Incorporating Handling Qualities Analysis into Rotorcraft Conceptual Design

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Abstract

This paper describes the initial development of a framework to incorporate handling qualities analyses into a rotorcraft conceptual design process. In particular, the paper describes how rotorcraft conceptual design level data can be used to generate flight dynamics models for handling qualities analyses. Also, methods are described that couple a basic stability augmentation system to the rotorcraft flight dynamics model to extend analysis to beyond that of the bare airframe. A methodology for calculating the handling qualities characteristics of the flight dynamics models and for comparing the results to ADS-33E criteria is described. Preliminary results from the application of the handling qualities analysis for variations in key rotorcraft design parameters of main rotor radius, blade chord, hub stiffness and flap moment of inertia are shown. Varying relationships, with counteracting trends for different handling qualities criteria and different flight speeds are exhibited, with the action of the control system playing a complex part in the outcomes. Overall, the paper demonstrates how a broad array of technical issues across flight dynamics stability and control, simulation and modeling, control law design and handling qualities testing and evaluation had to be confronted to implement even a moderately comprehensive handling qualities analysis of relatively low fidelity models. A key outstanding issue is to how to 'close the loop' with an overall design process, and options for the exploration of how to feedback handling qualities results to a conceptual design process are proposed for future work.

Notation

I_{xx}, I_{yy}, I_{zz}	Vehicle moments of inertia about roll, pitch and yaw axes
ΔL_{TOTAL}	perturbation in body axis rolling moment
ΔX_{TOTAL}	Total perturbation in body axis longitudinal force
h_R	Height of rotor above vehicle center of gravity
h_T	Height of tail rotor above vehicle center of gravity
h_{fin}	Height of vertical tail fin above vehicle center of gravity
Ω_T	Tail rotor angular speed
C_{y_β}	Side force coefficient due to sideslip derivative
I_{xz}	Vehicle product of inertia between roll and yaw axes
K_q	Pitch rate error feedback gain
K_θ	Pitch attitude error feedback gain
$L_{\beta_{1s}} = \frac{1}{I_{xx}}\frac{\partial L}{\partial \beta_{1s}}$	Aerodynamic stability derivative of body axis roll moment force due to rotor lateral flap perturbation
$L_p = \frac{1}{I_{xx}}\frac{\partial L}{\partial p}$	Aerodynamic stability derivative of body axis roll moment force due to roll rate perturbation
N_b	Main rotor number of blades
R_T	Tail rotor radius
S_{fin}	Area of vertical tail fin
$X_{\theta_{1s}} = \frac{1}{M}\frac{\partial X}{\partial \theta_{1s}}$	Aerodynamic control derivative of body axis longitudinal force due to longitudinal cyclic perturbation
$X_u = \frac{1}{M}\frac{\partial X}{\partial u}$	Aerodynamic stability derivative of body axis longitudinal force due to longitudinal velocity perturbation
$\dot{p}, \dot{r}$	Total body axes roll and yaw angular accelerations
θ_{trim}	Trim pitch attitude
λ_β	Main rotor flap frequency ratio
$\frac{\partial C_{t_T}}{\partial \mu_{z_T}}$	Partial derivative of tail rotor thrust coefficient with tail rotor normalized vertical velocity
$\Delta X_{gravity}$	Perturbation in body axis longitudinal force due to gravity

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$\Delta p, \Delta q, \Delta r$	Perturbation in body axis roll, pitch and yaw rates
$\Delta u, \Delta v, \Delta w$	Perturbation in body axis longitudinal, lateral, and vertical velocities
Ω	Main rotor angular speed
V	Vehicle airspeed
g	Acceleration due to gravity
p, q, r	Total body axes roll and yaw angular rates
α	Angle of attack
β	Angle of sideslip
γ	Main rotor Lock number $= \frac{\rho c a_0 R^4}{I_\beta}$
μ	Main rotor advance ratio

Introduction

In ref [1], Padfield notes that 25-50% of flight testing time in an aircraft development program might be spent on fixing handling qualities problems. Furthermore, in the same paper associated with this lecture, he went on to suggest that handling qualities were not given their proper place in the early design trade-space, and were often left until flight test to discover and 'put right'. It is not difficult to justify the argument that these handling qualities fixes are not only time consuming, but expensive. Padfield also recognized that part of the reason was that during the early days of helicopter development handling qualities were extremely difficult to predict.

Traditional approaches relied on heuristic data and rules of thumb and even with the help of numerical criteria and that they were justifiably treated as an outcome of the series of complex design decisions relating to the overall performance of the vehicle, its layout, structural integrity, and fixing other issues such as vibration problems. In these situations, it may have been advantageous to be able to analytically consider handling qualities factors on a design before it became somewhat 'frozen', either to predict issues or to provide sufficient margins in the design to facilitate 'easier fixes' to any unforeseen handling qualities problems that might occur later in the development process.

Conceptual design tools consist of analysis, synthesis, and optimization routines to size flight vehicles to find the best configurations to meet the required operational capabilities and performance, as well as reveal trends on the relative benefits certain configuration choices have on the resulting aircraft performance. The NDARC (NASA Design and Analysis of Rotorcraft) tool [2] provides such a capability to model general rotorcraft configurations, and estimate the performance and attributes of advanced rotor concepts. NDARC, like most conceptual design tools, uses low fidelity modeling to facilitate rapid calculations and is typically sufficient to analyze the flight performance of an aircraft in terms of characteristics such as range, payload, maximum speed, cruise speed etc. for a set of flight conditions and missions. NDARC, as typical for conceptual design tools, has no capability to consider handling qualities as part of its sizing and design optimization routine.

Aircraft conceptual design has long lacked sufficient analyses that consider stability, control, and handling qualities. Traditionally, conceptual design has been limited to static analyses of the bare-airframe designs, particularly for fixed-wing aircraft where designs tended to stay close to a well understood 'tube-and-wing' design with stiff structures and little aerodynamic interactions, as highlighted in ref [3]. This work, and another paper, ref [4], both encapsulate the multiple issues regarding the estimation of the vehicle flight dynamics based on the conceptual design data available and whether to perform handling qualities or stability and control analysis of the bare-airframe or to incorporate a control system.

Ref [4] specifically addresses the issue of predicting handling qualities with conceptual design level design data by incorporating probabilistic techniques to evaluate the uncertainties in the modeling. Sensitivity studies were demonstrated that not only inform the designer of handling qualities sensitivities to design parameters, but also provide a sensitivity to the uncertainty in the flight dynamics characteristic parameters themselves. This looks to be a promising effort that could add robustness to future approaches, where a conceptual design process incorporating handling qualities is focused on finding regions of the design space with maximum probability of achieving an objective target, instead of just maximizing the deterministic value of the objective.

Ref [3] takes a greater focus on the control aspects, and describes an approach that uses actuator and closed-loop pole placement constraints to optimize a control system for satisfactory handling qualities characteristics. The authors echoed the same sentiments of those in ref [4], whose control law developments were still a work-in-progress, in that the purpose is not to design operational flight control laws, but to include closed loop design variables in the conceptual designer's toolbox so that the questions can be answered: 'Can this aircraft configuration fly, and can it do so in a satisfactory manner?'. They state that conceptual designers have a high level need to know whether a suite of control effectors or a particular geometric configuration is capable of achieving mission goals. Without a preliminary control system design, they are unable to approximate the closed-loop dynamic performance, a necessity for the analysis of any modern aircraft.

In the rotorcraft domain, ref [5] describes a rotor design optimization study that simultaneously takes into account rotor dynamics and flight dynamics. The objective was to maximize the damping ratio of the least damped rotor mode, namely the lag progressive mode. The design variables comprised rotor, airframe, and flight control system parameters. The behavior constraints included rotor stability, rotor loads, and several handling qualities constraints from ADS-33, [6]. The simulation model included flexible blade dynamics, and a detailed representation of fuselage and empennage. Although the design case demonstrated is somewhat beyond what conceptual design might consider, it showed that a multidisciplinary approach yielded successful results and evidence of counteracting handling qualities and aeromechanics constraints in the optimization of the design. This investigation also incorporated closed loop control, and handling qualities constraints that encompassed more than the linear system poles used in the fixed-wing studies just mentioned, with ADS-33 bandwidth and quickness criteria evaluated (longitudinal axis only).

A more complete attempt at a whole vehicle study at a similar level of information as conceptual design is reported in ref [7]. This paper described work to extend a performance oriented code 'JANRAD' with a stability analysis capability. An approach to modeling the six degree of freedom flight dynamics of conventional helicopter configurations is reported, where stability and control derivatives could be generated at any point in the 'trimmable' flight envelope to create linear state-space models, and their eigenvalues and response transfer functions evaluated. However, this tool did not attempt any feedback of the handling qualities information into a design process or optimization.

The challenges of incorporating handling qualities analyses into conceptual design begin with the fact that conceptual design tools typically do not include the modeling necessary to represent the flight dynamics or a flight control system. Then there is the question of performing the handling qualities analyses, should the bare-airframe be considered, or an aircraft with a flight control system? These questions are particularly challenging when many rotorcraft airframes are inherently unstable, making automatic analyses problematic. Finally, there are questions about how handling qualities analyses can contribute to conceptual design; is it appropriate to include it all? If so, how does the inclusion of handling qualities considerations affect the evolution of a design at a conceptual design phase, and which design issues might be realistically addressed with the models available?

In the search for answers to a number of these questions, this paper describes the initial development of a framework to incorporate handling qualities analyses into a rotorcraft conceptual design process. The initial goal is to outline a methodology incorporating a set of potential solutions in a tool while presenting the lessons learnt. In particular, the paper describes how output from the NDARC rotorcraft conceptual design tool was used to generate flight dynamics models appropriate for handling qualities analyses. Also, methods are described that couple a basic stability augmentation system to the rotorcraft flight dynamics model to enable analyses that extend beyond that of the bare airframe. Next, the development and performance of analyses capable of calculating the handling qualities characteristics of the flight dynamics models are described. This is followed by the presentation of preliminary results of conducting handling qualities analyses on models that feature variations of the input conceptual design data. In the final discussion, the analysis of the results will guide a discussion of proposed methods to quantify and use handling qualities metrics for their incorporation in an overall design process.

