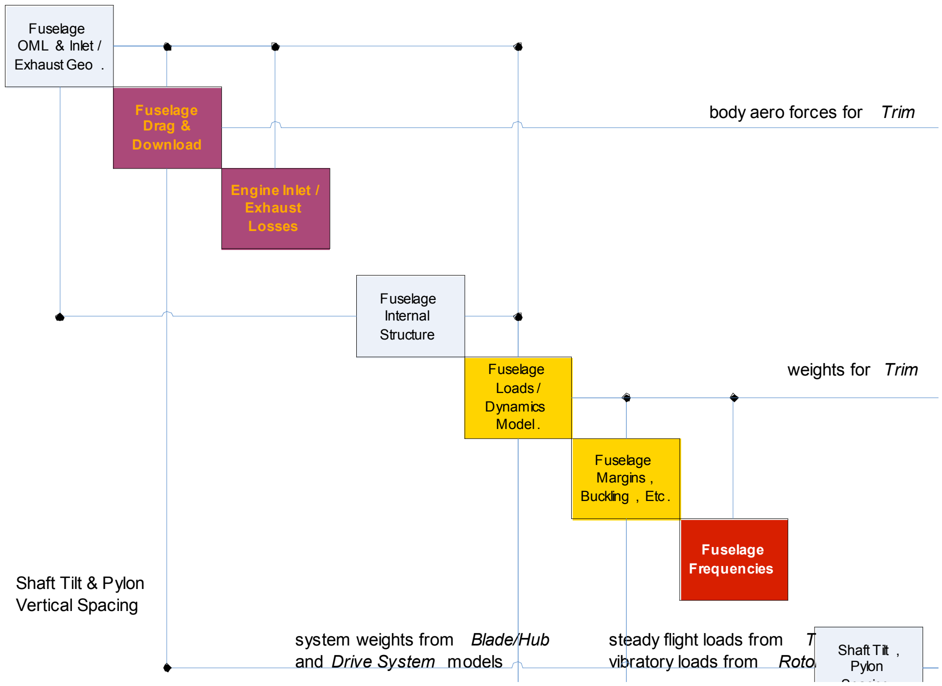


Figure 49. Airframe design process

Internal to airframe design are aerodynamic and structural elements. Fuselage OML definition is an important part of the fuselage loads and dynamics model because the structure is defined within that space. The connection of the fuselage internal structure design variables to the fuselage OML definition is somewhat unusual because, in this case, design definition in one element is directly constraining the design definition in another. This is because the OML must accommodate both the internal passenger/cargo/fuel volume and the internal structure. The strength of this coupling is difficult to predict; however, even if the coupling is not loose, sharing OML shape design variables can be employed with a relatively small set of common parameters.

Flying qualities and drive system design are the interfaces between the fuselage and rotor subsystems. These are portrayed in Figure 50 with descriptions of key inputs and outputs. Trim conditions, longitudinal cyclic trim, rotor location and tilt are sent to rotor aerodynamic, noise, and loads analyses, which employ either an isolated rotor or full aircraft model if rotor interference effects are important. Rotor vibration optimization typically uses two to three airspeeds, which mitigates trim dependent effects. Rotor aerodynamic performance optimization tends to be insensitive to the exact trim up to stall onset. Noise optimization is affected by changes to trim because of rotor inference airloads and blade-vortex interactions. Because noise optimization relies on trim design variables (shaft tilt, LCT), noise is very tightly coupled to trim. The amount of common design information, however, is small. Hub kinematic coupling ($\delta 3$) mostly effects low frequency blade flapping response and has little influence on power predictions. As for vibratory hub load predictions, these are driven by higher frequency responses. Blade loads should not be strongly affected by moderate changes in kinematic coupling; therefore these areas are loosely coupled to kinematic coupling. Rotor aerodynamic and structural models for trim and stability analysis tend to be lower fidelity; so trim optimization should not be sensitive to small changes to blade design parameters. Drive system life uses steady torque from rotor performance as a key part of the load spectrum. The impact of this load on the optimal drive system design is likely to be significant.

