

A CONCEPTUAL DESIGN METHODOLOGY FOR ROTORCRAFT MANEUVERABILITY

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Abstract

The method outlined in this paper facilitates considerations and decisions about rotorcraft maneuverability and agility during the conceptual design phase. Design tools for analyzing maneuverability at an early stage are generated and utilized through Design of Experiments and Response Surface Methods. Through these techniques and elements of probabilistic design, the designers gain a thorough understanding of the conceptual design space as it relates to the selected maneuverability metrics. The flexible procedure outlined support the designer's ability to set early design goals and make conceptual decisions supporting a more maneuverable, agile vehicle throughout the design process.

1 ACRONYMS

AHS	American Helicopter Society
CDF	Cumulative Distribution Function
DoE	Design of Experiments
EDF	Empirical Distribution Function
JPDM	Joint Probabilistic Decision Making
MADM	Multi-Attribute Decision Making
MCS	Monte Carlo Simulation
M&S	Modeling and Simulation
PDF	Probability Density Function
POS	Probability of Success
QFD	Quality Function Deployment
RFP	Request for Proposal
RSE(s)	Response Surface Equation(s)
RSM	Response Surface Methodology
TIES	Technology Identification, Evaluation and Selection

2 INTRODUCTION

Traditional rotorcraft design methodologies are most commonly based on simple performance and cost considerations, often through minimization of vehicle gross weight. Aircraft sizing is conventionally accomplished through a fuel balancing technique, such as the R_F method [1],

coupled with an engine selected to meet power requirements at mission conditions. Maneuverability may typically be addressed during aircraft sizing by simply ensuring that the aircraft has enough power installed to sustain a prescribed load factor. Comprehensive analysis for maneuverability and agility during preliminary design is typically performed offline iteratively.

Here a methodology is developed for rotorcraft sizing and synthesis based on a flexible mission with decision making emphasized for maximum vehicle maneuverability and agility. Rather than rely solely on traditional heuristics in design-analysis-redesign loop, the approach attempts to understand the design space inherent to a given concept early in the design by carefully analyzing the effect of our design parameters on maneuverability and agility [2]. A series of design metrics, such as blade loading margins, accelerations, and quickness (as defined in ADS-33E-PRF), are selected based on analysis of the operational maneuvers desired. In an effort to create an efficient and balanced system, these metrics can be considered alongside traditional design metrics such as gross weight, block speed, and cost.

A modeling and simulation environment is generated, integrating sizing tools with analysis tools capable of thoroughly and iteratively investigating

aircraft maneuverability and agility through both energy methods and non-linear analysis. The full environment includes both local and remote analysis tools working in parallel to minimize computation time. The aircraft is sized through a partially decoupled R_F method. Rather than size the engine purely for a specified maneuver, dash speed, or hover condition, power loading is introduced as a design variable, allowing the designer to determine the relative costs and benefits of adding power to the vehicle. Energy methods are utilized to predict vehicle performance characteristics and steady loading capabilities at various selected conditions. Additionally sized rotorcraft are simply modeled to obtain various ADS-33E-PRF metrics by analyzing various non-linear responses.

With the information available, traditional optimization techniques could be utilized at this point. However, here an attempt is made to fully understand the design space available in terms of the selected design metrics. The designer then utilizes elements of probabilistic design to make trade-offs and decide on goals for each metric, which can then be used to select a design point and determine the success of future design iterations.

3 GENERAL METHODOLOGY

The methodology developed for design for maneuverability was loosely adapted from portions of a general design methodology called the Technology Identification, Evaluation and Selection (TIES) method [3]. This method includes elements for defining the problem, modeling and simulation, design space exploration, and design selection. The methodology requires a defined concept, and concept identification can be accomplished independently of this methodology through any desired means. The method could also be adapted to include additional elements for implementing the evaluation and selection of technologies, but that effort is beyond the scope of this paper.

