BELL M427 FLIGHT TEST DATA GATHERING AND LEVEL-D SIMULATOR MODEL DEVELOPMENT

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Abstract

A joint program between Bell Helicopter Textron Canada, the Institute for Aerospace Research at Canada's National Research Council (NRC Aerospace) and several universities was initiated to design tools and techniques for developing flight data based Level D helicopter simulator models. An innovative modelling process adapted from proven fixed wing modelling techniques was applied to flight data for the Bell M427 helicopter. NRC Aerospace's parameter estimation software was used to determine the helicopter's small-perturbation stability-and-control derivatives at numerous trim points. The derivatives were then curve-fitted to produce a global model covering the entire flight envelope of the helicopter; flight data based on the FAA Helicopter Simulator Qualification Test Guide (Level D) manoeuvres were used to validate the aerodynamic model. The innovative techniques developed throughout the program have the potential of reducing the typical development timeline for flight data based Level D helicopter simulator models to six to eight months.

Fig. 1. Bell M427 helicopter

1 Introduction

Following NRC Aerospace's success in fixed-wing aircraft simulator model development [1-4], a joint research program between Bell Helicopter Textron Canada (BHTC), NRC Aerospace, and several universities was initiated in November 2003. The research program was motivated by the success of an earlier collaboration between NRC Aerospace and BHTC [5], and addressed various challenges associated with high fidelity helicopter aerodynamics modelling from a flight test generated database. Issues related to helicopter instrumentation, aerodynamic model development, and global model validation were investigated using flight data collected from a Bell M427 helicopter (Fig. 1).

The aim of this paper is to give a broad overview of the techniques developed through out the project, and to show their application to the Bell M427 helicopter. Specifically, the following topics will be considered:

- Flight data collection
- Streamlining of the parameter estimation software
- Air data calibration
- Efficient global aerodynamic model development
- Identification of non-linear dynamics using a residual analysis
- Validation of the flight aerodynamic model

1 Helicopter Aerodynamics Model Development and Validation Overview

1.1 Model Development Summary

NRC Aerospace's modified maximum likelihood estimation (MMLE) software was adapted from NASA fixed-wing MMLE software [6], and was used to determine the helicopter's small-perturbation stability and control derivatives at different helicopter configurations and trim conditions. These stability and control derivatives were then curve-fitted to produce a global aerodynamic model. With the core global model developed, complex dynamics were identified and appended to the model using a residual analysis that required comparing the model's response with flight data. Subsequently, the global model underwent a two-step validation process. The first step involved a quick validation using MMLE simulation. The second, more rigorous step of validation, was conducted using Proof-of-Match (POM) in NRC Aerospace's Matlab® and Simulink® based simulation environment.

1.2 The Bell M427 and its Instrumentation

The Bell M427 helicopter is a single main rotor, twin-engine helicopter with a maximum internal gross weight of 6,550 pounds and cruising speed of 138 knots. The advanced composite rotor and airframe are mounted on top of a skid type landing gear, and attached to an aluminum tail boom. Two Pratt and Whitney Canada PW207D turbo shaft engines mounted on the cabin roof directly drive a dual input transmission. Yaw control and anti-torque are provided with a conventional, two bladed tail rotor.

The test helicopter was fitted with a dedicated instrumentation system that measured fuselage and engine responses, main rotor speed, pitot-static pressures, airflow angles, control stick and swash-plate positions, and total temperature. In all, the flight test data suite consisted of over 55 parameters.

BHTC's Airborne Data Acquisition System (ADAS) was used during the flight tests. The unit filtered and conditioned analog sensor signals and converted them to a Pulse Code Modulation format for recording on an on-board tape system. The digital serial stream was also transmitted via telemetry to the ground station. The ADAS also incorporated a Pilot Display Unit mounted on the helicopter's glare shield to enable the pilot to monitor critical parameters during the tests.

1.3 Inertial Parameters and Air Data Sensors

The inertial measurement system used on the M427 incorporated three angular servo accelerometers and a laser gyro (pitch, roll, yaw attitudes and rates). Since the inertial measurement system was hard-mounted near the nominal planar centre of gravity location, inertial data was referred to the helicopter's instantaneous centre of gravity location during post-processing.

