Dynamic Stability Testing of the Orbiter Flight Control System/Flexible Body Interaction

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A new kind of ground vibration test has been developed that yields results directly useful to flight control designers. Inputs are applied to vehicle controllers with the flight control system powered-up. Sensor outputs and system commands are analyzed to measure system transient and frequency response, which are then compared with predictions. An end-to-end evaluation of the validity of the design analysis is thus obtained prior to flight test. Flex body dynamics, sensor and controller characteristics, and system software are all covered. This paper describes the tests on Space Shuttle Columbia in August 1980 and summarizes the results.

Introduction

STRUCTURAL dynamics engineers have long used vibration tests to determine the flex body characteristics of airplanes and spacecraft. Typically, shakers and special test instrumentation are employed in the tests, and data are analyzed after testing is completed. In due course, the vehicle modal data needed for flight control sytem (FCS) analysis and design verification are revised based on the test results.

For the Shuttle program, a new kind of modal test was developed, referred to as dynamic stability testing (DST), which yields results directly beneficial to the flight control community. The unique feature of the DST that distinguishes it from conventional control system testing is that open-loop gain and phase measurements are obtained between vehicle controller force inputs and system sensor outputs. (A predecessor was the Shuttle test described in Ref. 1; however, that test uses shakers instead of controllers to apply the input forces.) This kind of testing provides, prior to flight, an end-to-end evaluation of the validity of FCS design analysis and stability margin predictions, covering the effects of vehicle flexible body dynamics, FCS software, and the dynamics of sensors and controllers. No evaluation of aeroelastic effects is achieved because of the zero airspeed conditions of the DST.

Dynamic stability tests were performed on Orbiter vehicle OV-102 in August 1980 as part of the formal verification process that supported the STS-1 flight readiness review. This paper describes the tests and summarizes the most significant results. The same kind of DST was performed in August 1982 on Orbiter OV-099 with an installed inertial upper stage/tracking and data relay satellite payload.

Purpose of DST

The process used on the Shuttle program to certify flight readiness of the Orbiter flight control system culminates in a commit-to-flight decision based on verification of rigid-body performance, including handling quality evaluations from man-in-the-loop simulations, plus verification of FCS flex-body stability margins and performance. This paper is concerned only with the latter activity. The original flex stability verification plan was to perform frequency and time domain analyses of a documented and controlled analytical model over a representative set of flight conditions. Variations in value of critical parameters, which have been agreed on in advance, would be applied individually and in combination to insure stability under 3 σ conditions.

The data base for the flex FCS model would include analytically derived structural modal data, which were partly checked by full- and one-quarter-scale ground vibration tests. Aero forces and moments would include static effects due to steady-state loads and generalized aero force derivatives that are calculated from unsteady aerodynamic theory. The remaining element of the flex stability model consists of the characteristics of the FCS hardware and software.

The original plan, which is fundamentally conventional despite the technical sophistication of the analytical techniques used to generate the model, had the shortcoming that no end-to-end check of FCS hardware and software in a dynamic environment with actual flex-body responses can be obtained until flight. The vehicle level dynamic stability test was developed and implemented to eliminate that shortcoming. In a DST, input stimuli are applied to the Orbiter vehicle controllers to excite bending while the FCS is powered-up, and the measured responses from the operating FCS are compared with predicted responses derived from the flex FCS flight model suitably modified to represent the ground test configuration. This comparison will then substantiate the flight model and verify end-to-end flexible body performance, or it will provide data to revise the structural model. The objective is to detect any unmodeled dynamic interaction between the vehicle and FCS. Earlier Orbiter ground vibration test history provided ample justification for adding the DST: four previous ground tests revealed unmodeled phenomena that resulted in system design changes.

Test Description

The DST had two phases: 1) in closed-loop DST, the purpose was to verify that flex mode gain margins exceed 6 dB by incrementally increasing loop gains from nominal value to nominal +3 dB and nominal +6 dB; and 2) in open-loop DST, the objective was to obtain the fequency response (gain and phase) of the FCS gyro and accelerometer outputs to aerosurface actuator inputs.