The first step in this methodology is defining the problem by translating the customer's requirements into engineering characteristics that can be used to evaluate the system's design. This step is often accomplished through the

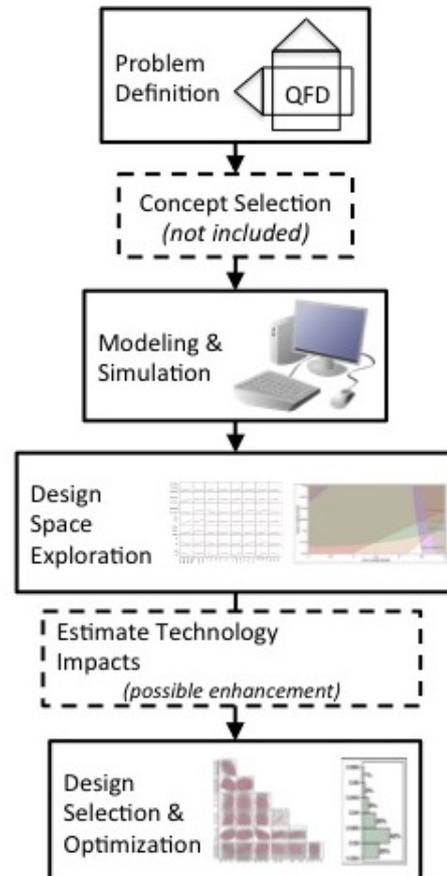


Figure 1: General Methodology

Quality Function Deployment (QFD) technique. In the TIES methodology, a suite of tools such as morphological analysis are often used to select one or more concepts to carry forward in the design process, but any means may be used in this methodology. In the early stages of design, effective tradeoffs can be facilitated by rapid assessment of designs. This is facilitated in this method through a modeling and simulation (M&S) environment to integrate the necessary sizing and analysis codes. This is coupled with the use of response surface methodology to explore the design space available. Finally, design optimization and selection is facilitated through the use of probabilistic design techniques [4]. An overview of the general methodology is shown in Figure 1

3.1 Defining the Problem

In this first step of the methodology, the designer seeks to define the problem at hand by trans-

lating the customer's requirements into a set of engineering characteristics that can be used to determine the success of the vehicle's design. The most common method for accomplishing this is through Quality Function Deployment (QFD). QFD uses a relational matrix to relate the customer requirements to engineering characteristics by qualitative degrees of their relation. Using the weighed requirements, the designer can then prioritize the engineering characteristics.

In the case considered, maneuverability and agility are considered as a primary desire for the design of the vehicle. Inherent vehicle engineering characteristics such as agility, control power, and maneuver blade loading are critical to the success of the design and should be considered during the conceptual design of the vehicle.

3.2 Modeling and Simulation Environment

The modeling and simulation (M&S) environment consists of a series of sizing, performance, and analysis codes integrated to allow rapid sizing and analysis of the vehicle. The tools are integrated through the use of ModelCenter, allowing a single interface for the sizing and analysis of a design solution. An outline of the M&S environment as described below is shown in Figure 2.

Sizing is accomplished through the development of a custom tool based on the R_F method. Vehicle gross weight is determined by matching the minimum gross weight at which the weight fraction of the fuel required for a mission is less than or equal to the weight fraction available for fuel on-board the aircraft. While the installed power of given design is usually determined by calculating the power needed to at the most stringent condition required by the mission, a unique approach is used for this method. Because the power margin available plays such a large role in determining the maneuverability of a rotorcraft, the installed power is calculated through a user defined power loading allowing the designer to prescribe a given power margin to the aircraft. This design parameter, defined as horsepower installed per pound of gross weight (hp/lb), is used to re-size at every iteration of gross weight. A rubber engine model was utilized to allow for accurate calculation of engine lapping and fuel