Airspeeds (static and dynamic air pressures) were measured on the test helicopter from both the ship's production system and a dedicated nose-boom instrumentation system. This instrumentation system tapped into independent project sensors for differential pressure measurements. Data recorded from both systems was corrected for position error during post processing.

Angles of attack and sideslip measurements were obtained from vanes mounted on the instrumentation nose-boom. Vane rotation was measured directly via rotary potentiometers.

1.4 Helicopter Aerodynamic Model Identification Process

The process of helicopter aerodynamic model identification (HAMI) can be broken down into the following steps (refer to Fig. 2):

1. Flight data acquisition, and post processing data quality check for ensuring data integrity.
2. Batch MMLE process for quick point model identification.

3. Efficient global model development by integrating point models into a continuous derivative model.
4. Detection of non-linear dynamics using higher-order dynamics optimisation.
5. Quick global model validation in the MMLE simulation environment followed by final validation using POM.

1.5 Flight Data Acquisition and Verification

Sensor signals were sent to the ground station via telemetry and stored on the host computers. A team of engineers monitored the data in real-time, provided immediate feedback regarding data quality, and advised the flight crew if safety limits were being approached. In addition, an offline data quality check incorporating flight path reconstruction with automatic checks for correlation, min-max and signal dropout was applied to all flight data during post processing.

1.6 Point Model Identification

The aerodynamic model is composed of six equations - one for each of the rigid body degrees of freedom - and takes the form shown in Eq. 1. F_{aero} in Eq. 1 represents the six components of aerodynamic forces and moments acting on the helicopter; both the forces and the moments are defined in the body axes reference frame. $x = (u,v,w,p,q,r)^T$ is a vector input representing the helicopter's body axis velocity components and angular rates, and $u = (\delta_{long}, \delta_{lat}, \delta_{coll}, \delta_{ped})^T$ is a vector containing the control stick positions. The aerodynamic force and moment components calculated from the aerodynamic model are provided to the body dynamics model to calculate the helicopter's response.

$$F_{aero} = Ax + Bu \qquad (1)$$

The A and B matrices in Eq. 1 consist of the stability and control derivatives, respectively. The derivatives describe the small perturbation dynamics of the helicopter around a specific trim condition and configuration. NRC Aerospace's MMLE parameter estimation technique was used to generate these derivatives in an automatic process.

The stability and control derivatives were determined for a concatenated data file containing 2-3-1-1 manoeuvres (alternated control steps inputs of 2, 3, 1 and 1 seconds) for

