Extraction of Flight Dynamics Data from Level D Qualification Flight Tests

Application to Training Simulators Model Fidelity Enhancement

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ABSTRACT

Between 2018 and 2020 the NATO Science and Technology Organization (STO) engaged a Research Task Group (RTG) on rotorcraft flight simulation model fidelity. The primary goal of this RTG was to apply and compare flight simulation model enhancement methods and fidelity assessment criteria based on flight-test case studies. Under the AVT panel 296 (Applied Vehicle Technology), 20 partners from NATO nations' industries, governmental research establishments and universities tested 7 different model updating or 'renovation' methods through comparison of simulation models vs flight data. Comparisons between update methods have been investigated to find best practices and suitability for different applications including advanced rotorcraft configurations. Most of the existing methods make extensive use of System Identification (SID) to generate improved-fidelity state-space models. Thereafter, these models are used as a reference for nonlinear model improvements.

Among the case-studies carried-out, ONERA, US-Army and THALES Training & Simulation run a collaborative work to investigate the potential use of flight data from simulator's Qualification Test Guides (QTG) in System Identification. The objective behind this work was to assess whether the state-space models resulting from this identification could be used and contribute to enhance the physics-based model. The renovation technique based on deltas of forces and moments was applied to select the most relevant derivatives of the identified model. The analysis of the derivatives helped identify some improvement axes of the physics-based model. This paper will present the work carried out in the scope of this collaboration.

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INTRODUCTION

Flight mechanics models used in helicopter training devices are certified following CS-FSTD(H) (Ref. 1) and FAA 14 Part 60 (Ref. 2) Standards requirements. These standards detail the acceptable match between flight and simulation time-histories, regarding the simulator usage type.

Not all the simulators need to follow the most stringent requirements but for Full Flight Simulators (FFS) the matching level is extremely high. The quantitative rating of model fidelity to Flight Tests (FT) is one of the criteria to be applied for the acceptance of the FFS flight mechanics. During the simulator qualification process, a set of qualitative tests are also performed by pilots in order to assess the match between the real helicopter behaviour (as known by the pilot) and the simulated one. In many cases, these subjective tests lead to new adjustments of the flight dynamics model. Consequently, this observation brings some evidence that the existing certification objective tests are not sufficient to capture the whole aspect of helicopters flight dynamics.

Some research activities have been led to identify shortfalls in level D certified simulation models objective requirements as discussed by Padfield et al. (Ref. 3). Amid the deficiencies identified, poor fidelity in Handling Qualities (HQ) reproduction is a major topic to investigate. The review of CS-FSTD(H) requirements shows that few Qualification Test Guide objective tests (QTG) address the aircraft intrinsic handling qualities. Therefore, one can expect that model fidelity enhancement would need a deep analysis of its parameters that impact the handling qualities.

The NATO Research Task Group AVT-296 aimed to explore an exhaustive list of methods for flight mechanics simulation fidelity enhancement, including training simulation applications. Twenty partners tested 7 different methods through several configurations of model vs flight data. Most of the existing methods make an extensive use of system identification to generate high fidelity state-space models. Thereafter, these models are used as reference basis for nonlinear model improvements.

The quality of the identification is strongly dependent on the quality of the flight data gathered. In principle, having recourse to system identification would need to realize a set of calibrated flights well representing the system dynamics, in the adequate range of frequencies. Frequency sweep tests are particularly well adapted to this purpose and have become, over years, standard tests for identification, complemented by time domain tests only when needed.

However, the realization of such flight tests remains an obstacle for data package providers. Limited availability of instrumented reference aircraft, operational constraints, associated costs and delays are some of the obstacles for gathering frequency sweeps. Furthermore, the simulator manufacturer also needs to fully handle these tests and deploy the SID process internally. This needs time and investment. Therefore, some manufacturers usually remain quite conservative in having recourse to SID and consequently applying the latest renovation methods for simulation fidelity improvements.

The purpose of this study was to investigate at what extent System Identification could be applied to QTG flight tests in order to extract a set of flight dynamics data, which would be used for nonlinear models enhancement. THALES Training & Simulation flight dynamics model (FLOOP) was used in this case-study as the candidate model to enhance. A “non-calibrated” model of the AW139 helicopter constituted the baseline model to match with QTG flight tests available on this helicopter. The renovation method based on “Force & Moment Increments” was used to identify the potential deficiencies of the model in Lateral-Directional Dynamics (LDD) simulation.

This approach could be a first step towards the deployment of SID within existing industrial process before fully integrating handling qualities criteria matching in simulator models renovation.

CASE-STUDY PRESENTATION: AW139 LATERAL-DIRECTIONAL DYNAMICS

In this case-study the renovation method based on corrective force and moment terms was applied to the THALES flight mechanics model of the AW139 helicopter.

The application focused on the lateral-directional behavior improvement at the optimal climb speed which is approximately 75 kn for this aircraft.

Flight tests were those from the regular QTG tests used for Level D certification of the simulator. They included lateral and pedal doublet inputs. However, some additional low frequency sweeps were performed on lateral axis. As expected, the data did not include frequency sweep tests on all axes and all frequency range; therefore, the data were not best suited to frequency-domain system identification of a 6-DOF state-space model.

Using the CIFER software suite as described by Tischler and Remple (Ref. 4), a reduced order (3-DOF) lateral-directional model could be identified for this application. The SID partial derivatives were used to complement lateral-directional forces and moments by linear corrective terms.

The helicopter – AW139

The Leonardo AW139 (Figure 1) is a medium-sized helicopter, powered by two Pratt & Whitney Canada PT6C-67C turboshaft engines. It is commonly used for transport and Emergency Medical Service (EMS).

Figure 1. The AW139 Long Nose Helicopter.

The main rotor is a five blade fully articulated rotor, equipped with elastomeric bearings for the flapping motions, lead-lag and pitch change articulations.

The tail rotor is a four blade fully articulated rotor, equipped with elastomeric bearings that allow flapping, lead-lag and feathering movements.

The main characteristics of the helicopter are presented below in Table 1.

Table 1. The AW139 Main Characteristics.

Type:	Manufacturer:	Class:
AW139	Leonardo Helicopters	Conventional single main rotor
Role:	**Accommodation:**	**Registration:**
Medium multi-purpose h/c	Max 15 passenger + 2 crew	
Empty:	**Maximum Take-off:**	**Useful Load:**
4 250 kg	6 400 kg	
Cruise speed	**VNE:**	
150 kt	167 kt at MSL	
Endurance	**Max sideward velocity:**	**Max rearward velocity:**
5 h 15	See RFM	See RFM
Engine	**Manufacturer:**	**Number:**
PW PT6C-67C	Pratt & Whitney Canada	2
Max power:	**Take-off Power:**	
2 x 746 kW	2 x 720 kW	

The flight dynamics model FLOOP

The THALES flight dynamics model used for this case study is a real-time, nonlinear, physics-based model.

The main rotor model is based on the Blade Element Theory (BET), using articulated rigid blades to compute aerodynamic forces and moments. The tail rotor model is an analytic model based on Bailey equations (Ref. 5). The inflow model is based on Pitt & Peters (Ref. 6).

The simulation of the airframe takes into account the inertia, the aerodynamic coefficients and the interactions with the rotor wake.

The renovation method – force and moment increments

In flight mechanics, state-space models are widely used to analyze rotorcraft handling qualities and dynamic responses. To complement shortfalls in responses predicted by simulation models, e.g. for the qualification test guide, state-space models can be used as a reference basis for nonlinear model updates to achieve an improved model fidelity.

The renovation method so called "force and moment increments" uses delta derivatives which are obtained by quantifying differences between stability and control derivatives from flight tests and flight simulations (FS). These derivatives are estimated by system identification techniques from flight tests and by linearization of nonlinear equations from simulation models. This renovation method has been thoroughly applied in the AVT panel 296 over 4 study-cases. Taghizad et al. (Ref. 7) reports this activity and discusses the benefits brought for different applications.

Frequency sweeps are best used for generating the FT data required for derivative identification, using frequency domain methods such as those implemented in CIFER® (Tischler with Remple (Ref. 4)).