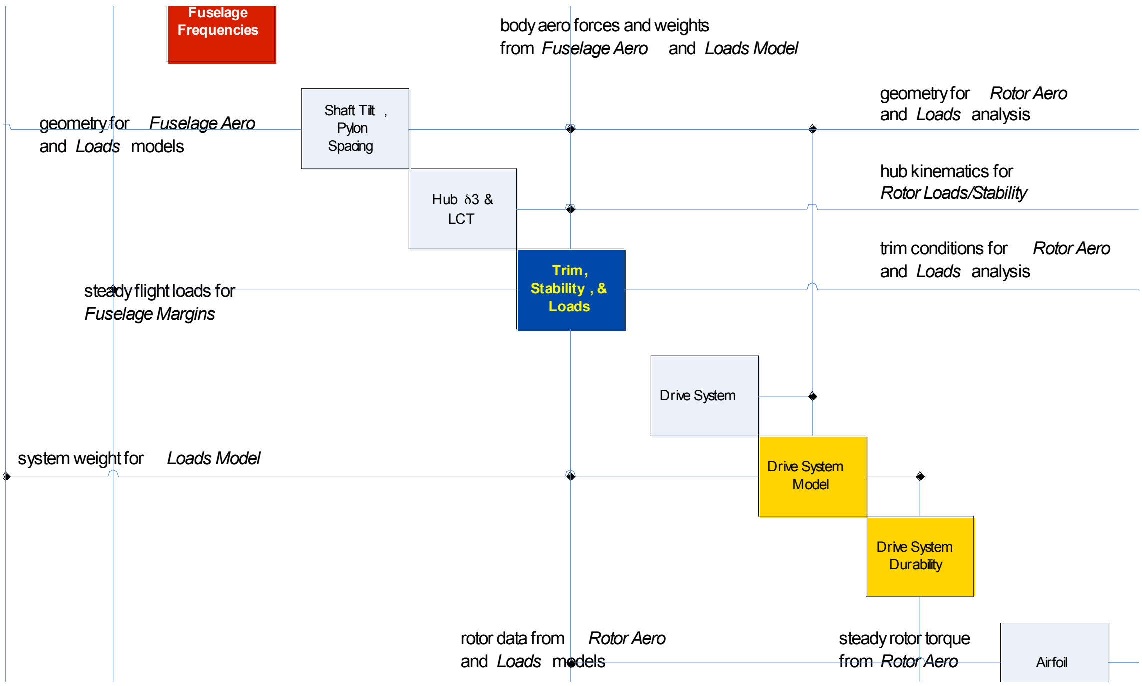


Figure 50. Flying qualities and drive system design process

Two interfaces between flying qualities and the drive system tie the two together. Pylon vertical spacing effectively prescribes the rotor shaft length, which may need to be stiffened if it becomes longer, and shaft tilt prescribes the gear angle for the transition from horizontal to vertical shafting. This has little impact on the overall design given the small range of variation the shaft tilt will have. The drive system model is used for rotor-rotor mode stability analysis, which evaluates a constraint on damping. Note that shaft tilt does little to change the torsion dynamic, and rotor shaft length (controlled by pylon height) is just one piece of the drive system and is usually not the softest. In terms of design, flying qualities and drive system design are loosely coupled.

Rotor Design, including aerodynamic, structural, and dynamics elements, is shown with more detail in Figure 51. External connections have already been considered. Internal connections between aerodynamics and structures/dynamics are probably stronger for the rotor than the airframe. This is because rotor analysis is inherently aeroelastic, and rotor aerodynamic forces are relatively strong, especially considering the small flexible blade structure. As seen in the figure, aerodynamic shape not only affects performance and noise, and loads and stability, but it strongly affects the structural model through the blade OML. The path blade/hub properties model to performance and noise is not as strong. In fact, this analysis is often performed using a rigid blade; however, blade deflections can be aerodynamically significant—one to two degrees, which should be accounted for in analysis. While it is not likely that aerodynamic design would directly influence blade structural design, blade aerodynamic design is often affected by structural and dynamic requirements. Airfoil pitching moment characteristics, blade twist, and stall are all well known for their effect on rotor loads.

