Flight Dynamics and Control Modeling with System Identification Validation of the Sikorsky X2 Technology™ Demonstrator

Cody Fegely
Senior Engineer
Handling Qualities and Flight Controls
Sikorsky Aircraft Corporation
Stratford, CT, USA

Ondrej Juhasz
Research Associate
San Jose State University
U.S. Army Aviation
Development Directorate (ADD)
Moffett Field, CA, USA

Hong Xin
Principal Engineer
Handling Qualities and Flight Controls
Sikorsky Aircraft Corporation
Fort Worth, TX, USA

Mark B. Tischler
Senior Scientist
U.S. Army Aviation
Development Directorate (ADD)
Moffett Field, CA, USA

ABSTRACT

Physics-based flight dynamic models are vital to the aircraft design process and are used for design loads prediction, flight control development, handling qualities evaluation, and in support of design and vehicle layout trade studies. These models must be validated with flight-data whenever available to increase confidence in model fidelity and to help determine model deficiencies. This paper presents the validation of coaxial compound helicopter flight dynamics models developed in GenHel and HeliUM by correlating with the X2TD flight test data. GenHel is the flight dynamics model used by Sikorsky and HeliUM is used at the U.S. Army ADD. Both modeling tools are modular in architecture, include flexible rotor blade models, and allow for complete free-flight analysis. Both tools have been extensively correlated against a variety of single-main-rotor flight test data. When applied to the X2TD configuration, both models show good correlation to flight data for steady-state and dynamic responses. The models accurately predict the bare-airframe X2TD frequency response from 0.2 to 1.0 Hz. Key modeling parameters are determined using an analytical model of the coupled rotor and fuselage, and then identified from flight data using system identification. When propagated back into the HeliUM model, the fidelity was increased to a larger frequency range and approached the response obtained from GenHel. The broken-loop and closed-loop behavior of the X2TD are also analyzed and match well with flight data.

INTRODUCTION

Validated flight dynamics models are critical to the design process. These models are used for design load predictions, flight control development, and handling qualities evaluation. This paper presents the development of flight dynamics and control models for the Sikorsky X2 Technology™ demonstrator (X2TD) using flight-test data for validation.

Flight dynamics models of single main rotor helicopters with articulated rotor systems have been extensively developed and validated in the past (Refs. 1-2). Many of these models are based on the real-time GenHel (General Helicopter Flight Dynamics Simulation) model of the UH-60 discussed in Ref. 3. Hingeless rotorcraft flight dynamics models have also been developed from first principles (Refs. 4-5), or identified from flight data (Ref. 6).The main source of flight test data on hingeless rotorcraft was the BO-105. Validated industry tools are also readily available for many existing rotorcraft configurations (Ref. 7). Flight data, and thus model validation, of advanced high speed configurations such as the X2TD is critical for understanding modeling requirements of future concepts.

This paper will present a time and frequency domain validation of the real-time Sikorsky GenHel and the HeliUM (Ref. 5) flight dynamics model with X2TD flight-test data. Both flight dynamics models accurately capture the key aircraft response in both hover and forward flight. In hover, both lateral and longitudinal aircraft responses are dominated by an unstable low frequency mode, the "hovering cubic" (Ref. 9). The aircraft responses for each axis are decoupled due to the cancellation of off-axis

Presented at the AHS 72nd Annual Forum, West Palm Beach, Florida, USA, May 17-19, 2016.

moments from the coaxial rotor system. By examining the aircraft trim point, pilot inputs, swashplate inputs, aircraft response, and the stability augmentation system (SAS) output, the full aircraft response including the control system can be modeled, validated, and analyzed.

AIRCRAFT DESCRIPTION

The X2TD shown in **Figure 1** was conceived with the purpose of doubling the speed of a conventional helicopter while maintaining all the attributes of a conventional helicopter. Those attributes include excellent hover performance, low speed maneuverability, and autorotation. Expanding on the Advancing Blade Concept (ABC) demonstrated by the XH-59A shown in **Figure 2**, the X2TD was a coaxial rotor helicopter with auxiliary propulsion. The X2TD featured fly-by-wire technology, active vibration control, low drag hubs, and high lift-to-drag hingeless rotors.

The X2TD achieved first flight on August 27, 2008 in Horsehead, NY. On September 15, 2010, the X2TD accomplished the program's objective of achieving 250 knots in level flight. The program objectives were accomplished in only 17 flights. The aircraft was retired on July 14, 2011 after 23 flights and 21.1 total flight hours. The X2TD was awarded the 2010 Robert J. Collier Trophy by the National Aeronautic Association.

Figure 1: Sikorsky X2 Technology™ Demonstrator

Figure 2: Sikorsky XH-59A
(shown without auxiliary propulsion)

MATH MODEL DESCRIPTIONS

State-Space GenHel X2TD Model

GenHel is a Sikorsky proprietary simulation environment that allows for complete free flight analysis and real-time simulation of any rotorcraft for which sufficient data are available. GenHel is capable of modeling the complete air vehicle including engine/fuel control dynamics, flight control system, elastic airframe deformation, and external load dynamics. It is a non-linear, time-domain based, total force simulation that is capable of running in real-time. GenHel is library-based, utilizing a modular architecture. The same model is used for desk-top design analysis, support of piloted simulation and drivers for system integration rigs. Computational modules are generic and operate using data supplied by separate data files. In this way GenHel is reconfigurable to emulate a variety of helicopters using the same generic modeling algorithms by simply changing the input data.

GenHel has been developed over many decades at Sikorsky and has been used for the flight dynamic modeling of all current production and development aircraft and various non-Sikorsky aircraft. It has been extensively correlated against a wide variety of flight test data and updated modules are added to the library as appropriate. In this way, each simulation derives the benefits of all the prior correlation efforts. In addition, the modular architecture allows one module to be replaced by another without requiring changes to any other part of the simulation or consequent re-validation.

Under Sikorsky IR&D funding, GenHel has been significantly enhanced in the past several years to include advanced modeling capabilities for elastic blades, nonlinear unsteady air-loads, and rotor mutual interference. A state-space solution architecture has also been implemented to GenHel. With a nonlinear solver and 2nd order integrator, the nonlinear dynamics equations are simultaneously solved at each time step.

<u>Coaxial Rotor Model Description</u>

In the State-Space GenHel (SSGH) X2 model, the coaxial rotors are modeled with elastic blades, nonlinear unsteady air-loads, and dynamic inflow with mutual interference. The estimated control system stiffness is also modeled.

The rotor hub and blades were modeled as modal elastic beams. The module was derived from several sources, including Sikorsky's RDYNE and KTRAN codes and the elastic blade equations found in Ref. 11. The structure model has been thoroughly validated by comparing with beam-element models such as KTRAN and RCAS. The GenHel model uses the same beam properties as an RCAS model, including bending and torsion stiffness, mass distribution and CG offset, and sectional moment of inertia. The blade mode shapes generated from the RCAS model are used as input to the GenHel model. For the X2 blades, six elastic modes (3 flapwise, 2 chordwise, 1 torsion) are used in the model. A nonlinear unsteady air-loads model was used in the SSGH X2TD model which was based on Leishman-Beddoes model in Ref. 12. The model was validated for various airfoils by correlating with 2-D wind-tunnel test data, Ref. 13.

Under a VLC Project, a finite-state rotor interference model has been developed and applied to coaxial rotor modeling, Refs. 14-15, which uses the same finite-state form as Peters-He model to model the rotor induced velocity at a circular disk off the rotor. The influence coefficient matrix (L matrix) and time constants (M matrix) of the model can be pre-calculated using either a pressure potential model (Refs. 14-15) or a free wake model (Ref. 16). The finite-state rotor interference model was integrated into GenHel where the L matrix and time constants are calculated via map lookup as functions of the wake skew angle and rotor loading. The coaxial rotor inflow/interference model has been correlated with various test data sets. In Ref. 14, the model prediction matched well with the measured radial and axial flow velocities at various axial locations above and below a "XV-15" coaxial rotor. The model also correlated well with the Harington Rotor (single and coaxial) measured data in both hover and forward flight wind-tunnel tests, Ref. 15.

Airframe Aerodynamic Model Description

The fuselage aerodynamic model in GenHel is table based and quasi-static. The three aerodynamic forces and three aerodynamic moments produced by the fuselage are non-linear and normalized by dynamic pressure. The six aerodynamic tables are functions of angle-of-attack and angle-of-yaw. The basis for the aerodynamic data used in the GenHel X2TD model is from a wind tunnel test conducted in 2012 at the UTRC (United Technologies Research Center) Pilot Wind Tunnel. The forces and moments are applied to the model at the fuselage reference point. The fuselage reference point in the GenHel X2TD model corresponds to the resolving point from the wind tunnel test.