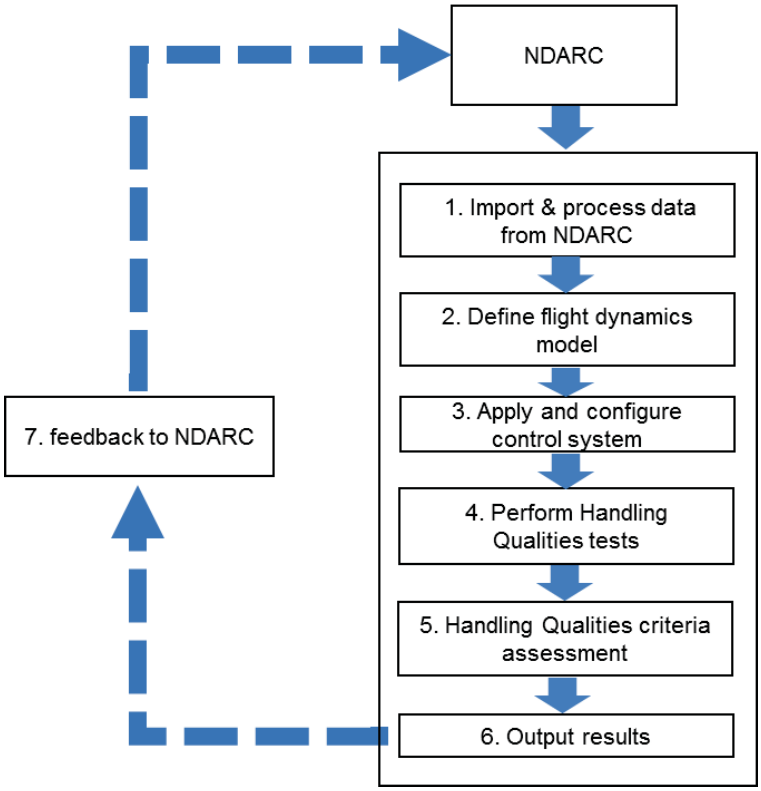


Figure 1 Tasks for proposed methodology to incorporate handling qualities into a NDARC-based conceptual design process

Technical Approach

The key actions to incorporate a handling qualities analysis into an NDARC-based conceptual design process outlined in this paper are shown in Figure 1. The process includes the following key tasks: Read in a vehicle configuration from NDARC, generate a flight dynamics model, apply a control system, perform a handling qualities analysis and then assess those handling qualities against various criteria and either output the results to the user or feed them back to NDARC to influence the design optimization. This section of the paper describes the development, implementation and performance of each these key constituent steps before going onto evaluating the process as a whole. The methodology was developed using MATLAB/SIMULINK which provided a suite of tools to support the prototyping of the required algorithms and models.

Importing Data from NDARC

NDARC generates an array of text-file based outputs and tools were developed that parsed these text files into MATLAB structure workspace variables. Key parameters from NDARC included the geometric, aerodynamic and trim data required to generate the flight dynamics simulation models.

Flight Dynamics Modeling

To generate the flight dynamics models, an approach based on linear stability and control derivatives was selected. A number of factors contributed to this, firstly a well-established theoretical approach based on linear stability and control derivatives exists to model the flight dynamic properties of rotors and vehicles using the kind of parameters usually defined by conceptual design analyses. Secondly, using closed expressions to calculate the stability derivatives directly, although initially time consuming to define, is computationally efficient. This is an advantageous feature in the context of design studies where the goal is normally to assess a broad design space evaluating numerous parameter variations

Typically, conceptual design tends to work with high-level 'global' parameters defining the overall vehicle and its major components. For example, rotors would be defined with a single radius, chord, blade inertia, and

flap frequency ratio, linear twist etc., other components such as fuselages, wings and empennage surfaces would be defined similarly, using overall dimensions such as span, chord, area and orientation. Aerodynamic data is normally limited to linear lift curve slopes and linear derivatives to represent other forces and moments.

Finally, using closed form expression linear stability derivative-based modeling confers engineering insight as interactions can also be assessed by directly examining the mathematical expressions. The linear models generated are also more manageable from a robustness perspective - typically, these models tend to be less susceptible to numerical instabilities and 'crashes' than more sophisticated full force and moment models or models featuring significant non-linear modeling. This is a desirable feature when automated analysis sweeps may be left unattended to explore a wide range of input parameters, which may be unbounded, over long periods of time.

Stability Derivative expression development

A set of semi-analytical, closed-form expressions were developed to compute the stability and control derivatives. The expressions are currently capable of calculating the stability and control derivatives for a conventional 4-bladed single main rotor helicopter with tail and fin surfaces, fuselage, and anti-torque tail rotor. The expressions cover the derivatives for the Six-Degree-of-Freedom (6-DoF) rigid body states and 2 rotor multi-blade coordinate states of lateral and longitudinal flapping, $x = \{u, v, w, p, q, r, \beta_{1s}, \beta_{1c}\}$ and 4 control inputs of main rotor collective, longitudinal and lateral cyclic, and tail rotor collective $u = \{\theta_0, \theta_{1s}, \theta_{1c}, \theta_{0T}\}$. The flapping dynamics are modeled using a first order approximation, following a similar approach to the 'hybrid' model described in ref [8], where the flapping equations have dropped the terms involving flap acceleration (i.e. no inertia). This simplification retains a representation of the regressive flapping mode, which typically has a natural frequency around half the rotor speed frequency. This is the primary rotor mode of concern for handling qualities, flight dynamics and control. This approach allows in a relatively simple formulation a representation of fuselage–rotor couplings that a 6-DoF model alone cannot capture. A similar notation of ref [8] to represent the flapping moment terms, the bar on the term denotes the differences to the aforementioned reference as follows, where τ_f is the rotor-flap time constant, for example, for the lateral flap moment:

$$e.g. \quad \overline{Lf}_{\theta_{1c}} = \frac{Lf_{\theta_{1c}}}{\tau_f} \tag{1}$$

The stability and control derivatives for which expressions have been derived are shown below in the A and B matrices respectively in equation 2. Note that (a), where a term is zero, it is explicitly not computed, and (b) that certain common terms such as the inertial and gravitational terms are not included in the matrices – these effects, along with the calculation of the vehicle Euler angles, are handled separately by other elements in the stitched model architecture, as described in the following section.

Example expressions for key terms in the roll axis equation: the roll moment due to roll rate derivative, Lp, roll moment due to lateral flap, $\partial L/\partial \beta_{1s}$, lateral flapping rate due to roll rate, $\partial \dot{\beta}_{1s}/\partial p$, and finally, lateral flapping rate due to lateral cyclic input, $\partial \dot{\beta}_{1s}/\partial \theta_{1c}$, are shown in equations 3, 4, 5 and 6 respectively.

$$A = \begin{bmatrix} X_u & X_v & X_w & X_p & X_q & 0 & 0 & X_{\beta_{1c}} \\ Y_u & Y_v & Y_w & Y_p & Y_q & Y_r & Y_{\beta_{1s}} & 0 \\ Z_u & Z_v & Z_w & Z_p & 0 & 0 & Z_{\beta_{1s}} & Z_{\beta_{1c}} \\ L_u & L_v & L_w & L_p & 0 & L_r & L_{\beta_{1s}} & L_{\beta_{1c}} \\ M_u & M_v & M_w & M_p & M_q & 0 & M_{\beta_{1s}} & M_{\beta_{1c}} \\ N_u & N_v & N_w & N_p & N_q & N_r & N_{\beta_{1s}} & N_{\beta_{1c}} \\ \overline{Lf}_u & \overline{Lf}_v & \overline{Lf}_w & \overline{Lf}_p & \overline{Lf}_q & \overline{Lf}_r & \overline{Lf}_{\beta_{1s}} & \overline{Lf}_{\beta_{1c}} \\ \overline{Mf}_u & \overline{Mf}_v & \overline{Mf}_w & \overline{Mf}_p & \overline{Mf}_q & \overline{Mf}_r & \overline{Mf}_{\beta_{1s}} & \overline{Mf}_{\beta_{1c}} \end{bmatrix} B = \begin{bmatrix} X_{\theta_0} & X_{\theta_{1s}} & X_{\theta_{1c}} & 0 \\ Y_{\theta_0} & Y_{\theta_{1s}} & Y_{\theta_{1c}} & Y_{\theta_{0T}} \\ Z_{\theta_0} & Z_{\theta_{1s}} & 0 & 0 \\ L_{\theta_0} & L_{\theta_{1s}} & L_{\theta_{1c}} & L_{\theta_{0T}} \\ M_{\theta_0} & M_{\theta_{1s}} & M_{\theta_{1c}} & 0 \\ N_{\theta_0} & N_{\theta_{1s}} & N_{\theta_{1c}} & N_{\theta_{0T}} \\ \overline{Lf}_{\theta_0} & \overline{Lf}_{\theta_{1s}} & \overline{Lf}_{\theta_{1c}} & 0 \\ \overline{Mf}_{\theta_0} & \overline{Mf}_{\theta_{1s}} & \overline{Mf}_{\theta_{1c}} & 0 \end{bmatrix} \tag{2}$$

$$L_p = \partial L / \partial p = \frac{\rho V S_{fin} C_{y_\beta} h_{fin}{}^2}{2 I_{xx}} + \frac{\rho \Omega_T R_T \pi R_T{}^2}{I_{xx}} \frac{\partial C_{t_T}}{\partial \mu_{z_T}} h_T{}^2 \tag{3}$$

$$L_{\beta_{1s}} = \partial L / \partial \beta_{1s} = \frac{N_b}{2I_{xx}}\left\{\left(\lambda_\beta{}^2 - 1\right)I_\beta \Omega^2\right\} - \rho(\Omega R)^2 \pi R^2 C_t h_R \tag{4}$$

$$\overline{Lf}_p = \partial \dot{\beta}_{1s} / \partial p = 1 + \overline{Lf}_{\beta_v} h_R \tag{5}$$

$$\overline{Lf}_{\theta_{1c}} = \partial \dot{\beta}_{1s} \Big/ \partial \theta_{1c} = \frac{\Omega}{\left(1+\left(\frac{16}{\gamma}\right)^2 - \frac{1}{2}\left(\frac{4}{3}\mu\right)^2\right)}\left(\left(\frac{16}{\gamma}\right)\left(1+\frac{\mu^2}{2}\right)\right) \tag{6}$$

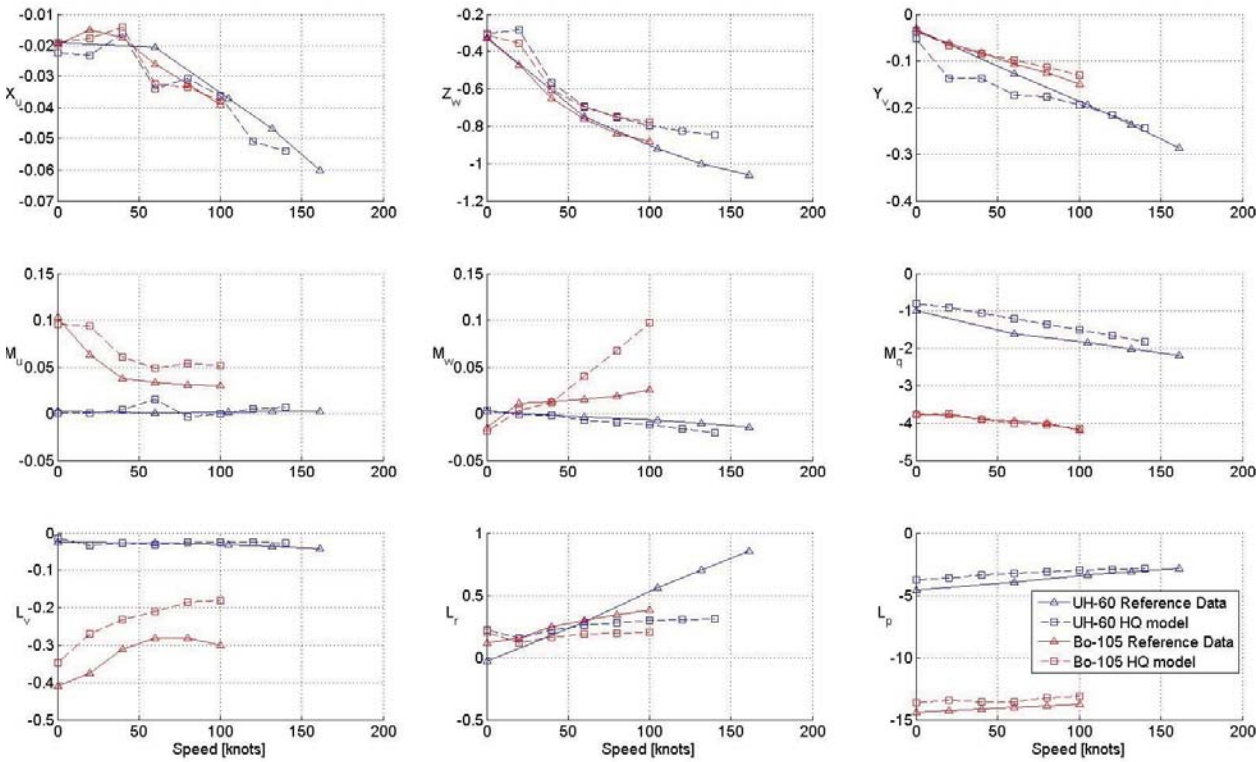


Figure 2 Comparison of stability derivatives from semi-analytical calculations to derivatives extracted from comparable non-linear full force and moment models.

