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Flying Qualities Applications of Frequency Responses Identified from Flight Data

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Despite increasingly accurate modeling technologies, it is still necessary to validate aircraft models with flight data. One area where this is especially critical is for flight control system development and flying qualities appraisals. Consistent with the frequency domain specification of flying qualities requirements, the method discussed is the identification of an aircraft's frequency responses from piloted frequency sweeps performed in flight. Pilot-generated frequency sweeps were performed on a range of transport aircraft, research aircraft, and simulators. The time histories from the sweeps were transformed into the frequency domain to yield frequency responses that were used for a variety of applications. In some applications, further analyses with the Low-Order Equivalent Systems method were used to identify dominant modes of the bare airframe and of elements of the aircraft's flight control system, as well as those of the augmented aircraft, which were applied to flying qualities criteria. In other applications, the frequency responses from one aircraft were compared to those from other aircraft to support handling qualities assessments in support of same type ratings and minor design changes. The techniques used in the analyses are summarized and several of these applications are reported.

Nomenclature

C	=	cost
F	=	control inceptor force, lb
G	=	gain, dB
K	=	weighting function gain
n_z	=	normal load factor, g
q	=	pitch rate, deg/s
s	=	Laplace variable
T	=	(equivalent) time delay, record length, s
δ	=	control inceptor deflection, in. or deg
ζ'	=	damping ratio of a second-order LOES
τ	=	time constant, s
ϕ	=	phase angle, deg
ω'	=	frequency of a second-order low-order equivalent system (LOES) rad/s

Subscripts

CC	=	control column
HOS	=	high-order system
ICR	=	instantaneous center of rotation
i	=	iteration number
LOES	=	low-order equivalent system
min	=	minimum
ph	=	aircraft phugoid oscillation
sp	=	aircraft short-period oscillation
θ	=	pitch attitude, deg

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Introduction

PILOTED frequency sweeps were performed in support of various Boeing transport aircraft and research programs at The Boeing Company facility in Long Beach, California. Subsequent analysis of the sweeps produced frequency responses that were used for various flying qualities applications.

Consistent with the preferred approach in Ref. 1, Low-Order Equivalent Systems (LOES) parameters were identified from frequency responses derived from flight data and then used to appraise the flying qualities of the entire aircraft's response. Although originally developed specifically for such applications, the use of LOES has been extended to identify dominant dynamics of various systems, including the components of flight control systems.

This paper documents the approach used for the collection and analysis of the piloted sweep data, identification of required parameters, and their application to flying qualities analyses. Case studies are presented, including production transport aircraft and research programs. The majority of the experience was obtained in the pitch axis, and so this paper will concentrate on that axis.

Approach

The approach developed for the use of piloted frequency sweeps for flying qualities applications follows four steps: 1) collection of the piloted frequency sweep data, 2) conversion of time histories to frequency responses, 3) identification of flying qualities parameters from these frequency responses, and 4) application of the parameters for flying qualities analyses. Each of these steps must be controlled carefully to ensure accurate results of sufficient quality for the subsequent steps.

Collection of Piloted Frequency Sweep Data

The quality of the frequency response is dictated by the quality of the time history data collected. Much effort was expended on ensuring that the highest quality of time history data possible was collected. This concerned both the data acquisition and the performance of the sweeps.

Data Requirements

With a dedicated flight test or research aircraft, the data acquisition system is usually of high quality. However, in some of the applications discussed in this paper, production aircraft were used. Thus, it was important to ensure that the instrumentation systems were of sufficient fidelity to provide data suitable for parameter identification and that all necessary parameters were recorded.

Important issues stressed for the instrumentation system include: calibration and fidelity of the sensors, synchronization of the data, and the sampling rate. Of course, the sampling rate and synchronization are interconnected. Both of these affect the correct phasing characteristics of the frequency response and, hence, determination of equivalent time delay from a LOES analysis. Thus, an accurate understanding of the data acquisition system is essential even before data are collected.

Performance of the Sweep

Recommendations for collection of frequency sweep data are included in Ref. 2. These include the frequency range for control inputs, length of the sweep, and magnitude of control inputs. These are all important for the successful transformation of the data into the frequency domain.

Generally, for transport aircraft flying qualities applications, the frequency range of interest is from 0.1 to 10 rad/s. This effectively covers the low frequency (which defines the response-type), the mid-frequency (the flying qualities), and the high frequency (to address pilot induced oscillation concerns).

The length of the sweep is critical because it determines the minimum frequency that can be identified during the subsequent transformation into the frequency domain. Tischler[3] recommends the data record length for a single sweep should be

$$T = 10\pi/\omega_{\min} \tag{1}$$

Thus, to identify dynamics at a frequency as low as 0.1 rad/s would require a total record length of at least 314 s. More often, the minimum recommended record length is specified as around 80–90 s,[2,3] which would allow dynamics at frequencies as low as 0.35 rad/s to be identified.

A compromise must be achieved between the duration of the sweep and the lowest frequencies that can be identified. The longer the sweep, the more fatigued the pilot will become, especially if performing multiple sweeps in succession. One solution is to concatenate multiple sweeps in the same flight condition to produce a longer record length. However, this approach does not guarantee success in correctly identifying the low-frequency dynamics. It is also necessary that any low-frequency modes are excited to a sufficient degree that their response is measurable.

For a conventional response-type transport aircraft, the phugoid mode is generally in the region around 0.1 rad/s, with its residual response apparent at frequencies above 0.2 rad/s. With the combined effects of the phugoid's low frequency and low damping, any appreciably sized input will produce a considerable response probably beyond the region of linear response, and often resulting in the aircraft deviating from trim. Thus, smaller pilot inputs have to be used at low frequencies to ensure the aircraft response stays within reasonable limits.

The consequence of the use of smaller control inputs at low frequencies is that the coherence between pilot input and aircraft response can be poor, resulting in difficulty generating an accurate frequency response at these low frequencies, often leading to phase problems for the entire response. Thus, the worth of data generation at such low frequencies is questionable, and so the use of shorter sweeps in the range of 90–120 s is, in the authors' experience, about optimum.

One approach to identification of phugoid dynamics is to perform a separate excitation and extract the required parameters in the time domain.[4] This approach was refined by performance of a phugoid excitation while collecting the frequency sweep data. The procedure followed is to perform one sweep, then the phugoid excitation, and then a repeat sweep. The two sweeps are for redundancy. Hopefully at least one should be sufficient for analysis, or the two could be concatenated for better results. Performing the phugoid excitation between the two sweeps allows the pilot to recover from the first, while also ensuring that the flight condition is representative of both sweeps.

The phugoid excitation, consisting of a column pull and release, can then be analyzed in the time domain to determine the natural frequency and damping of the mode. Given that a sufficiently capable LOES analysis tool is used, these parameters can then be used in a LOES analysis where they are fixed at legitimate values.