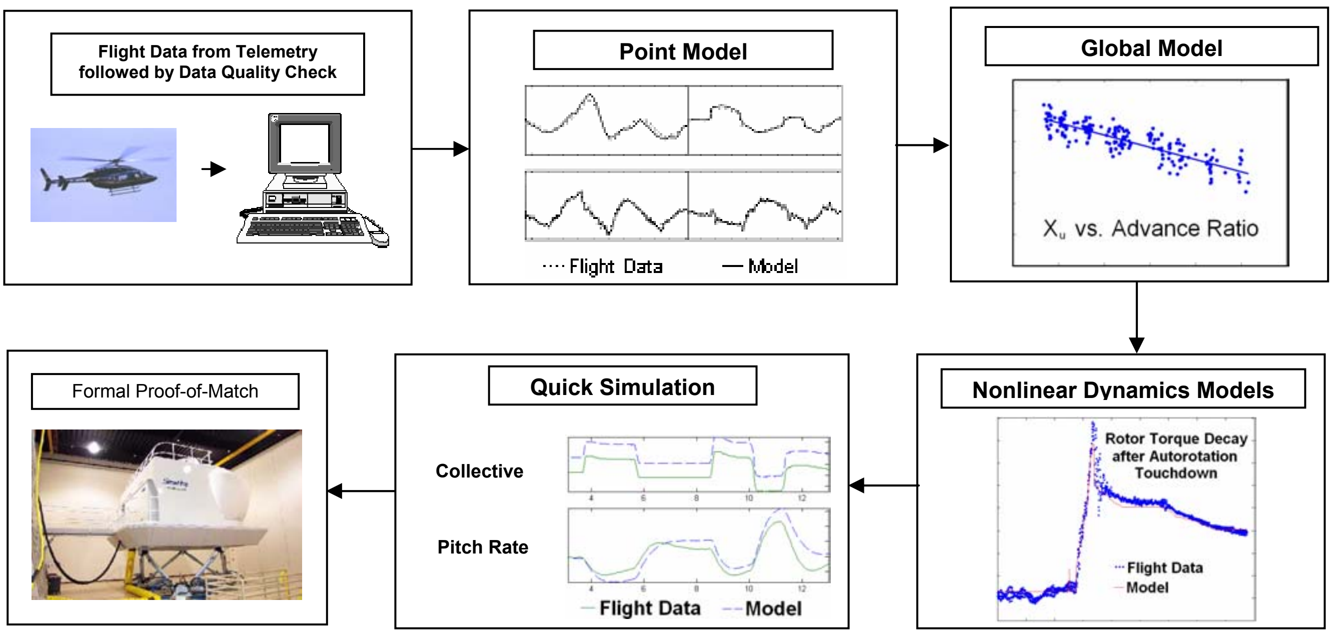

Fig. 2. Overview of the HAMI process

each control input (longitudinal and lateral cyclic, collective, and pedal). The concatenated data contains all the four axes coupling effects that were accounted for in the aerodynamic model.

In order to develop a comprehensive global model covering the entire flight envelope, numerous 2-3-1-1 manoeuvres for each control input in the up-and-away, hover, and auto-rotation fight regimes were necessary.

1.7 Global Model Development Process

A continuous global model was developed by regressing the point model stability and control derivatives from different configurations and trim points against the corresponding averaged trim states and flight conditions; these trim states and flight conditions were determined by averaging the two to five seconds of trim data prior to the start of each 2-3-1-1 maneuver. Since the global model allowed smooth interpolation between available point models, the behaviour of the helicopter could be simulated even if a point model near a particular configuration or trim point was not readily available.

Automatic fitting software was developed to correlate the derivatives using linear relationships. However, while the software was useful for developing a preliminary global model, further detailed analysis and fine-tuning of the model was done manually in Excel®.

1.8 Higher-Order Dynamics Optimization

Higher-order dynamics optimization is a regression technique that identifies cross-axis and higher-order dynamics. The process was used to minimize the difference (residual) between the global model's calculated force and moment components and measured force and moment components for unique maneuver time histories such as translational flight. The possibly non-linear dynamics contained in these residuals were regressed against corresponding states and/or flight conditons, and the resulting relationships were incorporated into the base global model. The process ultimately resulted in an augmented global model able to accurately capture the higher-order dynamics.

1.8.1 Modeling Main Rotor Speed and Torque during Autorotation

Higher-order dynamics optimization can be used for a variety of modeling tasks. In this project, it was also used to model main rotor torque (Q_{rotor}) and speed (*MR*) during autorotation.

In modeling Q_{rotor} and *MR*, it was necessary to determine three different models for each of the following phases of autorotation flight: autorotation entry, steady autorotation, and autorotation landing. Autorotation landing, here, refers to the period of an autorotation landing just prior to the flare and includes the decay of main rotor torque and speed after touchdown.

Similar to the approximation in [6], *MR* during all three phases of autorotation was modeled using the following equation (Eq. 2).

$$M\dot{R} = -c \times (MR)^2 \qquad (2)$$

In Eq. 2, *c* is a piecewise function consisting of three equations corresponding to each of the phases of autorotation mentioned above. In general, *c* is a function of the following variables (Eq. 3):

$$c = f(Q_{rotor}, \delta_{coll}, w, \dot{w}, TAS, \theta, \phi, MR) \qquad (3)$$

Similarly, Q_{rotor} was also modeled using a piecewise function. Q_{rotor} was found to be a function of the following variables (Eq. 4). Q_{eng} in Eq. 4 represents the total engine torque.

$$Q_{rotor} = f(Q_{eng}, MR, w, \delta_{coll}, \dot{\delta}_{coll}) \qquad (4)$$

1.9 Global Model Validation

MMLE simulation was used to quickly and easily assess the fidelity of the developing global model. This simulation environment did not contain a trim routine and stability and control derivatives were held constant over the simulation period; control position and measurement offsets were represented by general offsets. This level of validation could only confirm the model's fidelity about a particular trim point, and a more rigorous validation process followed once quick validation with MMLE was successfully completed. If MMLE validation failed, the global model was further refined using higher-order dynamics optimization.

