Bell V-280 System Identification and Model Validation with Flight Test Data using the Joint Input-Output Method

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ABSTRACT

With modern aerospace vehicle configurations, highly-coupled redundant flight control surfaces are becoming standard practice. For such vehicles, traditional System Identification (SID) methods may not accurately capture the individual contributions of effectors to the vehicle bare-airframe response. A Joint Input-Output (JIO) methodology was used to estimate the control power for each highly-correlated roll effector of the Bell V-280 hover configuration. The methodology was demonstrated using flight test data, where the identification results were compared to a high-fidelity hardware-in-the-loop simulation in the V-280 System Integration Lab.

NOTATION

p	Roll rate
DCP	Differential Collective Pitch
JIO	Joint Input-Output (Method)
δ_S,	Stick Inceptor Inputs

INTRODUCTION

The rotorcraft industry has long-recognized System Identification (SID) as an important part of fly-by-wire control law development. Using SID in early flight testing can reduce control law development risks and costs associated with in-flight optimization and handling qualities testing. SID methods are also valuable when trying to improve the correlation between flight test data and physics-based flight dynamics models. For traditional stick or effector sweep inputs, current frequency-domain SID tools can extract the aircraft flight dynamic model (Ref. 1). However, they may not be able to differentiate the contributions from highly-correlated control effectors. For aircraft with redundant controls, such as the Bell V-280 Valor tiltrotor in certain flight conditions, highly-correlated effectors require a more sophisticated SID approach to determine the control effectiveness of each effector. To address this challenge, the U.S. Army Combat Capabilities Development Command Aviation & Missile Center (CCDC AvMC) and the Universities Space Research Association (USRA) NASA Academic Mission Services (NAMS) are working to incorporate the Joint Input-Output (JIO) method (Ref. 2) into their Comprehensive Identification from Frequency Responses (CIFER®) SID toolset (Ref. 1).

The JIO method considers the inputs and outputs of the bare-airframe jointly as outputs to an intermediate reference input. The JIO Method was first used by Akaike (Ref. 3) in cross-spectral analysis to mitigate output noise correlation when identifying single-input-single-output systems operating in closed-loop. The JIO was further developed by Bretthauer with a derivation of multi-input-multi-output JIO in the frequency domain from spectral quantity matrices (Ref. 4), showing the equivalence of frequency domain and spectral approaches. JIO has been used recently for inflow model identification (Ref. 5) and bare-airframe aircraft identification (Refs. 2, 6-8). Ref. 2 provides a derivation for the JIO method for use in aircraft identification, including both simulation and flight-test examples, as well as provides a description for the determination of coherence for frequency responses identified using the JIO method. Ref. 2

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showed flight test results from a fixed-wing vehicle, where two different data sets were available for the same vehicle. The different data sets were used to correlate identified JIO frequency responses with identified frequency responses from the direct method and showed good agreement between the two methods. The approach validates that the JIO method produces accurate identification results for highly-correlated effectors. While bare-airframe identification using the JIO method has been used successfully for full-scale, manned, fixed-wing vehicles (Refs. 2 and 6), application to Vertical Takeoff and Landing (VTOL) vehicles has been limited to simulations or sub-scale and unmanned vehicles (Refs. 7 and 8). Most recently, the JIO Method has been applied to the V-280 simulation data by Berrigan (Ref. 9). This paper will focus on application of the JIO Method to V-280 flight test data.

The JIO method allows for identification of the individual contributions of each control effector when multiple highly-correlated control effectors exist, and has been successful in recent use for bare-airframe aircraft identification (Refs. 2, 6-8). Results from the JIO method will lead to a more accurate identification for validation of models, control law design, and performance.

Under the Joint Multi-Role Technology Demonstration (JMR TD) program, Bell and CCDC AvMC TDD have collaborated to improve flight control development methods of the Bell V-280 Valor. This work focuses on the collaborative development of methods to identify through flight test, the contributions of individual control effectors in hover.

The remainder of the paper includes a description of the V-280 system identification, including aircraft description and an overview of the system identification methodology. This is followed by a description of the flight test, the results of the identification or roll response to Differential Collective Pitch (DCP) and symmetric lateral cyclic.

V-280 SYSTEM IDENTIFICATION

Aircraft Description

The V-280 is Bell's next generation tiltrotor designed for a Future Long-Range Assault Aircraft (FLRAA) program of record. In the 27 months of flight test, Team Valor has accumulated 172 hours of flight time and 318 operating hours. The V-280 has exceeded 300 knots, without sacrificing range, payload capacity, or flying qualities.

Figure 1. V-280 in VTOL Mode flight.

The V-280's two engines are fixed horizontally on the wingtips, while the rotor pylons are rotated to allow for Vertical Take-Off and Landing (VTOL), hover, and forward flight. In the VTOL configuration, the aircraft uses a combination of rotor collective and cyclic inputs for control authority. As the aircraft transitions to cruise mode, the flight control system transitions to flaperons and ruddervators. The overall control system is well harmonized, yet presents a case where redundant control effectors are in use for major portions of the flight envelope.