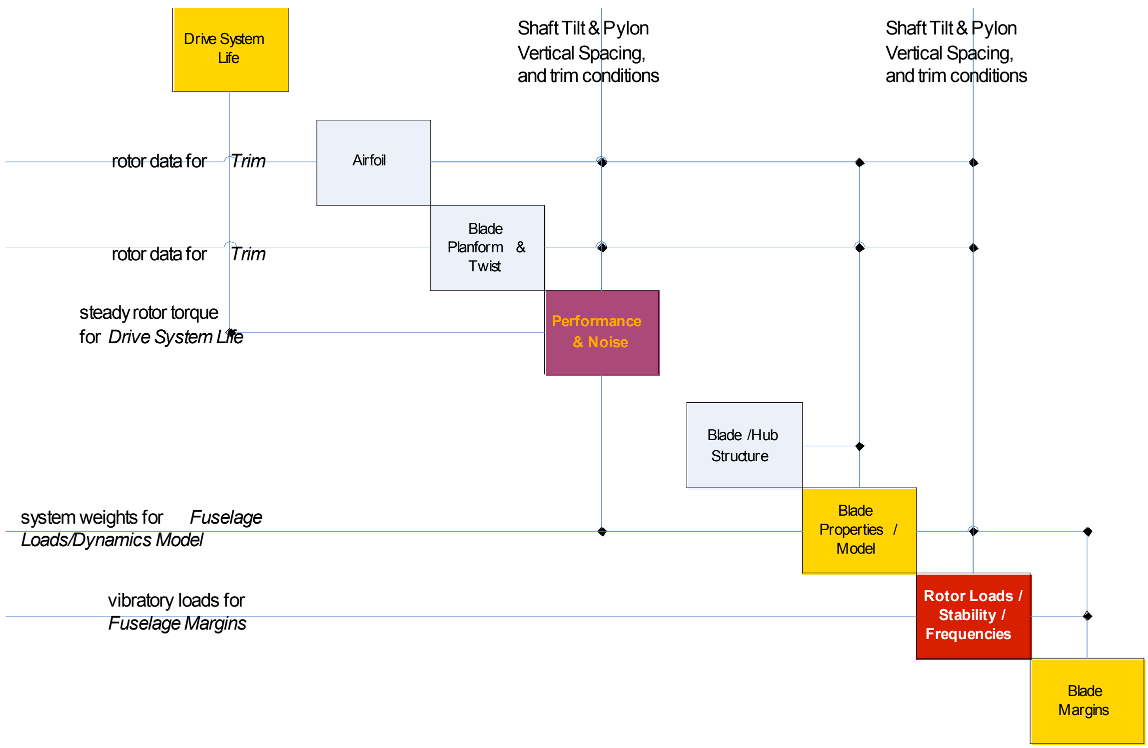


Figure 51. Rotor system design process

6.4. Collaborative Design Exploration

Optimal search methods can be applied to the design problem, but simply understanding that one design is better than another is not sufficient to make an informed design decision. In fact, the concept of a single optimal design is not applicable to rotorcraft because of the many objectives they must meet. There are many optima depending on how the objectives are prioritized. Design decision makers must be able to defend their position which requires understanding risks and trade-offs. Specifically, decision makers must understand a broad design space in terms of:

- How the choice of a design feature impacts all relevant engineering disciplines
- How the design performs at off-design conditions
- How slight perturbations might impact design performance
- Why a design feature is helpful or hurtful to each discipline and the overall design metric.

The rotorcraft MDO architecture must be able to provide this information—in other words, it must provide a map of the design space. Response surfaces lend themselves nicely for displaying this kind of map. Not only does it provide information on how the design will perform, it will show how neighboring designs will perform and how relaxing or tightening constraints can impact the design.

Consider for example the design information shown in Figure 52. Two important design variables are plotted as independent variables along the horizontal and vertical axes. These represent two variables that are shared between two (or more) disciplines or subsystems because of their strong impact on both. Contours of a critical design metric are constructed by interrogating the design space at the green dots and fitting a surface to the results. The interrogation of the design space is a flow down to the disciplines or subsystems (low level) of the shared variables (high level). At the low level there is freedom to find a feasible optimal design that uses the shared variables as fixed parameters; any appropriate optimal search method can be used. Thus, response values at the high level not only represent the value of critical design metric, they represent the best that the low level can achieve. If a feasible design cannot be found at the low level with the prescribed shared variables, the shared variables represent an infeasible design as shown in the figure.

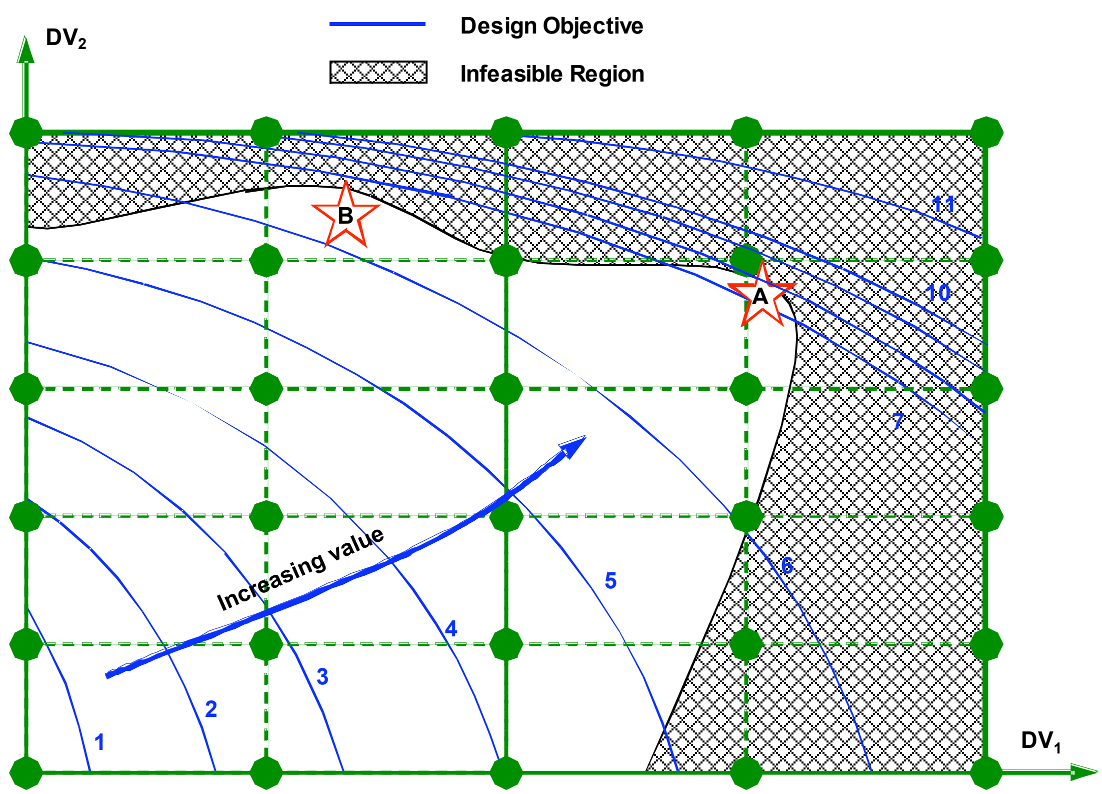


Figure 52. A view of a response surface map of a multidisciplinary design space

In this example the response surface clearly shows increasing values in the two design variables benefits the design objective. The second response surface for the constraint indicates boundaries in the design variables beyond which the design becomes infeasible.