Alternatively, the derivatives can also be estimated using classical time-domain identification methods [see Jategaonkar (Ref. 8), Klein and Morelli (Ref. 9)]. Derivatives can also be estimated from flight-test data using the Additive System Identification method reported by Cameron et al. (Ref. 10) and Agarwal et al. (Ref. 11) or the Linear Parameter Identification Using Adaptive Learning as described by Gursoy et al. (Ref. 12).

The same inputs and methods can be used to generate the derivatives from the simulation model. However, linearization tools are available within flight dynamics codes as described by Benoit et al. (Ref. 13). Such tools significantly simplify the process of stability and control derivatives generation as discussed by Lu et al. (Ref. 14) and Agarwal et al. (Ref. 11).

The delta derivatives obtained from the difference between identified and linearized derivatives are then used to compute additional force and moment terms. These terms are linearly added to the nonlinear equations of force and moment in order to generate additional accelerations needed to capture the lacking dynamics in the simulation model. When the derivative mismatches are identified, the physical source of the low fidelity can be more directly investigated.

Figure 2 presents this renovation method process. A comparison of FT identified and FS linear model derivatives is made to compute residual forces and moments. This requires that the same linear model structure be used for the flight and simulation data for quantifying the delta derivatives. Selection of the derivatives to renovate will depend on the nature of the model fidelity shortfall.

Applications can range from identifying deficiencies in all axes to renovating a selected axis, mode or derivative(s).

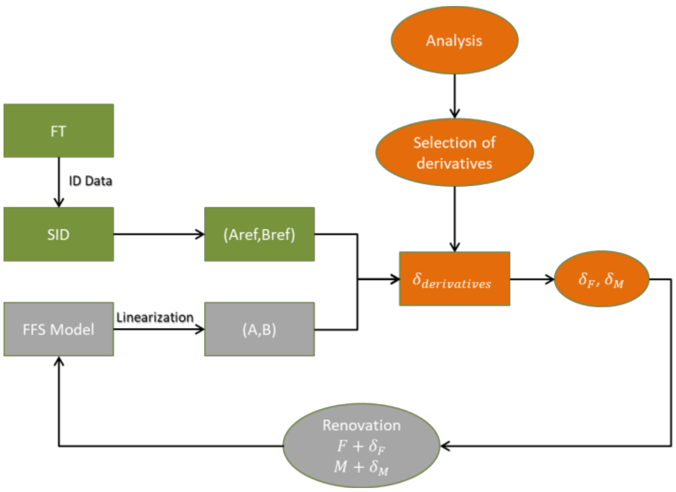

Figure 2. The renovation method by force and moment increments

The derivatives selection can be achieved either by carrying out a sensitivity calculation or through a physics-based study. The differences in the linear models are converted into force and moment derivatives, which can then be used in the update of, e.g. stability and the on-axis or off-axis responses of the helicopter.

Force and moment increments are computed as linear combinations of the relevant derivatives errors as presented below (EQ.1, EQ.2) for roll moment and vertical force. In this example the relevant derivatives are supposed to be L_p, L_v, L_r, L_{lat}, L_{ped} and Z_w.

$$\Delta L = I_{xx}[(L_{p\_ID} - L_{p\_lin})p + (L_{v\_ID} - L_{v\_lin})v + (L_{r\_ID} - L_{r\_lin})r + (L_{lat\_ID} - L_{lat\_lin})\delta_{lat} + (L_{ped\_ID} - L_{ped\_lin})\delta_{ped}] \quad \textbf{EQ. 1}$$

$$\Delta Z = Mass \times (Z_{w\_ID} - Z_{w\_lin})w \quad \textbf{EQ. 2}$$

I_{xx}, I_{zz} are the helicopter moments of inertia about roll and yaw axes, and Mass is the helicopter mass. Extension "_ID" designates derivatives from system identification whereas "_lin" designates those calculated from nonlinear model linearization.

These increments are then added to nonlinear forces and moments as illustrated below for the lateral moment and the vertical force.

$$L_{NL} = L_{NL-baseline} + \Delta L \quad \textbf{EQ. 3}$$

$$Z_{NL} = Z_{NL-baseline} + \Delta Z \quad \textbf{EQ. 4}$$

System Identification – CIFER® Software suite

The frequency-response identification method as embodied in the Comprehensive Identification from FrEquency Responses (CIFER®) software suite was used in this study. This system identification method and software is described in detail by Tischler and Remple (Ref. 4). Only a brief outline of the method will be given here. The identification process comprises three major steps: 1) Identification of the multi-input/multi-output (MIMO) frequency response matrix; 2) Development and identification of a parametric state-space stability and control derivative model that best matches the MIMO frequency response matrix; and, 3) Verification of the resulting state-space model with flight-data time responses not used in the identification process.

The first step is accomplished by having the pilot generate a stick input that adequately excites the helicopter over the frequency range of interest. Ideally for this identification approach, the input is a "frequency sweep" with a frequency progression from low to high frequency typically covering a range of 0.1-30 rad/sec. The input is such that the vehicle starts and ends in trim. A fast Fourier transform, using the chirp z-transform (CZT), and composite window averaging converts the data from the time- to frequency- domain. Then the MIMO frequency-response matrix is determined from the input spectral density and cross-spectral-density matrices,

$$\hat{H}(f) = \hat{G}_{xx}^{-1}(f)\hat{G}_{xy}(f) \quad \textbf{EQ. 5}$$

This MIMO frequency-response matrix solution yields the correct single-input/single-output (SISO) frequency responses when multiple control inputs are present and partially correlated in the test data, which is usually the case for helicopter tests. For single input tests, EQ.5 reduces to the more familiar scalar relationship. A key indicator of the accuracy of each resulting frequency response is the associated coherence function $\hat{\gamma}_{xy}^2(f)$ which is also determined from the spectral density functions as described by Tischler and Remple (Ref. 4). A coherence value nearing unity indicates a high signal-to-noise ratio of the flight-test data and a highly-accurate frequency response. High coherence is achieved using frequency-sweep inputs, owing to their rich spectral content, and persistent excitation throughout the flight maneuver.

After the frequency responses are calculated, the second step is to hypothesize a state-space stability-derivative model,

$$M\dot{x} = Fx + Gu(t - \tau) \quad \textbf{EQ. 6}$$

based on a physical understanding of the vehicle's primary flight dynamics. An optimization scheme employing a secant search then determines the free model parameters by minimizing the error in both magnitude and phase between the model and flight-test responses. The accuracy of the identified model is judged from the overall frequency-domain cost function J_{ave}, where $J_{ave} \le 100$ reflects an acceptable level of accuracy and $J_{\text{ave}} \le 50$ reflects an identified model that is nearly indistinguishable from the flight data. Confidence analyses are performed on the converged model by determining the Hessian matrix and resulting theoretical accuracy metrics: Cramer-Rao bounds $(CR_i, \%)$ and Insensitivities $(I_i, \%)$. Identified parameters that are insensitive $(I_i \le 10\%)$ or highly correlated $(CR_i \le 20\%)$ are sequentially eliminated, reducing the model complexity, and the optimization scheme is repeated.

The final step, after a satisfactory model has been determined, is to drive the model with flight-test doublet inputs (which were not used in the identification process) for comparison with flight-test responses. This final step verifies both the final model structure and its identified values.

QTG FLIGHT TESTS – AW139

General Presentation

The flight data were gathered on a fully instrumented aircraft. The type of maneuvers performed are mostly based on EASA (Ref. 1) and FAA (Ref. 2) requirements for the validation of Flight Simulator Training Devices (FSTD), i.e. performance data, step inputs, pulses, doublets, helicopter proper modes, trajectories, in various flight conditions (airspeed, weight and balance, etc.). The parameters that are recorded and the number of flight conditions exceed the minimum requirements of these standards.

Lateral-Directional Dynamics Flight Data

For this case study, the flight data that are used were recorded around the maximum climb speed, with AFCS off (least augmented case), in middle weight and center of gravity configuration. Three kinds of maneuvers were performed:

1. Lateral step input, as specified in CS-FSTD(H) for test 2.d.1.(i), both left and right
2. Pedals doublet, as specified in CS-FSTD(H) for test 2.d.3.(i)
3. Sine input of constant amplitude, applied on lateral cyclic stick

Each maneuver was repeated at least three times during the same flight. Steps and doublets were also performed again at least three times during a second flight.

