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Aeroservoelastic Encounters

Larry R. Felt,* Lawrence J. Huttsell,†
Thomas E. Noll,† and Dale E. Cooley†
Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

Aeroservoelasticity involves the interaction between aerodynamics, structural dynamics, and automatic flight control systems. It is an increasingly important design and test consideration in the synthesis and evaluation of high-gain automatic flight control systems on modern, flexible, structurally efficient aircraft. Recent Air Force experiences that emphasize the need for aeroservoelastic considerations on a variety of research, development, prototype, and production aircraft are presented in this paper. Typical analysis and test techniques available to predict and prevent adverse aeroservoelastic effects are presented. The results of two in-house aeroservoelastic analyses are presented. Recommendations regarding analysis tools, design requirements, and testing techniques are also made.

Aeroservoelasticity Background

Since World War II, aeroelastic considerations have become significantly more influential in the design and development of aircraft. The aerospace community has developed increasingly complex and complete analytic tools and test methods to predict and prevent adverse interaction between an aircraft's structural dynamics and unsteady aerodynamics. In general, problems such as static divergence, dynamic loads, and flutter have become well understood. Analytic tools, design requirements, and testing techniques based on years of experience have evolved.

More recently, the interaction between an aircraft's structural dynamics, aerodynamics, and automatic flight control system[1] has emerged as an important design consideration. This interaction is called aeroservoelasticity (ASE) and is illustrated by Fig. 1 (from Ref. 2). Classical flutter, which does not include interaction with automatic flight control system dynamics, is represented by the left leg of the interaction triangle (aeroelastic). Since steady-state and quasi-steady aerodynamics are a subset of unsteady aerodynamics, the lower leg (aeroservodynamic) represents classical, rigid-body flight control system synthesis.

Historically, the importance of ASE design considerations was caused by increases in the aircraft's structural efficiency, e.g., minimum weight to meet strength requirements, and by the increased use of high-authority, high-response automatic flight control systems. As aircraft designers strove to reduce the structural weight of each new aircraft, the flexibility of the structure increased. At the same time, flight control engineers developed new automatic flight control system functions that improved aircraft performance, stability, service life, ride quality, etc. Unfortunately, these efforts went on more or less independently until the effects of these two trends overlapped and significant and frequently degrading interactions occurred. Virtually all recently developed aircraft have had close encounters of the aeroservoelastic kind. This paper explores the latest Air Force Flight Dynamics Laboratory (AFFDL) experience with ASE analysis, design, and testing.

Analysis Techniques

Classical flutter analysis techniques are based on relatively detailed mathematical models of the flight vehicle's mass, stiffness, and geometry (Fig. 2). Structural dynamic characteristics are represented by generalized mass and stiffness matrices associated with generalized coordinates (modes of vibration). By assuming simple harmonic motion, unsteady airforces for each mode of vibration are calculated and assembled in generalized airforce matrices. However, the unsteady airforces caused by the modes of vibration have the effect of altering the modes of vibration as airspeed changes. Thus, the classical flutter stability calculation is similar to a feedback problem. When the path through the unsteady aerodynamics is open, the aircraft responds in its zero-airspeed, natural modes of vibration. With the path closed, as the airspeed increases, the effects of the unsteady aerodynamics on the structure could produce a stable or an unstable response. By introducing a damping factor into the equations of motion and solving these equations at several airspeeds, a unique flutter speed and frequency is determined.

ASE analyses can be performed with the classical flutter analysis equations of motion. Figure 2 illustrates the addition of an automatic flight control system control law to the flutter analysis representation. With the control surface deflection as a separate generalized coordinate, the same equations of motion can be modified and solved to determine the flutter speed with the active control system on. Care must be taken to insure consistency between the assumed frequencies of the control system dynamics and the frequencies of oscillation assumed within the classical flutter equations. This method[3,4] is somewhat laborious and, therefore, not useful in typical ASE design techniques.

Several techniques adopted from the flight control discipline can be efficiently combined with the classical flutter equations of motion of ASE analysis. Reference 5 contains an excellent discussion of these analysis techniques and their use in aeroservoelastic analysis and design. The fundamental problem in applying these techniques is that the control

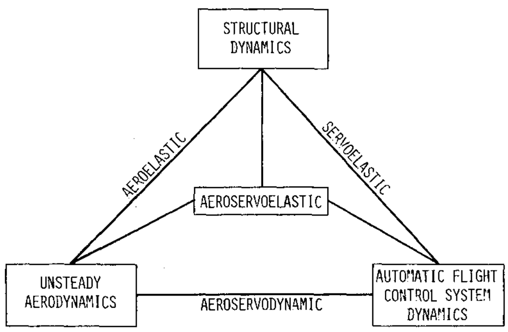

Fig. 1 Interaction triangle.