The block diagrams in Fig. 1 show the two configurations employed in the two phases. The various elements of the FCS are shown linked by solid lines; among these are rate gyros (RGA), accelerometers (AA), the digital processing system that includes the flight computer (GPC) and the multiplexer-

Presented as Paper 82-1531 at the AIAA Guidance and Control Conference, San Diego, Calif., Aug. 9-11, 1982; submitted Sept. 23, 1982; revision received June 17, 1983.

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demultiplexers (MDM), and the actuation system consisting of amplifiers and hydraulic actuators. Also shown is a block labeled SMTAS, for Shuttle modal test and analysis system.

The SMTAS data acquisition and processing section can acquire up to 64 channels of analog data, digitize the data at 50 samples/s, and then store the sampled data on disk/tape for later processing. An array processor is used in conjuction with a central processing unit to perform a fast Fourier analysis on the data to transform it from the time to the frequency domain. Hard copies of the frequency response plots are available within about 35 min following the completion of a test.

Physically, the vehicle was in the flight condition or as close to it as practical: it was in a horizontal position resting on its wheels. To uncouple the rigid-body modes associated with the suspension system from the vehicle flex modes, the tires were partly deflated and the oleos were pressurized to make them soft. The dynamics of this suspension system became a significant issue, as will be seen. Hydraulic and electrical power were supplied from the ground.

In the closed-loop test, input stimuli were generated by the flight computer and applied to gyro torquers. The gyro outputs were processed in the computer using flight software, and the resulting elevon/rudder commands were applied to the actuation system. The SMTAS was in a "listen" mode during the closed-loop test.

In the open-loop test, the FCS loop was opened between the computer and the actuation system. The SMTAS generated a preprogrammed sequence of sinusoidal stimuli, which were applied directly to the actuation system. RGA and AA outputs, FCS commands generated by the flight software, and elevon and rudder responses were fed into the SMTAS for data processing.

Important safety features were incorporated in SMTAS for the DST. The stimulus generator hardware contained equipment to prevent damage to the Shuttle FCS hardware in the event of test equipment malfunction or operator error. Also, critical vehicle measurements monitored in the SMTAS would have effected an automatic system shutdown.

Reference 2 gives further details of the test setup and procedure.

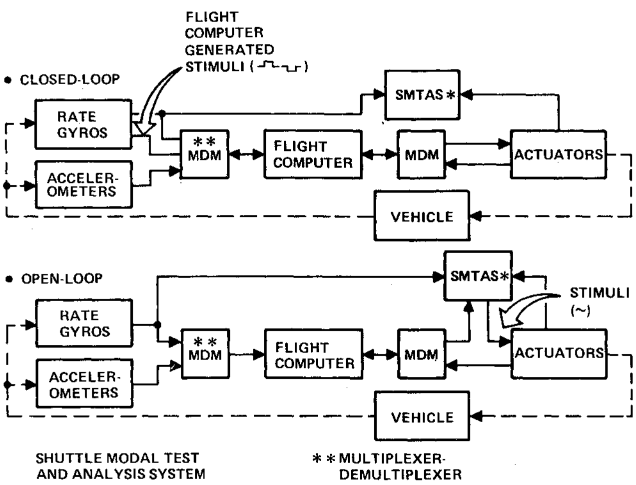

Fig. 1 Block diagrams of the closed- and open-loop configurations.

Closed-Loop Test

The Shuttle digital FCS was configured by a software patch to represent two flight conditions that were selected to give the highest modal gain conditions for entry and return-to-launch site (RTLS) abort. One condition corresponded to $M=3.4$ and the other to $M=0.6$. The latter condition exhibited no anomaly and will not be discussed further. The FCS configuration for $M=3.4$ is shown in simplified form in Fig. 2. The value of $\bar{q}$ was set at 85 lb/ft^2 in the software to give the maximum values of the loop gains, which are scheduled inversely with $\bar{q}$, for entry. The test case with loop gains increased by 6 dB covered the maximum gain condition for RTLS.