SYSTEM IDENTIFICATION

As explained above, frequency-sweeps are the preferred input type for the frequency-response identification method. In this paper, we were specifically interested in evaluating the efficacy of inputs for QTG evaluation to also be used for frequency-domain system identification, to see if these would suffice without additional frequency sweeps test points being needed. Initial evaluation of the QTG data base indicated that the aileron and rudder flight test input data were satisfactory to identify a 3 degree-of-freedom (3-DOF) state-space model. However, the elevator and collective test input data were not adequate to identify 3-DOF pitch-heave model, or a coupled 6-DOF (lateral, directional, longitudinal, heave) model. A flight-test value of the heave damping derivative ($Z_w = -0.606$ rad/sec) was determined from an identified transfer-function model of the pitch response and used in the simulation update process.

The lateral stick inputs and associated roll rate responses for 5 QTG input records are shown in Figure 3 and Figure 4.

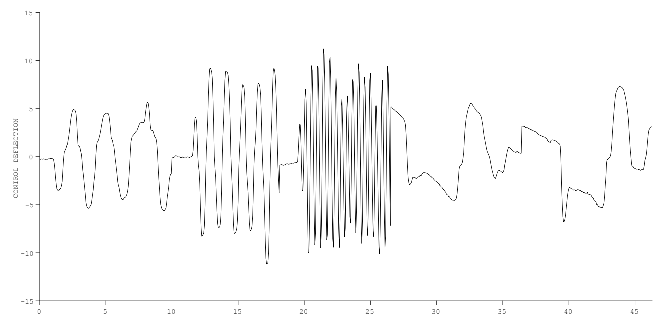

Figure 3. Lateral stick inputs (δ_{lat}, %) for 5 QTG flight-test records

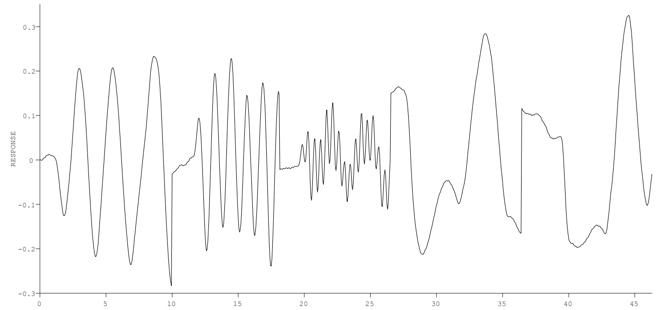

Figure 4. Roll rate response (p, rad/sec) for 5 QTG flight-test records.

Figure 5 to Figure 8 show example lateral-directional frequency responses for lateral stick inputs ($p/\delta_{\text{lat}}, a_y/\delta_{\text{lat}}$), and pedal inputs ($p/\delta_{\text{ped}}$, r/δ_{ped}) from flight data and the identified state-space model. The on-axis angular rate flight responses of roll rate response lateral stick p/δ_{lat} and yaw-rate response to pedal input r/δ_{ped} generally show acceptable coherence in the frequency range of the short-term response (1.0-10 rad/sec), although the off-axis response of p/δ_{ped} shows degraded coherence for the non-sweep input, in agreement with Tischler and Remple (Ref.

4). The lack of data for all responses in the low-frequency range (less than 1.0 rad/sec) is also due to the non-sweep type inputs. As a result, we can expect to achieve a state-space model that predicts the short-term time response well, but does not capture the low frequency response.

The identified 3-DOF lateral-directional model is shown in the dashed lines for each response.

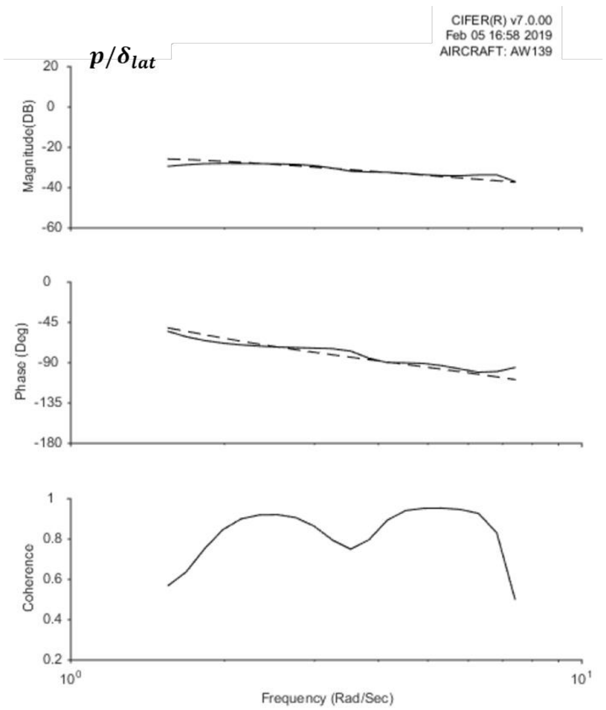

Figure 5. Lateral-directional frequency response – roll rate to lateral stick

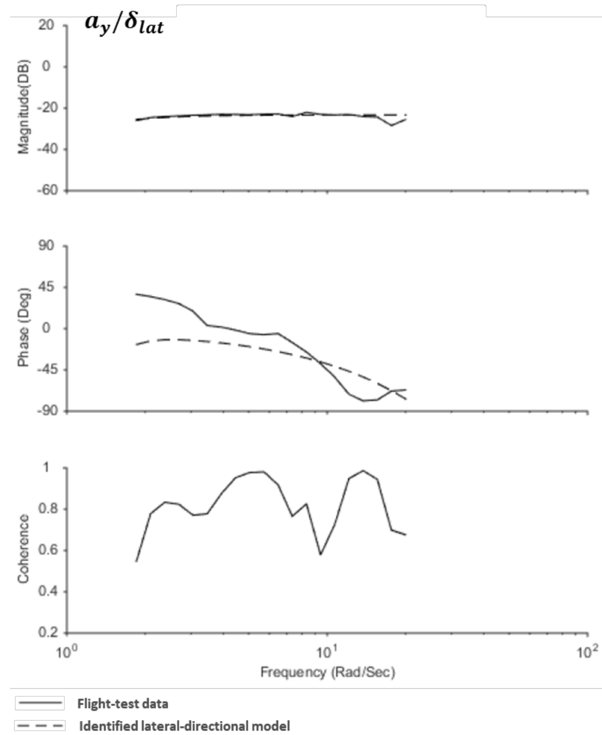

Figure 6. Lateral-directional frequency response – lateral acceleration to lateral stick