Another essential step in carefull control of the data collection is in training the pilots in simulators before the flights. This allows them to develop the correct control technique for the particular aircraft in the appropriate flight condition. This includes calibration between the required magnitude of input and resulting aircraft response.

During the data collection, coaching by a flight-test observer has proven beneficial. Watching the strip charts in real time, the observer counts down to the pilot when to reverse inputs, especially useful in the low-frequency portion of the sweep. Once the pilot has moved to mid-frequencies, it is no longer necessary to call the reversal in control inputs, but the observer still provides feedback on the progress through the frequencies. In this way, the observer controls the length of the sweep. Additionally, throughout the sweep, the observer provides feedback on the magnitude of the pilot's inputs and aircraft responses.

Fourier Transformation to Frequency Domain

The Fourier transformation of the time histories to the frequency domain was performed with the commercially available software package CIFER, developed by the U.S. Army Aeroflightdynamics Directorate.

When the guidance of Tischler[3] and Tischler and Cauffman[5] are followed with regard to filtering and windowing the data, good frequency responses were obtained with good quality, clean time history data of long duration with a high sample rate. Careful attention to the data quality reaps benefits in the utility of the consequent results.

For some applications, the generation of the frequency responses marks the end of the analysis. However, for other applications, identification of dynamic characteristics from the frequency responses is required.

Identification of Flying Qualities Parameters from Frequency Responses

In the simplest analyses, various parameters can be read directly from the frequency responses, such as frequencies and phases for bandwidth analyses.[6] However, for other analyses, more formal identification of the dynamics is required, and the LOES method is used.

LOES Method

The LOES method was originally developed to identify equivalent modes of high-order aircraft dynamics for comparison with existing low-order flying qualities criteria. A low-order transfer function is matched to a frequency response generated by a high-order linear transfer function representing a high-order system. Here, the method is extended by the use of a similar frequency domain match, but with the employment of flight or simulator time histories that may include nonlinearities as well as high-order effects.

By the use of LOES analyses, it is possible to identify both end-to-end dynamics (for example, pitch rate response to stick command, or sideslip to rudder) and also those of individual components. The former are usually used to generate flying qualities parameters to compare against established flying qualities criteria. The latter are used for model validation.

The matching of the LOES to the High-Order System (HOS) involves the minimization of a sum-of-squares cost function (incorrectly called mismatch in Ref. 1):

$$C = \sum (G_{\text{HOS}} - G_{\text{LOES}})^2 + K \sum (\phi_{\text{HOS}} - \phi_{\text{LOES}})^2 \tag{2}$$

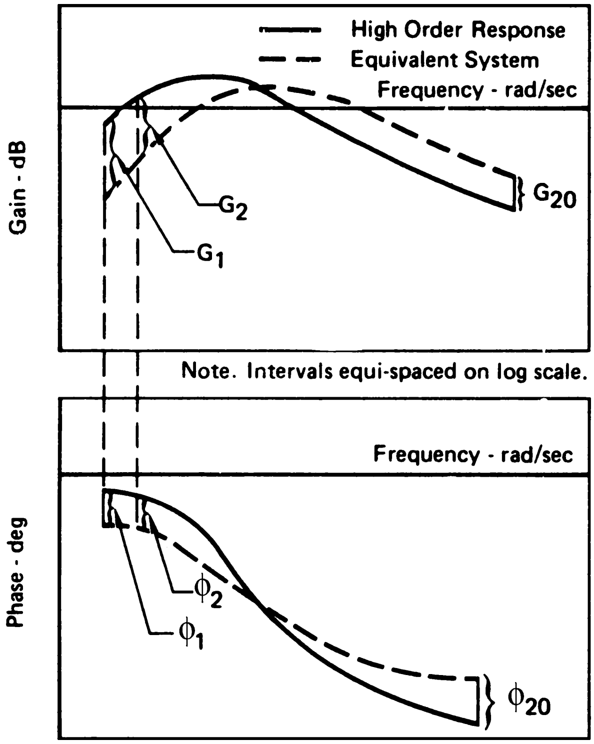

Fig. 1 Definition of LOES mismatch.[8]

With the gain in decibels and the phase in degrees, a weighting function K of around 0.02 is used.[7] Equation (2) is then evaluated at 20 discrete equispaced intervals on a log scale, between the minimum and maximum specified frequencies for the matching[8] (see Fig. 1):

$$C = \sum_{i-1}^{20} \left(G_i^2 + 0.02\phi_i^2\right) \tag{3}$$

The minimum and maximum frequencies used in the matching depend on the dynamics of interest and the frequency range for which high-quality data exist. Cost values of 25 or less represent good fits, but 50 or less is acceptable.

The mismatch, or residuals, between the high-order and low-order frequency responses can then be compared to the envelopes of Maximum Unnoticed Added Dynamics (MUAD),[1] as will be demonstrated in the examples in this paper.

Whereas for some applications, an independent fit of one frequency response can be performed, in others, simultaneous fits of multiple frequency responses are performed. As long as the responses share the same denominator, the difference between them will be only in the numerator terms. This approach was introduced to help constrain the numerator terms, when fits of just one response sometimes produced unrealistic numerator zeros.

A successful matching process requires a robust optimization algorithm. Furthermore, more advanced tools add features to aid the analyst by allowing, for example, individual roots of the low-order form to be fixed or freed during the matching process. Carefully fixed individual roots can lead to better results, but fixing must be performed with caution, always relating to the physical significance of the dynamics. For the analyses reported in this paper, a Boeing Company proprietary tool was used. The tool has proven extremely successful and allows the user great control in the matching process.

Further discussion of the LOES analysis approach can be found in Ref. 1, and the application to transport aircraft is discussed by Rossitto et al.[6]

Low-Order Forms

Essential in the successful application of LOES is the use of appropriate low-order forms. The appropriate low-order form will depend on the dynamics to be identified in the fit range of interest. Thus, it is also important that the orders chosen have physical significance. If they do not, there could be problems with the results of the analyses.

Similarly, the results of the LOES analyses must be inspected for physical significance. If the quality of the frequency response being fitted is poor, it is possible for a LOES analysis to produce erroneous results if not properly constrained.