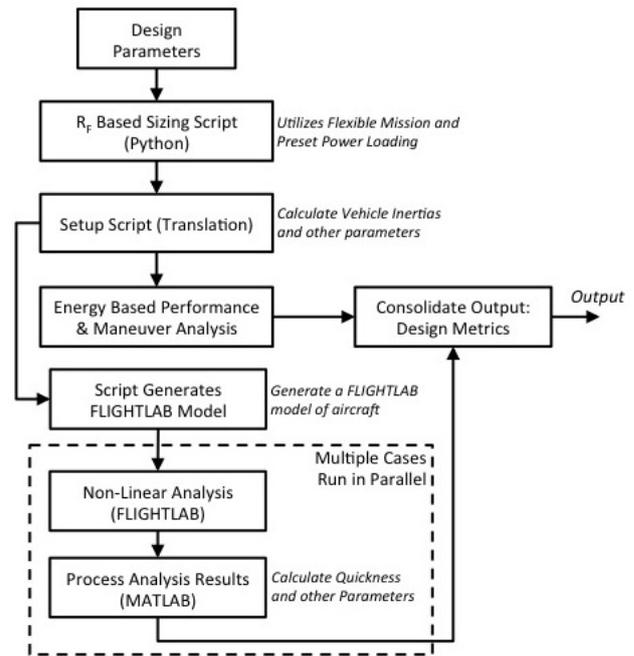


Figure 2: M&S Environment

consumption as the vehicle was sized. Additionally, utilizing empirical vehicle component empty weight components, estimates are made for vehicle inertias.

After the vehicle is sized, a performance and maneuver analysis script is run on the design. The analysis uses fairly straightforward energy methods to quickly estimate parameters such as the vehicle characteristic speeds (V_{BR} , V_{BE} , V_H), steady-state and dynamic blade loadings, transient and sustained turn capability, and acceleration capabilities. These parameters are useful not only to analyze overall vehicle performance, but as a sanity check against the higher fidelity tools used for additional analysis.

The sized vehicle information is also passed to a remote server as part of the M&S environment. Here a non-linear analysis is performed using Advanced Rotorcraft Technology Inc.'s FLIGHTLAB. FLIGHTLAB is a flight vehicle modeling and simulation tool that allows the creation of custom vehicle models by utilizing an environment of available modeling components. A script is utilized to automatically build a FLIGHTLAB model of an appropriate fidelity based on components that were pre-selected by the user and are customized with data from the sized vehicle. At this stage in the design process a simple unaug-

mented control system is utilized to understand the vehicle plant characteristics rather than try to iteratively build a flight control system. Model-Center was then employed to perform a series of parallel trim, linear, and non-linear simulations of the model in FLIGHTLAB. The time histories of the vehicle's simulated non-linear responses is then passed to a MATLAB script that analyzes various raw attributes of the attitude and rate responses. This allows for automatic calculation of stability, agility, and maneuverability parameters such as quickness, phase delay, and bandwidth (as defined by ADS-33E-PRF) [5].

Due to limits on available computing power and development time only a prescribed constant pilot input was utilized in the non-linear analysis during the application of this methodology. However room for refinement of this analysis exists, specifically in the addition of methods for automated response shaping to more accurately calculate the desired parameters. Specifically, an inverse simulation-based methodology was considered, but was not implemented due to schedule constraints. This approach would optimize the pilot input iteratively for each design created by the M&S environment [6].

3.3 Design Space Exploration

With the M&S environment created, the design space is explored through the application of Response Surface Methodology (RSM) [7]. RSM is a set of statistical and mathematical tools the goal of which is to capture the relationship between design input parameters and the metrics of interest created in the M&S environment through generation of response surface equations (RSEs). These RSEs eventually take the form a 2nd order polynomial equation for each metric, defining it as a response to changes in the designated design parameters (or inputs).

The RSEs are generated utilizing design of experiments (DoE) to determine the appropriate combinations of inputs to run through the M&S environment to generate the data necessary to run a regression and create the RSEs. This technique allows for a minimal number of these time consuming cases to be run while still achieving the required accuracy in the RSEs.