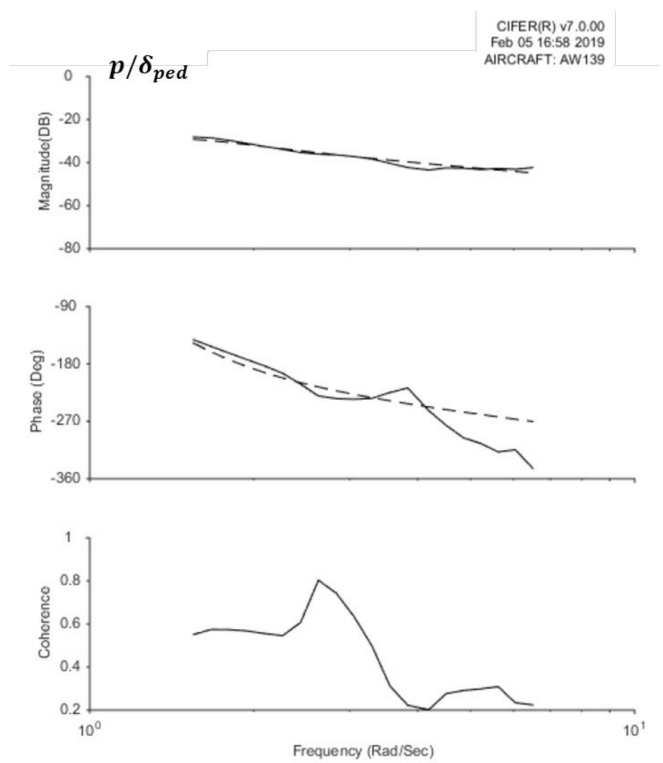

Figure 7. Lateral-directional frequency response – roll rate to pedals

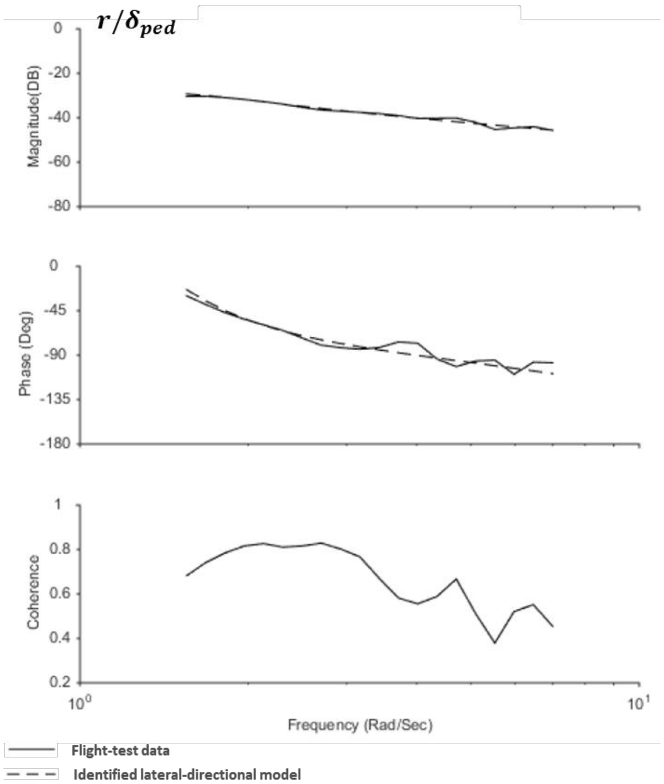

Figure 8. Lateral-directional frequency response – yaw rate to pedals

The identified model parameters and associated Cramer Rao bounds and Insensitivities are given in Table 2 and Table 3.

Table 2. : Identified lateral-directional state-space model for AW139 – stability derivatives

F-Matrix	VALUE	CR %	Insens %
YV	0.02552	7.311	3.058
YP	0.000 +	------	------
YR	0.9209	16.17	6.969
G	0.000 +	------	------
LV	-0.01449	22.11	6.795
LP	-1.214	13.59	4.558
LR	1.563	17.21	5.838
NV	0.01144	7.763	2.682
NP	0.000 +	------	------
NR	-0.9458	8.794	2.728

Table 3. Identified lateral-directional state-space model for AW139 – control derivatives

G-Matrix	VALUE	CR %	Insens %
Ylat	0.06835	3.953	1.966
Yped	0.000 +	------	------
Llat	0.1023	4.471	2.032
Lped	-0.03617	12.68	4.275
Nlat	0.000 +	------	------
Nped	0.03582	4.938	1.450
τ_{LAT}	0.06674	6.775	3.111
τ_{PED}	0.06674 *	------	------

\+ Eliminated during model structure determination
* Constraint: $\tau_{PED} = 1.0 * \tau_{LAT}$

Referring to EQ.6, $M = I$ in the present case. The Cramer Rao bounds are all below the target value of $CR \leq 20\%$ (except for LV just slightly exceeding this), indicating a highly reliable identification result for the available QTG data.

The cost functions for all response included in the identification are presented in Table 4. In addition, the heave damping was identified from the pitch rate transfer-function identification: $Z_w = -0.606$ rad/sec.

Table 4. Identification Cost Functions

Response	Cost
p /LAT	32.962
ay /LAT	197.328
p /PED	51.291
r /PED	10.816
ay /PED	6.695
v /PED	10.563
Average	51.609

Since the frequency responses used in the identification all emphasize the mid-frequency range, the low cost of the individual cost functions (except for a_y/δ_{lat}) and the low average cost function $J_{ave} = 51.6$ indicate an accurate lateral-directional model for the short-term response. Physically, the lateral drag derivative Y_v should be negative in Table 2, whereas the identified value is a very small *positive* value. This anomaly is due to the lack of adequate low-frequency data quality in the QTG test data. As mentioned later, the Y_v derivative was not sensitive for the model agreement and so was not included in the renovation process. Also, the pedal and lateral stick time delays were constrained in the identification to be the same (Table 3). Physically, these should be different values, but the data quality at high-frequency did not allow independent identification of the time delay values.

Table 5. Eigenvalues of identified lateral-directional model

Eigenvalues ($^{rad}/_{sec}$)		Mode
1	0.0235	Spiral
2	-1.1536	Roll
3	[ζ = 0.3594, ω = 1.3972]	Dutch Roll
4	[ζ = 0.3594, ω = 1.3972]	

The eigenvalues for the identified model are given in Table 5. The Dutch roll is lightly damped and close in frequency to the stable aperiodic roll mode. The spiral mode is at low frequency and is slightly unstable.

Finally, the model is verified in the time domain as shown for a lateral stick (Figure 9) and a pedal input (Figure 10). Both time domain verification results show good predictive capability for large on-axis amplitude responses (30-40 deg/sec).

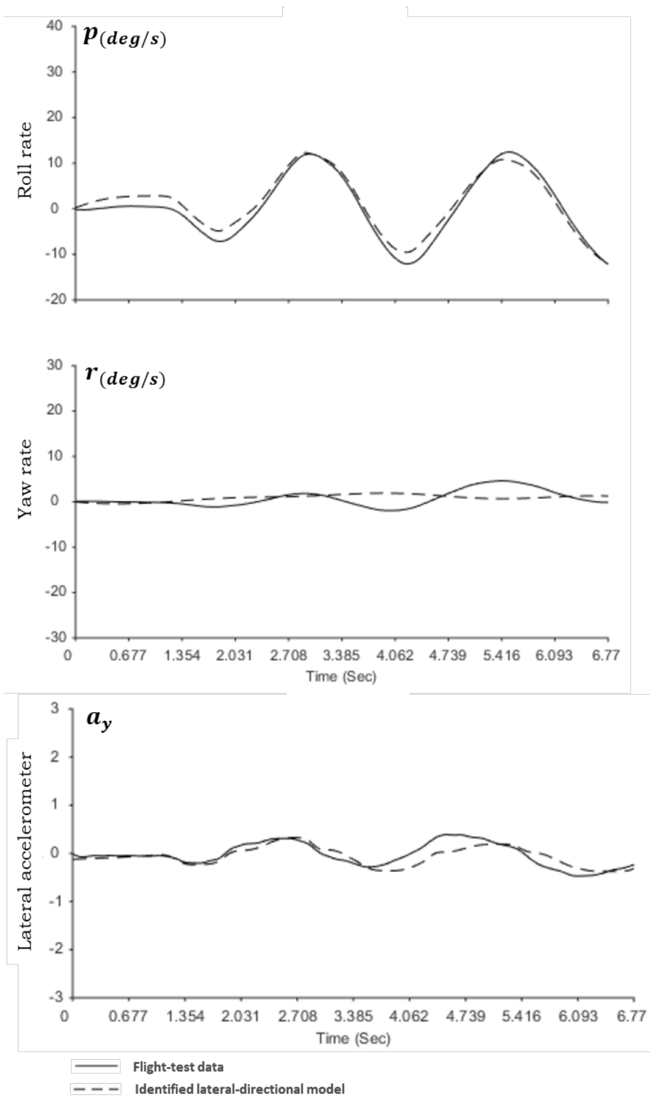

Figure 9. Lateral-directional model time-domain verification agreement for a lateral stick input