The empennage aerodynamic model in GenHel is also table based and quasi-static. The empennage is broken into a series of panels. Those panels include one for the horizontal stabilizer, one for the ventral fin, and two for the left and right vertical stabilizers. The aerodynamic data for the empennage is derived from the 2012 UTRC wind tunnel test. The empennage characteristics were derived by subtracting the isolated fuselage from the combined fuselage and empennage aerodynamics. By using this method to determine the empennage aerodynamics, the interference effects of the fuselage on the empennage in embedded in the empennage model. The aerodynamic forces and moments are applied to the model at the aerodynamic center of each of the panels.

The rotor-on-fuselage and rotor-on-empennage interference is modeled a series of lookup tables generated from Continuum Dynamics Incorporated's free-vortex wake (CHARM) model (Ref. 18).

Propeller Model Description

In the GenHel X2TD model, the propeller is modeled as a series of lookup tables based on performance data supplied by the vendor. The performance data supplied are the propeller thrust and power coefficients. The tables for the thrust coefficient and power coefficient are a function of blade collective pitch at 75% radius and advance ratio. The torque coefficient is calculated directly from the power coefficient. The aerodynamic in-plane forces and hub moments generated as a result of the propeller operating away from pure axial flight are calculated from the performance curves as shown in Ref. 22. The gyroscopic moments produced by the propeller during maneuvers are modeled as well.

HeliUM X2TD Model

HeliUM is a comprehensive rotorcraft simulation code originally developed at the University of Maryland. It has a long history of flight dynamics modeling with many flight test based validation efforts (Ref. 5). HeliUM derives from a high-order single main rotor helicopter model with a dynamic inflow wake model and flexible blades with coupled non-linear flap/lag/torsion dynamics. Blade, wing, and fuselage aerodynamics come from non-linear look up tables. It has a multibody form to allow for structural flexibility and an arbitrary aircraft configuration with multiple rotors (Ref. 19).

For X2TD modeling, the two lowest frequency blade structural modes are retained, a lag mode and a flap mode. These modes capture the key dynamics in the frequency range of interest for flight dynamics.

Additional modifications for X2TD modeling include:

- Inflow Coupling: The basic inflow model is a 3-state Peters-He (Ref. 17) dynamic inflow model. Inflow coupling assumes each rotor is immersed in the constant component inflow of the other rotor. Inflow coupling constants are based on analytical velocities above and below an individual rotor's flow fields (Ref. 20). In forward flight, this coupling was removed and each rotor has independent dynamic inflow dynamics
- Propeller: The propeller is modeled as a Bailey (Ref. 3) rotor and includes a uniform inflow degree of freedom.
- Airframe aerodynamics, aircraft geometry and rotor blade properties were provided by Sikorsky and are identical to the values used in the GenHel X2TD model.

X2TD FLIGHT DYNAMICS MODELING

Steady-State Trim Correlation

The steady-state, level flight correlation to X2TD flight test data was conducted in two ways. The first was a rotors-only correlation to flight test. The second was a full aircraft model correlation. For the rotors-only correlation, only results are shown for the GenHel X2TD model. For the full aircraft model correlation in steady-state, results are shown for both the GenHel and HeliUM X2TD models. The HeliUM model in this section contains similar physics as the GenHel model and does not include any of the updates from HeliUM Math Model Update section.

Rotors-Only

The model used for this correlation consisted of only the upper and lower rotors. The upper and lower rotor models were set to the trimmed flight conditions recorded from test. This included the atmosphere condition, airspeed, Euler angles, rotor speed, and swash plate control inputs for each rotor. The model was run to a periodic steady-state. The predicted rotor hub loads were compared to the test data. The shaft torques and the hub pitch moments of the upper and lower rotors are shown in **Figure 3 (a)** and **Figure 3 (b)**, respectively. It can be seen that the GenHel model is able to correlate fairly well with the X2TD flight test data in the entire speed range. Since the GenHel model is aligned with the test data, this indicates that the rotor structure, air-loads, inflow and mutual interference are correctly modeled in the GenHel model.

Full Aircraft Model

For the full aircraft model correlation, the GenHel and HeliUM X2TD models were trimmed to the same flight conditions as recorded during the test flights. The atmospheric condition, airspeed, pitch attitude, rotor speed, lateral lift offset, weight, and center-of-gravity location were all specified to align with the test flights. Since the aircraft has a non-unique trim, the aircraft was chosen to trim to a specified pitch attitude that matched the test data. The collective stick position and propeller collective pitch were a consequence of specifying the desired trim pitch attitude. **Figure 4** and **Figure 5** show the trim longitudinal and lateral cyclic pitch for a range of airspeeds for the upper and lower rotor, respectively. The predicted cyclic pitch usage from the GenHel and HeliUM models correlate well with the flight data. **Figure 6** compares the predicted propeller collective pitch and main rotor collective stick position to the flight data. The propeller collective pitch predicted by GenHel matches the value recorded from flight. This indicates the GenHel X2TD model has the correct total drag and matches the required propeller thrust for each airspeed. Due to differences in propeller modeling, HeliUM data is not present. Both the GenHel and HeliUM models under predict the trimmed main rotor collective stick position slightly.

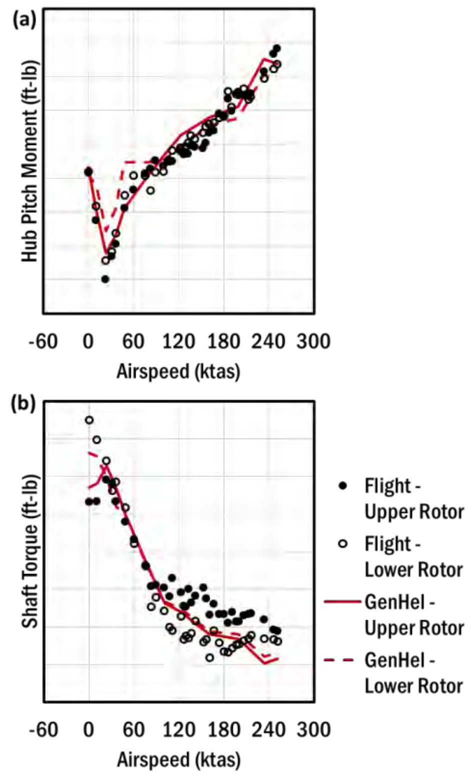

Figure 3: (a) Hub Pitching Moment vs. Airspeed (b) Shaft Torque vs. Airspeed

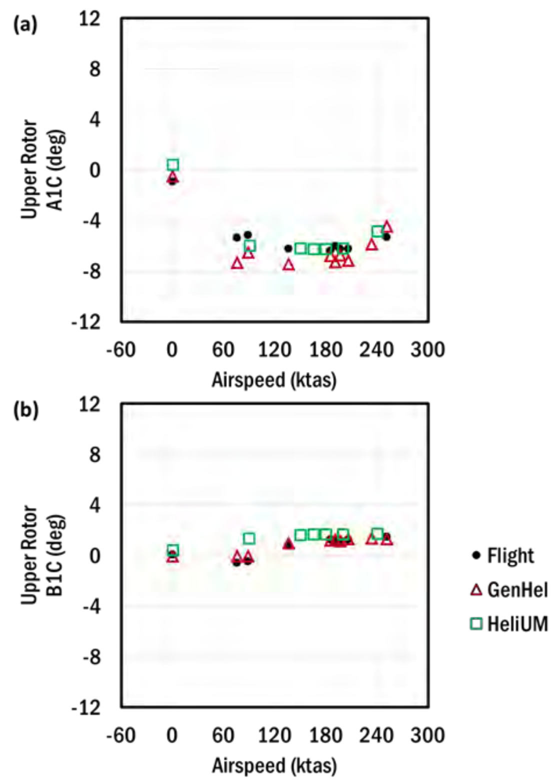

Figure 4: Upper Rotor Trim Cyclic Pitch (a) Longitudinal Cyclic Pitch vs. Airspeed (b) Lateral Cyclic Pitch vs. Airspeed