From this picture the decision maker can understand:

- There are two important design points; Design A is a global optimum and design B is a local optimum.

- For high values of the second design variable, the design objective becomes less sensitive to the first design variable

- Design A and B give nearly the same performance though they are very different designs.

- Small relaxation of the constraint near the region of Design A can lead to a relatively big payoff

The benefits of a global view of the design space are very important to the decision maker. However, constructing the response surface needed to create the design space roadmap is a non-trivial task for rotorcraft MDO. Generation of response surfaces suffers from what has been called the curse of dimensionality [42]. As the dimension of the problem increases, the number of function evaluations needed to construct the surface rises rapidly. If, for example, we choose to discretize the n-dimensional design space in a grid of dimension m, the number of evaluations if every grid point were analyzed would be m^n. For a modest design dimension of 10 and $m = 3$, the total evaluations would be 59,049. Adding another design dimension increases the number of function evaluation to 177,147. For high fidelity analyses where compute times can be long, the maximum number of dimensions can be severely limited. Luckily, there are more efficient methods, such as orthogonal arrays and fraction factorials, to select designs with which to populate the design space, though they are still subject to the curse of dimensionality. In addition there are response-model-based optimization methods that carefully select region in which new data are obtained [26].

Response surface methods limit the number of design variables that can be used in a high-fidelity rotorcraft MDO. The limit can be increased, though, with some innovative methods that must be built into the rotorcraft optimization architecture. One way is a variable fidelity approach whereby much of the design space is populated with low-order analysis and only select cases are analyzed with high-fidelity approaches [43].

The multi-level approach that is described here is inspired by the collaborative optimization method whereby the design space is expanded on the single disciplinary level and only a limited number of design variables are used at the global level. In collaborative optimization variables are separated into global and local categories. Global variables affect two or more disciplines; local variables on the other hand affect only one discipline, or at the most, weakly affect other disciplines. For example, rotor twist is assuredly a global variable.

In typical collaborative optimization, a gradient-based approach drives the search while a variety of optimization procedures can be pursued at the local level for each step of the global optimization process. More general methods have been described for decomposition into multi-level systems [44]. Here the global search is replaced by a global response surface, which is the surface along which collaborative optimization moves during search. A form of global collaborative optimization has also been developed and applied to the optimal design of a tiltrotor [45], but this approach retains and presents a picture of the global design space. Instead of optimizing at the global level, the rotorcraft optimization architecture will utilize a Design of Experiments approach for a handful of important global variables. Each candidate design in the DOE will be optimized on the local level. The DOE will lend itself to design exploration instead of optimization to provide designers with information to make educated decisions. The process is drawn in Figure 53.