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*Aerospace Engineer, Aeroelastic Group.
†Aerospace Engineer, Aeroelastic Group. Member AIAA.

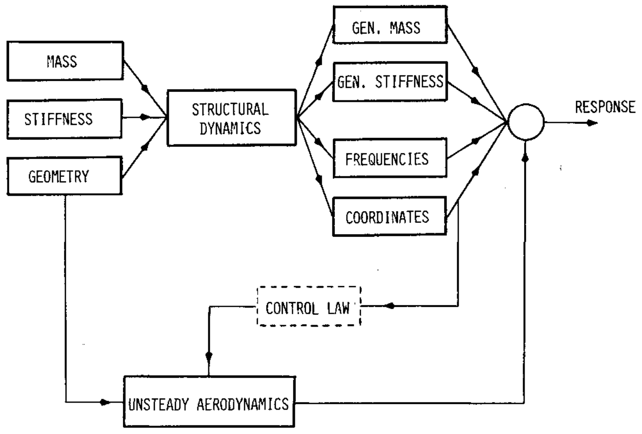

Fig. 2 Flow diagram for flutter formulation.

system equations are usually expressed in the frequency domain in terms of the Laplace variable, $s=\sigma+j\omega$. However, the classical flutter equations of motion rely on oscillatory aerodynamics which are a function of reduced frequency (a nondimensional parameter that is the product of a reference length and the frequency divided by the assumed velocity).

One of the ASE analysis techniques used by the AFFDL is based on Ref. 3. The equations of motion are reformulated such that a frequency parameter is the key variable (instead of reduced frequency). The complex unsteady aerodynamic coefficients are changed to match the change in the frequency parameter. The equations are solved at a constant velocity. This technique can be used with any unsteady aerodynamic theory that formulates complex coefficients based on reduced frequency. Specific examples of various ASE analysis techniques and methods used to evaluate system stability will be presented in the next section.

ASE Analyses Examples

The results of recent flutter and aeroservoelastic analyses conducted by the AFFDL are presented in this section. These analyses employed the FASTOP Flutter and Strength Optimization Program[6] and the ASEP Aeroservoelastic Program[3,7] to evaluate the dynamic characteristics of the unaugmented (system off) and the augmented (active control system on) aircraft. Two specific examples are presented. The first involves analyses of an AFFDL wing/store wind-tunnel flutter model which had an active control system for suppressing flutter. The second example involves control system/airframe interaction analyses on the YF-16 aircraft for both the tip-missiles-on and tip-missiles-off configurations.

Example 1—AFFDL Wind-Tunnel Model

Aeroservoelastic analyses using modified Nyquist control theory[8,9] were conducted at the AFFDL in support of a wind-tunnel test demonstration of wing/store flutter suppression.[10,11] During the program, three different external store configurations were selected for test and evaluation of the concept. The results of a preliminary analysis conducted for one of these store configurations are presented. This store configuration, configuration A in Fig. 3, consisted of an AIM-9E missile on a flexible launcher rail at the wing tip and an AIM-7S missile mounted on a rigid pylon located at about midspan. Since the model was a free-flying semispan representation of the YF-17 aircraft with plunge and pitch rigid-body degrees of freedom, only the symmetric modes were studied during this program.

For this study, doublet lattice unsteady aerodynamics and the P-k flutter solution option from the AFAM module of the FASTOP computer program were used. The entire flutter model, with the exception of the underwing pylon and store, was aerodynamically represented as a combination of aerodynamic panels, interference panels and slender bodies. Two rigid-body modes (pitch and plunge), the first seven calculated elastic modes of the model, and a trailing-edge control surface rotation mode were used in the flutter analysis. The underwing pylon and the horizontal tail were assumed rigid; the fuselage, however, was dynamically represented. Analyses conducted at Mach number 0.8 and sea-level conditions predicted an unaugmented flutter speed of approximately 203 KEAS at a frequency of 12.4 Hz. Note that none of the analysis data presented in this paper represent matched-point conditions, i.e., the assumed Mach number and air density do not correspond with the flutter speed. This approximation should not significantly affect the trend study results presented.