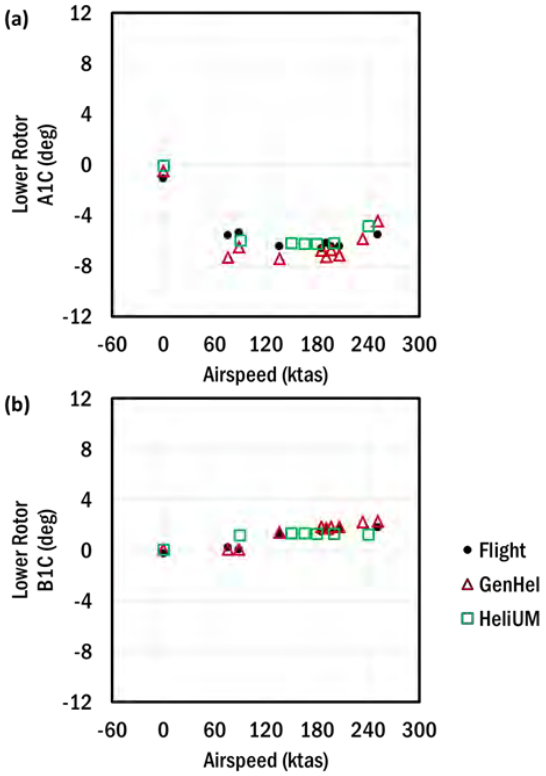

Figure 5: Lower Rotor Trim Cyclic Pitch (a) Longitudinal Cyclic Pitch vs. Airspeed (b) Lateral Cyclic Pitch vs. Airspeed

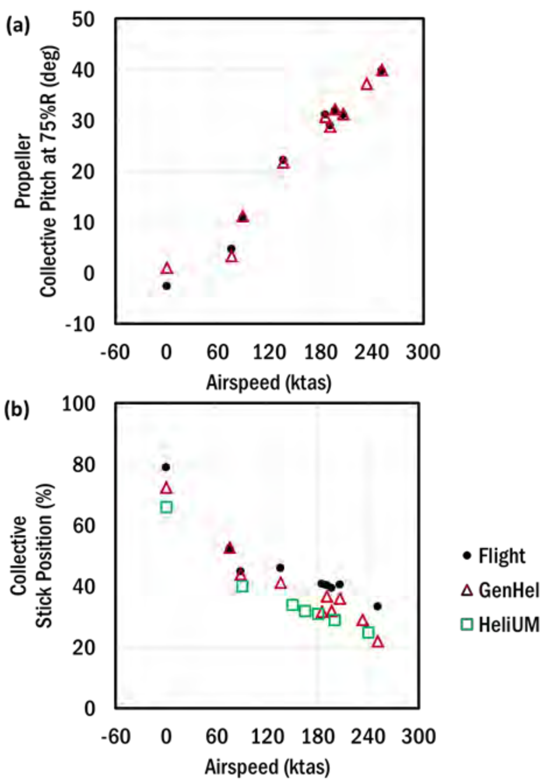

Figure 6: (a) Propeller Collective Pitch at 75%R vs. Airspeed (b) Collective Stick Position vs. Airspeed

Frequency Domain Validation

The overall bare-airframe validation based on X2TD flight-test data used the total commands (pilot + flight control) for each axis. Both math models include first-order actuator dynamics, IMU filtering, and an empirical time-delay to account for sensor delays.

Frequency sweeps were performed in hover in both lateral and longitudinal axes. In cruise, the frequency response was obtained in a non-standard way. Electronic frequency sweeps were not performed on the aircraft. Instead, piloted sweeps were used for roll and a series of 3, 2, 1, 1 pilot inputs were used for pitch. The sequence used during flight test was 2, 3, 1, 1, as shown in **Figure 7**. The pilot would apply four alternating inputs and hold each input for 2 seconds, 3 seconds, 1 second and 1 second. The reason for using this particular sequence was because the aircraft remained on the trim condition better throughout the series of inputs.

<u>System Identification</u>

Frequency responses were extracted from flight data and GenHel time histories in the roll and pitch axes using CIFER® (Ref. 8). CIFER® converts the frequency sweep time histories into the frequency domain using overlapping windows of varying time length and a chirp-Z transform. Multi-input conditioning is then performed to remove effects of off-axis inputs from the pilots. The coaxial rotor system of the X2TD naturally gives a decoupled response, so off-axis inputs did not have large effects in the on-axis response as they do for single main rotor helicopters. The individual windows of varying length are then combined into a single composite frequency response using coherence weighting and results in a wide bandwidth of high coherence data (Ref. 8).

In addition to the frequency response generation, the state-space model identification utility within CIFER® was used to provide physical updates to HeliUM model parameters. The state-space model structure was formulated based on first principles equations of motion and constraint equations were used to identify key parameters within the equations. Initial guesses for each parameter came from the original HeliUM model.

Additional details of CIFER® methodologies and capabilities are available in Ref. 8.

<u>Hover Responses</u>

Figure 8 and **Figure 9** depict the bare-airframe frequency response in hover for pitch and roll respectively. The flight data frequency response identification is seen to be very accurate over a broad frequency range of about 0.2-3 Hz for pitch and 0.2-5 Hz in roll, as seen from the high coherence function. The GenHel frequency responses were extracted from time-domain frequency sweeps and have excellent accuracy over the entire frequency range presented. The HeliUM frequency-response was determined directly from

the state-space model, as extracted using perturbation methods. GenHel and HeliUM accurately predict the pitch response from 0.2 to 2.0 Hz. For the roll response, both models under-predict the absolute gain from 0.3 to 2.0 Hz. GenHel and HeliUM both correctly predict the rotor regressive-flap mode at approximately 6 Hz. Both models predict the frequency of the lead-lag dipole to be 3 Hz, while it is closer to 2 Hz in flight data. The models predict different frequencies for the hovering cubic (0.1 – 0.2 Hz).

Cruise Responses

Figure 10 and **Figure 11** show the bare-airframe frequency response for pitch and roll in cruise. GenHel predicts the pitch response well at 200 knots between 0.2 to 1 Hz. HeliUM predicts a similar response to GenHel at short-term response frequencies above 0.7 Hz. The simple tail-rotor model in HeliUM may be the cause of the discrepancy below 0.7 Hz. The data quality is limited to 2 Hz in this axis.

HeliUM accurately predicts the roll response at 180 knots while GenHel slightly under-predicts the gain. Both models predict the regressive flap mode to be around 6 Hz. The lead-lag dipole is not as apparent in the cruise responses as it was in hover.

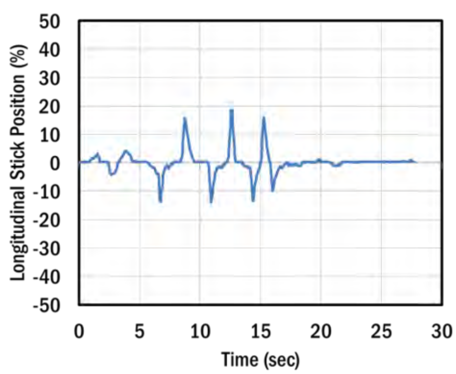

Figure 7: Pilot Input for Cruise Pitch Frequency Response

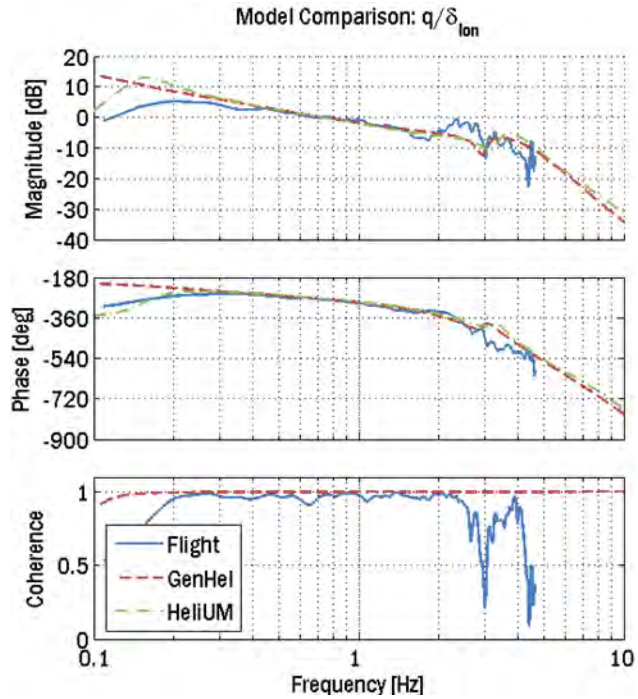

Figure 8: Hover Bare-Airframe Frequency Response in Pitch: Total Pitch Command to Pitch Rate