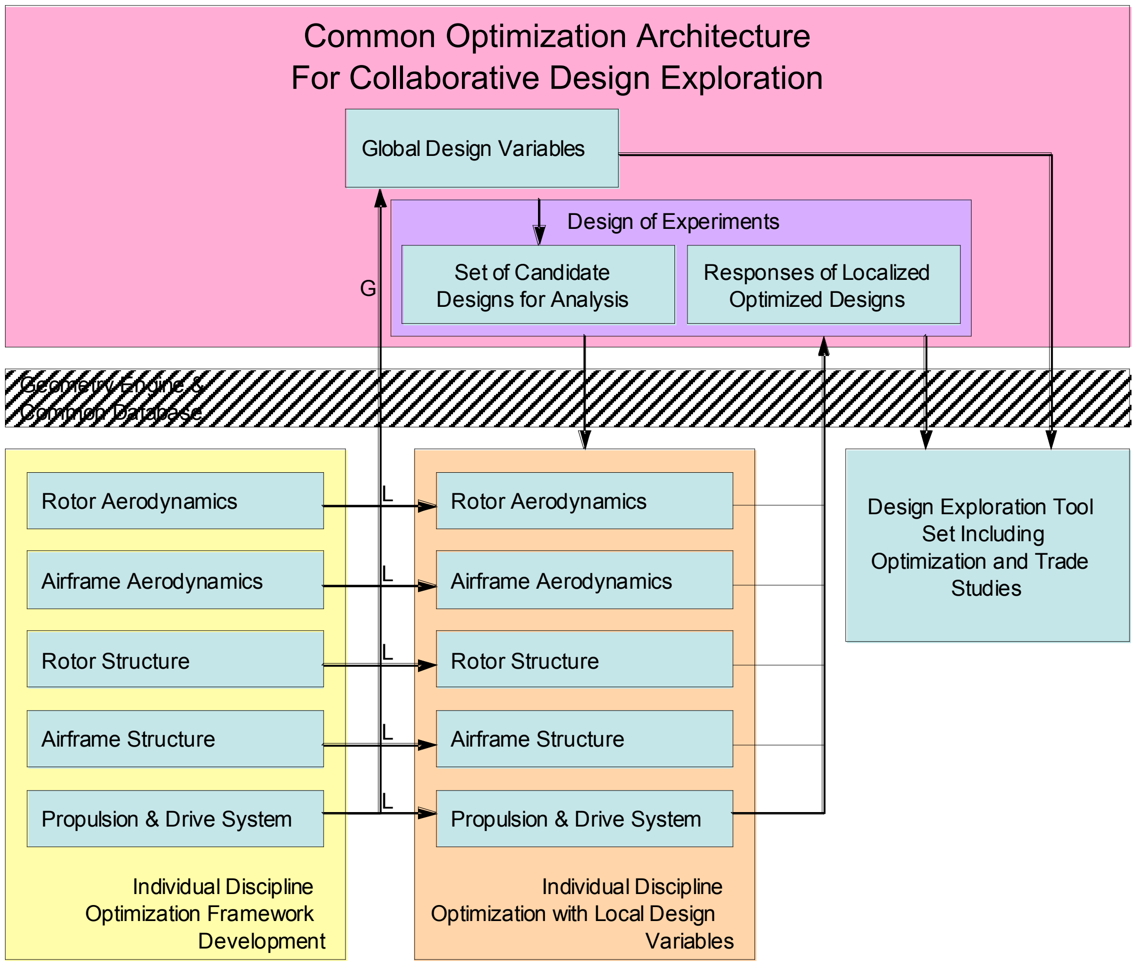


Figure 53. Common Optimization Architecture for Collaborative Design Exploration

The single disciplinary design problems have been identified in Section 4, and specifically design variables of the disciplinary design problems have been identified. Those variables that are common to two or more discipline are pulled out in the Common Optimization Architecture and are categorized as the rotorcraft MDO design variables. These, or more than likely, a subset of these will be used for collaborative design exploration. The disciplinary design variables which did not get identified as global variables are set aside for local sub-optimization.

In the Common Optimization Architecture, a set of candidate designs is chosen for analysis. Each of the disciplines will return an analysis of the best possible performance for that design given the latitude of modifying only local variables. The analyses will be surface fit and send to the design exploration tool set to produce plots like Figure 52 and to conduct optimization and trade studies.

7. Framework for Rotorcraft MDAO

The previous sections laid the groundwork for understanding rotorcraft design as an optimization problem, how high-fidelity analyses are applicable to rotorcraft optimization, and how these design problems interact. They also provided an example for the systematic build up of the foundation for the institution of an MDAO architecture. This section contains a five year plan that was refined through the activities described up to this point.

7.1. Buildup and Spiral Development for Rotorcraft MDAO

The establishment of a system for MDAO in rotorcraft design is a formidable task. Technical challenges will be pervasive. Realistic expectations suggest that significant manpower resources would be required to develop the infrastructure, set up the analyses, perform the design space exploration, and analyze and evaluate the results. It is recommended that initial institution of MDAO not extend far beyond the disciplines and subsystems that were considered in this report unless the configuration dependencies require more. The challenges represented here are more than sufficient to test the benefits of MDAO for rotorcraft and more than enough to tax the computing infrastructure. As a design framework, MDAO should be not configuration specific, though to some extent it certainly would have to be in the development of the framework. Few opportunities for entirely new designs means that current designs will be the subject of design updates, creating not only opportunities for MDAO but challenges in working with a highly constrained design.

Design of the proposed five year has been guided by performing some of the tasks on a small scale as described in this report. It has become clear that a spiral buildup is required: starting from the development of disciplinary optimization, to the multi-disciplinary integration within each subsystem, and finally to the fully-integrated MDAO for rotorcraft. At the same time, development of system architecture that provides the computing infrastructure must be ongoing. This sequence of development is portrayed in Figure 54.