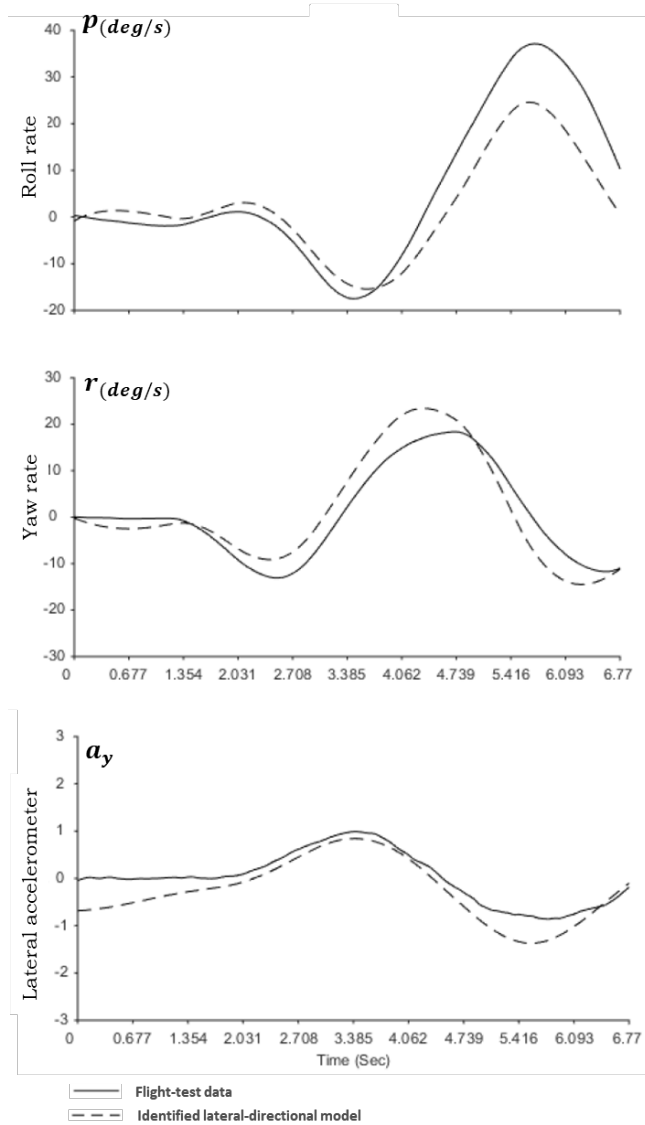

Figure 10. Lateral-directional model time-domain verification agreement for a pedal input

APPLICATION OF THE RENOVATION METHOD

Selection of relevant derivatives

Corrective terms were calculated on roll and yaw moments (ΔL and ΔN) and on lateral force (ΔY) and added to nonlinear forces and moments following the approach presented in equations EQ.1 and EQ.2. Table 6 presents the comparison of stability and control derivatives from system identification and physics based model linearization.

Table 6. Stability and control derivatives from AW139 model linearization and SID on FT

Stability derivative	FT	Model
Z_w	- 0.606	-1.0471
Y_v	0.02552	-0.135
Y_p	0^*	-0.198
Y_r	0.9209	0.4355
L_v	−0.01449	-0.0748
L_p	−1.214	-2.2763
L_r	1.563	-0.1483
N_v	0.01144	0.0319
N_p	0^*	-0.3114
N_r	−0.9458	-0.7175
Control derivative	**FT**	**Model**
Y_{lat}	0.06835	0.0752
Y_{ped}	0^*	0.0746
L_{lat}	0.1023	0.7405
L_{ped}	−0.03617	-0.0335
N_{lat}	0^*	-0.083
N_{ped}	0.03582	0.105
τ_{lat}	0.06674	
$\tau_{ped}=\tau_{lat}$	0.06674	---

*: Eliminated during model structure determination

Not all the derivatives are actively involved in lateral-directional dynamics mechanism. Therefore, the nonlinear model sensitivity to derivatives corrections has to be analyzed in order to select a coherent set of derivatives for lateral-directional fidelity enhancement.

In this case-study, since the number of parameters is limited, the sensitivity study was performed manually and produced the following outcome:

- L_p, L_r and N_r bring a real improvement.
- Y_{lat} brings minor improvements.

The other derivatives revealed to have far less or no impact on model fidelity improvement.

It has to be noted that regarding the yaw axis derivatives only N_r was identified to have a noticeable contribution to the lateral-directional dynamics. Tests showed that the nonlinear model output was almost insensitive to other yaw derivatives. This observation suggests 2 hypotheses: either the physical model does not need any improvement on yaw axis, or the yaw axis exhibits less contribution during this motion.

Table 6 shows that yaw axis derivatives obtained from SID are quite far from those extracted from the physical model. Therefore, the physical model needs also to be improved on this axis.

The most plausible explanation of the low effect of yaw derivatives in this study is that the lateral-directional dynamics could principally be driven by a dominant roll motion. This suggestion is corroborated with Figure 9 and Figure 10 results which show successively the helicopter response to lateral stick and pedals doublets. For the lateral double doublet (Figure 9), the response amplitude in the yaw axis is very small. For the pedal doublet (Figure 10) the off-axis response on roll rate reaches peaks of -18 and +40 deg/s, whereas the on-axis response oscillates only between -12 and +20 deg/s on yaw rate. These observations confirm that this helicopter should have a roll-dominant Dutch-Roll.

In conclusion, the derivatives selected for linear force and moment corrections were confirmed to be: L_p, L_r, N_r, Y_{lat} . Delta derivatives are calculated as linear combinations of derivatives errors and added to nonlinear forces and moments as illustrated below in Table 7.

Table 7. Force and Moment Increments

Delta Derivatives
$\Delta L = I_{xx}[(L_{p\_ID} - L_{p\_lin})p + (L_{r\_ID} - L_{r\_lin})r]$
$\Delta N = I_{zz} \times [(N_{r\_ID} - N_{r\_lin})r]$
$\Delta Y = Mass \times [(Y_{lat\_ID} - Y_{lat\_lin})\delta_{lat}]$
NL Force and moment upgrade
$L_{NL} = L_{NL-baseline} + \Delta L$
$N_{NL} = N_{NL-baseline} + \Delta N$
$Y_{NL} = Y_{NL-baseline} + \Delta Y$

Results

Figure 11 to Figure 14 present the corrective terms effect on the nonlinear model response for a set of 4 flight tests. The parameters presented in the graphics are defined as below:

- v is the lateral speed in body axes.
- p and r are the roll and yaw angular rates.
- phi (ϕ) and psi (ψ) are the bank angle and the heading.

For all cases tested, a real improvement is brought on the lateral axis responses, namely roll rate and bank angle. For 2 cases (Figure 13 and Figure 14), yaw axis dynamics are also notably improved.

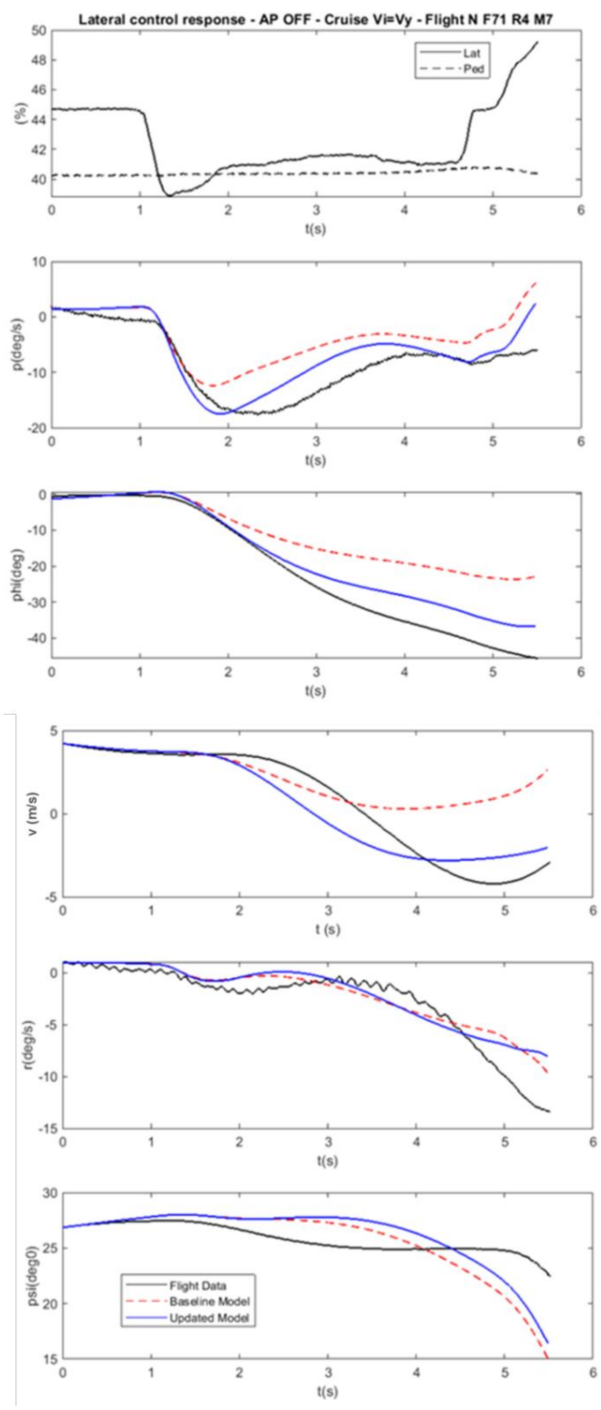

Figure 11. Flight case 1 - comparison with FT, before and after force and moment corrections