Torque commands were positive and negative 4 deg/s rate command pulses with 0.2 s duration to the pitch, roll, and

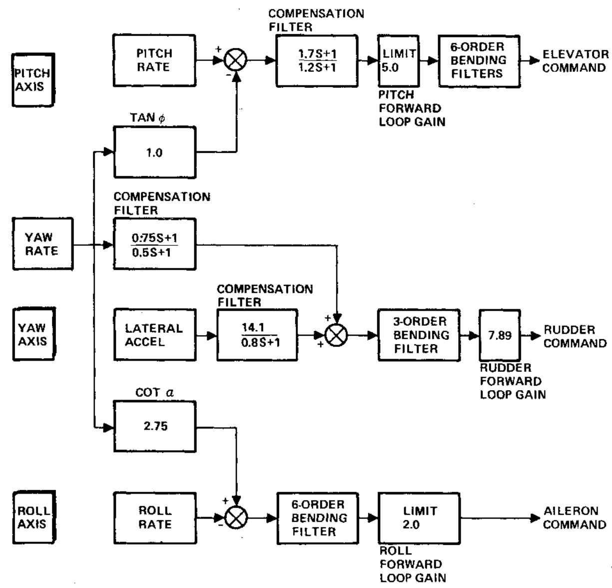

Fig. 2 Entry FCS configuration for closed-loop DST.

Table 1 Open-loop dynamic stbility test: aerosurface cycling sweeps

Sweep no.	Surface[a]	Axis	Range, Hz	Increment, Hz	Alterantions	Command amplitude, deg	Predicted max surface amplitude deg
1-1	RIE, LIE, ROE, LOE	Pitch	2-12.5	0.01	10	0.5	0.5
1-2	RIE, LIE, ROE, LOE	Pitch	12.5-18	0.01	10	1.0	0.2
2-1	RIE, LIE, ROE, LOE	Roll	2-12.5	0.01	10	0.5	0.5
2-2	RIE, LIE, ROE, LOE	Roll	12.5-18	0.01	10	1.0	0.2
3.1	Rudder	Yaw/roll	2-12.5	0.01	10	0.6	0.6
3-2	Rudder	Yaw/roll	12.5-18	0.01	10	2.0	0.2
8	RIE, LIE, ROE, LOE	Pitch	1.0-2.0	0.1	10	1.2	1.2
9	RIE, LIE, ROE, LOE	Roll	1.0-2.0	10	1.0	1.2	1.2

R,L = right, left; I,O = inboard, outboard; E = elevon. Note: Time was allotted for other sweeps, but they were not needed.

Table 2 Open-loop dynamic stability test: aerosurface cycling dwells

Dwell no.	Surface[a]	Axis	Number of frequencies	Frequency, Hz	Max predicted surface position, deg	Est dwell time, min
1	RIE, LIE, POE, LOE	Pitch	1	5.5	0.25	10
2	RIE, LIE, POE, LOE	Roll	1	3.3	0.25	10

[a] R,L = right, left; I,O = inboard, outboard; E = elevon.

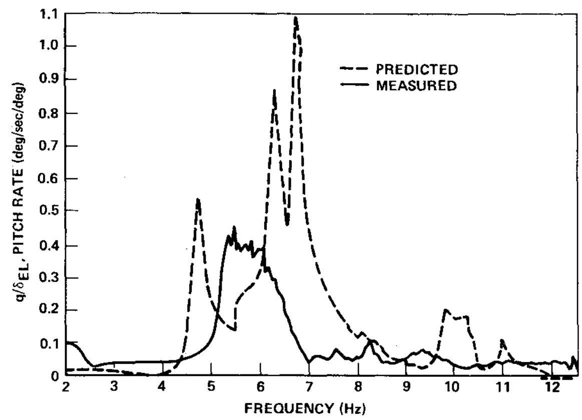

Fig. 3 RGA 3 pitch transfer function plot, sweep 1-1, elevon pitch input.

yaw rate gyros. The test was performed at nominal, +3 and +6 dB FCS gains.

Open-Loop Test

The open-loop test was also run with the FCS in the $M = 3.4$ configuration described above. Table 1 shows the frequency sweeps that were performed. Note that the 2-18 Hz range was split into two segments, 2-12.5 and 12.5-18 Hz, because of data storage limitation in SMTAS. The input amplitudes were chosen at a maximum practical level consistent with hydraulic system limitations and vehicle safety requirements. Prior to the actual run, check sweeps were made at one-half amplitude to insure vehicle safety. Ten alternations, or sign reversals, were obtained at each frequency. The frequency increments were 0.01 Hz.