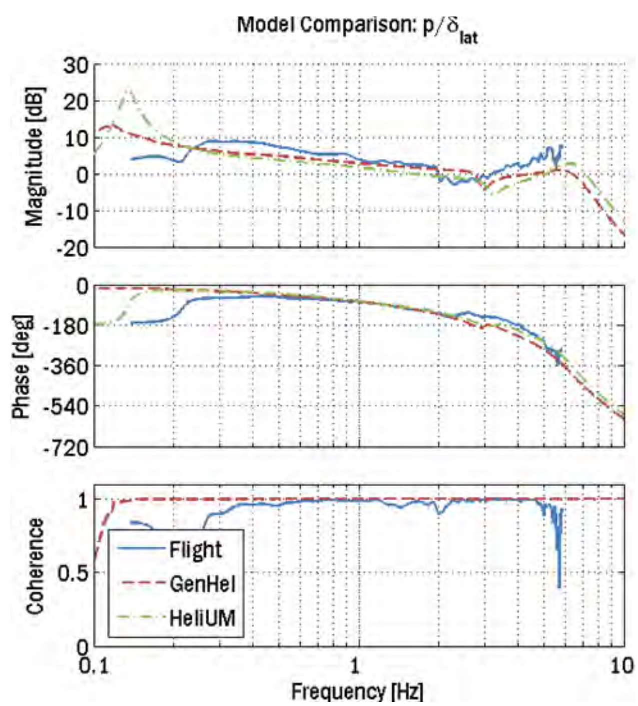

Figure 9: Hover Bare-Airframe Frequency Response in Roll: Total Roll Command to Roll Rate

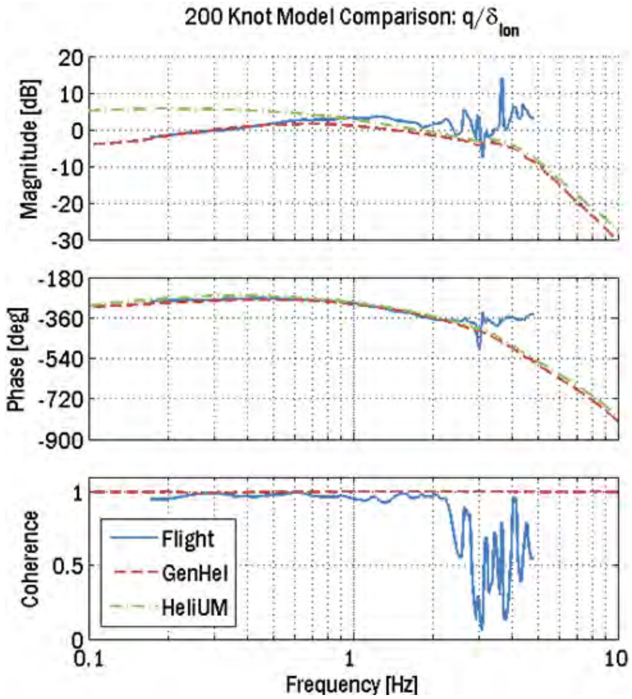

Figure 10: 200 knot Bare-Airframe Frequency Response in Pitch Total Pitch Command to Pitch Rate

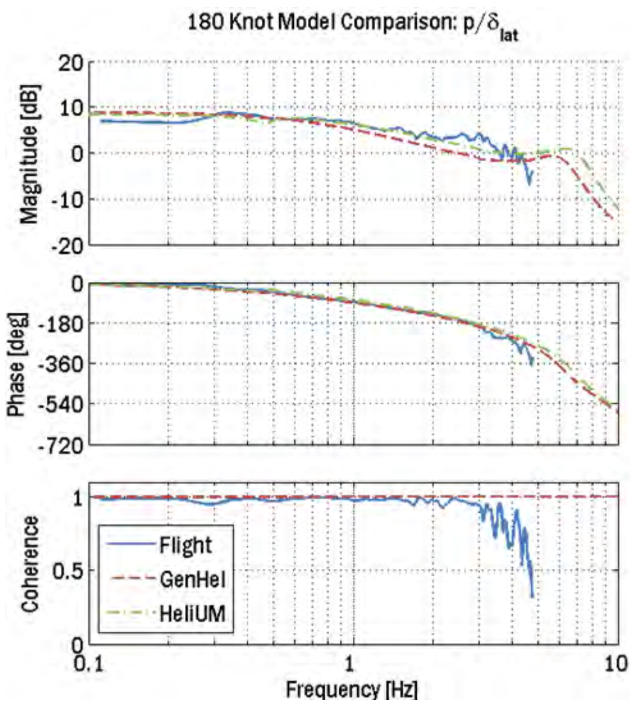

Figure 11: 180 knot Bare-Airframe Frequency Response in Roll Total Roll Command to Roll Rate

HeliUM Math Model Update

Comprehensive simulation models rely on a large quantity of input parameters for blade and aircraft properties. Many of these parameters are difficult to measure in lab tests, let alone during actual flight-test. Further, the analytical formulation of the model simplifies the vehicle geometry, introducing uncertainty into the definition of the input parameters. This is especially true for new/novel configurations like the X2TD that differ significantly from single main rotor helicopters. System identification is used herein to improve the correlation of the math model to flight data.

Identification of Hover Regressive-Flap/Fuselage Dynamics

Analytically derived coupled fuselage and blade flap equations of motion for the Sikorsky X2TD based on the work by Chen (Ref. 23) were used to derive flight-test data based updates to the math model. These analytical equations use a hinge-offset/flap spring to approximate the dynamics of the hingeless Sikorsky X2TD rotor. The coupled rotor-body equations of motion are (for a single rotor):

$$\begin{Bmatrix} \dot{p} \\ \dot{q} \\ \ddot{\beta}_{1c} \\ \ddot{\beta}_{1s} \\ \dot{\beta}_{1c} \\ \dot{\beta}_{1s} \end{Bmatrix} = \Omega \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & L_{B1s}/\Omega \\ 0 & 0 & 0 & 0 & M_{B1c}/\Omega & 0 \\ 2(1+\frac{eM_\beta}{I_\beta}) & \frac{\gamma}{2}(\frac{1}{4}-\frac{e}{3}) & -\gamma(\frac{1}{8}-\frac{e}{3}+\frac{e^2}{4}) & -2 & -\Omega\,(\nu_\beta^2-1) & -\gamma\Omega(\frac{1}{8}-\frac{e}{3}+\frac{e^2}{4}) \\ \frac{\gamma}{2}(\frac{1}{4}-\frac{e}{3}) & -2(1+\frac{eM_\beta}{I_\beta}) & 2 & -\gamma(\frac{1}{8}-\frac{e}{3}+\frac{e^2}{4}) & \gamma\Omega(\frac{1}{8}-\frac{e}{3}+\frac{e^2}{4}) & -\Omega\,(\nu_\beta^2-1) \\ 0 & 0 & 1/\Omega & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\Omega & 0 & 0 \end{bmatrix} \begin{Bmatrix} p \\ q \\ \dot{\beta}_{1c} \\ \dot{\beta}_{1s} \\ \beta_{1c} \\ \beta_{1s} \end{Bmatrix}$$

Equation 1

$$-\frac{\Omega^2\gamma}{2}\left(\frac{1}{4}-\frac{e}{3}\right)\begin{bmatrix} 0 & 0 \\ 0 & 0 \\ \theta_{\delta_{lon}}\cos(\Gamma) & \theta_{\delta_{lat}}\sin(\Gamma) \\ -\theta_{\delta_{lon}}\sin(\Gamma) & \theta_{\delta_{lat}}\cos(\Gamma) \\ 0 & 0 \\ 0 & 0 \end{bmatrix}\begin{Bmatrix} \delta_{lon} \\ \delta_{lat} \end{Bmatrix}$$

Equation 2

where (Ref. 8 and Ref. 24):

$$-L_{\beta 1s} = \frac{W_h h_r}{I_{xx}} + \frac{n_b M_\beta \Omega^2 e}{2I_{xx}} + \frac{n_b K_\beta}{2I_{xx}}$$

$$M_{\beta 1c} = \frac{W_h h_r}{I_{yy}} + \frac{n_b M_\beta \Omega^2 e}{2I_{yy}} + \frac{n_b K_\beta}{2I_{yy}}$$

$$\nu_\beta^2 = 1 + \frac{eM_\beta}{I_\beta} + \frac{K_\beta}{I_\beta \Omega^2}$$

$$\gamma = \frac{\rho acR^4}{I_\beta}$$

Equation 3, 4, 5, 6

An equivalent set of equations exist for the second rotor. The key drivers of dynamics in the frequency range of the regressive flap mode are the coupling between the fuselage and rotor dynamics through $L_{\beta 1s}$ and $M_{\beta 1c}$, and the blade flap frequency, ν_β. The $L_{\beta 1s}$ term (Eqn. (3)) is highly dependent on roll inertia, I_{xx} and the flap frequency, ν_β, which is based on the effective hinge-offset (e) and flap spring (K_β) as in Eqn. (5). The X2TD has a very small fuselage roll inertia of 340 slug-ft^2. Small errors in this value have a profound impact on the equations of motion and could lead to over-prediction of the coupled rotor-body flap modes. Flight-test derived values of roll inertia and flap frequency were sought to improve the model correlation to flight data.