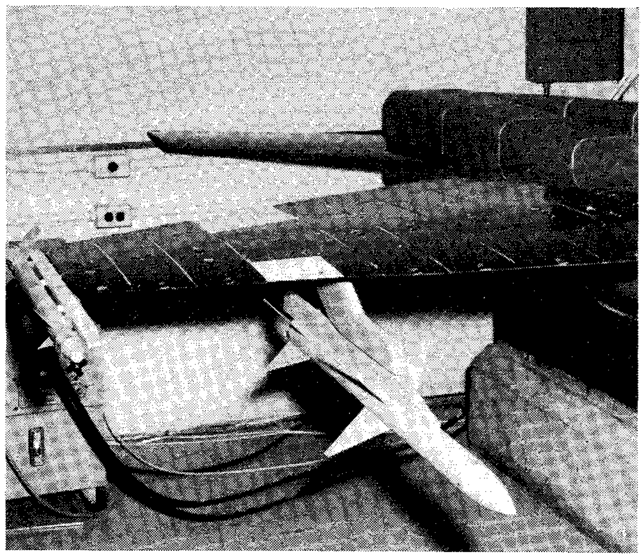

Fig. 3 Flutter model with AIM-9E and AIM-7S missiles installed.

Flutter analyses were also conducted with the ASEP frequency domain computer program. Using unsteady aerodynamics generated by FASTOP for the modes described earlier, determinant plots[12,13] (variation of phase angle with increasing frequency for the aeroelastic equations) were obtained. Two such plots are shown in Fig. 4 for two velocity conditions, one below flutter (180 KEAS) and the other above flutter (220 KEAS). As the frequency sweep passes through each modal frequency, a 180 deg phase change is obtained. At speeds below flutter (left side of Fig. 4), the trace of phase angle vs frequency is continually increasing and will pass through 180 deg for each assumed elastic mode. At speeds above the flutter speed (right side of Fig. 4), the trace will reverse direction when the frequency sweep passes through the flutter mode frequency. This phase reversal is an indication that the unaugmented aircraft is unstable. Small velocity increments are used to accurately establish the flutter onset velocity with this determinant phase method.

With the active flutter suppression system operating, a modified Nyquist criterion is used to evaluate the stability characteristics of the model. Figure 5 shows a preliminary representation of a trailing-edge control law for configuration A. Angular acceleration is fed back through a signal amplifier, a high-pass filter, and a phase-lag network. The airframe block shown in the forward loop represents the aeroelastic equations including doublet lattice unsteady aerodynamics. For a stable closed-loop system, modified Nyquist theory requires that the increasing frequency trace encircle the origin in a counterclockwise direction as many times as there are poles in the right half of the s plane. At speeds below flutter, the closed-loop system is stable if there are no encirclements of the origin; if there are, the encirclements will be clockwise and would indicate a control-

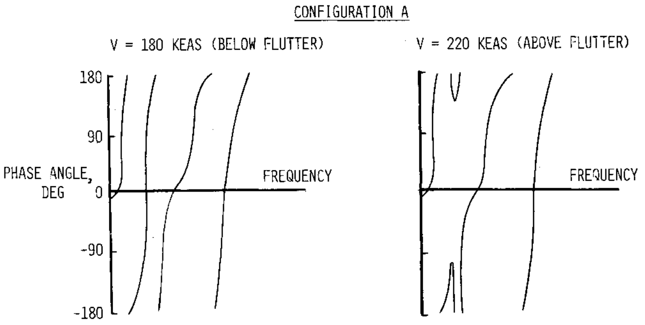

Fig. 4 Phase angle variation with frequency for the aeroelastic equations.

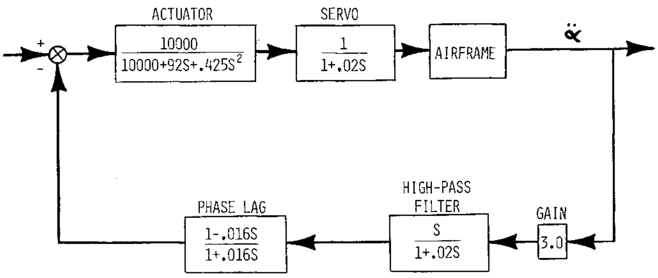

Fig. 5 Nominal active flutter suppression trailing-edge control law, configuration A.