Besides the sweeps, the two dwell tests tabulated in Table 2 were run. Selection of the 5.5 Hz pitch dwell and the 3.3 Hz roll dwell was made in real time after observing the results of the sweep tests.

Results

The most significant results of the DST were those that contributed to the validation of the analytical verification of FCS flight readiness for the first Shuttle flight. This validation was of critical importance to the Shuttle program because closed-loop operation of the FCS in a previous test, referred to as the "hot-fire" test, conducted in November 1979 had been unsuccessful. Hot-fire results became a major issue because they could not initially be explained analytically, and this raised questions about the validity of both the modeling technique and the modal data base. There followed an extensive review of the analytical methods, data base revisions, a redesign of the roll filter, and relocation of the two outboard rate gyros to put all four rate gyros on the centerline. This background led to the implementation of the dynamic stability test on vehicle OV-102 in August 1980. The objective of the closed-loop test was to prove that the revised FCS had gain margins of at least 6 dB. Completion of the test was considered mandatory prior to first flight. The open-loop test objective was to compare actual vs predicted frequency responses and thereby validate the verification analyses. Table 3 summarizes the results of the closed-loop test; further details can be found in Refs. 3 and 4.

Table 3 Closed-loop test results

Test gain	Pretest prediction: Linear	Pretest prediction: Nonlinear	EDST observations
Nom	Stable in all axes	Stable in all axes	2.4 Hz sustained symmetric elevon oscillation, 0.6 deg p-p
+3 dB	Stable, but lightly	Stable in all axes	2.4 Hz sustained symmetric elevon oscillation, 1.0 deg p-p
+6 dB	Unstable, slowly divergent 3.7 Hz lateral oscillation	2.7 Hz damped lateral	2.6 Hz sustained anti-symmetric elevon oscillation, 3.0 deg p-p

Both the 2.4 and 2.6 Hz anomalies have been attributed to landing gear dynamics, which were unique to the test configuration, as will be discussed later.

Open-Loop Test

From all the open-loop transfer function plots, Figs. 3-6 have been selected because they show the most important results. (Note that the plots were made using engineering units rather than decibels.) These results were:

1) The rigid-body response had a higher frequency, 2-2.2 Hz, than predicted (1.8 Hz was the highest frequency rigid-body mode) and a much higher amplitude, as seen in Fig. 3. Figure 4 shows the roll response to the pitch input and indicates significant coupling between the axes, which was unpredicted. It was concluded that these discrepancies were caused by incorrect modeling of the landing gear dynamics and are significant for explaining the closed-loop test anomalies mentioned above.

2) Figure 3 also shows that the first fuselage bending mode had a significantly higher frequency, 5.4 Hz, than the predicted 4.7 Hz. This effect is caused by payload bay door seal friction, which effectively stiffens the fuselage and increases the frequency of this mode. The model used for prediction did not include the effect of seal friction and, consequently, the predicted frequency was lower. As a result, for the purpose of formal verification analyses, the tolerances on the first fuselage mode frequency was changed to 4.5 Hz, −0, +20%.

3) It is also apparent from Fig. 3 that the actual pitch rate response at the symmetric wing mode, predicted at 6.4 Hz, and at the tail fore and aft mode, predicted at 6.7 Hz, is lower in amplitude and frequency than anticipated. This implies that the structural damping ratio is higher than the value of 0.01 that was assumed for the prediction. The value of 0.01 is the same as that used for formal verification analyses and is

known to be conservative. Thus, no change was necessary to verification plans as a consequence of these data. However, in any future dynamic stability test, a realistic expected value of the structural damping ratio will be used to predict responses, which will yield a better match with test data.

4) Figure 5 shows the roll rate response to rudder input stimuli. Note the large rigid-body response at 2.2 Hz mentioned earlier. The predominant flex mode is the antisymmetric fin bending mode, which has a frequency of 3.3 Hz rather than the predicted value of 3.6 Hz and an amplitude about 60% of the predicted value. This is a reasonable correlation for frequency, but again, structural damping is higher than the assumed 1%. Because of the lower frequency observed in the test, the frequency range for formal verification was changed to 3.52 Hz ± 7%.