The HeliUM model in hover is used to initialize the values above. A quasi-static reduction of the lag modes was used to remove lag dynamics from the solution, greatly simplifying the identification procedure. Inflow dynamics are held fixed at the original HeliUM values, and no inflow related parameters are identified. Small changes in the rotor and fuselage parameters in the equations above do not affect the dynamic inflow portion of the model.

The entire system of equations above reduce to a few unknowns, namely I_β, I_{xx}, I_{yy}, K_β, and e. M_β was constrained to be a factor of I_β, which is consistent for constant mass scaling along the blade span. The lateral axis control sensitivity, $\theta_{\delta lat}$, was also identified. The rest of the parameters, such as weight, number of blades, radius, etc. are held as constants. The equations are implemented within CIFER®'s state-space fitting utility DERIVID (Ref. 8) and replace the original values of the HeliUM model. The parameters are then optimized to minimize a coherence weighted cost-function of the flight data responses over a broad frequency range (0.5-10 Hz).

The identification results give a flap frequency estimate (using a hinge-offset/flap spring approximation) of 1.38/rev and fuselage roll inertia of 490 slug-ft2. Both values are well identified with Cramer-Rao bounds (CR% < 10) and Insensitivities (I% < 2) well within the guidelines given in Ref. 8. The 8% reduction in identified flap stiffness as compared to the finite-element approximation encompasses all components in the roll degree of freedom of the aircraft, including shaft and fuselage flexibility as well as any un-modeled flexibility in the hub (from linkages, hub/blade connections, etc.).

The identification results are compared with the original HeliUM response and flight data they were fit to in **Figure 12** and **Figure 13**. The final overall fit to flight data is 100, giving a very good agreement with the test data (Ref. 8).

The identification aligns the response to flight data around the rotor modes. The regressive flap mode was clearly over-predicted within HeliUM and is brought to lower frequencies in the CIFER ID result.

Physical Parameter Update

The flap frequency and roll inertia are then propagated back to the math model as necessary reductions in flap stiffness and an increase in roll inertia to match flight data. The stiffness of the innermost portion of the finite-element beam, corresponding to the hub, is reduced to align the flap frequency closer to flight data and the ID result. The fuselage roll inertia was assumed to be well estimated to within ±10% and was only increased within these allowances to 378 slug-ft^2.

Blade stiffness in lag was reduced to match flight data. Shaft torsional flexibility was not modeled and is the key factor in lowering lag frequency below the predicted value. The final updated HeliUM model is compared with flight in **Figure 14** and **Figure 15**.

The original models (GenHel and HeliUM) have similar and high mismatch costs (in excess of 300) relative to the flight data as shown in shown in **Table 1**, indicating degraded simulation fidelity (Ref. 8). With the corrections included, the updated HeliUM model has a cost of about 120, very close to recommended cost of J=100. The updated HeliUM model now aligns well with flight data over a broad frequency range including the low-frequency rigid-body and high-frequency rotor dynamics. Relatively small changes in a few key physical parameters greatly improved the overall ability of the model to track flight data.

Table 1: Frequency Response Costs of Fits Between Flight Data and Math Models

Axis	GenHel	HeliUM	HeliUM Updated
Roll	304	404	123
Pitch	303	324	120

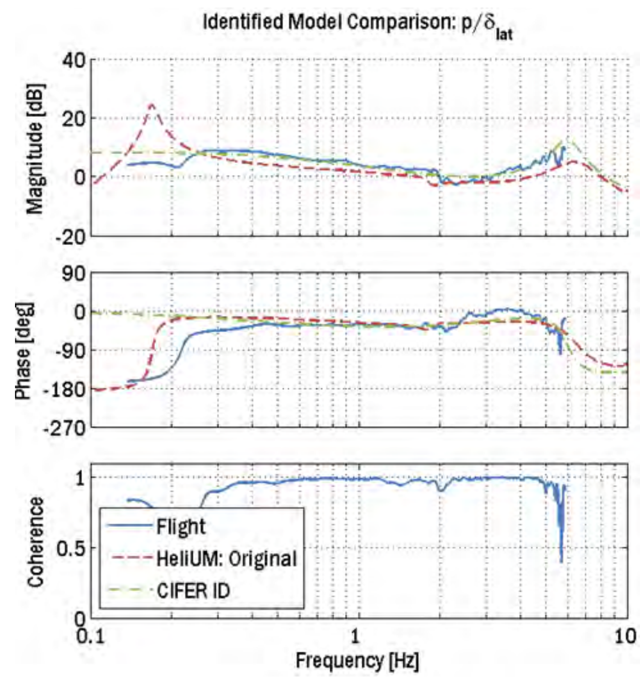

Figure 12: Identified Roll Response Comparisons with Flight Data and Original HeliUM Model

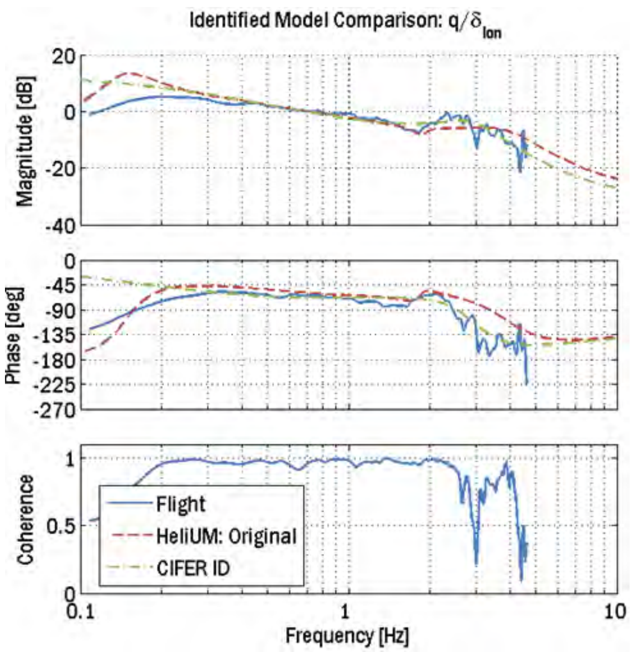

Figure 13: Identified Pitch Response Comparisons with Flight Data and Original HeliUM Model

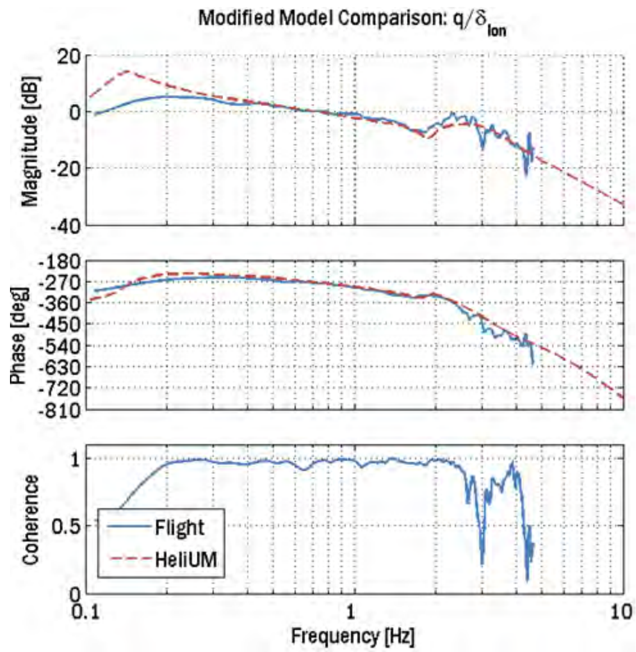

Figure 15: Updated HeliUM Pitch Response Comparison

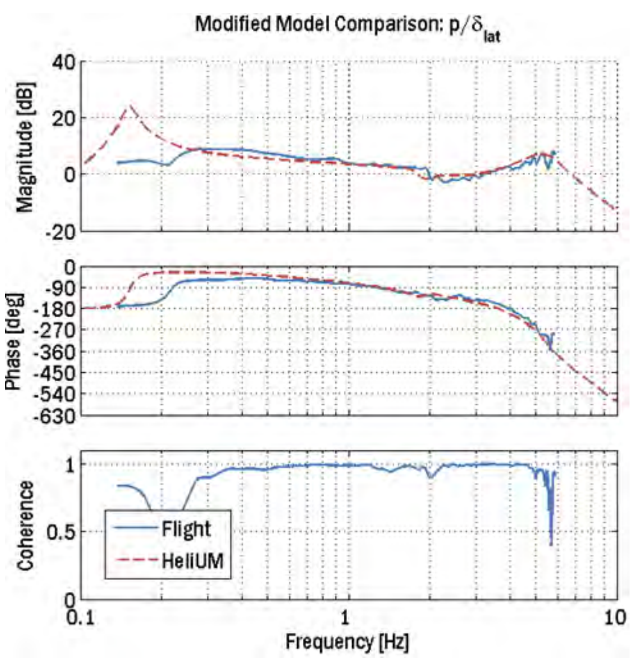

Figure 14: Updated HeliUM Roll Response Comparison

X2TD CLOSED-LOOP ANALYSIS

Hover: Frequency Domain

Controller

The X2TD has a lagged-rate feedback control architecture in both pitch and roll. The frequency responses of the SAS from flight data, the GenHel model, and a simplified Simulink® implementation of the block diagram are shown in **Figure 16** and **Figure 17** for the lateral and longitudinal axes, respectively. Both axes show the key characteristic of a lag at low frequency and a constant rate gain above 2.0 Hz. The SAS model from GenHel and Simulink both agree very well with the flight implementation, as can be expected.