Figure 2 shows a comparison of a subset of the derivatives computed by the closed expressions to those from two models that are similar to the Bo-105 and UH-60 helicopters. The Bo-105–like calculations are compared to derivatives published in ref [3], whereas the UH-60 calculations are compared to linear derivatives computed from linearization of a comparable FLIGHTLAB model.

The derivatives are compared for a range of speeds from hover up to forward flight. In order to facilitate the comparison, the derivatives for the handling qualities analysis models have been computed by reducing the flapping effects back to their quasi steady effect, leaving the 6-DoF rigid body states only. The comparisons are generally favorable especially for dominant derivatives such as roll and pitch damping derivatives, M_q and L_p and the speed damping derivatives such as X_u and Y_v. Other important terms such as M_w and M_u, and L_r also compare reasonably well, with most major trends captured. There are some mismatches, some of which are attributed to poor estimates for input trim data that were unavailable for the Bo-105.

Furthermore, it should be noted that the data from both reference models are from full force-and-moment models that include a number of effects not accounted for in the calculated stability derivatives, including dynamic inflow, aerodynamic interference and other higher order effects. Nevertheless, considering the relative simplicity of the modeling and input data, appreciably similar derivatives are being computed for rotorcraft of reasonably different size and rotor hub systems. This outcome confers confidence in the initial development phase of the research, providing a firm foundation for future modeling developments, and for the overall methodology.

Trim data f(Airspeed,…)	**Rotor** control inputs: $\theta_0, \theta_{1c}, \theta_{1s}, \theta_{0T}$, **Trim attitudes**, $\theta,\ \phi,\ \psi$, **Rotor Thrust coefficient**: C_t, **Atmospheric density**, ρ
Geometry data	**Rotor**: radius, chord, angular speed, location, Number of blades, linear twist rate, shaft tilt, flap moment of inertia, I_β, Hinge offset, e, and/or Hub stiffness, K_β, delta3 angle **Vehicle**: Center of gravity location, Radii of Gyration, K_x, K_y, K_z, Vehicle mass, M_a **Aerodynamic surface**s: location, span, chord or area
Aerodynamic data	**Rotor:** blade lift curve slope **Aerodynamic surfaces**: lift curve slope f(α or β), angle of incidence for zero lift **Fuselage**: reference area, force and moment linear derivatives with incidence

Table 1 Parameters required for stability derivative-based single main rotor flight dynamics model

Flight Dynamics Model Data Requirements

Table 1 shows the full set of parameters required from NDARC (or any other design source) to calculate the flight dynamics for the single main rotor configuration used in this paper. The total number of variables used to fully compute all the derivatives for the demonstration configuration (1 main rotor, tail rotor, fuselage, tail, fin) is of the order of around 50 variables, with a mixture of trim, geometric and aerodynamic data required. There are optional data input choices, such as defining the rotor with an equivalent hinge offset or a hub spring (or both) for modeling articulated and hingeless rotors. A key factor is that a certain amount of the flight state data such as the trim controls, attitudes and thrust coefficient, are inputs, rather than being computed by the handling qualities analysis model. Importing this information from the NDARC conceptual design tool is crucial to facilitating the use of a stability derivative based approach, as several of the trim states and controls are required for the derivative calculations. NDARC's performance-oriented calculations require reasonably accurate estimates of trim and therefore are likely to be satisfactory for handling qualities purposes. Using the NDARC calculated parameters also helps with the consistency of modeling as only the dynamic characteristics are computed and use as much of the NDARC calculation as possible, i.e. the dynamics model does not re-compute trim thrust coefficients or flap angles etc.

For conceptual design analysis and design optimization, mass is a crucial parameter, and as such, NDARC has algorithms for the estimation and accounting of vehicle mass. However, for the estimation of the flight dynamics the vehicle mass must be accompanied by the moments of inertia. However, the moments of inertia are not required for the trim and performance calculations of NDARC and therefore less attention is conferred on those. Currently, NDARC simply takes a user input of the radii of gyration, thus either an a priori knowledge of those parameters or a user estimate is required to define a variable important for flight dynamics. For the test models in this paper the inertias are known, however, in the future, where the NDARC design vehicle configuration is changing iteratively with a handling qualities analysis in a closed loop, an inertia estimation capability will be required, either provided by NDARC or the handling qualities model generation code.

Stitched Modeling approach

A 'stitched' model architecture, ref [10], using a 'quasi-Linear Parameter Varying' or 'qLPV' model technique, ref [11], was used for the overall flight dynamics simulation model. The approach effectively 'stitches' together numerous fixed-point linear state-space models to create a single model with a continuous representation of the vehicle dynamics across the full flight envelope. In this architecture, the derivatives for each fixed-point state space model are entered into lookup tables that are a function of typical parameters such as flight speed, altitude, or vehicle configuration. An example of this was developed for the tiltrotor model in ref [12], where the second independent lookup input variable was nacelle angle (airspeed was the first lookup table independent input variable).

One key characteristic of the stitched model technique, in addition to the lookup tables for the stability and control derivatives, (the 'A' and 'B' Matrices), is that the model includes lookup tables of the trim control inputs and states. The stitched model uses these to reproduce trim characteristics such as input gradients and attitude changes across the flight envelope, as well as to act as the datum point from which the perturbation linear dynamics are referenced to.

Another characteristic of the stitched model is that it models a certain amount of nonlinearity by separately computing the non-linear gravity component force perturbation. The 6-DoF perturbation aerodynamic forces and moments are computed by multiplying the A and B matrix derivatives by the perturbations in the appropriate states and controls, these terms are summed for each equation and then multiplied by the according mass or inertia term. Examples of this are shown for the longitudinal and roll equations of motion in equations 7 to 12. The two features of nonlinear gravity forces and nonlinear equations of motion, along with the trim and state lookup, give the stitched model quasi-nonlinear characteristics, and as such acts as a hybrid between a fixed-point, linear state space model and a full force-and-moment model. Further details on the theory and implementation of stitched models are in refs [10] and [12].

$$\Delta X_{gravity} = M_a g\big(sin(\theta) - sin(\theta_{trim})\big) \quad (7)$$

$$\Delta X_{TOTAL} = M_a\big(X_u \Delta u + X_w \Delta w + \cdots X_{\theta_{1s}} \Delta\theta_{1s} + \cdots\big) + \Delta X_{gravity} \quad (8)$$

$$\Delta L_{TOTAL} = I_{xx}\big(L_v \Delta v + L_p \Delta p + L_{\theta_{1c}} \Delta\theta_{1c} + \cdots\big) \quad (9)$$

$$\dot{u} = -(wq - vr) + \frac{\Delta X_{TOTAL}}{M_a} \quad (10)$$

$$\dot{p} = \frac{(I_{yy} - I_{zz})qr + I_{xz}(\dot{r} - pq) + \Delta L_{TOTAL}}{I_{xx}} \quad (11)$$

$$\dot{\phi} = p + q \sin\phi \tan\theta + r \cos\phi \tan\theta \quad (12)$$

Although the testing presented in the methodology in this paper is predominantly at point conditions, and thus the stitched model may be seen as unnecessary, the stitched model provided a convenient way to keep a general approach to the methodology development without making too many predeterminations on the nature of the subject models, either current or future. This is important in the context of the development of the overall methodology – the use of stitched model has caused the analysis to be developed in a way that few assumptions have been made about the analysis model such that changes in modeling approach (e.g. linear or non-linear, full-force and moment etc.) can be more easily incorporated by the analysis in the future. Furthermore, the author has used these models in other research (ref [13], [14] & [15]) projects featuring full-motion piloted simulation handling qualities experiments for a large civil tiltrotor. This work demonstrated that the stitched model can be used as a basis for a piloted simulation.

Stability and Control Augmentation

Many bare-airframe rotorcraft designs are inherently unstable, often in more than one axis, and also feature a number of control and dynamic response cross-couplings. Therefore it was considered prudent to provide a certain amount of stability augmentation to the models generated from the conceptual tool airframe designs. There are a couple of important reasons for this: firstly, the relevance of bare airframe analysis in an age when all modern and future rotorcraft designs feature sophisticated flight control systems is questionable, and therefore a representation of the action of stability and control augmentation was considered realistic and also potentially informative. Secondly, if the flight dynamics are unstable, it can make the testing required for ADS-33E handling qualities criteria assessment problematic, due to divergence of the simulation model from the intended test trim point, especially in the off-axis response.

The two main requirements to implement a control law for the conceptual design-based handling qualities models were as follows:

1. The control law architecture should be generic enough to deal with a variety of vehicle configurations and sizes and widely varying stability and control characteristics
2. A process to automatically select the gains to meet some form of stability or handling qualities target criteria was required.

A simple approach based on the use of model-following control law architecture (Figure 3), combined with a root locus control feedback gain selection algorithm was selected. Although it is recognized that there are tools that support the design of control systems, such as CONDUIT (ref [16]), the simple approach presented herein was considered more appropriate at this stage as it gave greater control of the individual component processes involved. The following sections will describe the key features of the control law architecture used in this study and how it was configured, including the development of a gain selection algorithm for the feedback of the control laws.

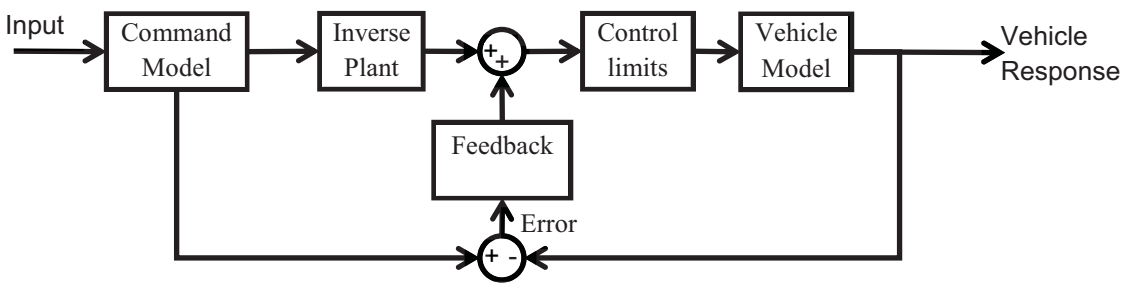


Figure 3 Model-following control architecture

The model following architecture consists of two key functions: 1. A command and inverse plant model which convert pilot stick inputs to idealized responses and then to swashplate input, 2. A feedback or regulator path which tries to minimize the error between measured aircraft response and the desired response coming from the command model. A convenient structure is provided whereby the command model response characteristics can be varied independently of the feedback control response stabilization characteristics and vice-versa. The command model was chosen to have a rate-response type, which is the most basic response type, and, as per ADS-33, it can be used in most mission task elements across the flight envelope by rotorcraft in fully attended operations and non-degraded visual environments (ref [6]). This is a convenient aspect, as the rate command based control law does not require mode switching or require blending at speed thresholds between hover and low speed operations and forward flight. The rate response in the roll, pitch, yaw and vertical axes use 1st order dynamic response shaping functions in the command model as follows:

$$\text{e.g. } \frac{p_{cmd}}{\delta_{lat}} = \frac{K_{lat}}{\tau_{lat}s+1} \tag{13}$$

Here, the desired rate response is governed by a proportional gain, K_{lat} and a response time constant, τ_{lat} which are respectively set to notional values of 1 and 0.3 for all axes for this study. The desired response signal is then split in two paths, one as the reference for the error calculation in the feedback control, and the other is fed to the inverse plant. The signal passed to the inverse model provides a certain amount of feed-forward input to the appropriate rotor inputs to give the desired response shape. The control system uses a reduced order inverse plant model in each axis. For lateral cyclic control, the inverse plant model transfer function is:

$$\theta_{1c}(t) = -\frac{p_c(t)\times L_p}{L_{\theta_{1c}}} \tag{14}$$

The feedback function of the control law is designed to augment the stability of the vehicle. The feedback uses rate and attitude feedback with proportional gains applied to the rate response errors (p, q, r, w) and to errors in the roll and pitch attitudes (ϕ, θ), where the error is defined as the commanded variable minus the current observed state, e.g.

$$p_e = p_c - p \tag{15}$$

Commanded attitudes are calculated via the integration of the command model rate signals $e.g. \theta_{cmd} \approx \int q_{cmd}$ as such, the feedback gain on the error of the commanded attitude (in pitch and roll only) follows that of Attitude Hold architectures, but the objective was only attitude stabilization and not a hold capability.