In a hover regime, the V-280 rotor control effectors involve both rotor differential collective pitch (DCP) and rotor lateral cyclic. As correlated effectors, these are of the most interest for the current JIO method application. DCP and lateral cyclic control methods are somewhat redundant in that either DCP or lateral cyclic can be used to control the vehicle in low speed flight. From a flight control perspective, the pilot's lateral stick displacement results in both DCP and symmetric lateral cyclic at both rotor heads. The proportions of DCP and lateral cyclic are determined by a fixed-ratio control allocation strategy. For helicopter-mode lateral control, the V-280 control laws will always command both DCP and lateral cyclic, meaning they are always fully-correlated.

System Identification Methodology

Referring to Fig. 2, the system identification goal is to determine a bare-airframe frequency response matrix $\mathbf{P} = [p/\delta_{DCP}\ p/\delta_{lat}]$. That bare-airframe response matrix is the basis for identifying parametric models (transfer-function and state-space models), which can then provide important information such as the control derivatives or effectiveness. This frequency-domain approach (Ref. 1) invokes the JIO method as an additional post-processing step to obtain the bare-airframe response to individual control effectors (Ref. 7). The closed-loop vehicle is excited using frequency sweeps of the control inceptors/effectors to smoothly excite a broad range of aircraft response frequencies. The time history signals for the sweep, control effectors, and aircraft response are recorded, then transformed into the frequency domain using CIFER® (Ref. 1).

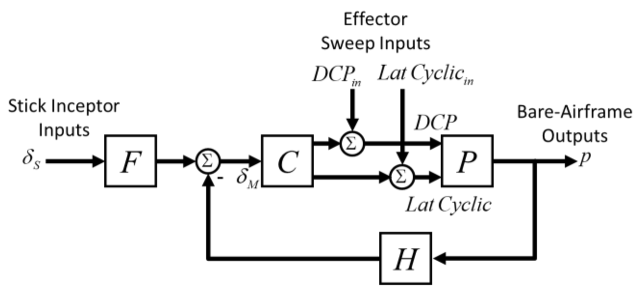

Figure 2. Top level V-280 closed-loop block diagram (lateral axis, hover).

The JIO method computes the bare-airframe frequency response matrix by first computing responses with respect to a reference signal chosen as the external sweep command for a given maneuver: pilot stick inceptor inputs (δ_S), DCP_{in}, or $Lat\ Cyclic_{in}$. Responses from reference signal to effector and bare-airframe outputs are computed jointly. Subsequently, the bare-airframe response matrix is simply the product of the effector-to-reference frequency response matrix inverse with the output-to-reference frequency response matrix. For the case of using sweeps at δ_S and DCP_{in}, the JIO equation is expressed as follows:

$$\left[\frac{p}{DCP} \quad \frac{p}{Lat\ Cyclic}\right] = \left[\frac{p}{\delta_S} \quad \frac{p}{DCP_{in}}\right] \begin{bmatrix} \frac{DCP}{\delta_S} & \frac{DCP}{DCP_{in}} \\ \frac{Lat\ Cyclic}{\delta_S} & \frac{Lat\ Cyclic}{DCP_{in}} \end{bmatrix}^{-1} \tag{1}$$

In scalar form, Eq. 1 can be thought of simply as a type of chain rule calculation of the bare-airframe response.

While the standard pilot stick inceptor inputs (δ_S) are excellent for obtaining frequency responses of the "effective" bare-airframe $\widehat{\boldsymbol{P}} = \boldsymbol{P} \cdot \boldsymbol{C}$, an issue arises for redundant control inputs. In such cases, the number of pilot stick inceptor inputs δ_S is less than the number of effector inputs: DCP and Lateral Cyclic. To use the JIO method, the effector-to-reference frequency response matrix must be invertible (Eqn. 1). Therefore, the matrix must be square (the number of reference signals must equal the number of effector signals). Alternatively, it is possible to exercise an approach that uses "engineering test commands" to directly sum with the control allocation outputs. The engineering test command is sent directly to the effector as DCP_{in}, or $Lat\ Cyclic_{in}$ shown in Figure 2. The excitation signal is an automated sinusoidal sweep (automated sweep), which excites a known frequency band of interest over a duration of 90s (Ref. 1). The automated sweep can be either summed in at the pilot inceptor or desired effector directly. In SIL testing, it was found that a combination (concatenation) of inceptor input, δ_S, and direct effector automated sweep DCP_{in} provided the best results for determining the effector control powers (Ref. 9). The approach also minimized the number of additional test points compared to standard SID methods.

TEST EXECUTION

Flight Test Execution

The V-280 performed hover flight testing at the Flight Research Center in Arlington, Texas. Flight conditions for testing were limited to total wind less than 10 kts and smooth air to reduce the influence of unmeasured inputs to the SID. Data collection was monitored using near real-time tools to ensure good data quality.

The system was excited using frequency sweeps applied in three different ways: manual piloted stick inceptor input, automated sweep at the inceptor input, and lastly, automated sweep at the effector. Sample time histories of a piloted lateral sweep input and an automated lateral sweep input are shown in Figs. 3 and 4. The sweep command at the inceptor is shown in blue, the control effector signals (DCP and lateral cyclic at the rotor) are shown in red, and the aircraft roll rate response is shown in green.