The final validation step was conducted using Proof-of-Match (POM). During this validation process, the stability and control derivatives were allowed to vary over the simulation period, and a trim routine was used to find an optimal solution for the trim parameters. A generic atmosphere model, and the aerodynamic and engine models were fully integrated in the POM simulation environment; the engine model was developed and validated from static and dynamic flight data test points. A flight control model was not developed; instead, the measured control positions were shifted accordingly to account for flight control system time delays.

The trim routines in the POM ensured that any subsequent simulation began from a trimmed state. They were integrated directly into the POM simulation environment, and relied on a MATLAB® sequential quadratic programming algorithm to search for the optimal trim parameters. The primary challenge in developing a trim routine was in choosing physically plausible sets of trim parameters that ensured convergence of the algorithm. Considerable effort was spent in designing maneuver specific trim routines. In total, 42 different trim routines were developed.

To determine if Level D flight model requirements were satisfied, the POM software was also designed to automatically apply the corresponding FAA AC 120 63 [7] tolerances to the Qualification Test Guide (QTG) simulation trajectories.

2 Flight Test Program

The flight test program, which consisted of 42 sorties and over 950 flight test maneuvers, was completed in approximately 43 flight hours between December 8, 2003 and April 20, 2004. The maneuvers included 175 trim snap shots, 230 2-3-1-1 multi-step input maneuvers, several beta sweeps conducted 200 ft over the runway, and over 725 QTG maneuvers for final model validation purposes.

In order to generate a global model that covered the entire flight envelope of the Bell M427, it was necessary to vary many parameters when conducting the 2-3-1-1 maneuvers. Table 1.0 specifies the parameters, and their variation.

Table 1: Parameters Varied During 2-3-1-1 Manoeuvres

Parameter	Min	Max
Weight	Light	Heavy
Longitudinal CG Position	FWD	AFT
Rate of Climb	-1000 fpm	+1000 fpm
Rotor Speed	100%	104%
Speed	30 kts	120 kts

3 Results for the Bell M427

3.1 Air Data Calibration

Prior to developing the model, angles of sideslip and attack were corrected for wash effects. Beta sweep maneuvers and longitudinal pulse inputs completed 500 ft above the runway were used to determine side wash and downwash corrections for angles of sideslip and attack. These manoeuvres were designed to allow the helicopter to experience its full range of angles of sideslip and attack.

NRC Aerospace's flight path reconstruction software was used to reconstruct the air data in these manoeuvres. The reconstructed and measured angles of sideslip and attack were compared to determine a scale factor and bias correction. Wash effects in the remaining flight data were corrected for by applying this scale factor and bias correction to the measured angles of sideslip and attack. In hover, the air data was particularly affected by rotor downwash; reconstructed air data directly replaced the measured air data in all hover flight data.

3.2 Point Model Identification Results

In order to examine the fidelity of the point model, the model response and flight data were compared. Fig. 3 shows one such comparison for an autorotation 2-3-1-1 manoeuvre conducted at sixty knots. The model response in the three components of acceleration, and rotational rates shows an excellent match with flight data.

A technique for determining a sufficiently accurate initial estimate of the derivatives was developed. With this initial estimate, the MMLE algorithm converged rapidly, and the need to tune the parameters of the algorithm to ensure convergence was practically eliminated. All 230 point models were identified using a single batch command in post-flight processing in less than two hours.

Model comparisons for all 230 point models were completed, and as Fig. 3 indicates, MMLE was proven to be tremendously successful and effective at modeling the complex dynamics of the Bell M427 helicopter.

3.3 Global Model Development Results

The continuous global model ensured smooth interpolation between the available point models, and allowed the helicopter to be modelled over its entire flight envelope in a simple and efficient manner.