When the number of design parameters in-

creases, the number of DoE cases required to generate accurate RSEs grows quickly. Thus screening tests are conducted first to determine the parameters that are responsible for the majority of the variability in the desired responses. The Pareto principle often applies here, stating that approximately 20% of the input variables are responsible for 80% of the variability in the response. Application of this principle allows the designer to reduce run time and work with a more manageable array of design parameters.

The first tool utilized in exploration of the design space is a prediction profiler, as illustrated in Figure 5. This powerful tool visualizes the RSEs with respect to each parameter and response and has several uses. The values indicated on the vertical axis of each response on the left-hand side of the tool illustrate the range of the metric that can be achieved by varying the input parameters within their respective ranges. Within the grid, the red dotted lines indicate a specific design point where the combination of input parameters associated with the vertical lines result in the response values associated with the horizontal lines. These boxes also contain trend lines indicating the sensitivity of each response to each parameter at that specific design point. Flatter trend lines indicate that a particular response is not particularly sensitive to a given input. However, a steep line indicate a response that is highly sensitive to a input from that parameter, given all other inputs are fixed. The slopes of the lines also indicate positive and negative relationships between inputs and responses. The profiler is interactive, allowing the designer to adjust the inputs and observe how each of sensitivities respond instantaneously. A change in any input will create a new series of trend lines as the user explores the design space available.

Another tool utilized to visualize and explore the design space is the design contour plot, as shown in Figure 6. Using this tool, the metrics of interest can be plotted as shaded constraints to understand the combined effect of varying each metric at a given region of the design space. The contour plot fixes each of the design parameters except for those making up the axes (in this case the major design parameters, power loading and disk loading). The shaded areas represents design space that does not meet the target values

desired by the designer. The remaining white space represents feasible design space where designs can meet or exceed all of the target values indicated by the designer. The responses and the fixed parameters can then be varied in real time, to understand how increasing or decreasing the desired value of each metric affects the design space. The plot can be customized to indicate where maximization, minimization or achieving a given interval is desirable for each metric.

In the case of this methodology of design for maneuverability, it is often the case that the designer does not have a specific threshold in mind for metrics such as quickness or acceleration capability, but rather seeks to understand what ranges are available to him, and manipulate the design into a region that achieves the best multi-objective compromise. These tools allow the designer to explore the design space available and understand the relationships among the design parameters and the metrics of interest.

This methodology was developed in support of a vehicle meant for near-immediate production. However, future refinement of this methodology might include the addition of estimating the effects of specific developing technologies as outlined in the original TIES methodology [3]. In this methodology, specific technologies are modeled through the means of k-factors applied in the M&S environment to model the effect of adding technologies to a design.

3.4 Design Optimization and Parameter Selection

Once the designer has a better understanding of the design space available, it is necessary to move forward and select desired values for each metric of interest as well as optimizing the design. This methodology utilizes elements of probabilistic design to select desired values for the design metrics. A Monte Carlo Simulation (MCS) is run using the RSEs to populate a large distribution of random designs (usually at least 10,000). Design parameters are assigned distributions based on their nature. Parameters that are entirely up to the designer can be assigned uniform distribution (as the design has no preference as to their value), while other parameters

that may be partially or entirely outside the control of the designer can be assigned distributions according to their nature. This produces a data set that can then be analyzed to create probability density functions (PDF) and cumulative distribution functions (CDF) for each of the design metrics, as well as utilized by other tools.

Creating PDFs and CDFs for each of the design metrics allow the designer to understand the relative difficulty of achieving a given metric value in his design space, as illustrated in Figure 3. The PDF is a histogram function, relating the frequency with which a design metric value was reached with that value. A CDF is created by integrating the PDF and relates the design metric values with the probability (0 - 100%) of reaching that value in the design space available. The designer can use these functions to determine the feasibility of reaching a particular goal value in the available design space.