5) All other modes show less amplitude than predicted, which again implies structural damping greater than was assumed for them.

Landing Gear Dynamics

To investigate the rigid-body mode anomaly at 2.2 Hz, a tire test was conducted, but results were inconclusive. It was concluded that the anomaly could only be explained by a combination of a stiffer tire than planned and a nearly rigid oleo. No evidence from any test indicated that the 2.2 Hz mode was a flight mode, and on the basis that the mode was unique to the DST suspension system, no further test was conducted. For post-test analysis of the closed-loop results, a close match between the model and the test results was obtained by adjusting frequency and damping parameters to reflect DST results, as shown in Table 4 and Fig. 7.

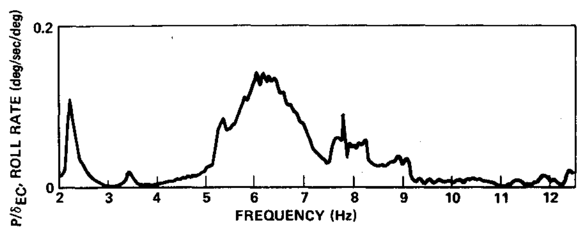

Fig. 4 RGA 3 roll transfer function plot, sweep 1-1, elevon pitch input.

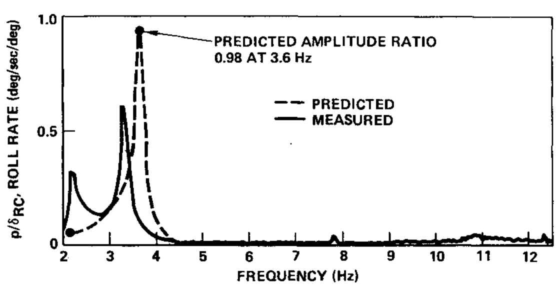

Fig. 5 RGA roll transfer function plot, sweep 3-1, rudder input.

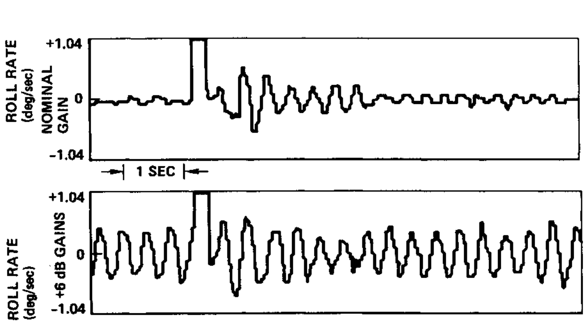

Fig. 6 Roll rate (25 Hz sample rate).

Table 4 Open-loop roll axis transfer function pretest vs post-test prediction: modal parameter changes for post-test analysis

Mode	Frequency, Hz Was	Frequency, Hz Is	Damping, % Was	Damping, % Is
First (rigid)	0.5	1.9	20	2
Sixth (rigid)	1.8	2.2	20	5
First (flex)	3.6	3.3	1	1

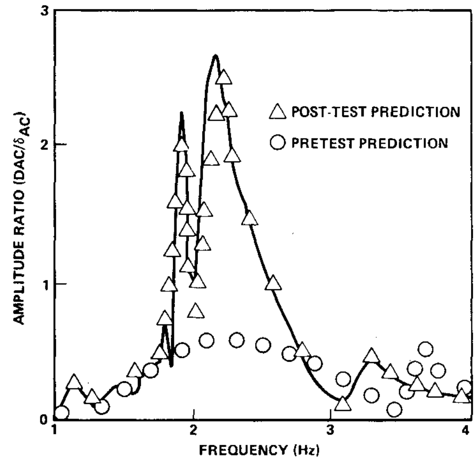

Fig. 7 Pretest and post-test roll transfer function predictions.