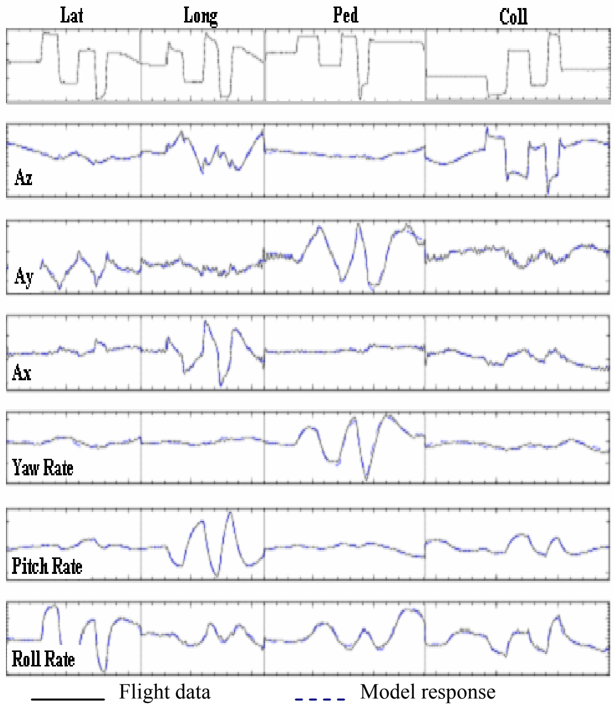

Fig. 3. Autorotation point model response at 60 kts for heavy/aft configuration

Fig. 4 shows an example of how each of the point model stability and control derivatives was combined to generate the global model. Point model estimates of X_u (longitudinal force due to *u* component velocity) from all up-and-away (UAA) 2-3-1-1 maneuvers were plotted versus advance ratio. As Fig. 4 indicates, X_u was found to be a strong function of advance ratio. Thus, using this relationship, it was possible to estimate X_u quickly and accurately over the entire flight envelope of the helicopter.

The curve fitting process was required for each of the sixty stability and control derivatives, and was repeated for the up-and-away, hover, and autorotation flight conditions. Thus, three separate global models were created.

In general, the point model stability and control derivatives were found to be functions of advance ratio, weight, centre of gravity position, and in some cases, main rotor torque.

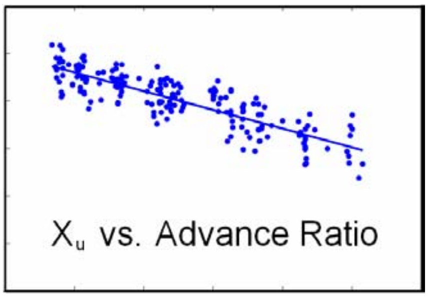

Fig. 4. X_u versus advance ratio

3.4 Global Model Error Analysis

The global model error in the three components of forces and moments was estimated using the trim flight data from 2-3-1-1 maneuvers and QTG flight data. Model error was measured as the root mean square of the equivalent control input required to compensate for the residual force and moment components not predicted by the model. For all the global models (UAA, hover, and autorotation), this error remained below 6% of the total range of control available. The derived error statistics indicate the robustness of the model for the full envelope of the flight data. Sample model error statistics for the UAA model are provided in Table 2.

Table 2: Sample Model Error Statistics for the UAA Global Model

	RMS Model Error	% RMS Error in Corresponding Control
Vertical Force	2 ft/s^2	Collective – 2%
Rolling Moment	0.3 rad/s^2	Lateral Cyclic – 1.5%
Pitching Moment	0.1 rad/s^2	Longitudinal Cyclic – 1.5%

3.5 MMLE Simulation - Quick Global Model Evaluation

MMLE simulation was used after curve fitting the stability and control derivatives, and provided a quick and easy way to evaluate the global model's fidelity. The UAA, hover and autorotation global models all required this initial validation step.

Fig. 5 shows the flight data and corresponding global model response for a UAA 2-3-1-1 manoeuvre. The model response is an excellent match with flight data and indicates that the global model fidelity is sufficient to warrant the final validation step in POM.