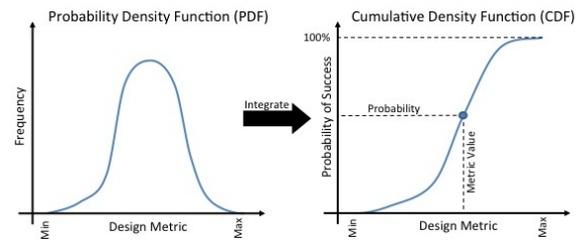


Figure 3: PDF & CDF

While these tools can tell us the likelihood of obtaining individual metric goals, they don't necessarily speak to the probability of obtaining multiple criteria simultaneously. Application of the Joint Probabilistic Decision Making (JPDM) technique incorporates a multi-criteria aspect to probabilistic design that can be used to assess the probability of satisfying multiple criteria simultaneously [8]. With the M&S environment and MCS, an Empirical Distribution Function (EDF) can be utilized to generate a model of the *joint cumulative probability distribution function*, as given in Eq. 1 and Eq. 2. The probability that the events $X_1 = x_1, X_2 = x_2, \dots, X_n = x_n$ happen concurrently, is denoted by $F(x_1, x_2, \dots, x_n)$. Using the EDF, a_i designate the sample values for each criteria obtained from MCS, while x_i are the goal values desired.

Feasibility of a design can then be measured

by determining the probability of it satisfying a given level of each of the design metrics. The Probability of Success (POS) for a given set of metric goals can be determined by combining the set of values with the joint probability distribution function, and if desired a set of weights for the metrics. For an EDF with m samples, this is defined in Eq. 3. Thus, the designer can select metric goals that provide for a maneuverable and agile vehicle while ensuring that some small but reasonable POS exists in the design space for the selected concept. Too high of a POS indicates goals that are too low and could be easily surpassed. Too low of a POS indicates that in future design iterations noise variables or unanticipated design changes could result in not meeting goals. Even with all the information available some measure of subjectivity is necessary to balance each of the goals and make a decision.

$$F(x_1, x_2, \dots, x_m) =$$

$$(1) \quad \frac{1}{m} \sum_{i=1}^m I(a_{i1} \leq x_1, a_{i2} \leq x_2, \dots, a_{in} \leq x_n)$$

$$(2) \quad \begin{cases} I(a_{i1} \leq x_1, a_{i2} \leq x_2, \dots, a_{in} \leq x_n) = \\ 1 & \text{for } (a_{i1}, a_{i2}, \dots, a_{in}) = (x_1, x_2, \dots, x_n) \\ 0 & \text{otherwise} \end{cases}$$

$$(3) \quad \text{POS} = \frac{1}{m} \sum_{j=1}^m I(\bar{x}_{jmin} \leq \bar{a}_j \leq \bar{x}_{jmax})$$

4 APPLICATION TO 2012 AHS COMPETITION

In 2012, the American Helicopter Society (AHS) International hosted their 29th annual student design competition, sponsored by Sikorsky. The request for proposal (RFP) called for a rotary wing pylon racer, in the style of the popular Red Bull Air Races, but with VTOL capability. No traditional mission profile was provided, but rather the RFP outlined a proposed race course the aircraft would fly during the race with a series of gates and maneuvers (including a hover and sideward flight portion) to be flown, as illustrated in Figure 4.



Figure 4: Pylon Racer Course Map

With the unique nature of the aircraft desired, a Georgia Institute of Technology graduate team participating in the competition developed and employed the subject methodology to design their vehicle. The problem definition phase utilized QFD methods to identify engineering characteristics such as high power margin, low steady state blade loading, and high control power quickness as critical to the design. This analysis, along with a detailed analysis of the race course, was used to develop a list of design metrics that would be used as the criteria by which to judge vehicle designs. These metrics are listed in Table 1 along with their eventual goal values (as discussed later in probabilistic design). The "eta surrogate" metric was conceived as surrogate to the efficiency consideration defined in the RFP. Without the means to feasibly and accurately predict course time at this stage in the design, a series of vehicle parameters were roughly correlated with course time and combined with estimated fuel burn to create the "eta surrogate" design metric.

The team used a combination of qualitative multi-attribute decision making (MADM) and

quantitative analysis to decide on a coaxial concept with a pusher prop, similar to the experimental Sikorsky X2. Using this concept, the team utilized the subject design methodology to determine the first iteration, conceptual design of their vehicle.