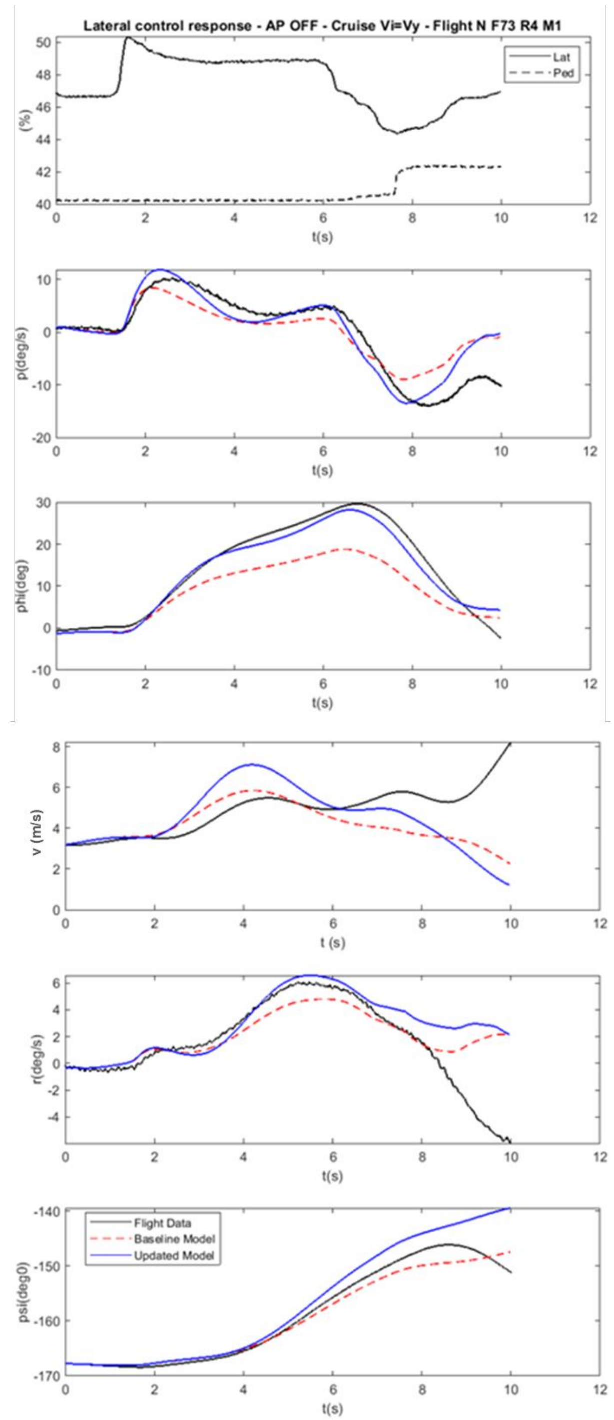

Figure 12. Flight case 2 - comparison with FT, before and after force and moment corrections

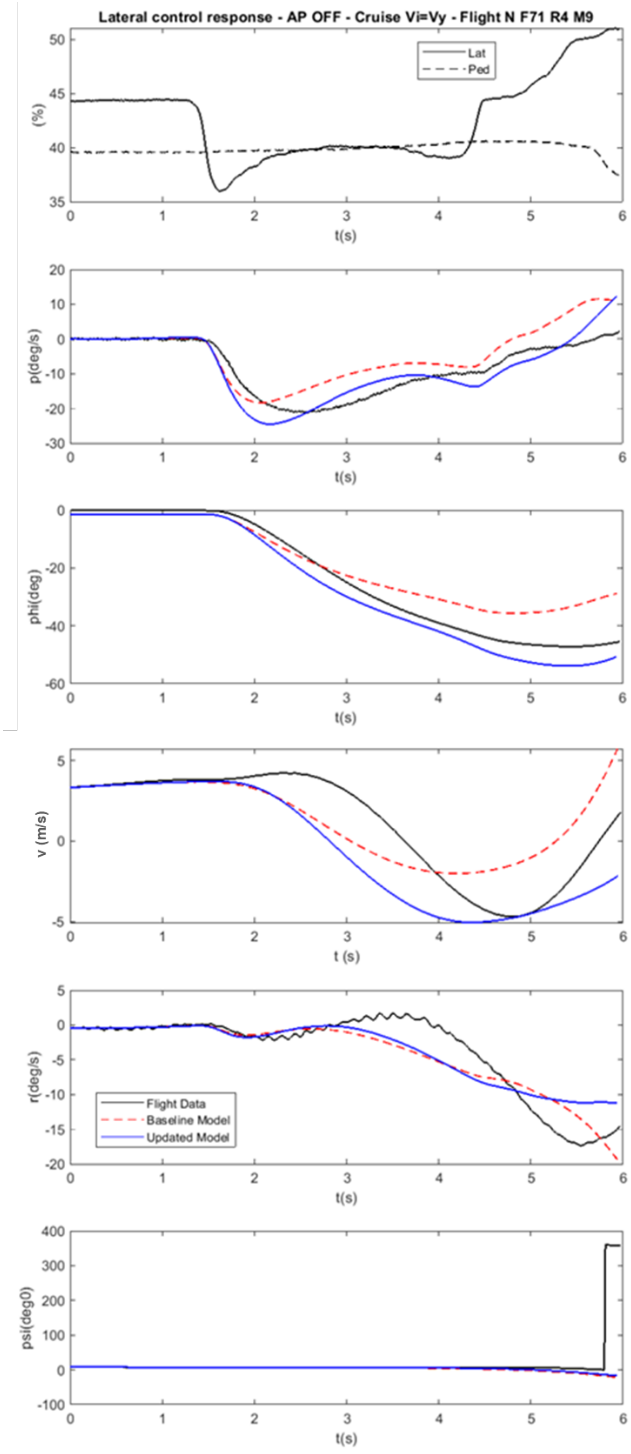

Figure 13. Flight case 3 - comparison with FT, before and after force and moment corrections