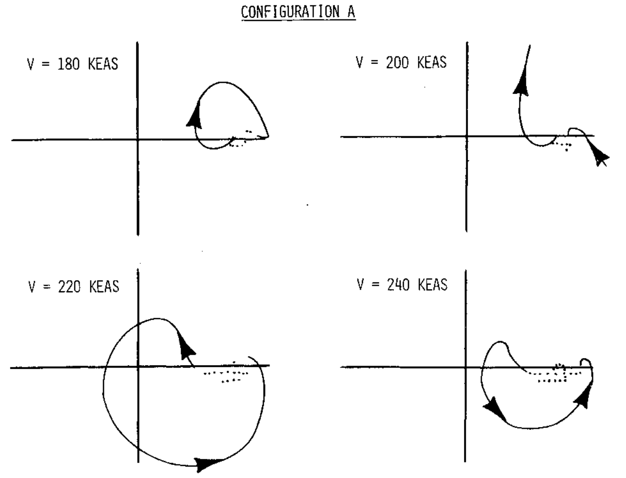

Fig. 6 Modified Nyquist plots for the nominal trailing-edge control law.

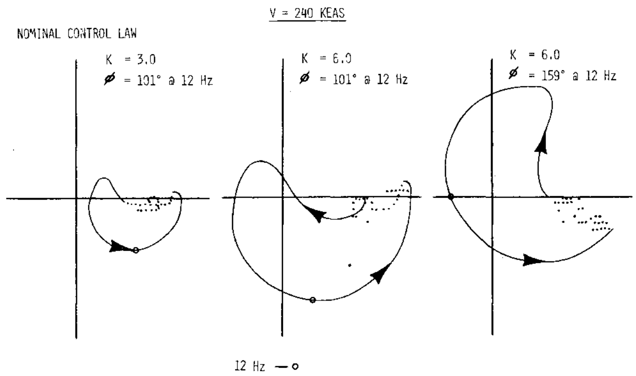

Fig. 7 Stability calculations for variations in gain and phase lag, configuration A, trailing-edge control.

system-induced instability. Since passive flutter is a pole in the right half of the s plane, at speeds above flutter, the Nyquist trace must encircle the origin once in the counterclockwise direction to be stable. If this is not the case, the model is unstable in the flutter mode or possibly in another elastic mode.

Figure 6 presents modified Nyquist plots for the nominal trailing-edge control law for configuration A. The figure shows plots for increasing airspeed. Loss of flutter control is predicted to occur between 220 and 240 KEAS, where the Nyquist traces no longer encircle the origin.

The Nyquist traces give valuable information for improving the stability of the system. Figure 7 illustrates how to use the Nyquist plot to further increase the flutter suppression system performance. The plot shown on the left of Fig. 7 represents the nominal control system for configuration A at 240 KEAS. By simply amplifying the plot, it is possible to cause the Nyquist path to encircle the origin. The middle plot represents the nominal control law with the gain increased by a factor of 2 for the same airspeed. The model is now stable in the flutter mode because of the counterclockwise encirclement of the origin. However, there is a mode just to the right of the origin that has a very low gain margin. If the gain were increased further, this portion of the curve could be pushed to the left causing a control-system-induced instability above the flutter speed. (There would no longer be an encirclement of the origin.) This potentially unstable mode can be further stabilized by adding phase lag (right plot). Phase lag causes a rotation of the plot around the $(+1,0)$ point in a clockwise direction. Since the phase lag is frequency dependent, each point on the plot will be rotated through a different angle. For this case, the phase lag causes the system to have significantly improved gain and phase margins.

Another useful plot in evaluating the stability characteristics of an aeroservoelastic system is the Bode plot, shown in Fig. 8. This plot represents the amplitude and phase angle versus frequency of the open-loop equations of motion. Once again, it is very easy to obtain gain and phase margins for a given control law and flight condition from the Bode plot, although it does require a more accurate plot in the frequency range of interest than the Nyquist plot. Figure 8 shows a Bode plot for the configuration A nominal trailing-edge control law at a speed above flutter. When the phase angle is -180 deg and the amplitude ratio is positive in the flutter mode, the system will be stable when the loop is closed. From the Bode plot, the gain margin is defined as the amplitude ratio, in decibels, when the phase angle is -180 deg., and the phase margin is defined as the difference between -180 deg and the phase angle when the amplitude ratio is 0 dB. In the frequency range of interest, near 12 Hz, the amplitude ratio becomes 0 dB twice and the phase angle becomes -180 deg twice. Thus, a gain margin and a phase margin can be obtained for both the flutter mode and the other critical elastic mode discussed earlier for the Nyquist plots.