Table 1: Design Metrics (Responses)

Variable	Units	Desire	Goal Value
Deceleration	(g)	min	≤ -0.6
Acceleration	(g)	max	≥ 0.45
C_T/σ (at V_{BR})	(1/ft ²)	min	≤ 0.033
C_T/σ (at V_H)	(1/ft ²)	min	≤ 0.035
Lon. Quickness	(1/sec)	max	≥ 1.0
Lat. Quickness	(1/sec)	max	≥ 0.66
Eta Surrogate	(-)	min	≤ 800

The M&S environment was assembled in Model Center as is shown in Figure 2 [10] [11]. In FLIGHTLAB, an generic airframe aerodynamic model was used, and scaled in accordance with a generic mode of flat-plate drag based on vehicle gross weight. Two simple disk models were used for the rotor connected to a simple control system with generic actuator models. The FLIGHTLAB model also modeled the auxiliary propeller through the use of a generic force that was scheduled with forward airspeed. That schedule could then be parametrically scaled as a percentage of the estimated equivalent drag area of the aircraft, through the use of a gain value corresponding to the user parameter. Based on the maneuver analysis performed on the RFP's race course, FLIGHTLAB scripts were utilized in the M&S environment to run the following analyses: pitch and roll step inputs at 90 KTAS, a yaw step input at 30 KTAS, as well as a scripted coordinated cyclic/collective input to model an acceleration from 30 KTAS and a deceleration from 90 KTAS.

Table 2 lists all relevant inputs to the M&S environment. The mission used for sizing was roughly defined according to the race course and other RFP requirements, with a 10nm dash at V_H representing the race. After a round of screening tests, seven design parameters were selected for modeling, and are marked in Table 2 with their representative ranges. Inputs marked in the table with a "(PRMT)" were parametrically calculated

in the environment based on the DOE inputs at a given iteration and M&S internal parameters [12].

Table 2: Design Parameters

Variable	Units	Value(s)
General Vehicle Sizing		
Disk Loading	lb/ft ²	(DOE) 4.0 - 7.0
Power Loading	hp/lb	(DOE) 0.15 - 0.3
Rotor(s) Blades	#	4
Rotor(s) Tip Speed	ft/s	(DOE) 625 - 725
Rotor Solidity (ea.)	-	(DOE) 0.07 - 0.10
Rotor(s) C_{D0}	-	0.05
Engines	#	1
Transmission Losses	%	0.05
Aux Power - Fwd Flt	%	(DOE) 0.4 - 0.8
Aux Prop Radius	ft	3.0
Aux Prop Tip Speed	ft/s	700
Aux Prop Solidity	-	0.15
Aux Prop C_{D0}	-	0.05
Main Rotor Parameters		
Blade Hinge Offset	%R	(DOE) 0.15 - 0.3
Blade Mass	slug	(PRMT)
Flap Inertia	lb-ft ²	(PRMT)
Flap Freq. Ratio	1/sec	(PRMT)
Blade Twist	°	-9.0
Tip Loss Factor	-	0.97
Blade C_L at 0°	-	0.0
Blade Root Cutout	%R	0.07
Rotor Pre-Cone	°	0.0
Rotor Lift Curve Slope	1/deg	6.28
Swashplate Phase Angle	deg	(PRMT)
Rotor Hub Separation	%R	(DOE) 0.1 - 0.25
Fuselage Parameters		
Vehicle Inertias	slug-ft ²	(PRMT)
Drag Reference Area	ft ²	(PRMT)
Empennage Parameters (NACA 0012 Airfoil)		
V. Stab. Airfoil	(NACA 0012)	
V. Stab. Area	ft ²	10.0
V. Stab. Sweep	°	10.0
V. Stab. Arm	ft	16
H. Stab. Airfoil	(NACA 0012)	
H. Stab. Area	ft ²	18.0
H. Stab. Sweep	°	0.0
H. Stab. Arm	ft	15.0

Once the DOE cases had been run, the data was used to create the appropriate RSE for each design metric. An example of the prediction profiler at what was selected as the eventual design point is shown in Figure 5. This tool was used interactively to explore the design space and understand the metric trends with relation to each of the design parameters. For instance, disk loading was demonstrated to have a strong positive influence on longitudinal quickness, but a slight negative influence on lateral quickness. Solidity was noted to have the opposite effect on these quickness parameters near the design point.