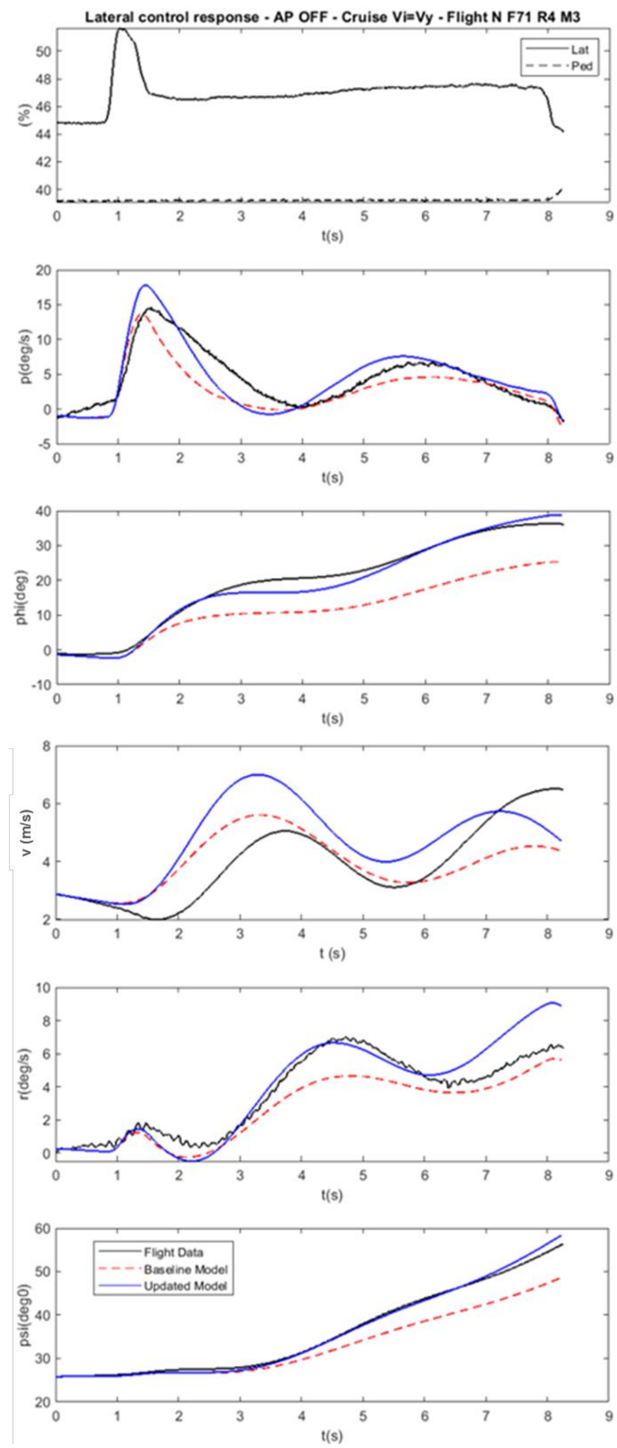

Figure 14. Flight case 4 - comparison with FT, before and after force and moment corrections

The lateral-directional oscillation (LDO) mode is shown in Table 8. The eigenvalues for the baseline model and the renovated model are compared with those from FT SID. The renovated model LDO prediction is significantly improved. Figure 15 presents the same results in the LDO requirements chart.

Table 8. AW139 Dutch-Roll (75 kn) from SID, Baseline model and Renovated model.

LDO eigenvalue	ζ	ω_n (rad/sec)
AW139 Baseline model	0.1322	2.2956
AW139 FT	0.3594	1.3972
AW139 Renovated model	0.4654	1.0594

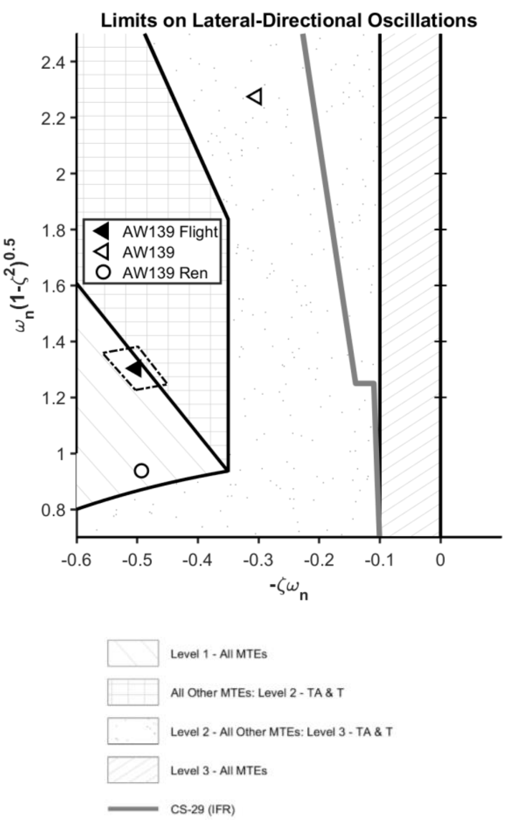

Figure 15. LDO characteristics of AW139 before and after renovation compared with flight

The results presented above show real improvement of the lateral axis dynamics and marginally of the yaw axis in response to lateral stick inputs. These conclusions are even more interesting as the derivatives are identified from QTG flight test data not ideally suited for system identification.

It emerges from this result that corrective force and moment linear terms can likely capture some physical effects potentially missing in the nonlinear model.

Identification of the baseline model deficiencies

Adding force and moment increments to flight mechanics models of training devices is a common (though ad-hoc) technique to improve model response such that it stays within QTG tolerances of the flight-test data. Using SID results to obtain accurate flight-test models of the aircraft characteristics provides for a systematic, verifiable, procedure to determine the aerodynamic 'delta' derivatives. The leverage of SID results can improve the flight model over a larger portion of the flight envelope, saving time and cost.

Beyond this advantage, applying force and moment increments method as described in this paper is also one interesting approach for analyzing and identifying potential sources of shortfalls in the nonlinear flight model. Indeed, state-space model derivatives are widely used to analyze rotorcraft flight mechanics, handling qualities and dynamic responses. To complement shortfalls in responses predicted by simulation models, e.g. for the qualification test guide (QTG), the derivatives can be used to track several sources of physics-based model deficiencies and help achieve improved model fidelity.

In Ref. 15, Padfield provides a detailed analysis of stability and control derivatives and links them to helicopter's main flight dynamics parameters. The relevant derivatives identified during the AW139 model renovation can thus be investigated and help understand where the model physics can be improved.

The case-study showed that L_p, L_r and N_r are the most relevant stability derivatives. L_p is the roll damping, and reflects helicopter's short-term, small and moderate amplitude, handling characteristics. Given the first-order response of roll-rate to lateral stick input (Tischler and Remple, Ref. 4), the time constant (time to reach 63% of steady state) of the fuselage roll rate is given by $-1/L_p$ (sec). This time constant is sensitive to rotor flap hinge characteristics (transfer of moment to the fuselage) but also to the fuselage response to rotor lateral moment (mainly fuselage inertia).

L_r and N_r are 2 derivatives which have a primary influence on the LDO (i.e. "Dutch roll oscillation") character of the helicopter. L_r is a coupling derivative which reflects a rolling moment due to yaw rate. Its physical origin is in the vertical offset of the tail rotor thrust and vertical fin side force from the aircraft center of mass.

N_r is the yaw damping derivative and has a first-order effect on the damping ratio of the LDO (Table 8). The N_r value is sensitive to tail rotor load dynamics and to the interference of the main rotor wake shed onto the tail rotor in forward flight. The frequency of the LDO mode is corrected via renovation to the N_v derivative.

Regarding the derivatives used for force and moment increments calculation the following model improvements were pointed out for further analysis:

Rotor flap hinge characteristics

The hub capacity to deliver rotor bending moment to the fuselage is mostly dependent on the flap hinge characteristics. The discrepancy observed in the L_p derivative could be a consequence of inaccurate values of the following parameters:

- Flap hinge offset
- Flap articulation stiffness and damping

Fuselage inertia,

In many cases simulator manufacturer doesn't have the accurate inertia of the fuselage. When insufficiently estimated, this parameter can impact the fuselage short term angular responses.

Main rotor interaction on Tail rotor

Tail rotor thrust is the primary parameter impacting yaw axis dynamics through the derivatives N_v, N_r. The efficiency of the tail rotor and associated stability derivatives N_v, N_r are significantly affected in forward fight by the interference with the shed wake of the main rotor.

AW139 Physics-based model enhancement

In this case-study, many of the potential shortfalls identified above are due to inaccurate or lacking helicopter intrinsic data such as the flap hinge characteristics (offset, stiffness and damping) or the fuselage inertia. As candidate improvement parameters, they can be tuned, either manually or in a gradient-based iterative process, in order to improve the fidelity with FT data. As these parameters are supposed to be constant over the flight envelope, it's important to tune them at different flight speeds.

Under the scope of work of AVT-296, the physics based-model tuning of the AW139 to resolve the potential deficiencies identified earlier were investigated. Figure 16 presents the results for one flight case. The improved nonlinear model is in green. The tuning also included coupling with pitch axis. The model renovated with force and moment increments (from previous section results) is also presented in blue for comparison. Comparisons of the improved nonlinear model with flight data (in black) show a good matching in the 3 angular responses.

Further work is needed to assess and improve the physics-based model fidelity at other flight conditions. As stated before, this work focused only on system ID as renovated based on a single flight condition, whereas a full Level D simulation validation and update study will require model renovation based on system ID at several flight speeds.