Feedback gain selection

The main challenge was to develop a method that selected gains for each of these feedbacks that conferred stability improvements, but without requiring overly large actuator demands as to be unrealistic, or cause new instabilities and/or oscillations due to high gain control. An approach based on a root locus design methodology was developed in order to select the gains. The gain selection process is outlined in the flowchart shown in Figure 4.

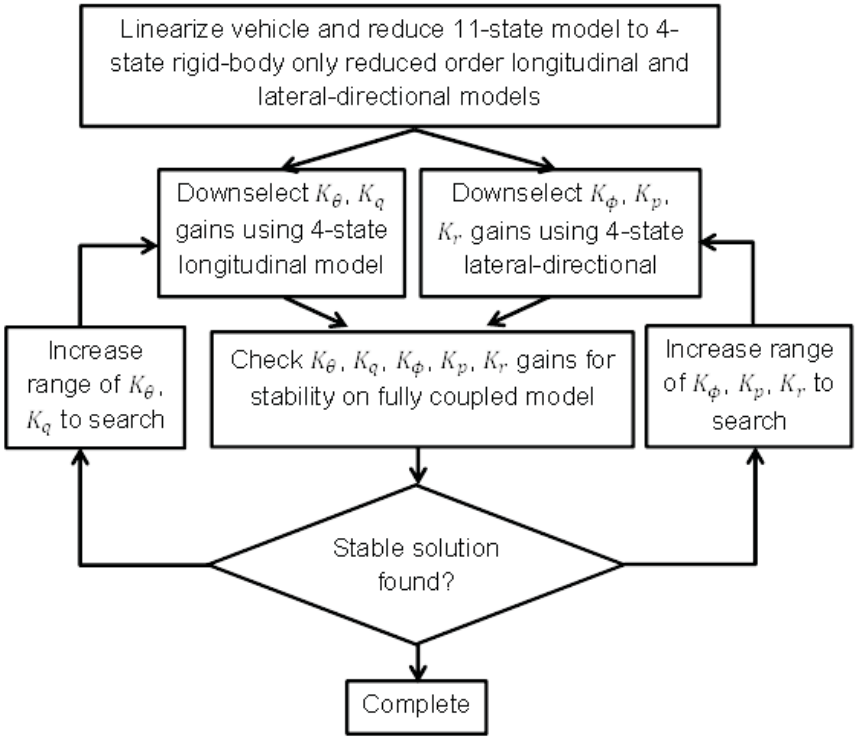


Figure 4 Flow-chart describing feedback gain selection process

The first stage is to split the full-order, coupled linearized state-space model into 2 reduced-order 4-state models of the decoupled longitudinal (u, w, q, θ) and lateral-directional (v, p, r, ϕ) dynamics by partitioning the A matrix. The next stage calculates the eigenvalues for the reduced order closed loop systems for combinations of gains from predetermined arrays of gains. The starting gain arrays cover a range of values of 0 to 0.5 degree of control per degree error – considered to be conservative, low gain values. The use of the reduced order decoupled models greatly accelerates this process where only 2 gain arrays are considered for longitudinal dynamics and 3 for the lateral-directional dynamics. A full matrix search on the fully coupled systems becomes computationally expensive and unwieldy. The closed loop dynamics are computed as follows:

$$\overline{A}_{closed\ loop} = \overline{A}_{open\ loop} + \overline{B}_{open\ loop}\overline{M}\overline{K} \quad (16)$$

where $\overline{K}$ is a matrix of the feedback gains, e.g. for the longitudinal axis:

$$\overline{K} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & K_q & 0 \\ 0 & 0 & 0 & K_\theta \end{bmatrix} \quad (17)$$

$\overline{M}$ is the feedback control allocation matrix, determining which inputs are applied to which feedback states e.g. for the 4-state reduced order representation of the longitudinal dynamics:

$$\overline{M} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 \end{bmatrix} \quad (18)$$

$$\overline{B}_{open\ loop} = \begin{bmatrix} X_{\theta_0} & X_{\theta_{1s}} \\ Z_{\theta_0} & Z_{\theta_{1s}} \\ M_{\theta_0} & M_{\theta_{1s}} \\ 0 & 0 \end{bmatrix} \quad (19)$$

$$\overline{A}_{open\ loop} = \begin{bmatrix} X_u & X_w & X_q - W_0 & -gcos\theta_0 \\ Z_u & Z_w & Z_q + U_0 & -gsin\theta_0 \\ M_u & M_w & M_q & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad (20)$$

This is done for each combination of elements in the arrays of each gain, for example, for the longitudinal axis, if there are $n \times K_\theta$ gains and $m \times K_q$ gains then $n \times m$ gain combinations are evaluated. This process is illustrated in Figure 5, shown in black are the eigenvalues evaluated for all the combinations of gains from the K_θ and K_q arrays. The 'identified' critical eigenvalue pairs are plotted green, which are the eigenvalues for gain sets meeting the following criteria:

- No unstable modes
- Any oscillatory modes above a certain frequency (to ignore very low frequency modes)
- Within a certain percentage of a target damping ratio, in this case a value of 0.707, indicated by the blue line extending from the origin.

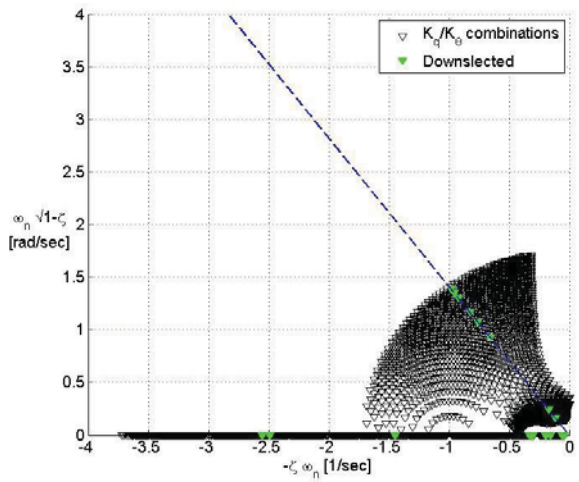
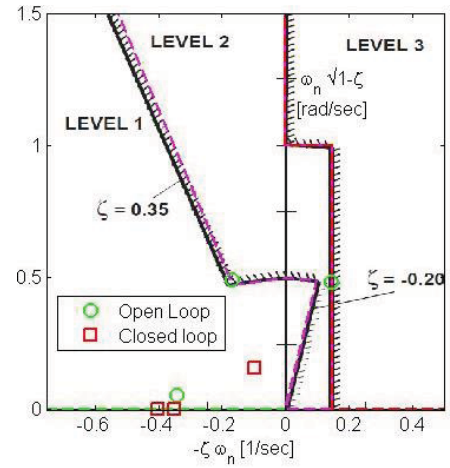


Figure 5 Closed loop eigenvalues for reduced order, longitudinal models for varying pitch rate and attitude gains

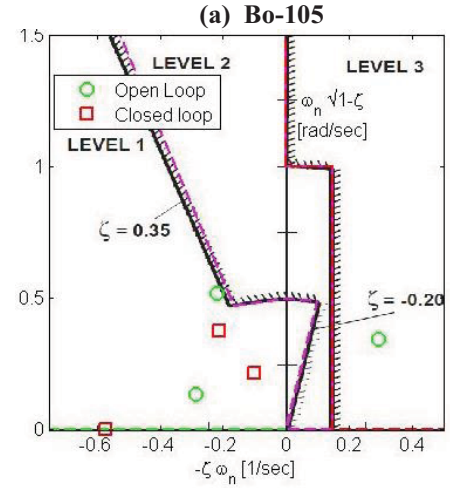
The downselected gain sets for the longitudinal axes are then combined with the downselected lateral-directional gains determined by the same process and applied to the full order (11-state) linear state-space model to check that the coupled system remains stable. If all the eigenvalues of the closed-loop full order model are stable, the process is then complete and the final gains are chosen by either maximizing or minimizing the least stable closed loop pole (user specified), if not, then the process is repeated with gain search arrays with increased values.

The algorithm has been tested on three test models, two of which are single main rotor models generated by the semi-analytical expressions, one approximating to the Bo-105, and the other approximating to the UH-60A. The third test model is of a Large Civil Tiltrotor (LCTR2), with predefined flight dynamics and control allocation, developed for the studies in refs [12] to [15].

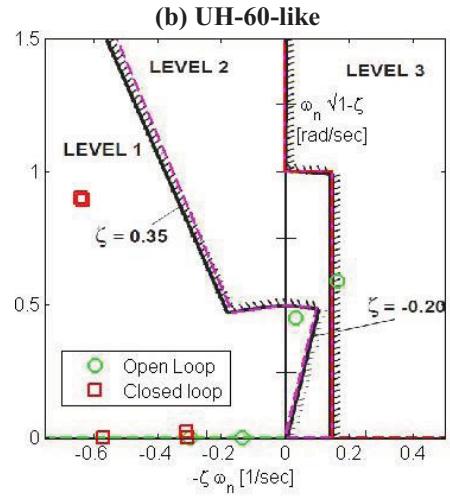
Figure 6 (a) through (c) show the comparison of the open loop (bare airframe) eigenvalues to the closed-loop systems after the feedback gain selection algorithm has been run for the three aforementioned test models at hover. In the figures, the ADS-33E boundaries for the hover and low-speed longitudinal/lateral oscillations are also shown for comparison. All three un-augmented vehicles exhibit at least one unstable mode at the hover flight condition, which after the gain selection, is stabilized, as shown by the square symbols.