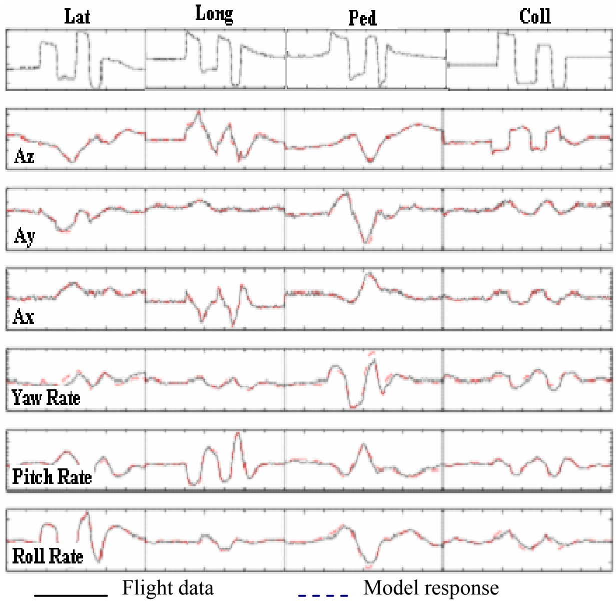

Fig. 5. UAA global model validation using mle – heavy/aft configuration at 100 kts, 1000 fpm descent, and 6000ft HD

3.6 Higher-Order Dynamics Optimization Results

Higher-order dynamics optimization was used to identify and append complex dynamics into the global model. Two different methods called "trim averaging" and "selected point" were developed. Trim averaging was used for light/aft critical azimuth low airspeed handling qualities, ground effect, and one engine inoperative (OEI) flight. Selected point was used for heavy/fwd critical azimuth low airspeed handling qualities, takeoff, landing, and autorotation entry.

The trim averaging method required finding trim periods in the flight data, and determining the force and moment residuals using the averaged trim flight data. Essentially, trim averaging extended the model's capability beyond the flight conditions encountered in 2-3-1-1 maneuvers.

The selected point method did not require trim flight data. With this method many more residuals could be calculated, however, each residual was calculated using flight data from only a single data point. Unlike trim averaging, the selected point method allowed the non-linear dynamics associated with helicopter responses outside the small-perturbation domain to be identified.

Fig. 6 shows how the selected-point method was successfully used to model the non-linear dynamics of translational flight. The first two plots in Fig. 6 show the performance of the core UAA model in translational flight; the simulated helicopter trajectory (shown by the dashed lines) begins to diverge almost immediately. Applying the higher-order dynamics optimization software to this data provides a non-linear model for the residual dynamics, as shown in the middle plot in Fig. 6. As the last two plots in Fig. 6 indicate, after appending the residual dynamics model into the core UAA model, the match is significantly improved.

3.7 Proof-of-Match of the Aerodynamic Model

The following sequence of maneuvers were matched during POM validation: 2-3-1-1 manoeuvres, longitudinal, lateral, and directional handling qualities maneuvers, out of ground effect and in ground effect (IGE) hover, autorotation, critical azimuth low airspeed handling qualities, takeoff, and landing.

Initial conditions for simulation were obtained from flight data. Minor adjustments to these values were sometimes required to ensure that simulated responses remained within FAA prescribed tolerances [7]. Generally, these adjustments remained below measurement accuracy bounds. Any control position changes returned by the trim routine were treated as constant offsets applied throughout the simulation.

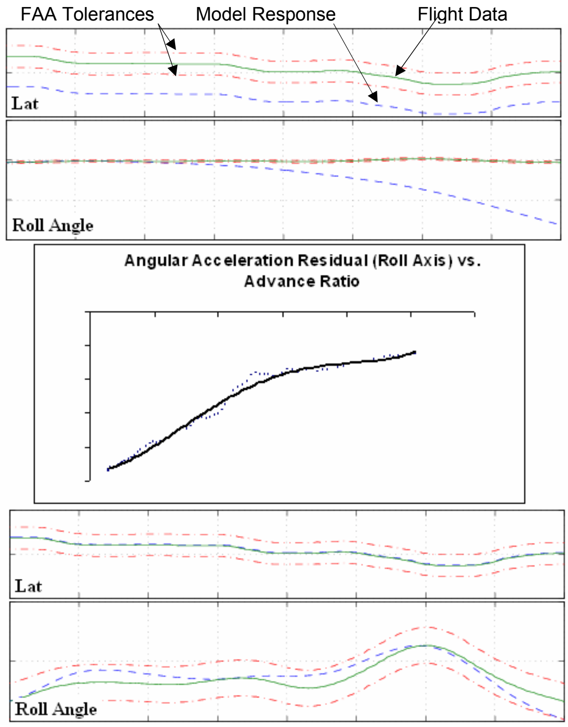

Fig. 6. Higher-order dynamics optimization using selected-point method

In addition, for some takeoff and landing maneuvers, wind profiles or proportional-derivative (PD) controllers for applying minor control position changes were required to combat pronounced wind shear effects. Wind profile magnitudes were limited to the air traffic controller's estimate, and control changes were strictly bounded below half the allowable FAA control position tolerances [7].