So, the renovation improvements of the full flight envelope model will require system ID results at several flight conditions across the flight envelope (typical 4 flight conditions at low altitude and 4 flight conditions at medium altitudes; see Tischler and Remple, Ref. 4). However, the potential brought by the renovation method based on force and moment increments can greatly contribute to improve the first principle physics-modelling of the nonlinear flight simulation.

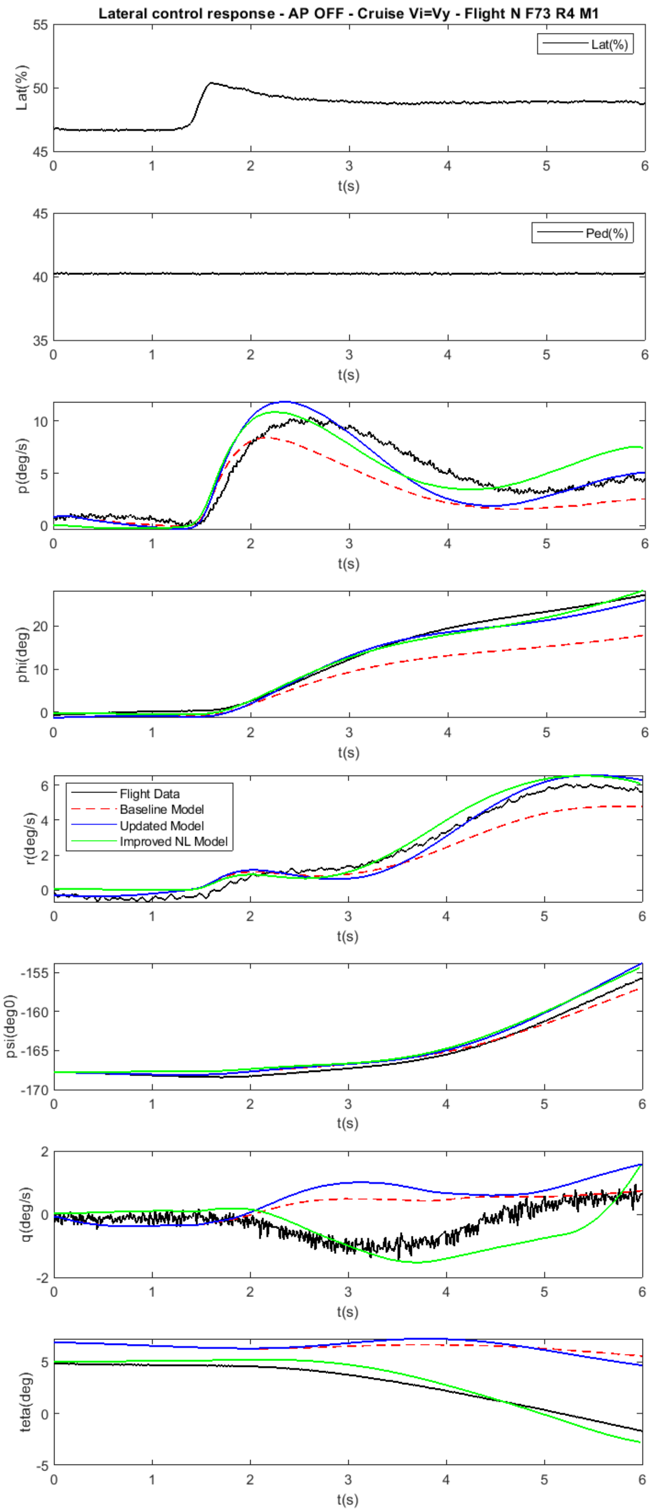

Figure 16. Flight case 2 - comparison with FT, after physics-based model improvement

DISCUSSION

As stated earlier, the objective of this case-study was to investigate whether the existing QTG flight data could be used to extract some essential flight dynamics data and use them to renovate/improve the physics-based model.

The approach comprised 3 steps:

1. Investigate the applicability of using QTG flight test data for the use of System Identification methods to estimate stability and control derivatives (wherein, frequency sweep tests are the ideal flight-test inputs).

2. Apply the renovation method based on force and moment increments, first to improve the model fidelity, second to identify physics-based model shortfalls and improvement

3. Apply some of the improvement axes to the physics-based model

Regarding System Identification, frequency sweep tests are particularly well adapted to this purpose and have become, over years, standard tests for identification, complemented by time domain tests for model verification (Tischler and Remple, Ref. 4). Therefore, using QTG flight data for stability and control derivatives estimation could appear as a "step back" from frequency sweep testing. However, these QTG tests are commonly used during simulators' certification development process. Furthermore, the realization of frequency sweep flight tests remains an obstacle for data package providers due to the additional flight test costs and increased accuracy of required instrumentation. Moreover, these tests need to be fully handled before becoming a part of simulators' development process, and in general, require additional specialized test manoeuvres and special knowledge by rotorcraft system ID subject matter experts (SMEs). This means time and investment. Therefore, some manufacturers usually remain quite conservative in resorting to SID.

The case-study on AW139 QTG flights provides interesting thoughts to this discussion. It was found that applying frequency domain identification as developed by Tischler and Remple (Ref. 4) can provide with good ID fidelity and a set of extracted derivatives capturing some physical aspect of the flight dynamics. The exercise showed that roll damping (L_p), roll coupling to yaw (L_r) and yaw damping (N_r) could be identified with good fidelity. It comes out from this investigation that, even if the authors preach in favour of extensively developing dedicated SID flight tests in this process, undeniably the exercise shows that a solid approach in System Identification as developed in CIFER software suite can help capture some of the helicopter dynamics, even with QTG data not ideally suited to this purpose.

Regarding the renovation technique based on deltas of force and moment, it was applied successfully to the case-study. The study showed that it was possible to select a set of relevant derivatives for the case studied (lateral-directional dynamics). The direct addition of these force and moment increments demonstrated real model enhancement when matching with flight data. The Dutch-Roll characteristics prediction in terms of frequency and damping was also improved in comparison with SID results.

Moreover, the analysis of the derivatives helped identify several key improvements of the physics-based model. These improvements revealed to be effective in model fidelity enhancement. Obviously, these limited improvements are not sufficient to cover the full-flight envelope. Therefore, during the model calibration process, simulator manufacturers resort to some artificial adjustment parameters in order to fully comply with the FAA and the EASA model certification requirements. These parameters are essential to the process of model certification. They are used to overcome complex modelling issues that, if they could be solved with physical equations, it would be at the cost of much increased complexity that is not always compatible with real time simulation commitments.

The experience in this study recommends pushing as far as possible the physics-based model improvement before introducing artificial adjustment parameters in the equations. Following this effort, the need for artificial parameters adjustment could be significantly reduced. The approach proposed in this paper gives a systematic procedure to enhance physics-based models.

CONCLUSIONS

In 2018 the NATO Science and Technology Organization (STO) engaged a Research Task Group (RTG) on rotorcraft flight simulation model fidelity. The primary goal of this RTG was to apply and compare flight simulation model enhancement methods and fidelity assessment criteria based on flight-test case studies.

Among the case-studies one collaborative work investigated the potential use of QTG flight data in System Identification. The objective of this work was to assess whether the state-space models resulting from such identification could be used to enhance the physics-based model. The results presented in this paper lead to the following conclusions:

1. The use of QTG flight data in obtaining the complete set of 6-DOF system ID derivatives for model renovation, is not ideally suited as achieved via frequency-sweep tests, but can provide a more limited 3-DoF lateral-directional model with adequate fidelity for lateral-directional model renovation.

2. The identified derivatives could be used within the renovation method based on force and moment increments. The method was successfully applied to the specific case of lateral-directional simulation fidelity enhancement.

3. Force and moments increments are usually used by simulator manufacturers during their model certification process and determined using ad-hoc methods. However, the system ID-based method as applied within the STO Research Task Group proposes a systematic and physically meaningful way to calculate the force and moment deltas.

4. The relevant derivatives used in the study-case fed a physics-based model analysis and helped identify several modelling gaps. Furthermore, the physics-based model improvement included solutions to these gaps and showed real possibilities for simulation fidelity enhancement.

5. Resorting to System Identification, even with QTG flight data, can contribute to better understand the physics-based model shortfalls and to take the adequate actions to enhance the model, before introducing artificial tuning parameters.

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