(a) Bo-105



(b) UH-60-like



(c) LCTR2

Figure 6 Comparison of open-loop and closed-loop poles after application of feedback gains

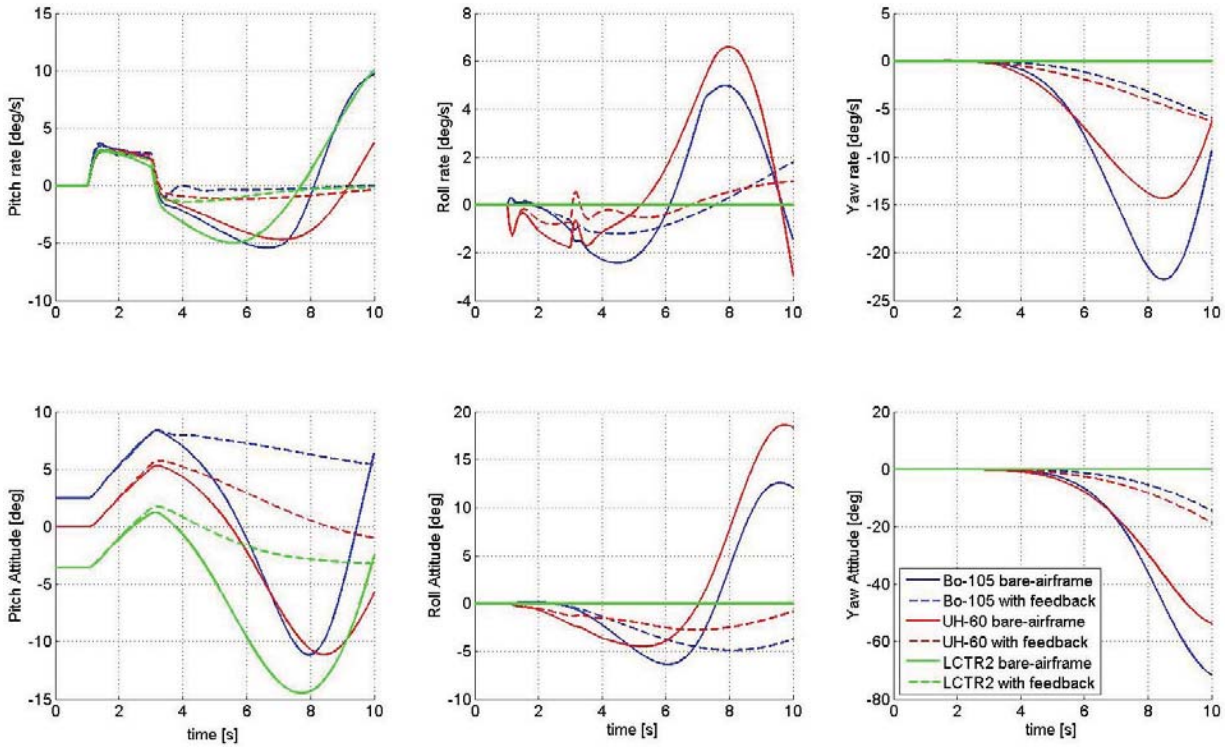


Figure 7 Comparison of time histories of the response of Bo-105, UH-60-like and LCTR2 models to step pulse in longitudinal control before and after stability augmentation

A further comparison of the performance of the gain selection algorithm for the three test models is shown in Figure 7, which compares time responses to a longitudinal input of the vehicles at hover, with and without the feedback applied. It shows that the long-term response of the vehicles are generally improved with reduced deviation from the trim state, and a stable, rather than oscillatory divergent response, in both the on and off-axis response (roll/yaw), especially for the Bo-105 and UH-60-like models.

Handling Qualities Testing

Once the vehicle model is generated and the control system defined and configured, a handling qualities assessment can be performed. Ref [3] describes how the maneuver envelope of an aircraft can be expressed in terms of the frequency and amplitude of the dynamic response. A spectrum of short-, mid-, and long-term frequencies and small, moderate, and large input amplitudes encompass all the task demands that the pilot and vehicle are likely to encounter. This framework naturally delineates into the three fundamental flight dynamics analyses: trim, stability and response. At zero to very low frequency is trim, and at zero to low amplitudes is stability, and as amplitude increases issues of response become the focus up until the maximum limits of maneuver response are reached. This follows a natural physical relationship that the highest frequency responses cannot be large amplitude and vice-versa, with various mechanisms from actuator rate limits, control saturation, aerodynamic force and structural limits all playing their role in enforcing this. The US Army Aeronautical Design Standard, ADS-33E-PRF, ref [6] provides a suitable framework and methodology for analyzing the handling qualities of rotorcraft across the span of dynamic response characteristic behaviors. Implementing automatic handling qualities analyses based on ADS-33 will be described in the remainder of this section.

Use of ADS-33E as a basis

Across the rotorcraft industry, the concepts, methodology and criteria of ADS-33 have become common parlance for assessing rotorcraft handling qualities. Developed through the 1970s, 80s and into the 1990s, ADS-33 was a distinct step forward in handling qualities engineering with its philosophy based on the construct of the Mission Task Element (MTE)

and laying down clearly quantified and objective criteria for measurable parameters which are strongly substantiated by flight test and simulation research. In its typical usage, ADS-33 uses a complementary approach of subjective piloted assessment in the MTEs providing Handling Qualities Ratings (HQRs) combined with the objective criteria for an overall assessment of handling qualities.

The objective ADS-33 vehicle response characteristic criteria are founded in the concepts introduced in the previous subsection with criteria broken down along lines of response amplitude and frequency. Frequency and time domain analyses are used to evaluate the full range of frequency and amplitude responses from low amplitude/high frequency using parameters such as bandwidth, mid-term agility parameters such as quickness, out to maximum maneuver capability control response criteria. The ADS-33 objective criteria constitute well-defined parameters and methodologies for their identification and are the natural basis for any quantitative handling qualities assessment of rotorcraft.

Handling qualities testing methodology

A set of algorithms were developed to run a selected range of key ADS-33 handling qualities criteria tests on the rotorcraft models. As described in the introduction, the primary focus of the research initially was to develop the overall methodology, including a basic capability in each of the tasks outlined in Figure 1. As such, the development of the handling qualities testing component was designed to encompass a sufficient variety of ADS-33 criteria tests to be representative of the problem without overburdening the overall development process by implementing every possible test. Table 2 lists the ADS-33 handling qualities tests currently implemented. Also indicated in the table are the specific ADS-33E-PRF requirements being tested and their approximate location in the frequency-amplitude response spectrum.

The majority of the ADS-33 testing is performed through the generation of time histories from simulation runs, the exception being the pole-zero stability analyses. For each flight condition, hover or straight and level forward flight at various speeds, the model is initialized by trimming to obtain the equilibrium control inputs and roll and pitch attitudes. Next, test inputs are defined and applied in a series of simulation runs which may feature frequency sweeps, pulse or step inputs or a linearization process.

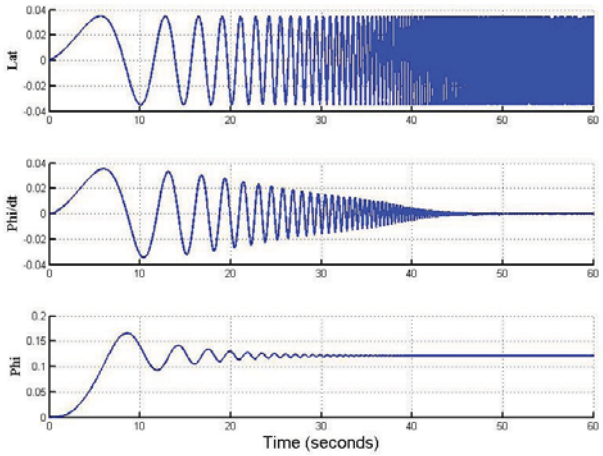
Finally, the simulation output is recorded and processed for the final handling qualities assessment. This approach was chosen over linear systems analyses that directly calculate the system characteristics from state-space or transfer function models because it offered a certain amount of future-proofing to developments in terms of using non-linear models or transferring the algorithms to other codes or languages, i.e. a methodology was desired that did not overly rely on a particular software analysis toolbox or implementation. The following subsection considers a subset of the tests listed in Table 2 (highlighted in gray) for further description to demonstrate how the handling qualities analyses are performed.

	Roll	Pitch	Yaw	Vertical
Small Amplitude/High Frequency	Attitude Bandwidth **(3.3.2.1, 3.4.6.1)**	Attitude Bandwidth **(3.3.2.1)**	Attitude Bandwidth **(3.3.5.1, 3.4.8.1)**	-
Small Amplitude/ Low/Medium Frequency (mode stability)	Oscillatory Requirements 4 **(3.3.2.3, 3.4.9.1)**	Oscillatory Requirements **(3.3.2.3, 3.4.1.2)**	Oscillatory Requirements **(3.4.9.1)**	-
Medium Amplitude/ Medium Frequency	Attitude Quickness **(3.3.3, 3.4.6.2)**	Attitude Quickness **(3.3.3)**	Attitude Quickness **(3.3.6)**	Response to Collective **(3.3.10.1, 3.4.3.2)**
Large Amplitude/Low Frequency	Large amplitude attitude change **(3.3.4, 3.4.6.3)**	Large amplitude attitude change **(3.3.4)**	Large amplitude attitude change **(3.3.8)**	-
Interaxis coupling	Roll due to pitch **(3.3.9.2, 3.3.9.3, 3.4.5.2, 3.4.5.4)**	Pitch due to roll **(3.3.9.2, 3.3.9.3, 3.4.5.3, 3.4.5.4)**	Yaw due to collective **(3.3.9.1)**	-

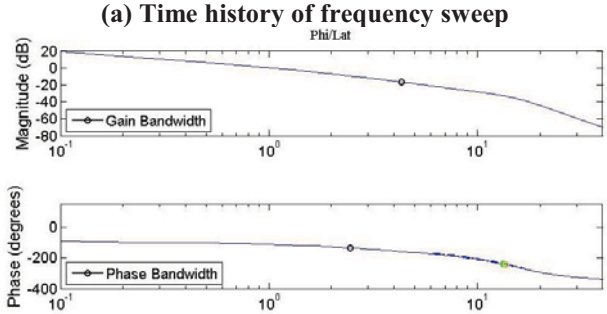
Table 2 ADS-33E-PRF Handling qualities criteria tests implemented

Attitude Bandwidth Testing (Roll Axis)

The attitude bandwidth testing is based on a frequency domain analysis of the vehicle attitude response to a sinusoidal frequency sweep input applied in a simulation run. The time histories of typical inputs and outputs for a roll axis attitude bandwidth test for the Bo-105 example model with a stability augmentation control system enabled are shown in Figure 8(a). These time histories are used to calculate the magnitude, phase and coherence of the roll attitude frequency response to the lateral input, as plotted in Figure 8(b). From these, the phase and gain bandwidth, and phase delay, are evaluated as defined in ADS-33.



(a) Time history of frequency sweep



(b) Bode plot

Figure 8 Time history of roll-axis frequency sweep and computed Bode plot of frequency response to compute attitude bandwidth and phase delay

The final stage of the test is the evaluation against the ADS-33 criteria – this is illustrated in Figure 9. Here the minimum value between the roll attitude phase and gain bandwidth, which is the procedure for a rate response type according to ADS-33, is plotted against the computed phase delay. It can be seen that against the ADS-33 criteria, the roll attitude bandwidth is well into the Level 1 region. This is the technique used throughout the handling qualities analysis routines where if the parameter is to be compared to regions on an ADS-33 criteria chart, then the data point is plotted on the chart and evaluated to be within a particular region defined by the appropriate ADS-33 handling qualities boundaries.