In a typical application to identify the pitch axis modes for application to flying qualities criteria, either an independent fit of pitch rate alone, or a simultaneous fit of both pitch rate and normal acceleration could be performed. The appropriate low-order forms for such fits are presented in Eqs. (4) and (5), respectively:

$$\frac{q(s)}{\delta_{\mathrm{CC}}(s)} = \frac{K_q s\left(s + 1/\tau_{\theta_1}\right)\left(s + 1/\tau_{\theta_2}\right)e^{-T_\theta s}}{\left[s^2 + 2\zeta_p'\omega_p' s + \omega_p'^2\right]\left[s^2 + 2\zeta_{\mathrm{sp}}'\omega_{\mathrm{sp}}' s + \omega_{\mathrm{sp}}'^2\right]} \tag{4}$$

$$\frac{n_{z_{\mathrm{ICR}}}(s)}{\delta_{\mathrm{CC}}(s)} = \frac{K_{n_z}\left(s+1/\tau_{n_{z_1}}\right)\left(s+1/\tau_{n_{z_2}}\right)\left(s+1/\tau_{n_{z_3}}\right)\left(s+1/\tau_{n_{z_4}}\right)e^{-T_{n_z}s}}{\left[s^2 + 2\zeta_p'\omega_p' s + \omega_p'^2\right]\left[s^2 + 2\zeta_{\mathrm{sp}}'\omega_{\mathrm{sp}}' s + \omega_{\mathrm{sp}}'^2\right]} \tag{5}$$

Depending on the application and quality of frequency responses, several of these dynamics could be fixed in the matching process. As discussed earlier, it is legitimate to fix the phugoid dynamics at values determined from flight-derived data. This approach helps establish the correct dynamics at the lower frequencies where the frequency response may be less accurate. This, in turn, aids a more accurate fit in the short-period region because any residual dynamics from the phugoid should be accounted for correctly. In some cases, it might be appropriate to fix the time delay, such as when the dynamics of the bare airframe are determined, but this should be done with caution.

In other applications, LOES has been used to identify the dynamics of individual or lumped components. In these cases, it is important that the order of the numerator and denominator are chosen to match the frequency response data in the frequency range of the fit. An example is the identification of control inceptor dynamics, for which, typically, a zero over second-low-order form is appropriate [Eq. (6)]:

$$\frac{\delta(s)}{F(s)} = \frac{K e^{-Ts}}{[s^2 + 2\zeta'\omega' s + \omega'^2]} \tag{6}$$

In these applications, it is necessary to ensure that the appropriate signals have been recorded during the sweeps. This is especially important for the identification of components, which may require additional instrumentation to the normally installed end-to-end measurements.

To identify the equivalent time delays correctly, it is imperative that the data are correctly synchronized. Any error in the synchronization of the data will affect the equivalent time delay calculated and, in extremes, could also affect the dynamics.

Flying Qualities Applications

The frequency responses obtained from the piloted frequency sweeps lend themselves well to analyses consistent with current military flying qualities requirements. Reference 1 specifies the Control Anticipation Parameter (CAP) through LOES as the preferred short-term pitch response criterion. The bandwidth criterion is identified as an alternative. Parameters for both of these criteria can be obtained from the frequency responses, either through LOES (CAP) or directly (bandwidth).

In the commercial aircraft certification arena, applicable to the examples of this paper, no such criteria are specified. In the absence of any applicable commercial criteria, the approach of the military-derived criteria was used for internal company verification of aircraft dynamics, flying qualities, and freedom from Pilot-Induced Oscillation (PIO) tendencies.

Flying Qualities Criteria

Although not used for certification purposes, appraisals against the CAP (through LOES) and bandwidth criteria were performed for several aircraft. These appraisals were not undertaken for hard pass/fail assessments against the military requirements, but more as a means of assessment of the aircraft's short-term dynamic response characteristics. For these purposes, criteria boundaries extensively validated with in-flight simulation data for transport aircraft were used.[6] These appraisals included criteria for both flying qualities and PIO.

Example Applications

Piloted frequency sweeps were performed on a number of Boeing Company aircraft built in Long Beach, California. Analyses of the sweep data were performed for a number of different purposes. In some applications, all four steps in the approach discussed earlier were performed. In others, fewer steps were required. These applications will be discussed in the following sections.

Additionally, the analysis of piloted frequency sweeps was used to support a number of research applications. These include model validation for piloted flying qualities experiments in the U.S. Air Force's Total In-Flight Simulator (TIFS), operated by Calspan, and also the Delft University of Technology's SIMONA Research Simulator. Data from these applications are presented to illustrate the approach outlined earlier.

TIFS Experiments

During the early 1990s The Boeing Company undertook a series of flying qualities experiments that investigated the short-term pitch axis flying qualities of very large transport aircraft. The Generic Large Transport (GLT) aircraft model was developed for these experiments, which were performed on the U.S. Air Force's TIFS.[6]

The TIFS utilizes a model following approach to simulation.[9] The evaluation pilot's control inceptor commands are fed as inputs to the model computer, which calculates the modeled aircraft responses to be reproduced. These responses, along with the TIFS motion sensor signals, are used to generate feedforward and response error signals, which drive the control effectors on the TIFS, forcing the TIFS to follow the modeled aircraft responses.

Systems identification with frequency sweep analysis will be illustrated for two examples, namely, verification of the accuracy of 1) the modeled aircraft dynamics within the TIFS model computer and their reproduction by the TIFS itself, and 2) the TIFS model following system.

Identification of Dynamics

Thirty-five pitch axis configurations, all based on the GLT aircraft model, were evaluated during the TIFS experiment. Most of these configurations were of a conventional angle-of-attack response type, whereas a few investigated pitch attitude and flight-path response types. Only the angle-of-attack response-type configurations will be addressed here.

During checkout flights before the flying qualities evaluations, piloted frequency sweeps were performed with a number of the configurations. Both model and TIFS responses were recorded. These sweeps underwent initial analysis at Calspan to verify the accuracy of the models before the piloted evaluations. These sweeps were also analyzed by The Boeing Company after the evaluations to verify the accuracy of the modeling and to quantify the dynamics by the use of the LOES method.

The LOES analyses concentrated on the experiment variables of interest, the short-period dynamics, and equivalent time delay. Therefore, all numerator zeros and the phugoid poles were fixed during the matching process. Because these characteristics were constant throughout the experiment and should have been accurately modeled in the TIFS, it was determined that fixing them would not induce errors in the matching process. Fixing the numerator zeros permitted an independent fit of pitch rate only. A simultaneous fit of pitch rate and normal acceleration was not necessary.

Thus, a third-order over fourth-order low-order form was used to match the pitch rate to control column position frequency response [Eq. (4)]. The variables that were left free in the matching process were the equivalent short-period poles and the equivalent time delay.

Table 1 LOES analysis results

Dynamics	ω_{sp}, rad/s	ζ_{sp}	T_θ, s	Cost
Design	1.225	0.7	0.125	——
Model	1.220	0.71	0.150	2
TIFS	1.360	0.81	0.200	14

Because the TIFS parameters included real-world measurement effects, they were somewhat noisier than the equivalent model parameters and, therefore, less well suited to the verification that the correct dynamics were being reproduced by the TIFS. Thus, analyses of both the model and the TIFS responses to pilot inputs were performed.

Examples of the LOES fits for one sweep are presented in Figs. 2 (model response) and 3 (TIFS response). The solid lines in Figs. 2a and 3a represent the frequency responses from the sweep. The dashed lines represent the LOES fits. The mismatches between the high- and low-order responses are shown in Figs. 2b and 3b, bounded by the MUAD envelopes from Ref. 1. The accuracy of the fits above 0.3 rad/s is apparent. The inaccuracy at lower frequencies is due to the difficulty in identification of the lightly damped low-frequency phugoid mode in the transformation from time to frequency domain, likely due to insufficient aircraft excitation at these frequencies. Recall that the mismatch here is caused because the phugoid is fixed at the design values (dashed line), whereas the sweep response (solid line) does not reflect the presence of the phugoid.