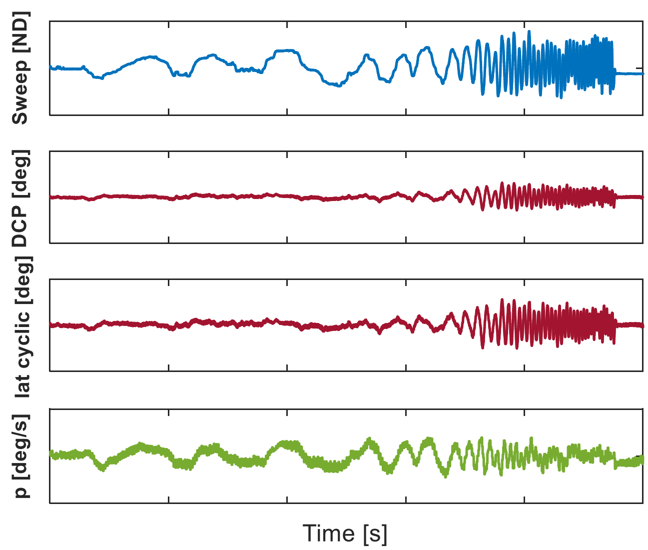

Figure 3. Piloted lateral stick sweep in hover shows that DCP and Lateral Cyclic (at the rotor head) are highly-correlated.

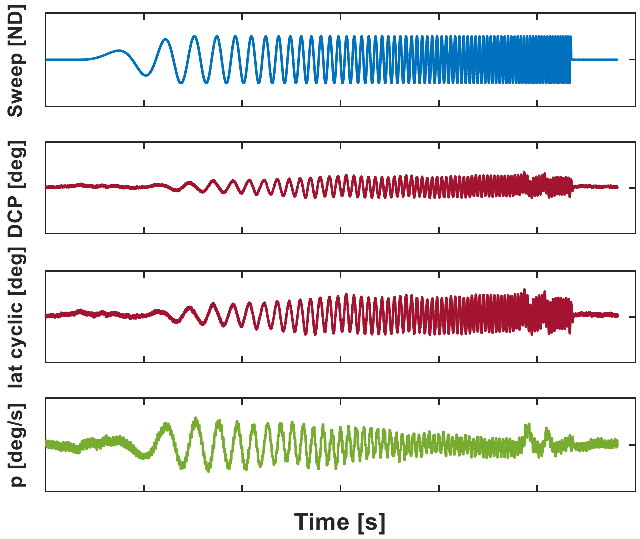

Figure 4. Automated lateral stick sweep in hover shows that DCP and Lateral Cyclic (at the rotor head) are highly-correlated.

Since DCP and lateral cyclic are generated from the same inceptor and are directly geared, the effector signals have very similar frequency content at any point in time, indicating that the controls are highly-correlated.

As there are two highly-correlated control effectors (DCP and lateral cyclic), the JIO method requires two sets of linearly independent frequency sweeps. The lateral stick sweep is a standard frequency sweep used in routine system identification procedures: from Fig 2, a sweep input at δ_S is allocated through $\boldsymbol{C}$ to both DCP and lateral cyclic. To enable JIO to be used, a second frequency sweep is sent directly to the DCP effector as DCP_{in} of Fig.2. Here, the bare-airframe responds ($\boldsymbol{P}$), but the response is feedback ($\boldsymbol{H}$) and allocated through ($\boldsymbol{C}$), resulting in both DCP and lateral cyclic becoming correlated. The resulting time histories for the DCP_{in} effector sweep are shown in Fig. 5. Similar to the lateral stick sweep, the DCP effector sweep results in correlation between the DCP effector and the lateral cyclic effector. The correlation can be observed in Fig. 5 by the very similar frequency content of the effectors at any point in time.

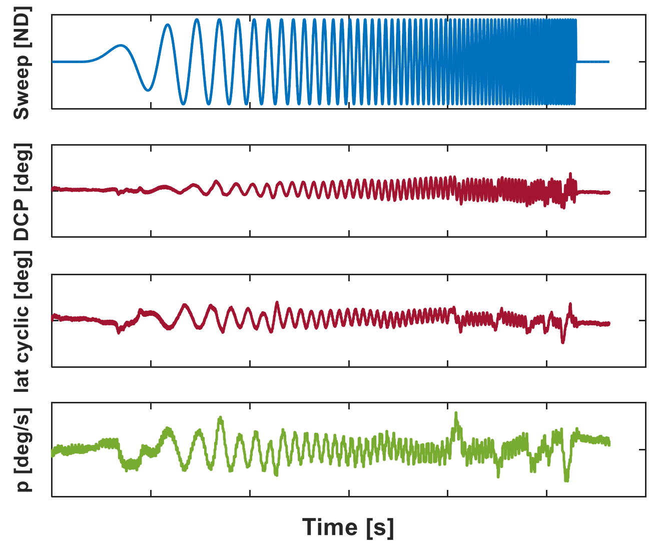

Figure 5. Automated DCP effector sweep in hover shows that DCP and Lateral Cyclic (at the rotor head) are highly-correlated.