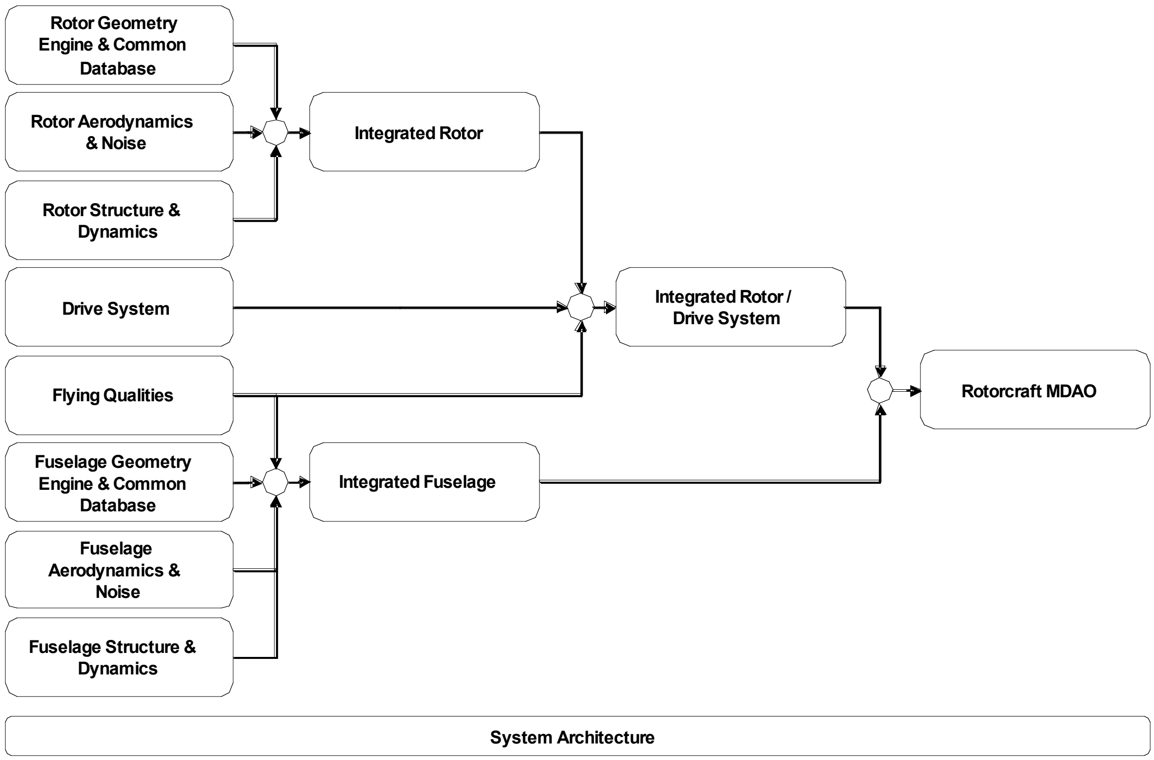


Figure 54. Development sequence for rotorcraft MDAO

7.2. Five Year Plan for Rotorcraft MDAO

Year 1

Conceptual design point of departure

Development of the architecture of an MDAO system should be associated with an actual design. The difficulty would be developing a design system sufficiently ahead of the design itself. The benefit would be to force the architecture to meet the requirements of real-world design needs. While generality of aircraft configuration is ideal, initially building complete generality into a system would make the design and execution of the system cumbersome. The infrastructure should have the flexibility to be modified for different design efforts according to unique needs. The important flow-downs from the conceptual design point of departure are design objectives.

Single disciplinary optimization problems

This task will formalize the operation of disciplinary experts, from stress, structures, aerodynamics, flying qualities, propulsion, and dynamics. Subsystems for MDAO will include airframe, rotor, and drive system. Design leads, or disciplinary experts will prepare formal statements of optimal design—pertaining to the discipline and to a specific subsystem—stating objectives, constraints, design variables, and fixed parameters. Design cases for vehicle loads and performance will be identified, and requirements as well as cost and manufacturability concepts will be specified.

Geometry and common database, and system architecture will be developed concurrently with the design problem definitions. These developments will be ongoing but computing process integration must be selected first so that subsequent integration efforts can be tied together.

Year 2

Single Disciplinary Optimization Feasibility

High-fidelity tools will be identified; and run-time considered. Testing of analysis will be performed to establish confidence in the accuracy considering the given configuration. Optimal search strategies will be selected as appropriate to the analysis run time, design variable type, problem size (number of design variables) so that optimization time frame can meet the needs of the design cycle time.

Disciplinary design problems will be tested independently. This will entail not only testing of the computing infrastructure but experimentation of optimization: how to use the optimization codes (use of penalty functions, push-off factors, step sizes, population sizes in genetic algorithms, etc. that define how the search runs), how to be confident that a global optimum might be found (different starting points in gradient-based search, control parameters in stochastic search, etc.).

Year 3

Spiral buildup to MDAO in Preliminary Design

An interdisciplinary map will be generated based on the individual design problems as stated. Disciplinary design problems will be gradually merged first by discipline within each subsystem. At this point the system architecture will be in place to allow sampling of the design space to assist in the determination of interaction strengths to allow either statistical or graphical methods for examining interactions. Sampling size will depend on computational requirements. Subsystem design using collaborative design exploration will be executed and tested.

Year 4

Spiral buildup to MDAO in Preliminary Design—continued

Rotor and drive subsystems will be merged next, then all subsystems together. Design space sampling and collaborative design space exploration will be executed and tested as before.

Year 5

Analysis and Validation

The above-defined MDAO solution will be validated. The validation will be focused on analysis and will answer questions regarding the design's feasibility, on-point performance, off-design performance, response surface accuracy, sensitivity to constraint and requirements, and robustness. Method validation will also address the usability of the MDAO system and the practicality of performing high-fidelity MDAO. Additional validation can include comparison to existing designs if possible: Is the aerodynamic performance as good or better? Are vibrations lower? Are the system weights lighter?