Table 1 presents the results of the LOES analyses for the sweep case presented in Figs. 2 and 3, together with the design dynamics. The results for the short-period frequency and damping demonstrate that the model reproduced the design dynamics accurately. The poorer accuracy for the TIFS response is due to the noisier frequency response, evident in Fig. 3a compared to Fig. 2a, and the poorer quality of the fit, evident in Fig. 3b compared to Fig. 2b. The error between the design time delay and the equivalent time delays calculated were attributed to data asynchronization. Overall, the measured errors were considered to have minimal effect on the results of the experiment when plotted on a flying qualities criterion.

Model Following Appraisal

Whereas the comparison of the LOES results from the model and the TIFS analyses provided some insight into the quality of the TIFS model following system, a yet more insightful approach was also followed. By comparison of the error signal between the model and the TIFS frequency responses for various responses (from the frequency sweep analyses discussed earlier), an appraisal of the TIFS model following could be made at all frequencies of interest.

In the longitudinal degrees of freedom, the error signals of true airspeed rate of change, angle-of-attack, pitch rate, flight path, and normal load factor were compared against the LOES MUAD envelopes. An example for the pitch rate response is shown in Fig. 4. The validity of the use of the LOES mismatch envelopes for this appraisal has not been established, but they provide a basis from which to start.

In Fig. 4, it is apparent that the error between the model pitch rate and the TIFS pitch rate is minimal up to around $2\frac{1}{2}$ rad/s. Between $3\frac{1}{2}$ and 6 rad/s, the error exceeds the upper limit of the envelope because TIFS attempts to provide lead to its response to ensure good phase characteristics at these higher frequencies. This lead effect becomes less effective above 5 rad/s, as the lag in the TIFS pitch rate response increases.

A detailed discussion of the model following appraisal and use of the MUAD envelopes for this purpose can be found in Ref. 6.

This insight into the quality of the model following at different frequencies for different responses permitted an assessment of the frequency ranges where the response was accurate in each response. This frequency range could then be related to the likely frequencies at which the pilot would be controlling that response. For instance, the quality of the true airspeed rate of change was poor above around

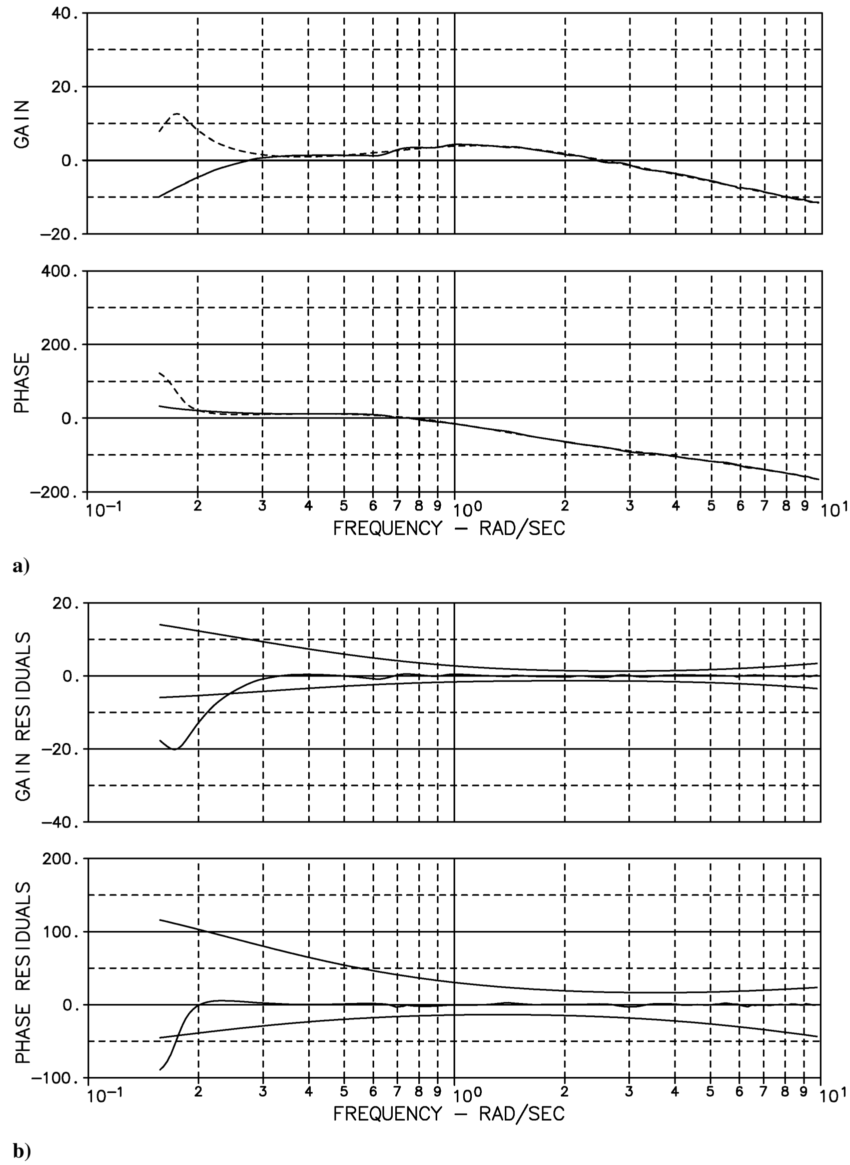

Fig. 2 LOES analysis of model response, q_{model}/δ_{cc}: a) high-order/low-order system comparison: ——, HOS and - - - -, LOES and b) mismatch with MUAD envelopes.

0.8 rad/s. However, pilots usually control airspeed at lower frequencies than pitch attitude, and so accuracy at higher frequencies is less important.

Overall, the conclusion from the frequency domain appraisal of the TIFS model following quality was that it was sufficiently accurate for the purposes of the TIFS experiment.

MD-11 Low-Altitude Stability Enhancement (LASE)

In 2000, an upgrade to the flight control system of the MD-11 included the Low-Altitude Stability Enhancement (LASE). One element of LASE was the extension of the pitch damper to low altitudes. Previously, this function had only been incorporated above 15,000 ft.

The impetus for this change was the upcoming MD-10 program. Under the MD-10 program, DC-10s were being upgraded to include the MD-11 two-crew cockpit. One goal of this program was to achieve a same type rating for the MD-10 and MD-11. The same type rating allows the pilots to maintain their currency on both aircraft by flying either one, or both in combination. In contrast, currencies on the DC-10 and MD-11 have to be met independently.