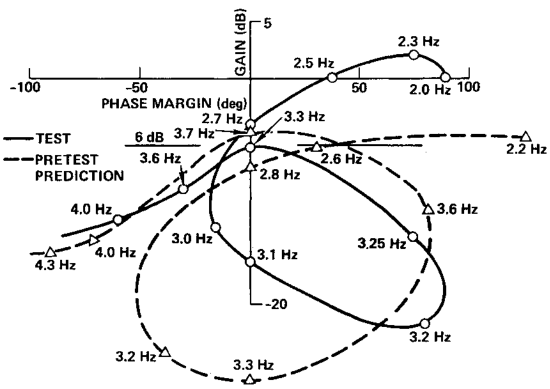

Fig. 8 Open-loop roll Nichols chart, sweep 2-1.

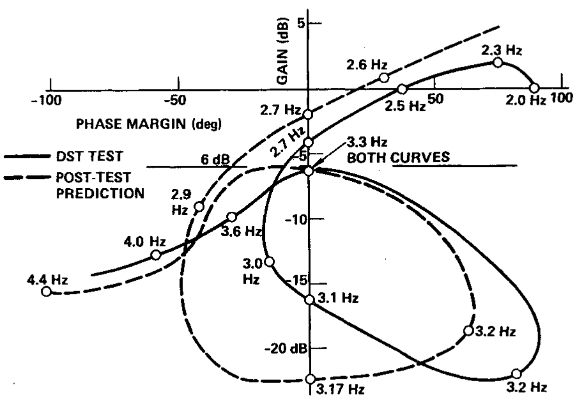

Fig. 9 Open-loop roll Nichols chart – DST vs post-test prediction with landing gear revision.

Closed-Loop Roll Axis Instability Resolution

On example of how open-loop DST results were used to resolve test anomalies and increase confidence in verification analysis is provided by the disposition of the 2.6 Hz oscillation that occurred in the closed-loop test when the loop gain was increased 6 dB (See Fig. 6.) Recall from Table 4 that, for elevated loop gain, linear analysis predicted a slowly divergent 3.7 Hz oscillation, which is close to the predicted lowest antisymmetric flex mode. The linear prediction yielded the dashed-line locus in the Nichols chart in Fig. 8, which indicates less than 6dB margin at 3.7 Hz. On the other hand, nonlinear time domain predictions showed a stable, damped oscillation at 2.7 Hz, which corresponds to a peak of the entry FCS bending filter. In the Fig. 8 Nichols chart, the predicted locus shows well over 6 dB margin at that frequency.

Examination of the roll rate response in Fig. 6 at the elevated gain shows the 2.7 Hz instability, but also indicates modulation by a 0.6 Hz difference frequency. From the discussion of open-loop results above, recall that the predicted 3.6 Hz fin antisymmetric frequency was actually at 3.3 Hz, which can explain the observed 0.6 Hz modulation of the 2.6 Hz oscillation. It was concluded that the system was unstable at 2.7 Hz and marginally stable at 3.3 Hz. To explain the 2.7 Hz instability where there is no inflight bending mode, it is necessary to take into account the landing gear dynamics. When the landing gear model was revised as described in Table 4, the Nichols chart for the roll axis is modified to the form in Fig. 9. The resulting post-test prediction now clearly shows less than 6 dB margin at 2.7 Hz and barely 6 dB at 3.3 Hz. The conclusion is that the closed-loop roll anomaly can be explained by the lower-than-predicted frequency of the fin mode (3.3 vs 3.6), the landing gear dynamics peculiar to the ground test configuration, and the peak in the aileron bending filter frequency response.

On this basis, the anomaly was resolved prior to the STS-1 flight readiness review. The key to the resolution was the open-loop data that revealed the unpredicted landing gear dynamics and the correct bending frequency of the antisymmetric fin mode.

Conclusions

The DST procedure described in this report provided a key part of the formal flight readiness verification for the Shuttle FCS. Flight since DST demonstrated no flex stability problems, confirming the validity of the FCS design and verification process. Such a test should be considered for adoption whenever the complexity of a new vehicle or a major revision to an existing configuration puts a premium on greater confidence in the FCS design data base.

Acknowledgments

The DST program was accomplished through the efforts of personnel from NASA Johnson and Kennedy Space Flight Centers, Honeywell, Inc., and Rockwell International. This paper is a report of their work.

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