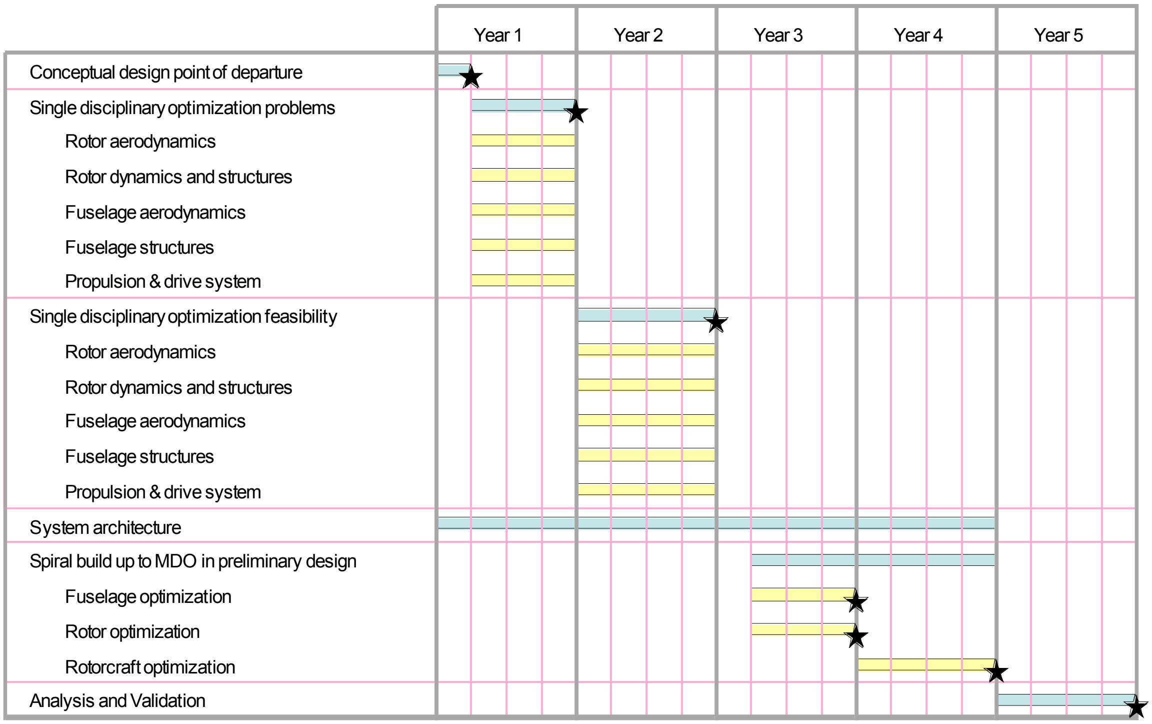


Figure 55. Schedule for development of rotorcraft MDAO

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Appendix

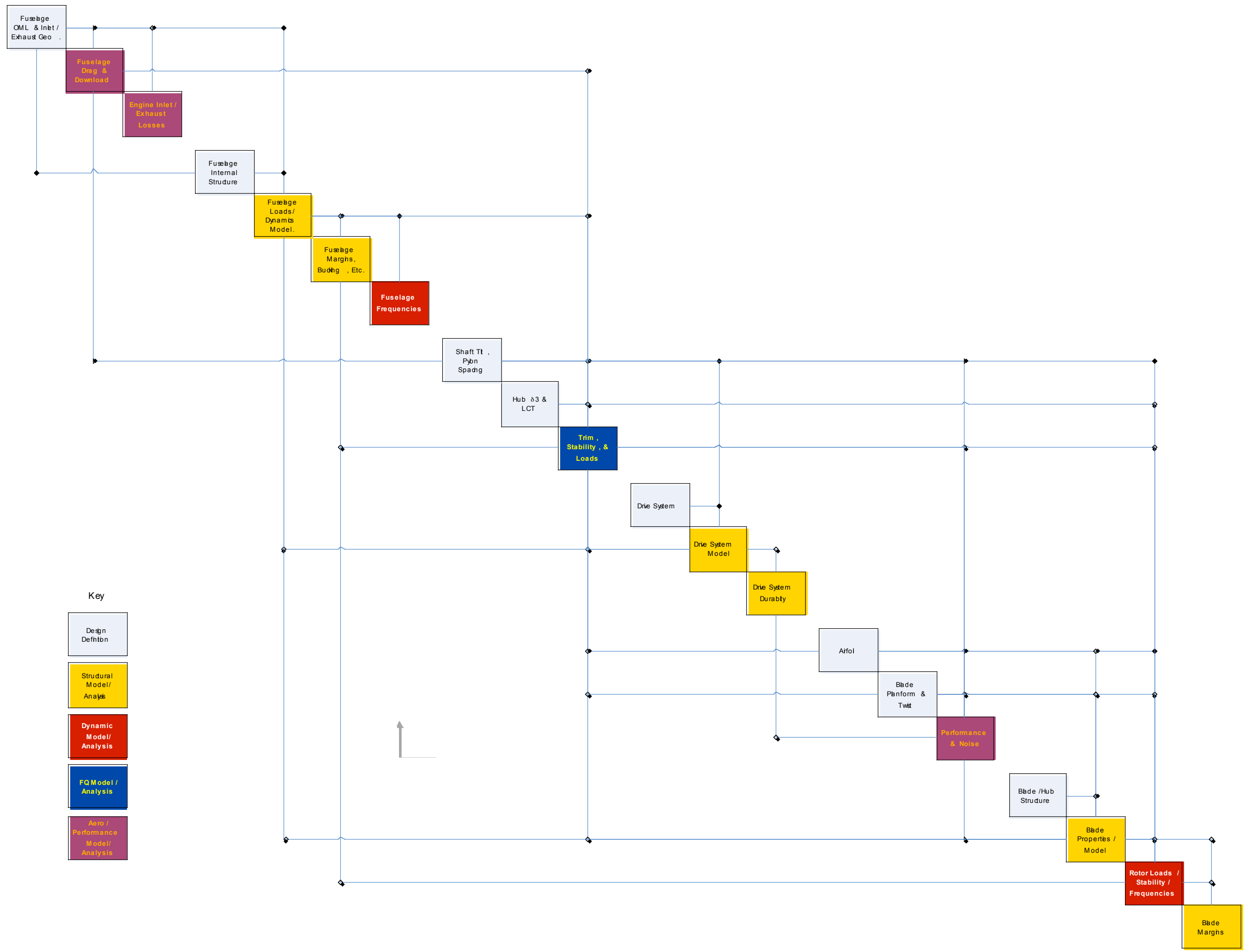

Figure 56. High level process with details.