However, the MD-11, although very similar to the MD-10, operates with a range of center-of-gravity locations that extends further aft than that of the MD-10. Without LASE, the MD-11's handling characteristics were different than those of the MD-10 at their respective aft centers of gravity. The handling of the MD-11 could easily be matched to that of the MD-10 with the incorporation of the LASE low-gain pitch rate feedback, which is effectively a pitch damper. Whereas the change to the MD-11 was imperceptible to most pilots, it brought the handling of the aircraft in line with that of the MD-10 throughout their respective flight envelopes.

Model Validation

For the development of LASE, it was necessary to use an accurate model of the MD-11's longitudinal dynamic response. This included the aerodynamic response of the bare airframe, as well as the control system and actuators.

To confirm the accuracy of the existing aerodynamic model of the aircraft, piloted frequency sweeps were performed on a production MD-11 before delivery. Unfortunately, the scope of the analyses was limited by the instrumentation system on the aircraft. Only standard databus information was available. This included the elevator positions and the control column force for the inputs, and standard inertial reference unit data for outputs. The data were only available at 10 Hz. Furthermore, the measurement of control column force was a somewhat noisy signal, never intended for such applications.

The time histories from the sweeps were analyzed by the use of the approach identified earlier, which yielded frequency responses for the bare airframe and the end-to-end response from control column force to aircraft response.

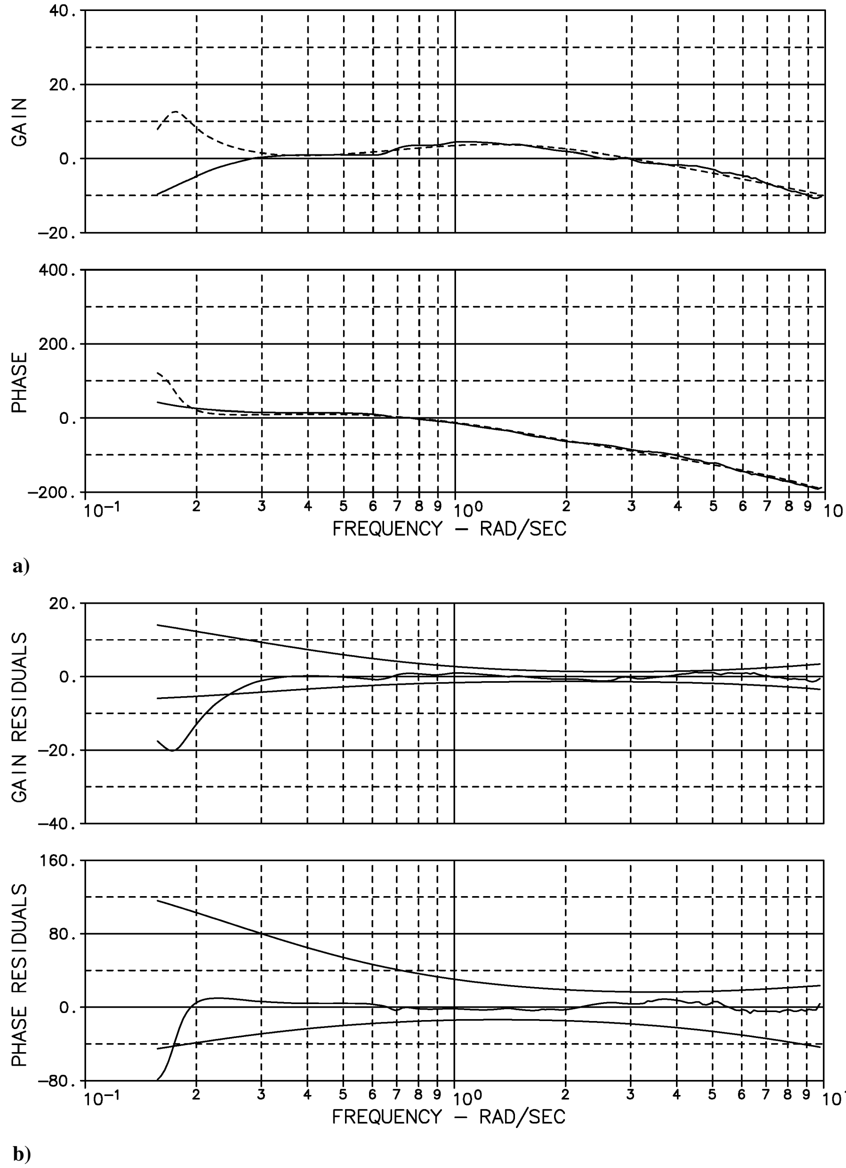

Fig. 3 LOES analysis of TIFS response, q_{TIFS}/δ_{cc}: a) high-order/low-order system comparison: ——, HOS and - - - -, LOES and b) mismatch with MUAD envelopes.

The pilot-generated input from one of the sweeps was then used to drive the simulation model of the MD-11. The resulting time histories from the simulation model were then analyzed in the same way as the flight data. The two sets of frequency responses for the bare airframe (aircraft response to elevator position) were then compared to confirm the accuracy of the aerodynamic model of the MD-11.

A LOES analysis of the bare airframe was performed, simultaneously matching the pitch rate [third- over fourth-order, Eq. (4)] and normal acceleration [fourth- over fourth-order, Eq. (5)] responses from the piloted sweep. The phugoid dynamics were fixed at those determined from the phugoid excitation performed in flight. Because the bare airframe was being identified, the time delay was fixed at zero. Fixing both the low-frequency phugoid dynamics and the high-frequency time delay improved the fit in the short-period frequency range while maintaining accuracy throughout the fit range. Fixing the time delay was only possible after the data had been synchronized correctly.

Because the instrumentation on the predelivery aircraft was insufficient to determine the dynamics of the actuators or other elements of the aircraft's flight control system, other sources were used to develop models of these. By the use of these models and the results of the LOES analysis for the bare airframe, an end-to-end nonlinear model from control column force to aircraft response was then developed.

Again, the pilot-generated input from one of the sweeps was used to drive this nonlinear model. The resulting time histories were analyzed in the same way as before, and the frequency responses were compared to those from the aircraft. The accuracy of the model for development of LASE was confirmed.

LASE Implementation

Once implemented in the flight control system, LASE underwent a flight-test program for company compliance and Federal Aviation Administration (FAA) and Joint Airworthiness Authority (JAA) certification. A production aircraft was instrumented for all key parameters. These included control column force and position, elevator position, and aircraft responses measured by a dedicated flight-test instrumentation package located close to the center of gravity of the aircraft.