Additionally, the design space was explored through the use of an interactive contour plot, an example of which is shown in Figure 6. This

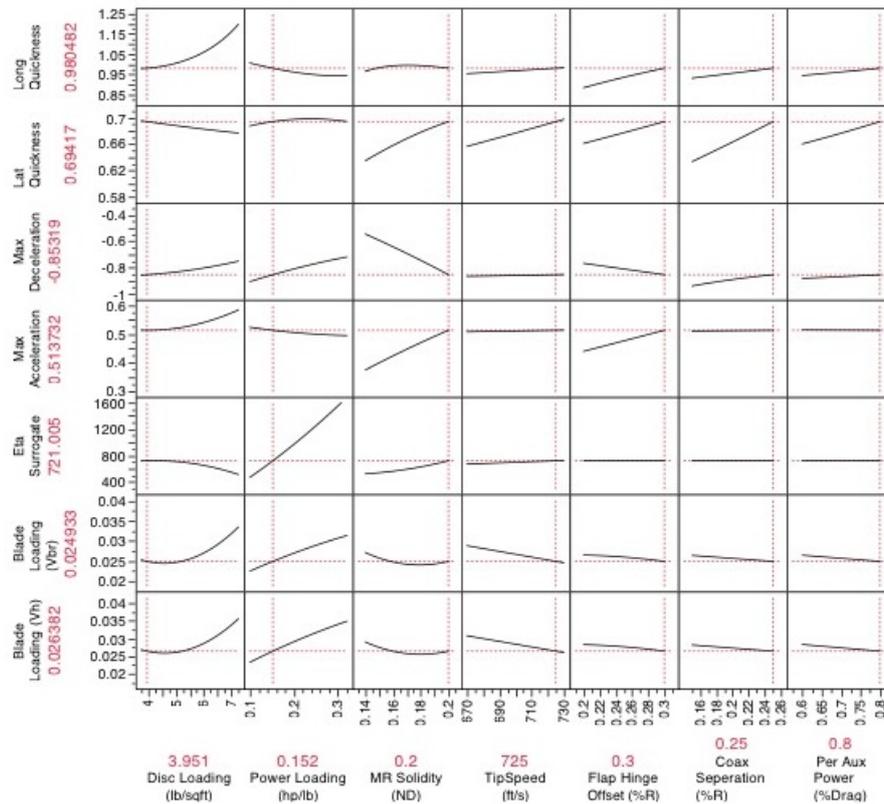


Figure 5: Prediction Profiler

particular snapshot of the interactive contour plot shows the design space available at the eventual design point, with the metrics set at their eventual goal values. The design metrics are modeled here as constraints on the feasible design space, illustrated in white. The metric goals can then be moved by the designer to understand how they each contribute to limiting to the feasible design space.

Once the design space was appropriately understood, the design team moved forward with a MCS, generating 20,000 random designs. Here PDFs and CDFs were generated to allow the design team to understand the individual metric distributions. Next, elements of JPDM were utilized to determine goal values for each of the design metrics. Figure 7 shows an example of lateral quickness and acceleration with density contours illustrating the joint distribution. The highlighted region shows the design space available meeting the eventual goals for both metrics. Eventually each of the joint distributions were used by the designers with data filtering to decide on the goal values listed in Table 1.