The correlation between the two bare-airframe inputs for the sweeps shown can be quantitatively assessed using the cross-control coherence (Ref. 1) of lateral cyclic to DCP, as shown in Fig. 6. The cross-control coherence is shown for both the lateral inceptor sweep (Figs. 3 and 4) and DCP effector sweep (Fig.5). The cross-control coherence is nearly 1.0 for the majority of the identified frequency range, indicating that DCP and lateral cyclic are completely correlated. Tischler, (Ref. 1), indicates that MIMO conditioning using the direct (standard) method can accurately extract the MIMO frequency response matrix when the cross-control coherence is less than 0.5.

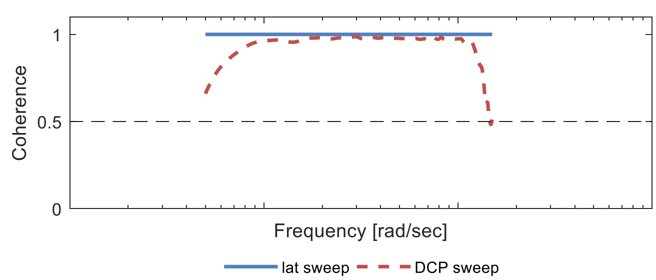

Figure 6. Lateral cyclic to DCP coherence is close to 1 for the entire frequency range, indicating complete cross-control correlation between the effectors.

The qualitative and quantitative measures indicate very high DCP and lateral cyclic correlation. Thus, the JIO process can be used to accurately obtain frequency responses with respect to individual control effectors.

SIL Test Execution

The V-280 SIL integrates real aircraft hardware (flight control computer, avionics, pilot inceptors, and actuators) and a 6 DOF math model based on Generic TiltRotor (GTR) for aircraft response. GTR includes modeling for other dynamic components such as the engine, drive train, and sensor models. The GTR flight loads are applied to the aircraft actuators through load actuators. In the SIL, frequency sweeps were performed in the same three ways as flight test, test execution and analysis of all the SIL data is shown in Ref. 9.

Results

Flight Test Frequency Response Identification

The lateral stick and DCP effector frequency sweep time histories attained in flight were processed within CIFER® utilizing the JIO methodology to obtain frequency responses. Measured signals included pilot and effector inputs, as well as vehicle response. A sample closed-loop roll rate frequency response to lateral stick, is shown in Fig. 7, where both piloted and automated sweeps are compared.

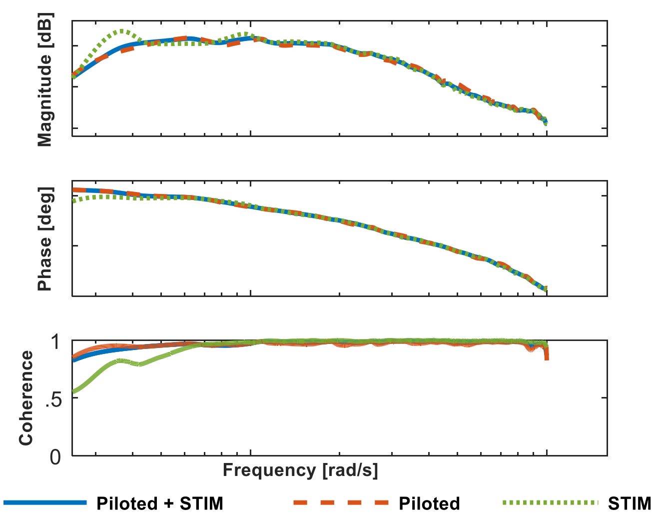

Figure 7. Roll rate due to lateral stick (closed-loop) frequency response for automated versus piloted frequency sweeps.

JIO results were obtained from automated sweeps (labeled as “STIM”), from piloted sweeps (labeled as “Piloted”), and also by combining (concatenating) both automated and piloted sweep records (“labeled as “STIM+Piloted”). The primary difference between each data set can be observed at the lower-mid section of the frequency range, where there are differences in coherence (and thus data quality).

Sample bare-airframe roll rate frequency responses to DCP input are shown in Fig.8 for the automated (STIM), piloted, and concatenated piloted and STIM frequency sweeps. The standard SID guidance is to use piloted sweeps (Ref. 1). When a sweep is performed by a pilot, a specific frequency may be excited more than once or at a different rate as an inherent result of this being a manual sweep with human variability, which can provide more content. However, given the biomechanics of the cockpit, reliably obtaining multiple quality data sets from piloted sweeps can be time consuming

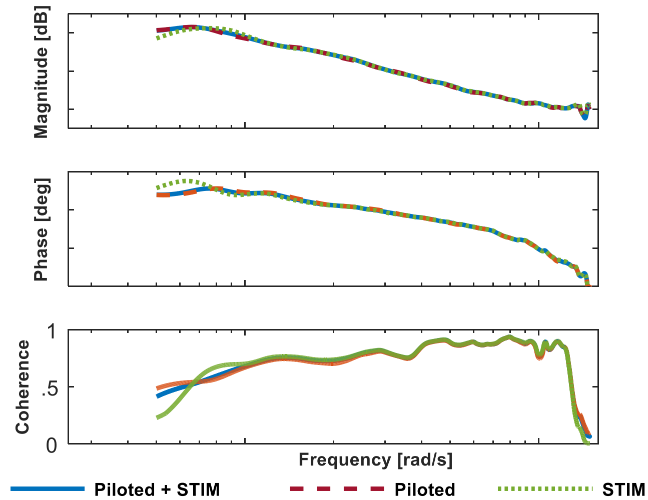

Figure 8. Roll rate due to DCP frequency response for automated versus piloted frequency sweeps.