The piloted frequency sweeps were performed in the aircraft as described earlier. The sweeps were analyzed with the same technique. LOES analyses were performed to identify the required flying qualities parameters for the CAP-related criteria of Ref. 1. Bandwidth parameters were taken directly from the appropriate frequency responses. Both the CAP and bandwidth parameters were compared to the current criteria developed by Rossitto et al.[6]

The results of the criteria appraisals confirmed the designed effect of the LASE augmentation. Furthermore, the aircraft was

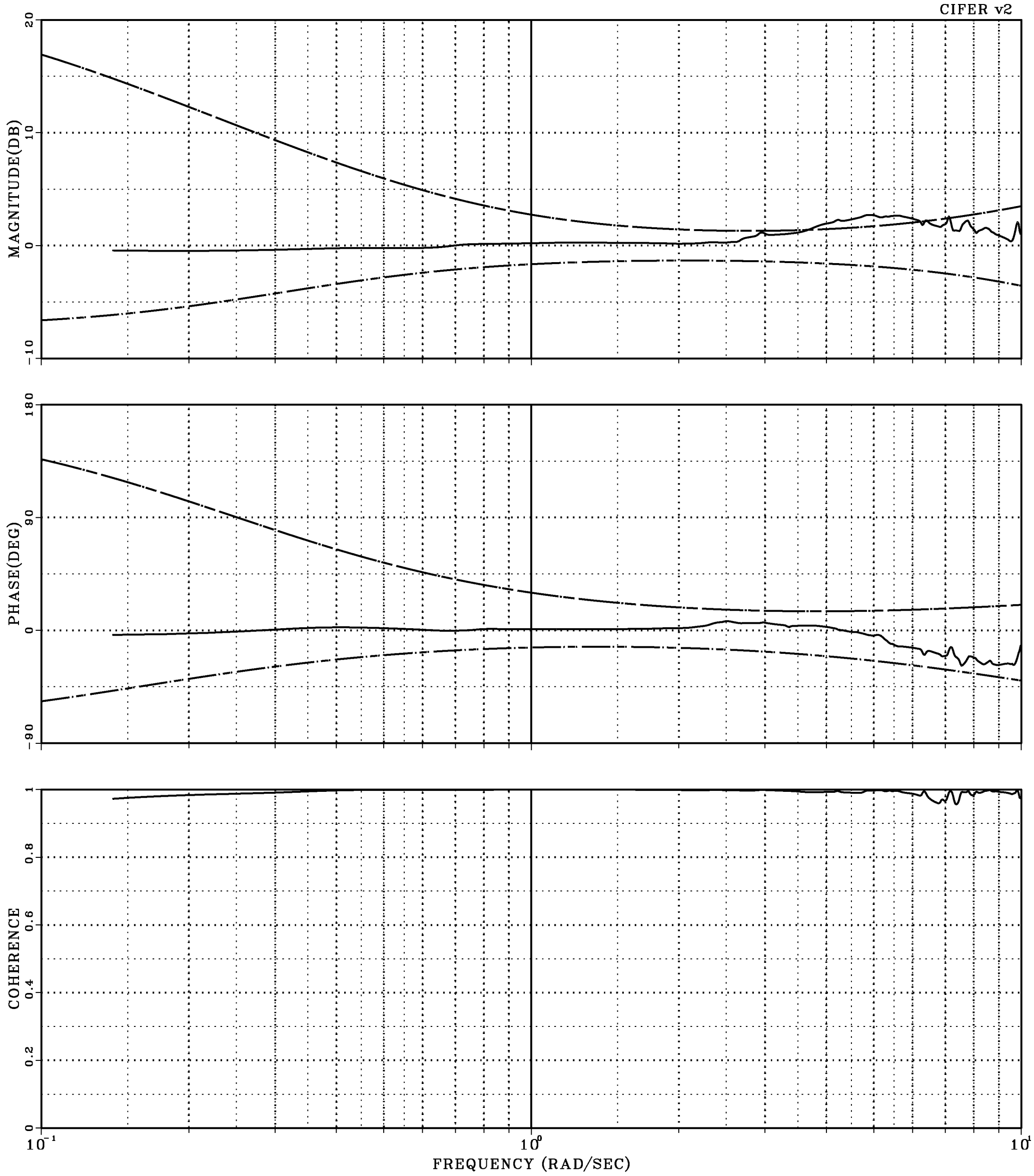

Fig. 4 TIFS/model pitch rate model following appraisal.

confirmed to meet internal company requirements for freedom from PIO tendencies, based on the bandwidth PIO criterion.[6] The frequency responses from the flight-derived sweeps were also compared to those from the nonlinear model developed during the development of LASE. The comparison confirmed the accuracy of the model.

MD-10/MD-11 Same Type Rating

As discussed earlier, the MD-10 and MD-11 are operated under a same type rating. To confirm that the aircraft indeed possess similar handling qualities, frequency sweeps were also performed on an MD-10 in the same flight condition as were performed on the MD-11 with LASE.

The approach to collection and analysis of the data was the same as for the MD-11, discussed earlier. A dedicated flight-test aircraft was used for the testing (a DC-10 that had been converted to the MD-10 configuration). The aircraft was instrumented similarly to the MD-11 used for the LASE certification. As in the preceding cases, pilot training and coaching were employed.

The results of the bandwidth and CAP analyses showed that the two aircraft possess almost identical flying qualities in the given flight condition. Any differences between the two would be imperceptible to pilots and are minimal compared to the variations exhibited in an aircraft's normal flight envelope.

Boeing 717

Frequency sweeps were performed on two Boeing 717 aircraft. The first series were performed during the original certification. The second series were performed during flight testing for a control column redesign.

Original Certification

The Boeing 717 is the latest in a family of aircraft that originated with the DC-9, which first flew in 1965. Whereas the MD-90 utilized a hydraulically actuated elevator, the Boeing 717 reverted to the conventional aeroboosted tab-driven elevator of the original DC-9, with no flight control augmentation. This system would not be expected to create PIO problems, based on over 30 years of in-service history with earlier models.

However, at the time of the 717's certification in 1999, the FAA was in the process of introducing new requirements to demonstrate an aircraft's freedom from PIO tendencies. It was not known at the time whether these would be based purely on quantitative data, purely qualitative piloted evaluations, or some combination of the two. To be prepared for all possibilities, frequency sweeps were performed during company testing to collect data to support the assertion that the aircraft possesses no PIO tendencies. Primarily, the bandwidth PIO criterion and equivalent time delay were used as the metrics.

The original certification program sweeps were performed on a dedicated flight-test aircraft that was fully instrumented for the required parameters. The instrumentation system was well understood, which allowed for corrections for data synchronization. Additionally, all required data were available at 50 Hz.

By the use of the procedures identified earlier, sweeps were performed in four flight conditions representative of climb, cruise, approach, and landing configurations. These sweeps were then analyzed to produce the CAP and bandwidth parameters for comparison to the validated criteria. [The low-order forms of Eqs. (4) and (5) were used in the LOES matching.] The primary interest was to demonstrate that the aircraft meets the phase delay requirements of the bandwidth criterion and that the equivalent time delay is within acceptable limits.

In addition, the aircraft's flying qualities were compared to those of the company requirements to show that the aircraft has acceptable flying qualities throughout its flight envelope.

Although not the subject of this paper, sweeps were also performed in the roll axis. The roll axis was of interest due to the implementation of electric signaling for the spoilers, which replaced the mechanical cams that had been used on previous versions of the DC-9 series of aircraft. Although criteria for the roll axis are not as mature as those for the pitch axis, the equivalent time delays and phase delays calculated from the analyses were sufficiently low to demonstrate that the aircraft is free from lateral PIO concerns.