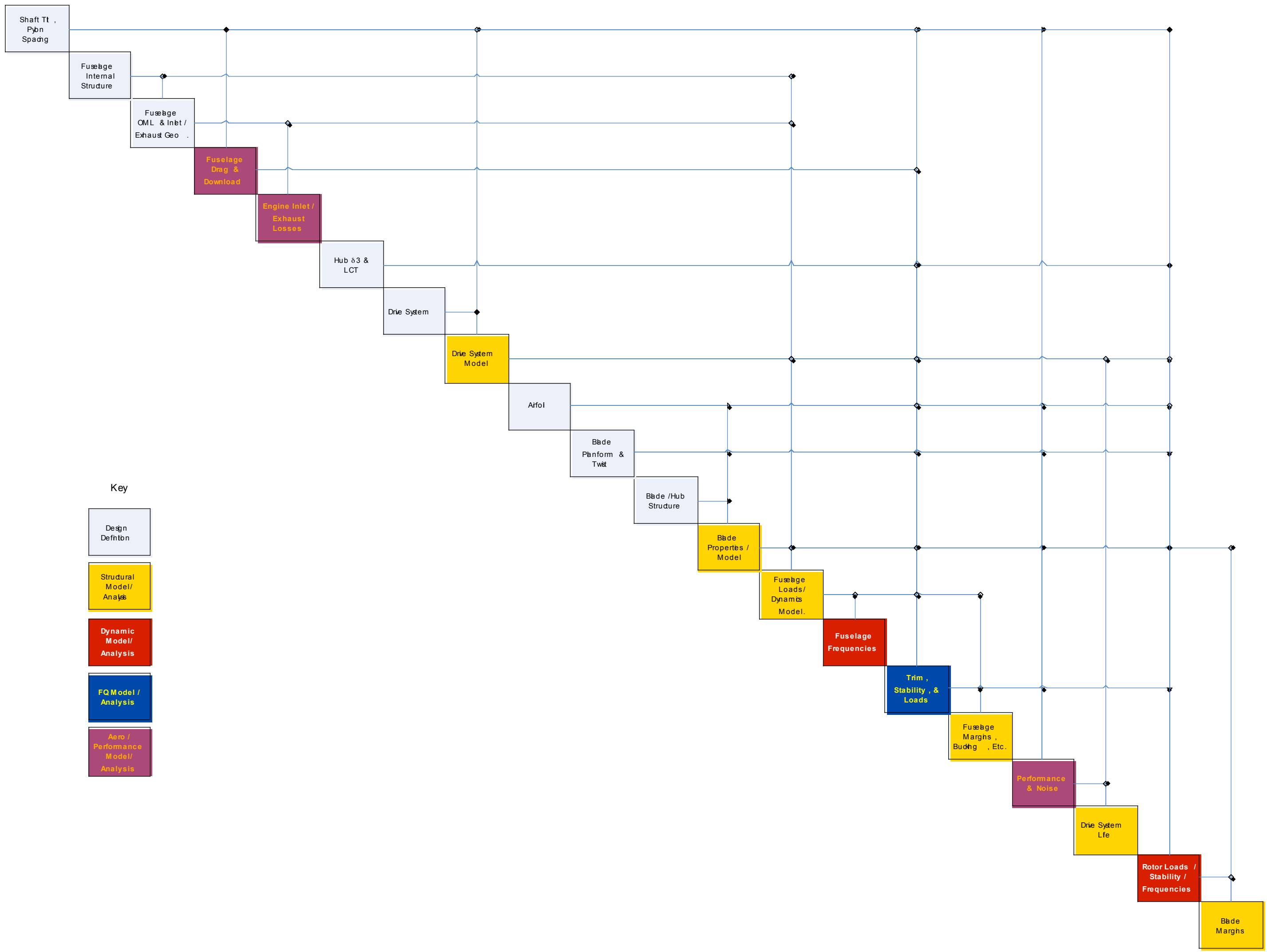

Figure 57. High level process with details—sequenced.

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14. ABSTRACT
A plan is presented for the development of a high fidelity multidisciplinary optimization process for rotorcraft. The plan formulates individual disciplinary design problems, identifies practical high-fidelity tools and processes that can be incorporated in an automated optimization environment, and establishes statements of the multidisciplinary design problem including objectives, constraints, design variables, and cross-disciplinary dependencies. Five key disciplinary areas are selected in the development plan. These are rotor aerodynamics, rotor structures and dynamics, fuselage aerodynamics, fuselage structures, and propulsion / drive system. Flying qualities and noise are included as ancillary areas. Consistency across engineering disciplines is maintained with a central geometry engine that supports all multidisciplinary analysis. The multidisciplinary optimization process targets the preliminary design cycle where gross elements of the helicopter have been defined. These might include number of rotors and rotor configuration (tandem, coaxial, etc.). It is at this stage that sufficient configuration information is defined to perform high-fidelity analysis. At the same time there is enough design freedom to influence a design. The rotorcraft multidisciplinary optimization tool is built and substantiated throughout its development cycle in a staged approach by incorporating disciplines sequentially.

15. SUBJECT TERMS
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