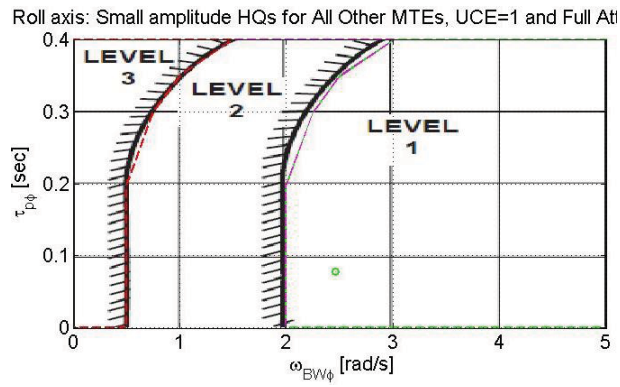


Figure 9 Bo-105 Roll axis attitude bandwidth and phase delay on ADS-33E-PRF handling qualities criteria chart

Attitude Quickness Testing (Roll Axis)

Attitude quickness is considered a moderate amplitude vehicle response criterion by ADS-33. It requires the vehicle to undergo rapid attitude changes from one steady attitude to another. The criterion seeks to identify in the time domain the maximum ratio of the peak rate response to the attitude change achieved in a maneuver over a range of attitude changes. The test algorithm for this criterion uses a two stage process; Firstly, an open loop step input in the control axis of interest is made to generate an estimate of the relationship between input magnitude and the steady rate response. This information is used to initialize the second stage of the process whereby the vehicle is run in a sequence of simulation runs using square pulse inputs of varying size and length, as shown in Figure 10. The process starts with a selected minimum input length and begins by first increasing the input amplitude up until the maximum attitude change required is achieved. This process then loops over a range of input lengths, each pulse input increasing in period after each loop of increasing input amplitudes. As such, the process generates a collection of attitude quickness curves shown in Figure 11, from which the analysis code selects the maximum quickness achieved. Attitude quickness differs somewhat to criteria such as bandwidth in that it is not defined by a single point, so a method was devised as to adjudge whether a collection of points are overall Level 1, 2, or 3. The current

method looks at the percentage of points occupying each region, currently a threshold point of 90% or more in a single region (can be set to whatever the user requests) determines the assigned handling qualities level, otherwise the worse region that the curve enters is the assigned handling quality level. This aspect is not from the ADS-33 methodology but provides some flexibility for users to make a judgment whether they consider a certain majority of points from the simulation analysis to give the appropriate result. It also confers a way to provide some robustness to a spurious point that might otherwise skew the overall outcome.

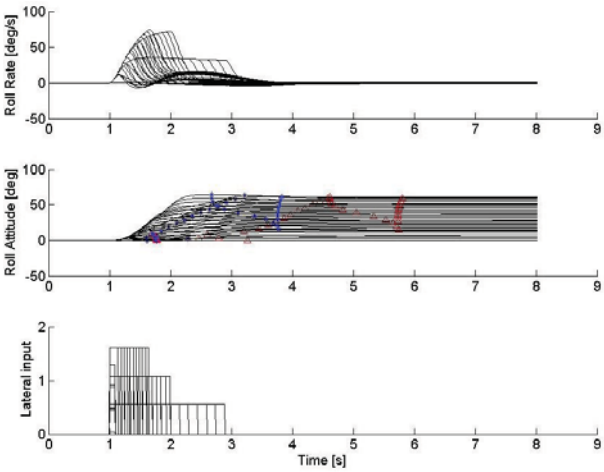


Figure 10 Time histories of roll axis attitude quickness testing input and output parameters

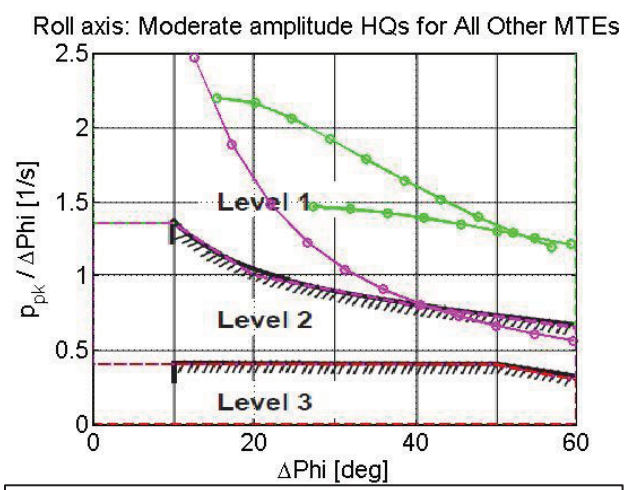
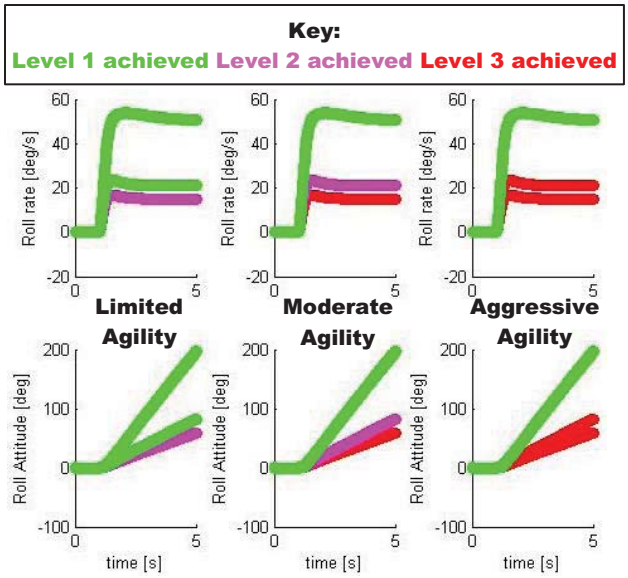


Figure 11 ADS-33E Quickness criteria (roll axis)

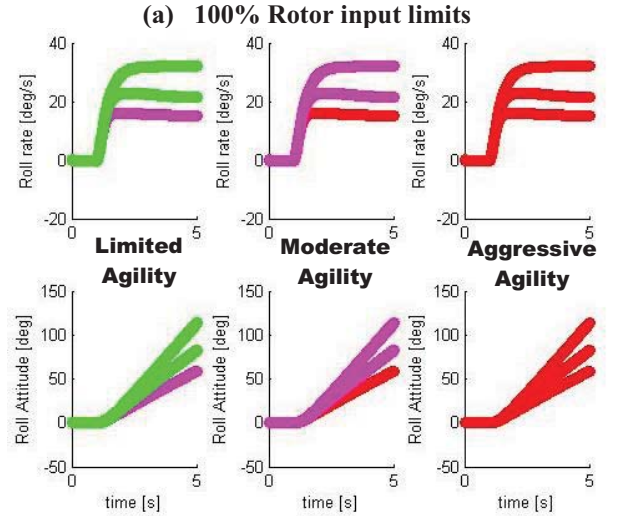
Large Amplitude Response (Roll Axis)

The large amplitude response testing was a relatively straightforward test to implement compared to the other criteria, as it simply requires maximum control input steps to be made and then the maximum rate or attitude response to be measured. However, for the current level of model fidelity, more philosophical issues arose around the meaningfulness of such a test. This is because the linear models used feature little or no physical limitations, i.e. there are no nonlinear aerodynamic effects such as aerodynamic stall or high angle of attack drag increase or limits such as rotor thrust, engine power, actuator or structural limits represented. This aspect also somewhat applies to the quickness testing but there are two justifications for retaining this type of test at this stage. (a) Maintaining a general approach to the methodology development – the current model is linear and generally not applicable for large amplitude motion but subsequent developments may lead to the use of higher fidelity models that are more appropriate. (b) A simplified synthesis of the effect on this handling qualities parameter can be evaluated on a linear model by limiting the control inputs. In this way an effect on the large amplitude criteria can be generated by using simple position saturation limits on the value of the rotor cyclic, collective or aerodynamic surface inputs applied to the vehicle model. This prevents the test procedure from applying a control input of any size to the model to generate the desired Level 1 response, and thus when comparing designs, gives a sense of the maximum control force/moment and damping capability for some equivalent maximum control input size.

Figure 12 (a) and (b) show the typical output from a roll-axis large amplitude response handling qualities test, the results shown are for the UH-60-like rotorcraft model in hover. The plots show the time response of both the roll rate and roll attitude. There are three pairs of axes for each test run with each plot having different criteria applied to enforce the plot color for the ADS-33 limited, moderate and aggressive agility categories. In this way, the curve is colored according to the agility category used; this is evident in Figure 12(b) where, as an example, the rotor input limits were reduced to 33% of the nominal values. In this case, it can be seen that although vehicle maximum rate response for the vehicle for limited agility (1st column of plots) category remained Level 1 (green) when compared to its 100% input limit cases in (a), the handling qualities for the moderate and aggressive MTE categories were degraded to Levels 2 (magenta) and 3 (red) respectively.



(a) 100% Rotor input limits



(b) 33% Rotor input limits

Figure 12 Time histories from roll axis large amplitude testing

In the current implementation, each axis of large amplitude attitude change response testing confers three distinct handling quality level scores for each of the MTE categories of limited, moderate and aggressive agility. In forward flight, ADS-33 specifies criteria only for the roll axis, thus a fourth HQ score is provided in forward flight testing (not shown) . Looking forward, the provision of a score for all the possible categories may be unnecessary, as part of a future implementation the overall conceptual design problem definition might include an interpretation of the NDARC mission into a more refined set of ADS-33 requirements and thus specify which of the agility requirements should be used. In fact, this idea is applicable to a number of the ADS-33 test parameters which are evaluated against a range of criteria that is dependent on the MTE, visual conditions and pilot attentional demands relevant to the mission intended for the vehicle in question.

Preliminary Results

Preliminary results from the execution of the majority of the process outlined in Figure 1 are presented and discussed in the following section. The element omitted from the process is the final feedback of the handling qualities analysis results back to the conceptual design process, i.e. the NDARC tool, an aspect that will be discussed further in the final discussion. Nevertheless, the following results represent a near complete analysis loop demonstrating a method that includes the import of conceptual design data, flight dynamics model generation, the application and configuration of a control law, and then the execution and presentation of a handling qualities analysis using those models.

		Pitch	Roll	Yaw	Vertical
1	Small Amplitude [Bandwidth and Phase delay] (hover) - Target acquisition and tracking	1	2	2	
2	Small Amplitude [Bandwidth and Phase delay] (hover) - All other MTEs, full attended op...	1	1	1	
3	Small Amplitude [Bandwidth and Phase delay] (hover) - All other MTEs, divided attentio...	1	1	1	
4	Moderate Amplitude [Quickness] (hover) - Target acquisition and tracking	1	2	1	
5	Moderate Amplitude [Quickness] (hover) - All other MTEs	1	1	1	
6	Midterm Response to Control inputs (hover) - Pitch and Roll Oscillations	1	1		
7	Large Amplitude [maximum rate/atittude] (hover) - Limited Agility	1	1	1	
8	Large Amplitude [maximum rate/atittude] (hover) - Moderate Agility	1	1	1	
9	Large Amplitude [maximum rate/atittude] (hover) - Aggresive Agility	2	1	2	
10	Yaw due to collective coupling (hover)			1	
11	Response due to collective controller (hover)				1
12	Pitch/Roll due to Roll/Pitch: HQs for Aggressive Agility	1	1		
13	Requirements for Pitch due roll and roll due to pitch for Target Acquisition and Tracking	2	2		

Figure 13 Table of handling qualities Levels assigned generated from handling qualities methodology

Figure 13 shows complete results from a handling qualities analysis of the UH-60-like model at hover, with the stability augmentation enabled. The table shows the handling qualities Levels achieved by the model for each axis applicable to each criterion for the ADS-33E criteria currently. A prominent result is that a great deal of the criteria is assigned Level 1 handling qualities. This is an outcome that has been observed for all the test models (Bo-105-like and LCTR2, not shown) and is probably the outcome of two key factors, firstly the two vehicles that are representative of existing designs (UH-60 and Bo-105-like) are likely to have reasonably good basic handling qualities in the light of their longevity of use and successful service. The level of modeling fidelity is also important, in particular there are a variety of un-modeled lags, delays, nonlinearities and couplings that would be attributed to actuator dynamics and limits, engine power, torque and dynamic limits and aerodynamic effects such as inflow dynamics, stall, and interference effects that all would contribute to handling qualities degradations.