Control Column Redesign

In 2002, the FAA introduced new rules concerning flight data recorders. In addition to recording control column force, it is now necessary that flight data recorders also record control column position. This new rule required a change to the design of the control column of the 717 to accommodate the sensors required for the accurate measurement of control column position.

Along with accommodation of the sensors, a company proposal was made to upgrade the column design using fewer parts, thereby also reducing the cost of manufacture. This redesign included the redistribution of the bob weight. A condition for the approval of the redesign was that the flying qualities of the aircraft must not be altered because there was to be no requirement for additional training of pilots. The redesign must be transparent to pilots who fly aircraft with both control columns.

For this application, the frequency sweep analyses were used to compare the dynamics of the re-designed column to those of the original column, which were obtained from the sweeps performed

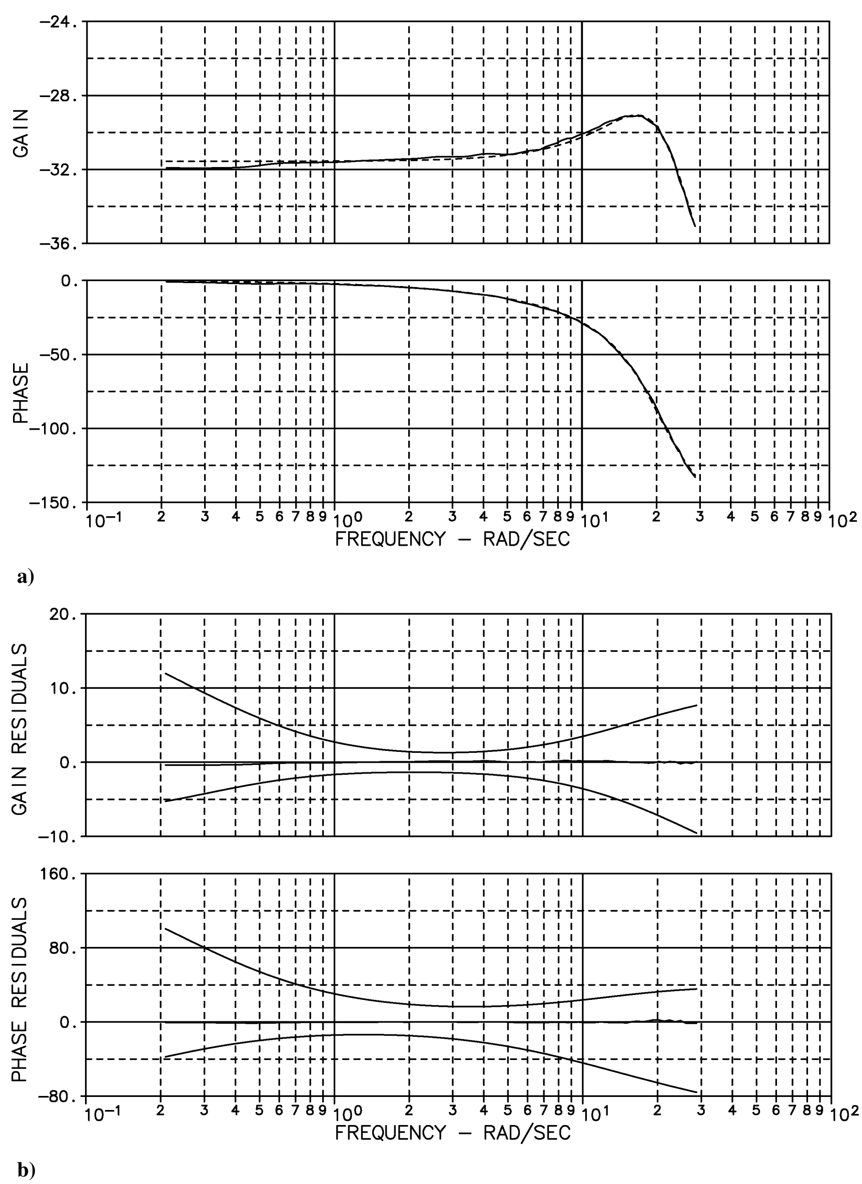

Fig. 5 LOES analysis of control column, δ_{cc}/F_{cc}: a) high-order/low-order system comparison: ——, HOS and - - - -, LOES and b) mismatch with MUAD envelopes.

for original certification. Furthermore, the end-to-end flying qualities were also compared to ensure that the new column had not introduced changes to the aircraft's flying qualities that would be perceptible to pilots.

A predelivery production aircraft was used for the development and certification flight testing of the new control column. The aircraft was instrumented for all necessary parameters, with particular attention paid to the control column force and position measurements. All data were synchronized and available at 50 Hz.

Frequency sweeps were performed in three of the four flight conditions used for the original certification sweeps. Best efforts were made to match the flight conditions, which were close for weight, speed, and altitude. Center of gravity was the least closely matched of all parameters, but was a reasonable representation of the range of flight conditions used in the original testing.

Comparison of the frequency responses of the control column from the original certification sweeps and from the new column identified only minor differences. These minor differences were attributed to the slight discrepancies in the flight conditions of the two sets of data and the different instrumentation systems used on the two aircraft. The differences were minimal compared to those between flight conditions for the same aircraft and were judged to be well below the threshold of perception of pilots, a conclusion supported by qualitative piloted evaluations.

Slight differences were also identified in the end-to-end frequency responses, which supported the attribution of these differences to variations in flight condition and instrumentation system. Again, the differences were minor and imperceptible to pilots, which supported the goal that the re-design would not cause a change in flying qualities that would require pilots to undertake additional training. This conclusion correlated with the qualitative evaluations of the pilots who flew the aircraft for the development and certification of the redesigned control column, thus allowing the aircraft to meet the FAA certification requirements.

Delft University of Technology SIMONA Research Simulator

Although not an aircraft application, the same frequency sweep analysis approach was used during model validation for this piloted simulation experiment. The results are included here to illustrate the analyses.