and costly. An automated sweep will provide consistent content, which can be seen when comparing the roll rates in Fig.3 (piloted) and Fig.4 (automated). The automated input in Fig.4, provides a smoother response that will be consistent for each record. However, it lacks the variability a pilot would provide. The recommendation is to fly both automated and manual piloted sweeps, and use at least two data records, selected for the highest quality. This combination provides the richer content from the piloted inputs, while improving consistency and reducing flight test time.

In addition to the JIO methodology, the frequency sweep time histories were also processed with the traditional SISO technique (assuming all response is due to one effector at a time and neglecting the other). The roll rate frequency response to each lateral effector (DCP and lateral cyclic), is shown in Fig. 9. This figure shows both the JIO computed frequency response and the SISO frequency responses for the cases where one input is neglected. Responses are shown for both DCP and lateral cyclic effector inputs. The difference between the JIO and SISO frequency response for DCP is negligible, indicating that the SISO solution is satisfactory for DCP in that particular sweep. However, the JIO frequency response for lateral cyclic is much smaller in magnitude than the SISO calculated response. This is expected, given that DCP has a much larger contribution to roll in hover and cannot be ignored. Thus, the SISO solution yields incorrect results as it cannot split the control power between the two fully-correlated effectors and should not be used for lateral cyclic.

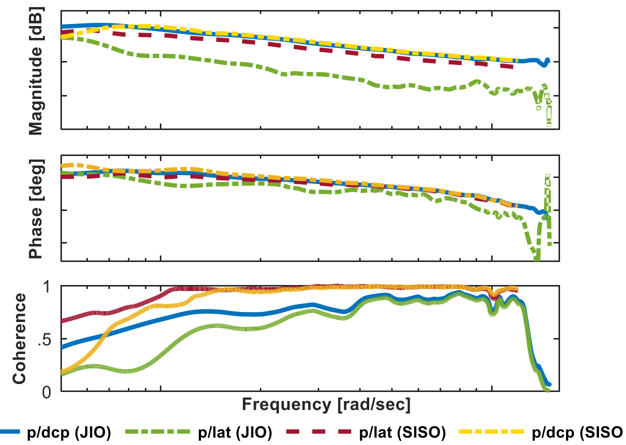

Figure 9. DCP and Lateral Cyclic to roll rate frequency response.

Comparison of Flight Test and SIL Frequency Responses

Comparison of flight test and SIL frequency responses (Figs. 10 and 11) determined from using the JIO approximation methods for DCP and lateral cyclic show good agreement validating that the SIL accurately predicts the flight test response.

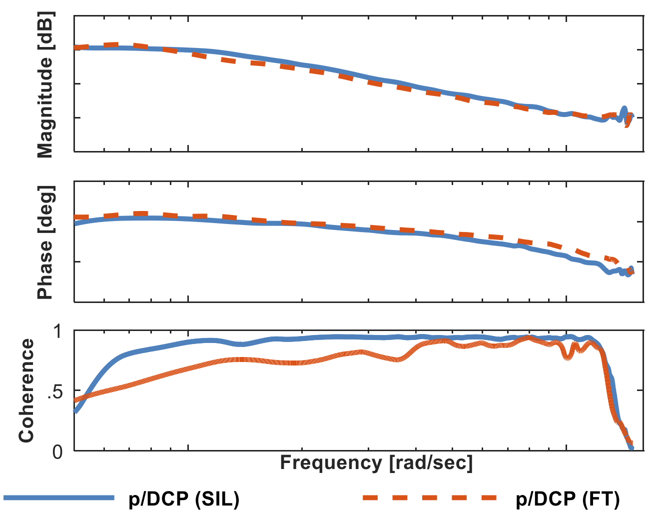

Figure 10. Flight Test and SIL comparison of DCP to roll rate frequency response.

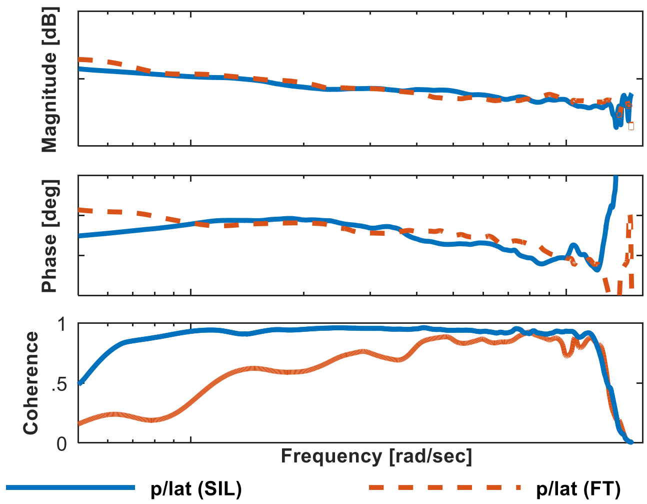

Figure 11. Flight Test and SIL comparison of Lateral Cyclic to roll rate frequency response.