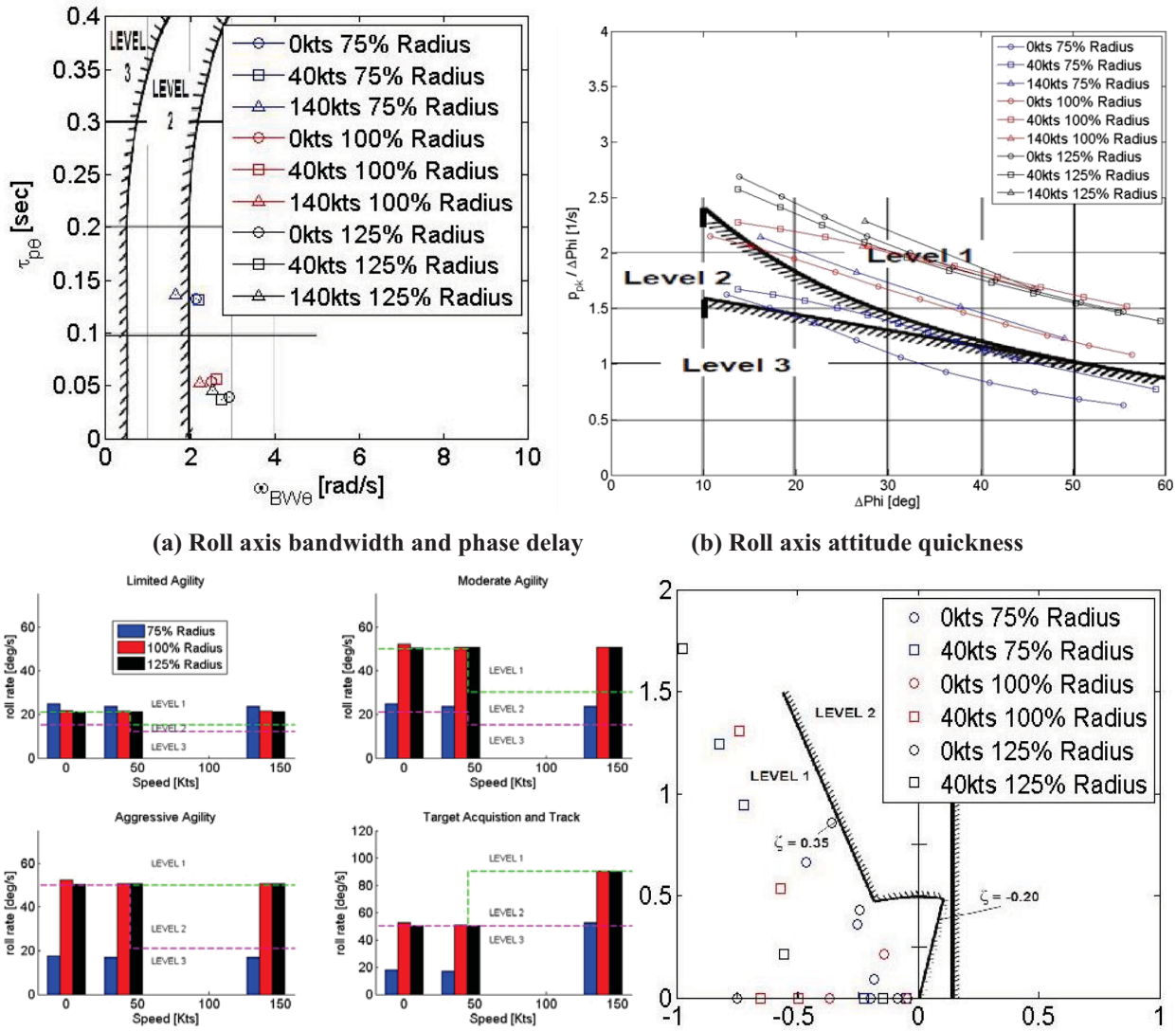
This raises one of the research questions highlighted in the introduction of this paper – 'what can be learned by a handling qualities analysis at this level of modeling fidelity?' a level that is consistent with the vehicle modeling/information/data available from the conceptual design process. In light of the handling qualities results just presented, an argument could be made that greater modeling fidelity is required, especially if an accurate appraisal of the absolute level of handling qualities is required. However, there is a trade-off to be considered; adding modeling complexity and fidelity will incur cost, in terms of computational cost, data requirements and perhaps reduced engineering insight. An alternative viewpoint is perhaps the criteria as they now exist need to be somehow adjusted to factor in the level of modeling fidelity used for the conceptual design handling qualities analysis.

Handling Qualities sensitivity analysis

A demonstration of the handling qualities sensitivity to design parameters is illustrated in Figure 14(a)-(d) and Figure 15(a)-(d). Figure 14(a)-(d) illustrates a subset of the handling qualities parameters evaluated for the roll axis of the UH-60-like configuration model, (control and stability system applied) for a variation of the main rotor radius design parameter, and a range of speeds. The handling qualities parameters have been selected to provide an impression of the effect of the variation of the rotor radius across the frequency-amplitude response spectrum. Figure 14 (a) shows the roll axis bandwidth/phase delay criteria, it can be seen that although all the points reside within the level 1 region (All other MTEs, full attended operations and UCE=1 category), the variation in the roll axis bandwidth is 0.5-1 rad/s between the lowest bandwidth at 75% radius and highest for the 125% rotor. This is a reasonably significant variation, especially when it is considered that there is only a difference of 1.5 rad/s from the Level 1 to the Level 3 boundary. The phase delay is more significantly affected, with the 75% rotor more than twice the value of the 100% rotor. This is intuitive, as the key contribution to the lag represented by the phase delay is the rotor flap time constant, which is inversely proportional to rotor radius to the power of 4 via the Lock number (equation 21, hover approximation) – the smaller the radius, the greater the flap time constant (all other aspects fixed).

$$\tau_f = {}^{16}/_{\gamma\Omega} \tag{21}$$

Similar trends are observed for the quickness parameter in Figure 14 (b), where the 75% rotor exhibits worse handling qualities with borderline Level 1 and Level 3, while the 125% rotor is better. As seen for the bandwidth, the variation with airspeed is not distinct, with no particular difference with speed observed for a given radius. Figure 14 (c) shows the roll axis large amplitude response (control limits applied) for the radius and speed variations, for the 4 agility categories. Here, the trends do not follow those observed for the bandwidth and quickness, with the 75% radius rotor having a lower large amplitude response capability than the 100% radius, but not much observable difference between the 100% and 125% rotor. Figure 14 (d) shows the low speed roll/pitch midterm response criteria, which is essentially an analysis of the vehicle stability. This criterion is only applicable to hover and low speed, hence only the hover (0kts) and 40kt points are shown. No discernable trends are observed, which is somewhat to be expected, as these results are strongly influenced by the action of the stability control augmentation. Ultimately, the action of the control system is to return similar stability characteristics for each of the vehicles with the varied rotor radius. What is not indicated by this analysis, and perhaps a useful handling qualities indicator, is how much feedback control activity is required to achieve these similar stability characteristics, a subject discussed later in this paper.



(a) Roll axis bandwidth and phase delay **(b) Roll axis attitude quickness**

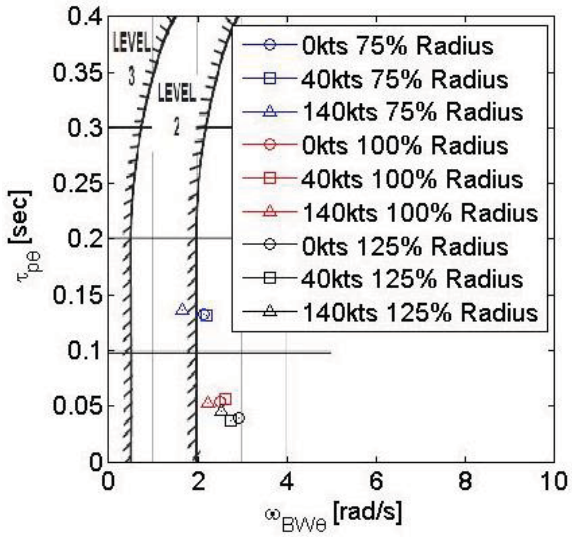
(c) Roll axis large amplitude response **(d) Hover/Low-speed Pitch/Roll oscillations**

Figure 14 Results of main rotor radius variations on various ADS-33E Handling qualities (roll axis) criteria at hover and forward flight for UH-60-like model

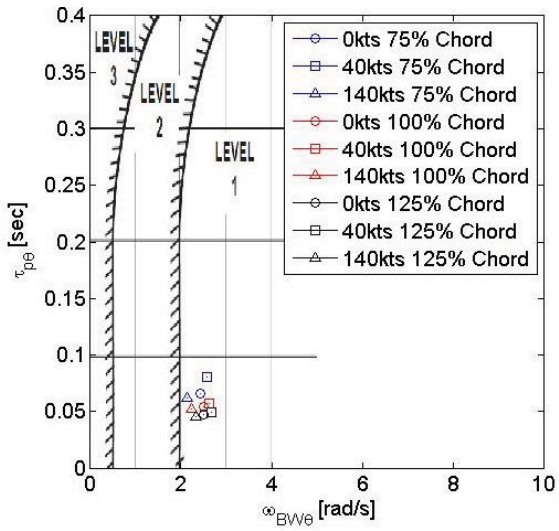
Figure 15(a) to (d) presents a different comparison, in this instance, a single handling qualities criteria, roll axis bandwidth/phase delay, is compared for the variation of 4 vehicle model input parameters: main rotor radius, main rotor blade chord, main rotor hub spring stiffness, and main rotor flap moment of inertia. Each of the parameters was varied entirely independently, with no consideration made for real-world interdependencies, such as variation in radius also impacting flap moment of inertia. This would differ from an analysis fully integrated into a conceptual design process, where the design code would provide a fully 'consistent' input dataset. Nevertheless, the single parameter variation analysis provides a useful initial demonstration and helps somewhat in reducing the complexity in interpreting the input-output dependencies.