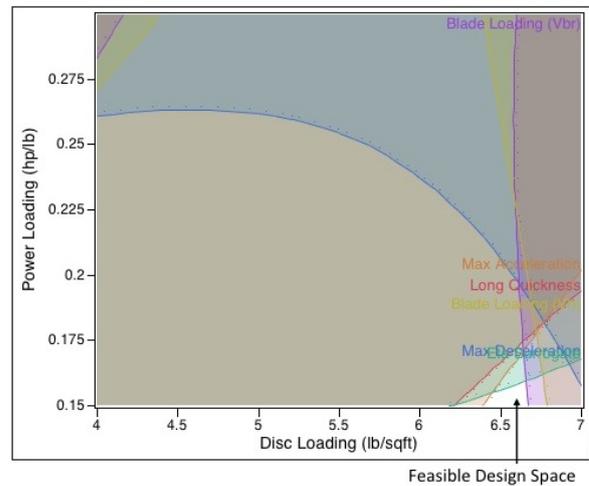


Figure 6: Design Space Contour Plot

With goal values established for the design metrics, the designers moved forward with the first conceptual design iteration. With continuous RSEs available for each metric over the design space, a gradient decent optimization was utilized to determine the design point. The final design point was checked in the M&S environment to validate the RSE accuracy. The parameters

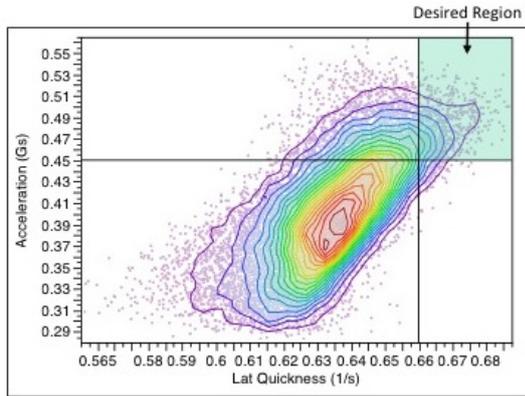


Figure 7: Joint Distribution Example

and corresponding design metrics for the design point are shown in Table 3.

Table 3: Conceptual Design Point

Design Parameter	Value
Disk Loading	6.57 lb/sqft
Power Loading	0.152 hp/lb
Solidity	0.20
Tip Speed	725 ft/s
Aux Power Gain	0.8
Rotor Hinge Offset	0.30 radii
Rotor Separation	0.25 radii
Design Metric	Value
Deceleration	-0.781 g's
Acceleration	.558 g's
C_T/σ (at V_{BR})	0.0299 1/ft ²
C_T/σ (at V_H)	0.0317 1/ft ²
Long. Quickness	1.10 1/sec
Lat. Quickness	0.667 1/sec
Eta Surrogate	606

5 SUMMARY

The methodology presented in this paper was developed to integrate design for maneuverability and agility during the conceptual design phase. Through defining the problem, the designer can determine the means by which design iterations will be judged. Incorporating maneuverability and agility at this stage leads to the definition of specific design metrics for these elements. The designer can then measure how these metrics are affected by design decisions through integra-

tion of tools for maneuverability in a modeling and simulation. Finally, with design space exploration and design selection the method allows the designer to better understand the design space available in terms of maneuverability and agility, and make decisions about design goals and specific design parameters.

An example of how to employ this methodology is shown through the conceptual design of a coaxial vehicle with a pusher prop in response to the 2012 AHS design competition's RFP for a rotary wing pylon racer. In this case, a conventional point-to-point mission was not defined for the vehicle, and the design was only required to be able to perform a series of maneuvers as quickly and efficiently as possible. The design space is explored, and probabilistic design techniques are used to select goals for the metrics. The first design iteration is completed when a design point is selected with a simple optimization.

This generic procedure was developed as a flexible methodology to allow designers to consider maneuverability and agility early in the design process. The methodology is applicable to the design of virtually any rotorcraft concept and mission where consideration of a vehicle's inherent maneuverability is critical to the success of the design. The methodology also allows for future refinement and additions, especially with the noted possible additions of inverse simulation-based techniques to refine non-linear analysis, and estimating technology impacts through k-factors.

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