Broken-Loop

The lateral and longitudinal broken-loop responses are shown in **Figure 18** and **Figure 19**. For both axes, it can be seen that the desired response of a pure integrator is obtained in the area of the crossover frequency. The aircraft also has excellent stability margins (Ref. 21). The phase margin is well in excess of the 45 deg. requirement for both axes. The gain margins are also within requirements. These responses highlight the need for accurate simulation models that capture dynamics around the rotor modes correctly. The phase curve cross the -180 degree line at the frequencies of the regressive lag and flap modes. There is excellent agreement of the updated HeliUM model with the flight data indicating that the stability margins are well predicted.

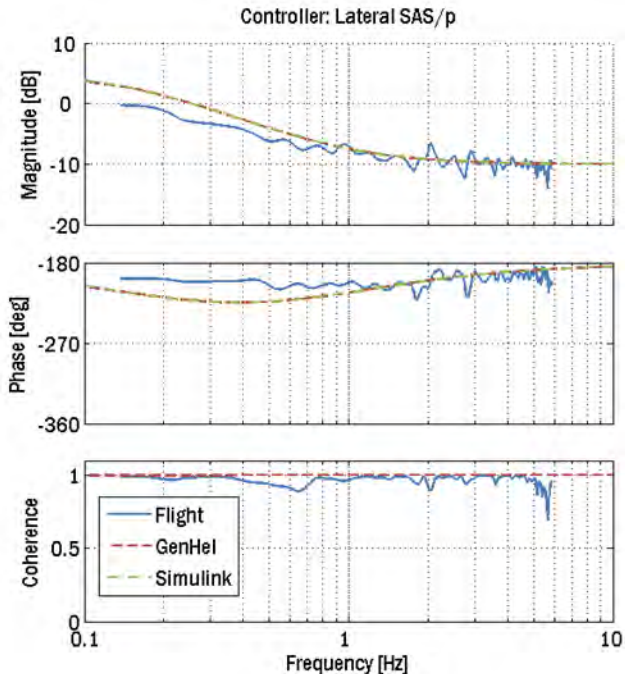

Figure 16: Lateral Control System Response to Roll Rate

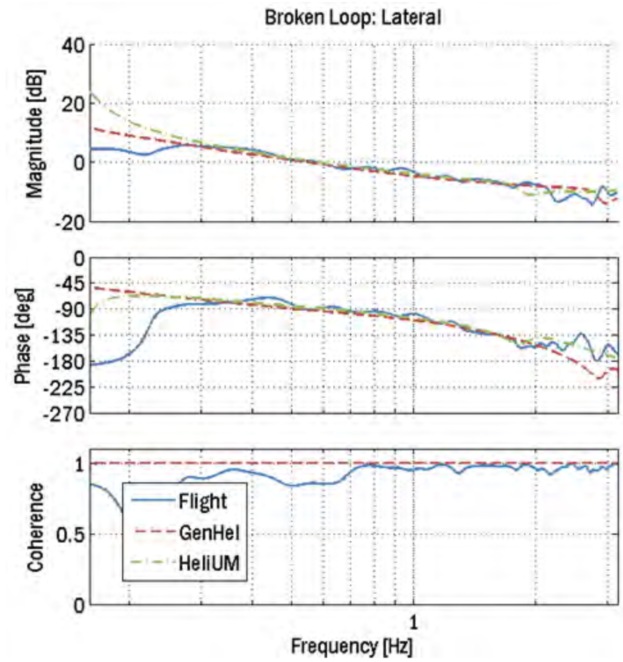

Figure 18: Lateral Broken-Loop Response

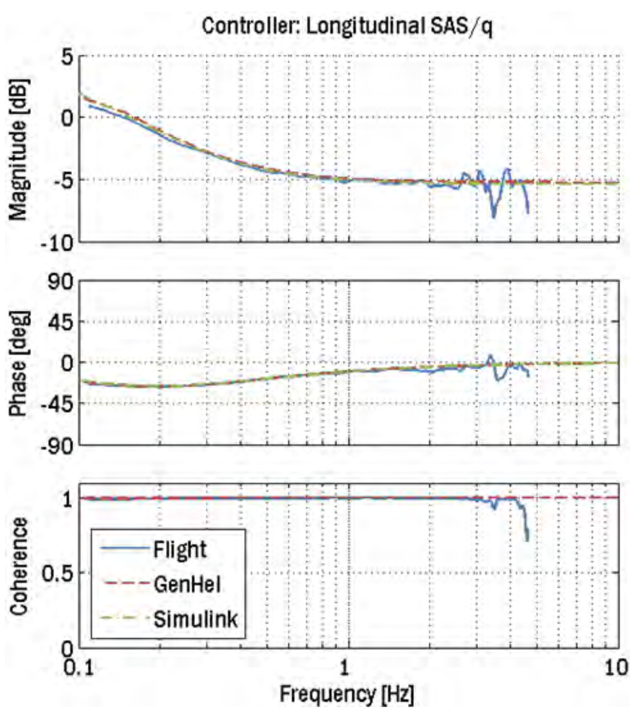

Figure 17: Longitudinal Control System Response to Pitch Rate

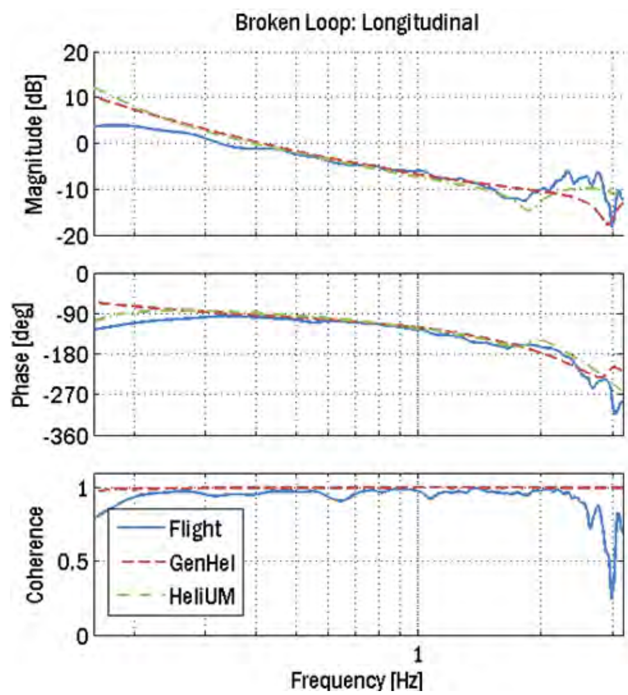

Figure 19: Longitudinal Broken-Loop Response

Closed-Loop and Bandwidth

The closed-loop responses in **Figure 21** show the aircraft response to pilot inputs with the control system engaged.

In the lateral axis, the GenHel and HeliUM models slightly under-predict the magnitude of the response at low frequency. The corrected HeliUM curve captures the dynamics of the lag and flap modes at 2 and 4 Hz, respectively.

The two models correctly capture the dynamics at low frequency in the longitudinal response. Rotor lag dynamics are apparent in this response at 2 Hz.

The responses fall within the Level 1 region of both the “All Other MTEs-UCE=1 and Fully Attended Operations” and the more aggressive “Target Acquisition and Tracking” ADS-33E bandwidth specifications for both axes as shown in **Figure 22** and **Figure 23**.

The update made to the HeliUM model based upon the system identification greatly improved the broken-loop and closed-loop responses when compared to the flight data. These empirical changes to account for missing dynamics in the math model were not applied to the GenHel model.