The radius variation is the same result as plotted in Figure 15(a) and is included for comparison only. Figure 15(b) shows that the effect due to chord variation, again for a 75%/125% variation from a nominal 100%, has a similar but much reduced effect to that for a radius change, with the 75% chord generally producing the lowest bandwidth, and the 125% chord the highest and the inverse relationship for the phase delay. The effect due to a variation in the hub spring stiffness, and blade inertia shown in Figure 15(c) and

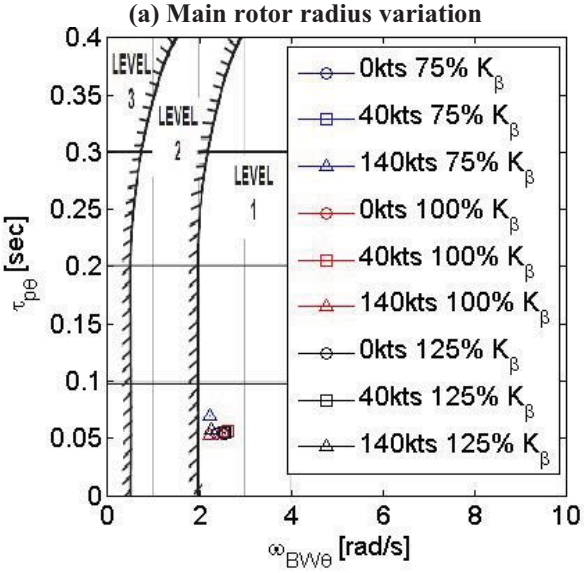
(d) are minimal for this handling qualities parameter. This is due to the fact that the command and inverse model in the control system compensates for any variations in the bare airframe dynamics to return similar bandwidth characteristics. The variation of blade inertia has the inverse effect on the roll bandwidth to that of the chord. Both terms respectively appear in the numerator and denominator of the Lock number but are only linearly proportional to the rotor flap time constant and so have a less significant effect than the rotor radius variation.



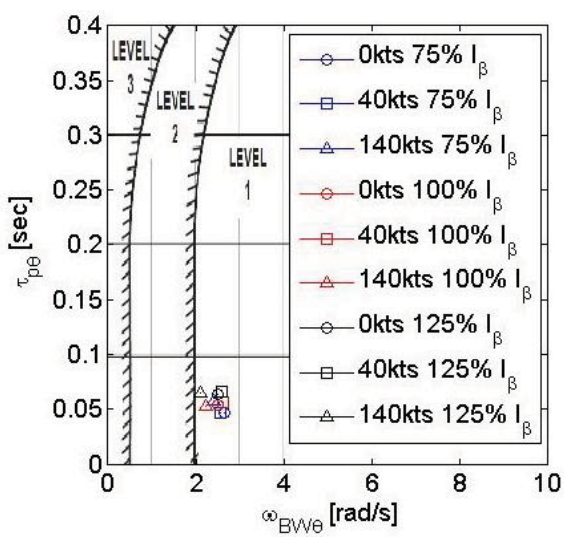
(a) Main rotor radius variation



(b) Main rotor blade chord variation



(c) Main rotor hub stiffness variation



(d) Main rotor blade inertia variation

Figure 15 Results of 4 design parameter variations on ADS-33E Handling qualities roll axis bandwidth/phase delay criteria at hover and forward flight for UH-60-like model

Final Discussion

In summary, the results in the previous section demonstrated that the analysis for a limited subset of design parameter variations, output handling qualities parameters, and evaluation flight conditions, generated a complex picture. Even the analysis using single parameter variations did not always produce clearly discernable dependencies and trends. This is not an unsurprising result as the underlying expressions governing the flight dynamics of the vehicles have a complex relationship with the input design parameters, with the same terms often appearing multiple times in many counteracting stability and control derivatives. The action of the control system also masked the effects of the design parameter variations on the handling qualities parameters and so closer inspection of the control system actions is crucial.

However, calculating the effect of the input design parameters on higher-level handling qualities parameters helps to provide a more direct reflection on the complex handling qualities relationships than techniques that purely examine the fundamental flight dynamics terms might. Nevertheless, it is evident that the outstanding challenge of translating handling qualities analysis to a form suitable for a conceptual design process is not insignificant. The remainder of this section of the paper will review the progress of the work, encompassing both the results and methodology, to guide a discussion of areas requiring further development and analysis.

To reiterate, the ultimate goal of the work presented in this paper is the realization of a design process that fully integrates handling qualities into a rotorcraft conceptual design process. The progress so far indicates that there are multifarious handling qualities parameters and relationships between those parameters and possible design variables; the question is how to quantify the handling qualities to guide a design downselection or optimization process? Incorporating all the possible handling qualities parameters individually as design targets might be unwieldy and difficult to converge a design upon, and thus some form of grouping of the criteria may be required to reduce the number of variables.

Using the handling qualities Levels assigned for each criterion to either compute a total score or an average is one possible option. However, use of the handling qualities level ratings in their integer form may not confer enough granularity, especially if points go beyond a Level 3 or Level 1 boundary, as illustrated by the results in Figure 14 (a) where all the results are Level 1, but with different margins. As such, the points for each criterion could be converted to a continuous form to provide sensitivity within each handling qualities level, as demonstrated by ref [16]. For the overall handling qualities assessment a single overall handling qualities score could be a possibility, although a greater breakdown is likely to be desirable. Options could be to divide the handling qualities into subgroups along the lines of axis of response, roll, pitch, yaw, vertical, etc. An alternative approach might be to categorize along the lines of the frequency-amplitude of response, with a single handling qualities score computed for short term response (bandwidth), moderate amplitude (quickness), and large amplitude (control power), with other categories for interaxis couplings and stability, in this format, the different axes of response are subsumed within each category. Modern optimization tools may render these concerns unnecessary and ultimately the number of parameters included is dependent on the 'weight' that handling qualities are conferred by the conceptual designer and on the 'confidence' in the results calculated.

Two particular issues arose when considering these types of unpiloted handling qualities evaluations. First is one of the questions raised in the introduction, is it more appropriate to compare bare-airframe designs or vehicles with stability and control augmentation applied? Arguments can be made for either case; on the one hand, comparing bare-airframes without augmentation would seem to be a more fair and unambiguous approach without the effect on control law augmentation obfuscating a direct comparison. However, on the other hand, it is somewhat unrealistic to analyze bare-airframes as no modern sophisticated rotorcraft would fly without some form of control augmentation. In such a scenario, poor bare-airframe stability characteristics might unduly count against a design that might otherwise possess desirable characteristics and would be perfectly feasible to operate once stability and control augmentation were applied. Furthermore, comparisons in stability augmentation margins, and other control related factors will be important when comparing designs as the

handling qualities parameter variations may be minimal but the control system compensation may not. Secondly, a practical aspect exists as many of the rotorcraft designs are likely to exhibit a large amount of instability in their natural (bare-airframe) flight dynamic response, as well as strong control and dynamic response inter-axis couplings. Using a control law to ameliorate and mitigate these effects is desirable to make the testing more tractable by protecting against model divergence induced by unstable dynamics. However the bare-airframe should not be completely forgotten, depending on the 'reliability' of the augmentation. ADS-33 allows, with a probability of less than 2.5 $x10^{-3}$ per flight hour, degradations to level 2 within the operational flight envelope, and Level 3 within the service flight envelope. Other specific failures are defined, such as single failures that cause complete or partial loss of the flight control system 'shall not cause dangerous or intolerable flying qualities'. Whether this is something handling qualities analysis at a conceptual design level can address is an open question but it indicates that the bare-airframe cannot be completely 'unflyable', certainly if current standards are applied.

Finally, as indicated in the previous paragraph, the presence of the control and stability augmentation offers alternatives to directly comparing the ADS-33 handling qualities for designs. Two designs with equivalent handling qualities might be dissociated from another by examining how much stabilization and control action is required to attain a particular level of handling qualities. One of the indicators for evaluating this aspect could be to look at the magnitude of the feedback gains required to confer certain levels of stability and damping of the response. A vehicle design requiring more gain than another might be deemed inferior as high gain might lead to negative effects such as high actuator activity, rate limiting or saturation. These actuator aspects could also be evaluated directly through the examination of actuator RMS (e.g. ref [16]), or the use of control system criteria such as the Open-Loop Onset Point (OLOP) design criteria (ref [17]), which is used to predict the potential handling qualities impact associated with actuator rate limiting.

Summary and Conclusions

This paper has described a process to generate and analyze the handling qualities of models derived from the output of the NDARC conceptual design tool. Overall, the work presented in this paper has demonstrated how a broad array of technical issues across flight dynamics stability and control, simulation and modeling, control law design and handling qualities testing and evaluation had to be confronted to implement even a moderately comprehensive handling qualities analysis of relatively low fidelity models. Although it is too early to determine many conclusions about what questions such a methodology might most effectively answer and how best it might be deployed, it is considered that a good foundation for the next phase has been established. The following conclusions and lessons learnt are submitted:

- The output data of the conceptual design tool NDARC provided sufficient information to define a basic rotorcraft flight dynamics model. A caveat is that the vehicle moment of inertia characteristics will require estimation if the NDARC tool does not provide them.
- The application of a control system to primarily augment the stability of the bare-airframe flight dynamics models is advantageous as it provides models with better baseline characteristics for handling qualities analysis, reducing the risk of model divergence. It also offers additional handling qualities analysis options such as evaluating the level of augmentation and actuator demands required to achieve certain stability and response characteristics.
- Preliminary results from variations of example vehicle design variables showed measurable handling qualities outcomes. However, assigning them a Level 1,2 or 3 rating may not be a suitable method of quantifying the handling qualities in a vehicle design optimization and a more continuous measure of 'handling quality' may be required.
- The current ADS-33 handling qualities boundaries may not be meaningful for fidelity of the flight dynamics models currently being derived from the conceptual design data. Possible options are to move the boundaries to compensate for modeling simplifications, to increase fidelity, or to represent higher fidelity effects indirectly by using techniques such as equivalent delays, etc.

Future Work

Referring back to Figure 1, one of the key outstanding issues is how to 'close the loop' with an overall

conceptual design process. A number of avenues for exploration of how to feedback useful handling qualities results have been proposed, and will form the core aspects of future work which will most likely encompass these aspects:

1. Determining handling qualities boundaries appropriate for conceptual design. This may entail adjustment of boundaries of current criteria to reflect modeling simplifications or the estimated margins that simplified dynamics confer, or introduction of higher fidelity effects or their representation through synthesized delays or other techniques.
2. An analysis of the control system requirements in terms of the level of augmentation required, actuator demands and margins against future unforeseen handling qualities issues (i.e. achieving greater than Level 1-2 boundary in a conceptual design).

Another key area for future analysis and development relates to the modeling capabilities of the tool. Two aspects are of particular interest: 1. The number of vehicle configurations that can be modeled 2. Developing a greater understanding of the trade-offs between model fidelity and complexity and the design process, i.e. what can be credibly assessed and what is the most critical aspect – accuracy, or the ability to rapidly predict handling qualities trends over a broad array of design cases.

Adding modeling capability to increase the types of vehicle configurations is the logical next step once the overall methodology has been established. Thus far, the focus has been to build up a baseline capability and thus modeling based on the established single main rotor configuration was a natural start point. Looking forward, the key aspect to future developments will be the implementation of increased modularity to stability and control derivative calculations for the key vehicle subcomponents (rotors, wings, surfaces etc.). Here, the goal will be to provide a framework such that arbitrary numbers, locations and orientation of each subcomponent can be efficiently managed when defining the complete vehicle derivatives. With the addition of modeling enhancements, this will permit a number of other rotorcraft configurations to be examined including tiltrotors, co-axials and winged compounds.

Addressing the modeling fidelity aspects is an ongoing effort. Thus far, the analysis applicable to this area has been limited to the comparisons presented in the flight dynamics modeling section. These have demonstrated that the stability and control derivatives being computed from the input data are reasonably representative when compared to other modeling codes. However, if this tool is to be used in actual studies, additional validation effort is required, including comparisons to handling qualities analyses conducted on equivalent vehicles from higher fidelity simulations or flight test. Furthermore, greater involvement of conceptual design subject matter experts in the future developments will be an important factor to developing an understanding of the design questions that have a strong interaction with handling qualities, which will ultimately guide how to best deploy the methodologies being developed.

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