Transfer Function Identification

Once frequency responses have been identified, a low-order transfer function approximation can be identified to determine effective stability and control derivatives. For a hovering vehicle, a low-order 2nd over 3rd order transfer function for roll rate can be derived in terms of stability and control derivatives (Ref. 10), with an effective time delay added to account for higher-order effects such as rotor-inflow, actuator, and sensor dynamics:

$$\frac{p(s)}{\delta(s)} = \frac{L_\delta\left[s^2+\left(-Y_v+\left(\frac{Y_\delta}{L_\delta}\right)L_v\right)s\right]}{s^3+(-Y_v-L_p)s^2+Y_vL_ps-gL_v}\,e^{-\tau s} \qquad (2)$$

Here, δ is a control effector (e.g. DCP or lateral cyclic) and L_δ is the associated roll control derivative. The 2nd over 3rd order transfer function provides a good overall approximation of the pertinent aircraft derivatives over a wide frequency range. However, identification of the actual derivatives requires additional considerations. Thus, while the 2nd over 3rd order approximations can be valuable, a simpler approximation is desired to obtain the control derivatives directly. This can be done by assuming that the frequency range being identified corresponds only to the control derivative, and that all other stability derivatives and corresponding dynamic modes act at sufficiently low frequency such that they can be neglected (i.e., can assume that Y_v=L_v=L_p=0). Under this assumption, the roll transfer function simplifies to a 0th over 1st, k/s type of approximation:

$$\frac{p(s)}{\delta(s)} = \frac{L_\delta[s^2]}{s^3}e^{-\tau s} = \frac{L_\delta}{s}e^{-\tau s} \qquad (3)$$

The k/s approximation provides the associated control derivative directly as L_δ = k. This high-frequency approximation will provide the most accurate initial estimate of the control derivative, under the assumption that all other derivatives and modes have sufficient frequency separation from where the control derivative is effective. Also, due to the simplistic nature of the approximation with only two parameters (L_δ and τ), the identification process is very robust to any local perturbations in the frequency response due to noise or random error.

The k/s low order approximation is used to estimate the control derivatives from the roll rate frequency responses. Transfer function coefficients are identified in CIFER®, and the control derivatives can be directly identified as the leading numerator coefficient, under the assumption that all applicability requirements have been met.

A sample frequency response for DCP to roll rate is shown in Fig. 12, which compares the JIO frequency responses identified from the flight test relative to the identified transfer function approximations. A k/s transfer function, indicated as "Model" is identified on the basis of only high frequency portions of the frequency sweep. The identified transfer function has excellent agreement with the flight test data, having a cost function J < 50 (per CIFER's definition) for the applicable frequency range. The J<50 cost function indicates that the identified transfer function and flight test data are nearly indistinguishable (Ref. 1).

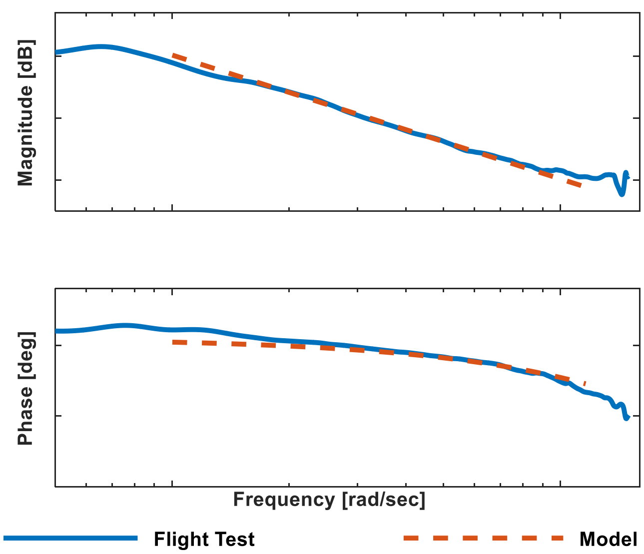

Figure 12. DCP to roll rate frequency response from JIO and low order transfer function approximation.

Similarly, a frequency response for roll rate to lateral cyclic is shown in Fig. 13, which compares the JIO frequency responses identified from the flight test data relative to the identified transfer function approximations. A k/s transfer function (high frequency only) is identified, also having excellent an agreement with the flight test data for a cost function J < 50 for the applicable frequency ranges. This result indicates again that the identified transfer function and flight test data are nearly indistinguishable (Ref. 1).