3.8 Proof-of-Match Results

In the sequence of plots that follows, the solid lines indicate flight data, while the dashed lines indicate the simulated response. Corresponding FAA tolerances for the maneuver [7] are plotted as dashed lines directly offset from the flight data.

Fig. 7 illustrates the model response for a longitudinal cyclic control input. The longitudinal cyclic control position trims only slightly above the pilot's input, and the pitch rate and pitch and roll angles match the flight data very well throughout the simulation.

A spiral stability maneuver is shown in Fig. 8. In this case, the trimmed lateral cyclic position is barely offset from the pilot input, and the roll rate, and roll and yaw angles provide an excellent match with flight data even for roll angles in excess of 25 degrees.

Fig. 9 describes the Bell M427 in an IGE hover at 18 ft AGL. The longitudinal and lateral cyclic positions trim well and simulated pitch and roll angles are within the FAA prescribed tolerances.

Fig. 10 demonstrates a low airspeed, critical azimuth maneuver. The maneuver consists of forward flight at 25 knots, 7 ft AGL, and 90-degree relative wind heading. Both the longitudinal and lateral cyclic controls trim well, and the pitch and roll angles are an excellent match with flight data. Fig. 11 presents an autorotation entry maneuver. In this maneuver the helicopter reacts to both a large collective input, and sudden loss in engine torque. The on-axis response (pitch rate and angle) shows an excellent match with flight data.

Fig. 12 presents a complete takeoff trajectory from hover to 200 ft AGL. To account for wind shear effects during POM, the control positions were changed using a PD controller; however, the control position bounds are set at 5%, half of the 10% of total deflection allowed by the FAA [7]. As the figure indicates, the control position changes are bounded below half the allowable tolerances and the model response (pitch angle, true airspeed, and altitude) are an excellent match with the flight data.

4 Conclusions

Development and application of the HAMI technique to identify a mathematical model of the Bell M427 helicopter have indicated the following:

- MMLE is quick, effective and successful. The point model stability and control derivatives describing the Bell M427's dynamics were determined automatically.