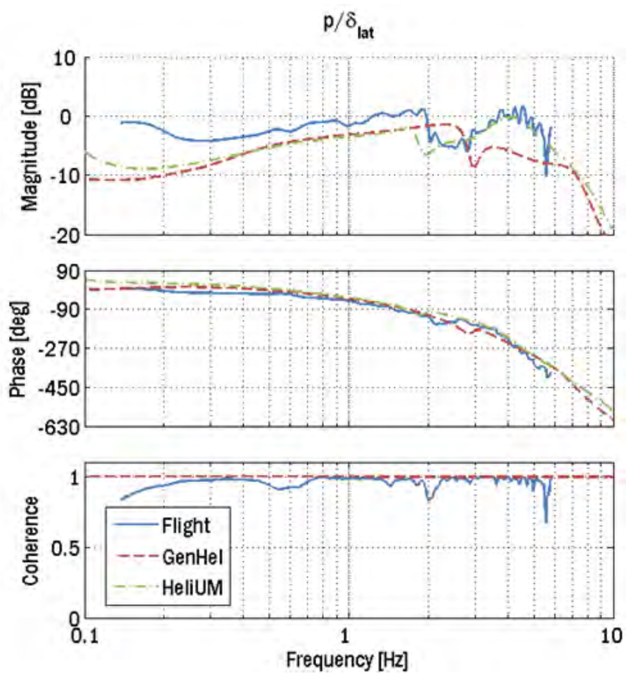

Figure 20: Lateral Closed-Loop Response

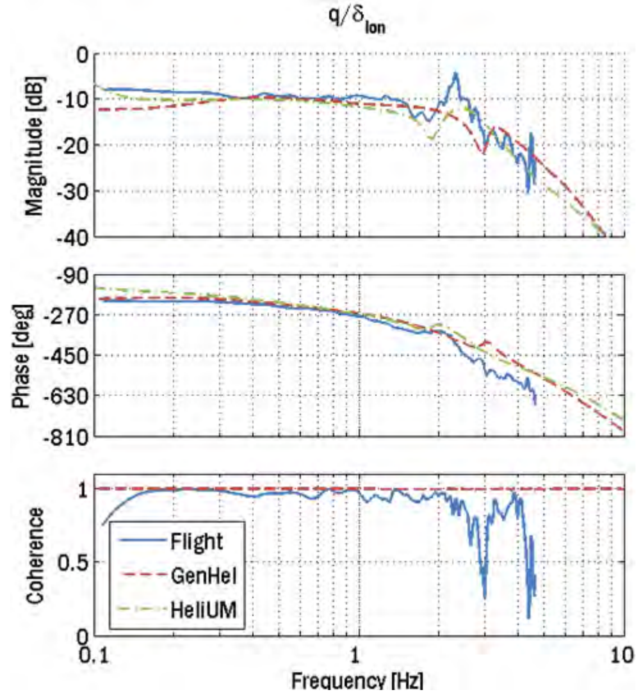

Figure 21: Longitudinal Closed-Loop Response

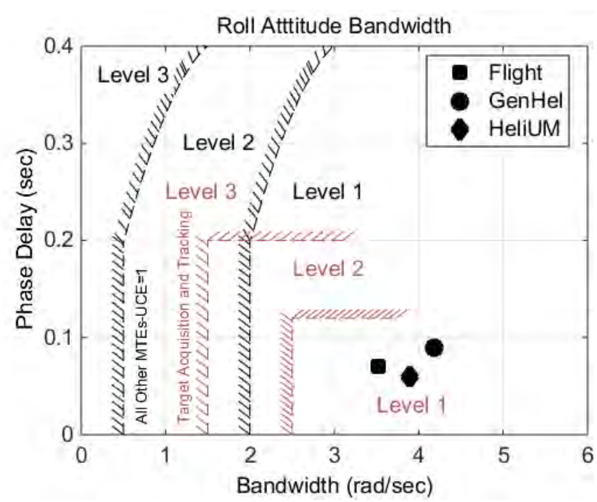

Figure 22: Lateral ADS-33E Bandwidth Comparisons

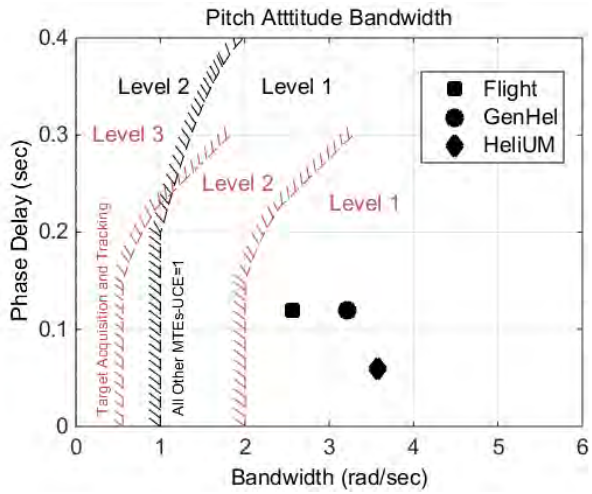

Figure 23: Longitudinal ADS-33E Bandwidth Comparisons

Cruise: Time Domain

The GenHel and HeliUM models were trimmed to the same ambient condition, airspeed, rotor speed, lateral lift offset, pitch attitude and mass properties as the test flight. The feedback gains for the stability augmentation system (SAS) were also aligned to the test flight. The stick and pedal inputs recorded from flight test were re-played though the GenHel and HeliUM models. The time histories of the closed-loop body and rotor dynamic responses were recorded and compared to the measured data.

The time histories of the body pitch attitude and pitch rate in response to a pitch doublet at 200 knots are shown in **Figure 24**. Both the GenHel and HeliUM models predict the initial response to the control input well when compared to the flight test data but over predict the amount of damping after the control input is removed.

The time histories of the body roll attitude and roll rate in response to a roll doublet at 200 knots are shown in **Figure 25**. Overall, both models match very well with flight data. The GenHel model is slightly slower to respond than flight test, and the HeliUM response slightly over-predicts the damping. Time histories of the rotor responses during the same maneuver are shown in **Figure 26**, including the blade 12.5%R normal bending moments of the upper rotor and the blade tip proximity between the upper and lower rotors. As seen in **Figure 26 (a)**, the blade normal bending moment of the upper rotor is well predicted by the GenHel model, while the blade proximity between the two rotors is slightly under predicted comparing to the flight test data.

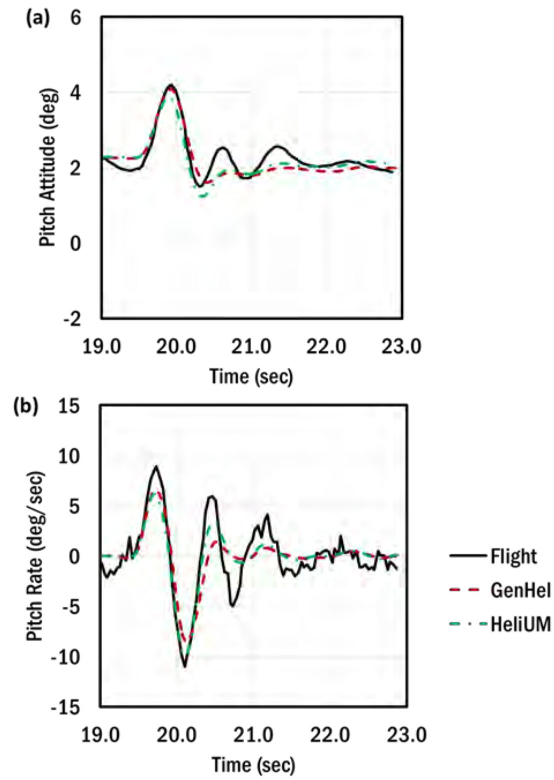

Figure 24: Body Dynamic Response to Pitch Doublet at 200 knots
(a) Pitch Attitude vs. Time (b) Pitch Rate vs. Time

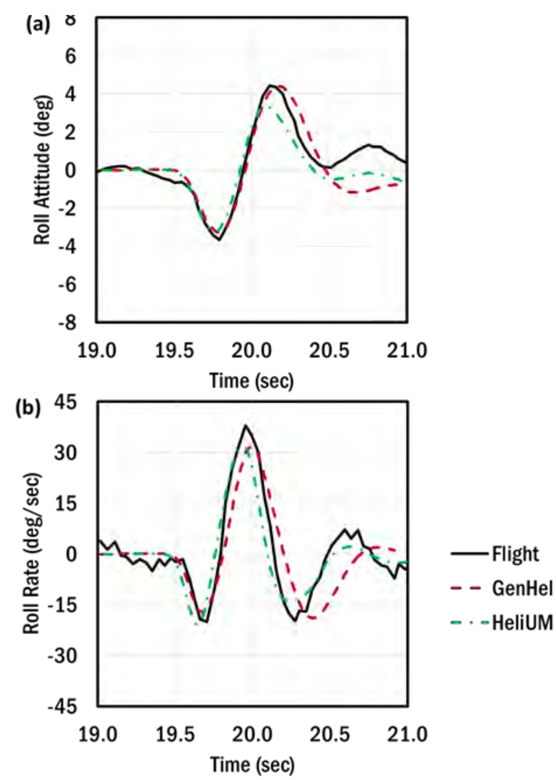

Figure 25: Body Dynamic Response to Roll Doublet at 200 knots
(a) Roll Attitude vs. Time (b) Roll Rate vs. Time