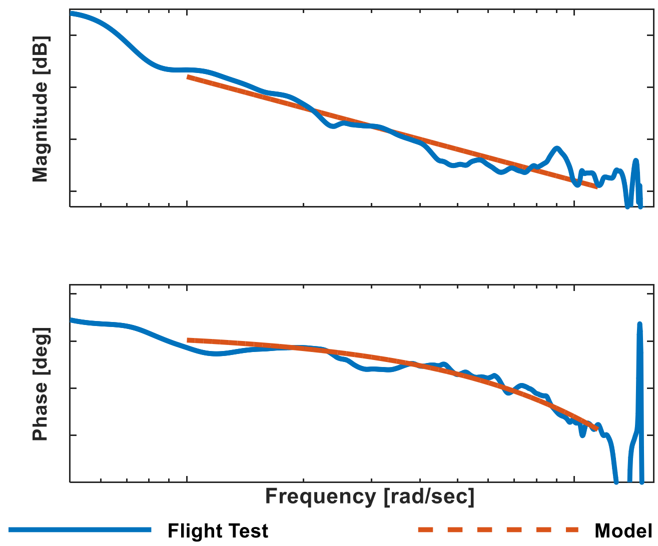

Figure 13. Lateral Cyclic to roll rate frequency response from JIO and low order transfer function approximation.

While determination of the roll control effectiveness is important to the control allocation design, the primary parameter of interest is the ratio of control effectiveness for the two control effectors (DCP at the rotor and Lateral Cyclic at the rotor). One way to directly obtain the ratio of control effectiveness is to compute the ratio of p/DCP and p/(lateral cyclic) frequency responses. At high frequency, this frequency response ratio simplifies to:

$$\frac{\left(\frac{p(s)}{DCP(s)}\right)}{\left(\frac{p(s)}{lat\ cyc(s)}\right)} = \frac{\left(\frac{L_{DCP}}{s}e^{-\tau_{DCP}s}\right)}{\left(\frac{L_{lat\ cyc}}{s}e^{-\tau_{lat\ cyc}s}\right)} = \frac{L_{DCP}}{L_{lat\ cyc}}e^{(-\tau_{DCP}+\tau_{lat\ cyc})s} \tag{4}$$

Thus, at high frequency, the ratio of p/DCP and p/(lateral cyclic) directly provides the ratio L_{DCP} / $L_{lat\ cyclic}$ which is the ratio of the control effectiveness of DCP to lateral cyclic. The frequency response ratio of p/DCP and p/(lateral cyclic) is shown in Fig. 14, along with the "high frequency" identified transfer function from Eq. 4. Thus, at high frequency, the ratio of p/DCP and p/(lateral cyclic) directly provides the ratio L_{DCP} / $L_{lat\ cyclic}$ which is the ratio of the control effectiveness of DCP to latera cyclic. The frequency response ratio of p/DCP and p/(lateral cyclic) is shown in Fig. 14, along with the high frequency identified transfer function from Eq. 4. The identified control effectiveness ratio has excellent agreement with the flight test data, with a cost function J < 50 for the applicable frequency range.

Identification of the control effectiveness ratio through this frequency response division provides a similar result compared to identifying individual control effectiveness for DCP and lateral cyclic and then taking the ratio. The benefit of the frequency response division is that this method is more robust to any scatter in the p/DCP and p/(lateral cyclic) frequency responses, as that scatter is properly accounted for in the frequency response division rather than being absorbed in the identified individual control effectiveness for DCP or lateral cyclic. This also allows for cost functions of the identified control effectiveness ratio to be directly computed, which is not directly available from taking the ratio of individual control effectiveness for DCP and lateral cyclic.

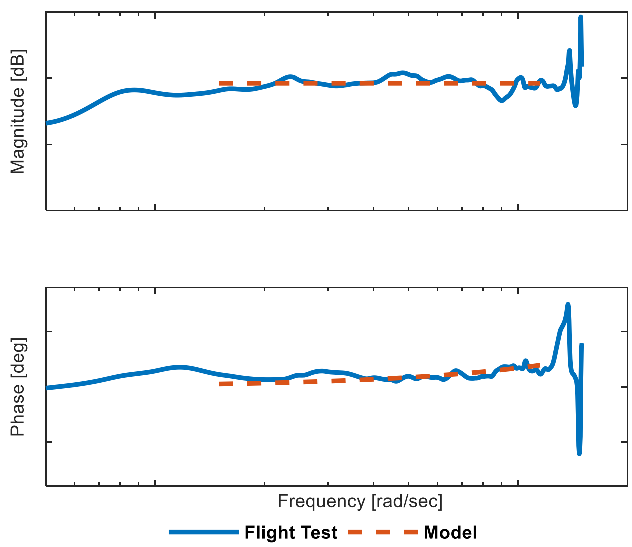

Figure 14. Ratio of p/DCP and p/(lateral cyclic) frequency response from JIO and transfer function approximation.

Comparison of Control Effectiveness

Both DCP and Lateral Cyclic Transfer functions were identified for roll rate frequency responses for both flight test and SIL data. The identified control effectiveness from each identified transfer function are shown as bar-chart representations in Figs. 15 and 16. Comparison of DCP control effectiveness (both identified results from flight test and from SIL) are in good agreement, simultaneously giving confidence to flight identified values from the JIO approximation methods and, also validating the SIL.