The Boeing Company and the Delft University of Technology (TU Delft) are currently undertaking a series of experiments on the TU Delft SIMONA Research Simulator (SRS) investigating transport aircraft flying qualities and simulation fidelity. The first phase

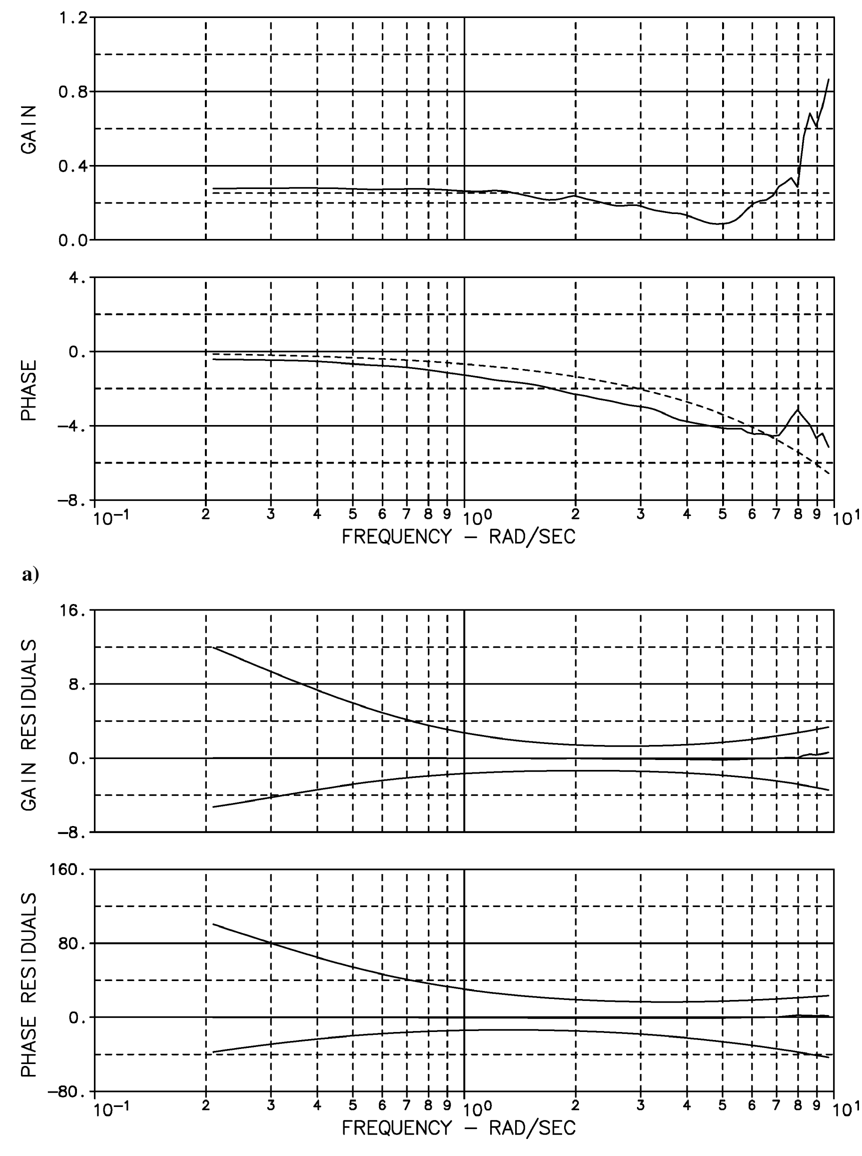

Fig. 6 LOES analysis of motion system, $q_{command}/q_{platform}$: a) high-order/low-order system comparison: ——, HOS and - - - -, LOES and b) mismatch with MUAD envelopes.

of these experiments is the replication in the SRS of the GLT experiments previously performed on the TIFS.

Comparison of the results obtained from the TIFS to those of a previous replication on the NASA Ames Research Center Vertical Motion Simulator (VMS) identified the importance of accurately matching the implementations of the experiments.[10] Therefore, much attention is being directed to the correct implementation of the GLT model in SIMONA and to the quality of the cues provided.[11]

Piloted frequency sweeps were used to determine the control inceptor dynamics. Additionally, computer-generated sweeps were used to determine the accuracy of the aircraft model and motion system time delays. Although the use of computer generated sweeps is a departure from the approach of the rest of this paper, it was suited to the particular application.

Once the control inceptor dynamics were established, all interest was directed to the dynamics downstream of the control inceptor. Thus, because of the nature of the simulation, it was possible to insert a computer-generated signal in place of a manual control column sweep. This had the advantage of repeatability and did not require a trained pilot to perform the sweep. Therefore, this approach was adopted for much of the verification of the aircraft modeling and motion system time delays.

Identification of Feel System Dynamics

Piloted frequency sweeps were used for the identification of the control column dynamics. (Piloted frequency sweeps were also used successfully to identify the dynamics of the control wheel and rudder pedal.) Whereas for flying qualities the frequency range of interest is usually below 10 rad/s, control inceptor dynamics are usually above 10 rad/s, ideally around 20 rad/s for nonintrusive inceptors for transport aircraft. Thus, it is necessary to ensure that the frequency content of the input is of sufficiently high frequency.

As with flying qualities applications, two sweeps were performed for redundancy purposes. Special attention was paid to the high frequencies, consistent with the desired frequency of the control column response. These sweeps were then transformed into the frequency domain. The frequency responses were then fitted to a zero-over second-order low-order system [Eq. (6)] consistent with the classical second-order appearance of the frequency response. The fit was performed between 0.3 and 30 rad/s. Figure 5a shows the frequency response derived from one of the piloted frequency sweeps of the control column, together with the low-order fit. The match is clearly very accurate, confirmed by the minimal mismatch in Fig. 5b. The results of the LOES analysis identified the control column to have a natural frequency of 20.4 rad/s and a damping ratio of 0.41, with a cost of 0.6.

Identification of Motion System Time Delays

To ensure that the correct end-to-end dynamics and time delays were modeled, it was necessary to identify the dynamic characteristics of the motion system in all axes. Computer-generated sweeps were used for this purpose, with the inputs directed to the frequency range between 0.1 and 12 rad/s, sufficient to identify the response of interest

Independently, computer-generated signals were used in place of control column, control wheel, and rudder pedal to drive the simulator. Appropriate input/output pairs were analyzed to identify the characteristics in all axes. Inspection of the frequency responses identified that the motion system introduced negligible dynamics in the frequency range between 0.1 and 10 rad/s, and so the responses could be accurately described by an equivalent time delay only.

LOES matches of the motion system frequency responses were performed to identify the time delays. A first- over first-order low-order system was defined, with both the pole and zero fixed at 100 rad/s, well above the fit range of 0.3–10 rad/s. Thus, only the time delay was free in the fitting. An example of one analysis is presented in Fig. 6 for the pitch degree of freedom. Inspection of the frequency responses in Fig. 6a might suggest a poor fit, but that is a function of the vertical axis scaling. (Gain is in decibels.) The minimal mismatch in Fig. 6b is consistent with the cost of 0.5 obtained for the fit, which identified an equivalent time delay of 0.012 s.

Conclusions

Piloted frequency sweeps were performed on a number of transport aircraft, as well as research aircraft and simulators in support of production certification programs.

Through careful attention paid at all stages of data collection and analysis, high-quality frequency responses were produced from the sweeps.

Analysis of the frequency responses with the LOES method produced accurate dynamic models of the bare airframe, augmented aircraft, and fight control system components.

In some applications, the results of the LOES analysis were used for flying qualities appraisals against validated criteria.

In other applications, the models derived from the LOES analyses were used to develop accurate models for flight control system design.

In yet other applications, the results of the LOES analyses were used to verify the accuracy of model implementations in various piloted flying qualities experiments.

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