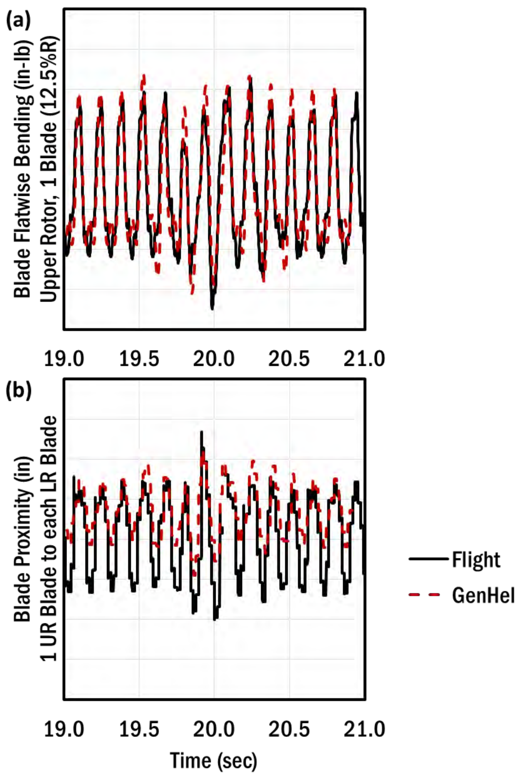

Figure 26: Rotor Dynamic Response to Roll Doublet at 200 knots (a) Upper Rotor Blade Normal Bending vs. Time (b) Blade Proximity vs. Time

DISCUSSION AND CONCLUSIONS

Validated, physics-based flight dynamics models are instrumental in the aircraft design process and are used for load prediction, control system design, and handling qualities analysis. These models provide vital predictive capability for both future and follow-on concepts.

This paper presented the development and validation of two high-order math models used for rotorcraft flight dynamics modeling. Both the Sikorsky GenHel and HeliUM models have had long pedigrees of applications to single-main-rotor helicopters, and have now been successfully applied to the novel hingeless coaxial pusher configuration.

Based on the work presented in this paper, the following conclusion can be made:

- The GenHel and HeliUM X2TD models show excellent correlation to flight test for steady-state and dynamic responses in both the time and frequency domains in the piloted frequency range (up to 2 Hz).
- Both flight dynamics models predict rotor modes at very similar frequencies to each other. Both models over-predict the frequency of the regressive-lag rotor mode. The frequency of the regressive-flap mode is also over-predicted, but to a lesser extent.
- Using a system identification approach using analytical equations of motion, a few key physical parameters were changed to provide an empirical update to match the frequency response of the test data over a wide range of frequencies (0.1 to 10 Hz) including the low frequency rigid-body and high frequency rotor dynamics. Relatively small adjustments (under 10 percent) were needed to be made to the HeliUM model to significantly improve the frequency response correlation to flight test.
- The X2TD pitch and roll responses fall within the Level 1 region of the ADS-33E pitch and roll bandwidth specification.

REFERENCES

[1] Kim, F. D., Celi, R., and Tischler, M. B., "Higher-Order State-Space Simulation Models of Helicopter Flight Mechanics," *Journal of the American Helicopter Society*, Vol. 38, No. 4, October 1993.

[2] Ballin, M. G. and Dalang-Secr´etan, M. A., "Validation of the Dynamic Response of a Blade-Element UH-60 Simulation Model in Hovering Flight," *Journal of the American Helicopter Society*, Vol. 36, No. 4, October 1991, pp. 77–88.

[3] Howlett, J. J., "UH-60A Black Hawk Engineering Simulation Program - Volume II - Mathematical Model," NASA CR 166309, December 1981.

[4] Theodore, C. and Celi, R., "Helicopter Flight Dynamic Simulation with Refined Aerodynamics and Flexible Blade Modeling," *Journal of the American Helicopter Society*, Vol. 39, No. 4, July-August 2002, pp. 577–586.

[5] Celi, R., "HeliUM 2 Flight Dynamic Simulation Model: Developments, Technical Concepts, and Applications," American Helicopter Society 71st Annual Forum, May 2015, Virginia Beach, VA.

[6] Tischler, M. B. and Cauffman, M. G., "Frequency-Response Method for Rotorcraft System Identification: Flight Applications to BO 105 Coupled Rotor/Fuselage Dynamics," *Journal of the American Helicopter Society*, Vol. 37, No. 3, October 1992, pp. 3–17.

[7] Du Val, R. W., "A Real-Time Multi-Body Dynamics Architecture for Rotorcraft Simulations," RAeS and AHS International Conference on The Challenge of Realistic Rotorcraft Simulation, November 2001, London, UK.

[8] Tischler, M. B. and Remple, R. K., *Aircraft and Rotorcraft System Identification: Engineering Methods with Flight Test Examples*, AIAA, 2nd ed., 2012, Reston, VA.

[9] McRuer, D. T., Ashkenas, I. L., and Graham, D., Aircraft Dynamics and Automatic Control, Princeton University Press, 1973, Princeton, NJ.

[10] Anonymous, "Aeronautical Design Standard-33E-PRF, Performance Specification, Handling Qualities Requirements for Military Rotorcraft," US Army AMCOM, March 2000.

[11] Johnson, W., *Helicopter Theory*, Dover Publications, Inc., New York, NY, 1994.

[12] Leishman, J., *Principles of Helicopter Aerodynamics*, Cambridge University Press, New York, NY, 2nd ed., 2006, Chapter 8.

[13] Garelick, G. J., "GenHel Rotor Blade Airfoil Unsteady Aerodynamic Model," American Helicopter Society 68th Annual Forum, May 2012, Fort Worth, TX.

[14] Prasad, J. V. R., Nowak, M., and Xin, H., "Finite State Inflow Models for a Coaxial Rotor in Hover," 38th European Rotorcraft Forum, September 2012, Amsterdam, Netherlands.

[15] Nowak, M., Prasad, J. V. R., Xin, H., and Peters, D. A., "A Potential Flow Model for Coaxial Rotors in Forward Flight," 39th European Rotorcraft Forum, September 2013, Moscow, Russia.

[16] Xin, H., Goss, J. D., and Parkes, C., "Development of a Three-State Rotor Interference Model and Application to Coaxial Rotor Inflow Modeling," American Helicopter Society Aeromechanics Specialists Conference, January 2014, San Francisco, CA.

[17] Peters, D. A. and He, C. J., "Correlation of Measured Induced Velocities with a Finite-State Wake Model," *Journal of the American Helicopter Society*, Vol. 36, No. 3, July 1991, pp. 59–70.

[18] Quackenbush, T. R., Wachspress, D. A., Boschtisch, A. H., and Curbishley, T. B., "A Comprehensive Hierarchical Aeromechanics Rotorcraft Model (CHARM) for General Rotor/Surface Interaction," Continuum Dynamics Inc., CDI Report No. 99-03, January 1999.

[19] Juhasz, O., Celi, R., Ivler, C. M., Tischler, M. B., and Berger, T., "Flight Dynamic Simulation Modeling of Large Flexible Tiltrotor Aircraft," American Helicopter Society 68th Annual Forum, May 2012, FortWorth, TX.

[20] Juhasz, O., Syal, M., Celi, R., Khromov, V., Rand, O., Ruzicka, G. C., and Strawn, R. C., "Comparison of Three Coaxial Aerodynamic Prediction Methods Including Validation with Model Test Data," *Journal of the American Helicopter Society*, Vol. 59, No. 3, July 2014.

[21] Anonymous, "Flight Control Systems - Design, Installation, and Test of Piloted Aircraft, General Specifications for," MIL-DTL-9490E, Department of Defense Interface Standard, February 2006.

[22] Fage, A., *Airscrews in Theory and Experiment*, Constable & Company LTD, 1920, Chapter XI.

[23] Chen, R.T.N., "Effects of Primary Rotor Parameters on Flapping Dynamics", NASA TP-1431, January 1980.

[24] Heffley, R.K., Bourne, S.M., Curtiss, H.C., Hindson, W.S., Hess, R.A., "Study of Helicopter Roll Control Effectiveness Criteria", NASA CR-177404, April 1986.

[25] Walsh, D., Weiner, S., Arifian, K., Lawrence, T., Wilson, M., Millott, T., Blackwell, R., "High Speed Testing of the Sikorsky X2 Technology™ Demonstrator," American Helicopter Society 67th Annual Forum, May 2011, Virginia Beach, VA.