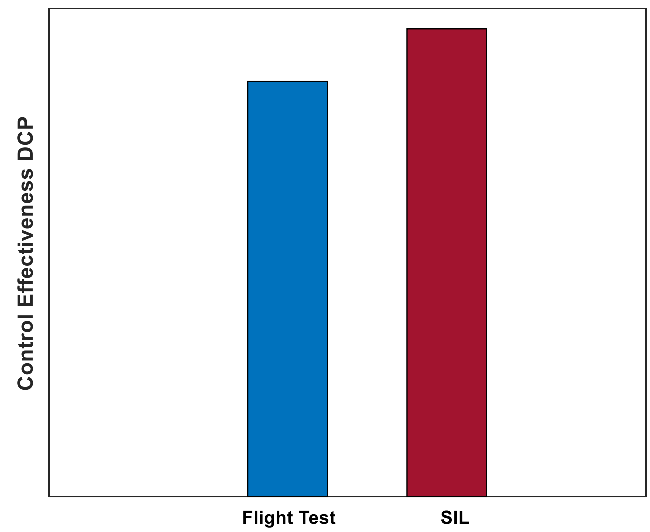

Figure 15. Flight Test and SIL comparison of identified roll control effectiveness for DCP.

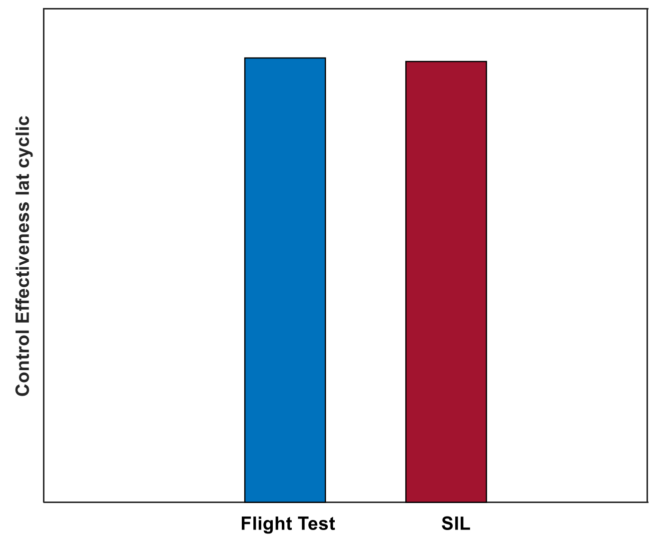

Figure 16. Flight Test and SIL comparison of identified roll control effectiveness for lateral cyclic.

Comparison of the JIO identified control effectiveness for lateral cyclic, indicates flight test and the SIL are also in good agreement. These results indicate that the JIO frequency responses and identified control effectiveness is an accurate and viable method for identifying control effectiveness for the V-280 in hover for both flight test and simulation data.

Finally, a comparison of the ratio of control effectiveness of DCP / (lateral cyclic) can be produced by simply dividing the control effectiveness (control derivatives) of DCP by lateral cyclic. The results of the control effectiveness ratios are displayed in bar-chart form in Fig. 17. As expected from Fig. 15 and 16, the JIO results from flight test data are in good agreement with the results from the SIL.

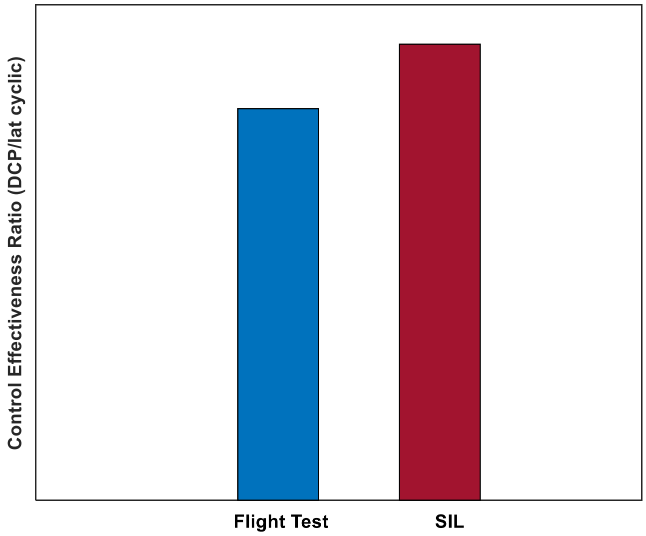

Figure 17. Ratio of roll control effectiveness for DCP/(lateral cyclic).

CONCLUSIONS

For tiltrotors such as the Bell V-280 Valor, flight conditions with highly-correlated effectors require an additional post processing step to the current SID approach to determine the control effectiveness of each effector. Key elements of this work include:

1) Using flight test data, the JIO methodology was able to extract frequency responses from correlated effectors.
2) Control effectiveness can be directly identified from frequency responses using high frequency, low order transfer function approximations.
3) The V-280 SIL was validated against flight test data and accurately captures the frequency responses and control effectiveness examined herein.
4) A combination of standard sweeps from the piloted stick with additional effector sweeps provided the best quality data for performing system identification with the JIO methodology while optimizing flight test time.
5) To minimize flight test time, only one of the correlated effectors needs to be individually swept per axis if the pilot stick inceptor is also swept.

ACKNOWLEDGMENTS

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