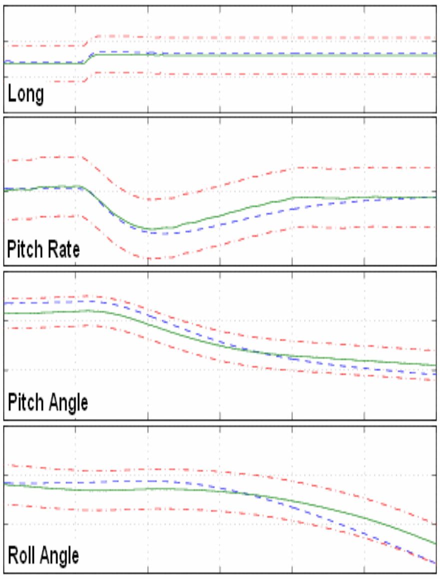

Fig. 7. Longitudinal cyclic input response

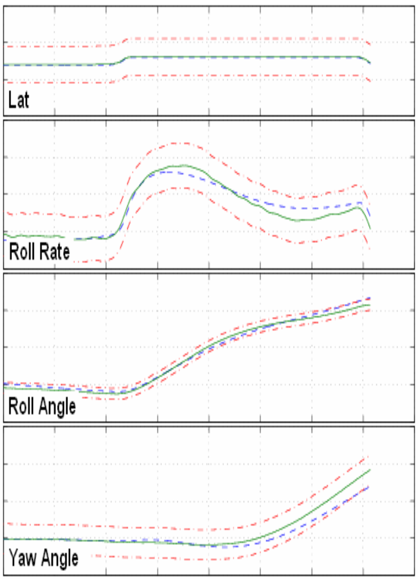

Fig. 8. Spiral stability

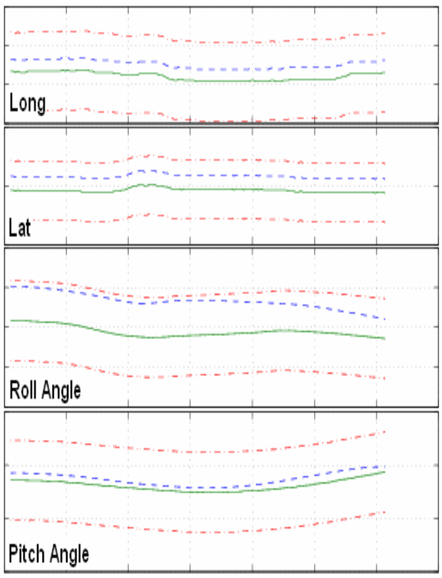

Fig. 9. IGE hover (18 ft AGL)

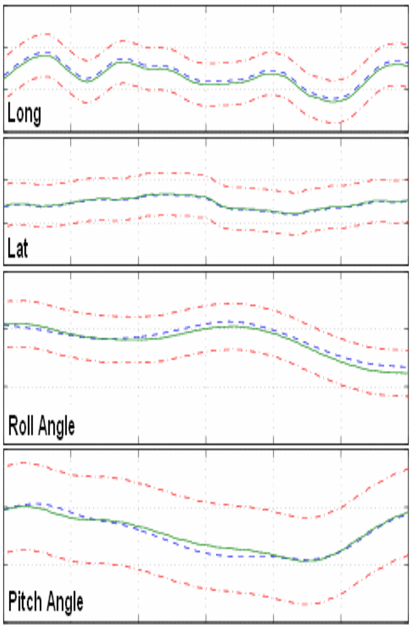

Fig. 10. Critical azimuth manoeuvre

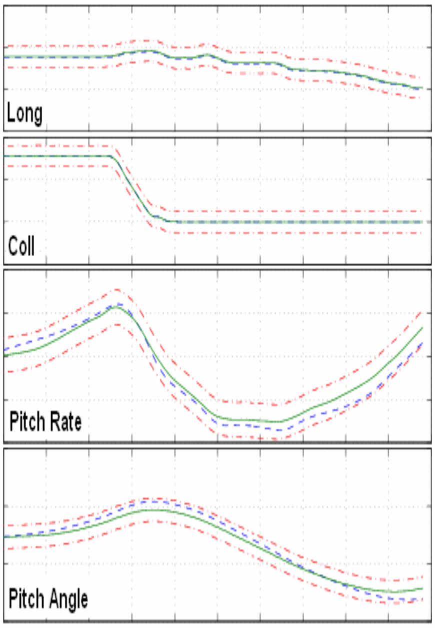

Fig. 11. Autorotation entry

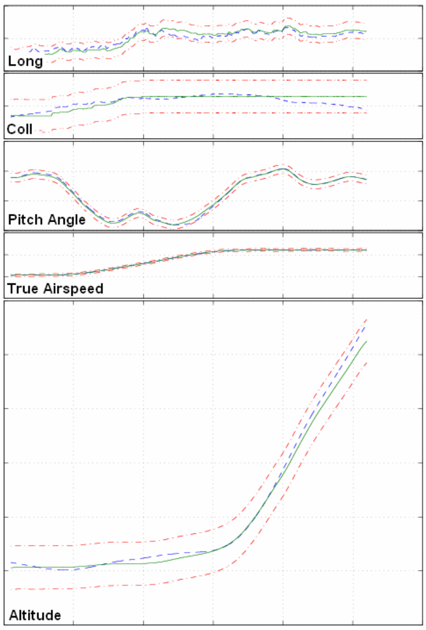

Fig. 12. Takeoff from hover to 200 ft AGL

- The helicopter global model development process is practical. A continuous aerodynamic model spanning the full flight envelope of the Bell M427 was developed.
- MMLE simulation provides a rapid assessment of the fidelity of the developing global model.
- The POM process ensures that the aerodynamic model is validated to the FAA's AC 120 63 Helicopter Simulator Qualification Guidelines.

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