Root locus is another technique used quite often by control system and dynamic specialists to assess system stability. This technique, however, requires that the unsteady aerodynamics be represented by functions of the Laplace variable. Figure 9 shows a typical root-locus plot for elastic modes of interest and a modified Nyquist plot for similar flight conditions. The Nyquist plot consists of a trace that is a function of frequency for a fixed control law. Each loop of the Nyquist path represents an elastic mode. The damping of each mode in this case is related to the size of the loop and the frequency. Gain and phase margins can be easily determined from the modified Nyquist plot. The root-locus plot consists of several traces, each one of which represents a mode used in the analysis, as well as control system roots. The traces are a function of some variable such as gain, phase angle, or airspeed. The damping of each elastic mode is related to the angle between a line from the origin of the s plane to the mode in question, and the vertical axis. Gain and phase margins cannot be obtained by inspection of the plot without the use

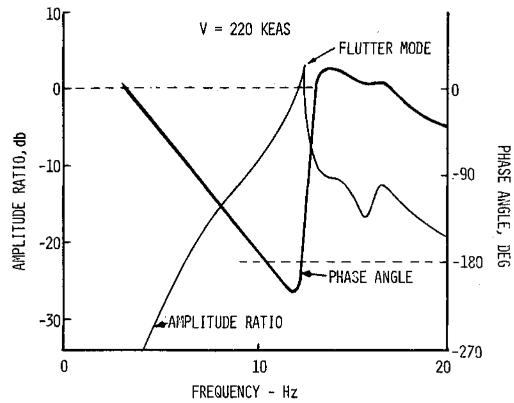

Fig. 8 Bode plot for the nominal trailing-edge control law.

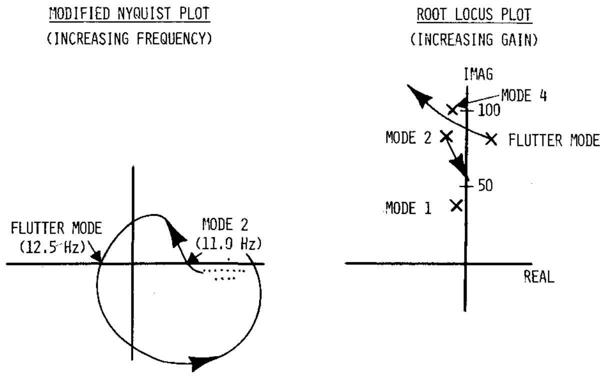

Fig. 9 Stability evaluation techniques.

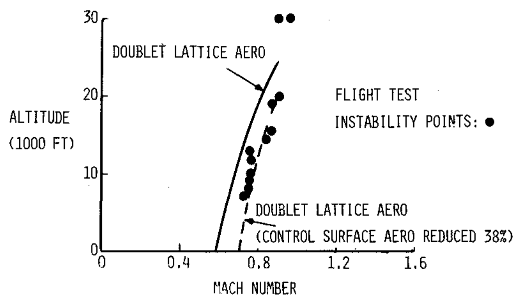

Fig. 10 Comparison of calculated and flight test stability boundaries, missiles-on.

of several plots, i.e., variations of gain at nominal phase and variations of phase at nominal gain.

Example 2—YF-16 Aircraft

The results of another AFFDL aeroservoelastic analysis are presented for the YF-16, which encountered two different instabilities during early flight tests.[14] With the tip missiles installed, the instability occurred at 6.5 Hz and involved coupling of the roll augmentation system with the first antisymmetric mode (wing bending/missile pitching). Figure 10 shows the flight-test data and the analysis results[7] using the ASEP procedure discussed earlier. The analysis using the doublet lattice aerodynamics gives conservative results. One reason for this conservatism is the overprediction of the control surface aerodynamic forces. For example, the analysis predicts a steady rolling moment coefficient due to aileron deflection of -0.217 and wind-tunnel results indicate a value of -0.134 for this same term. As shown in Fig. 10, a 38% reduction in control surface aerodynamics yields results that fit the flight-test data very well.

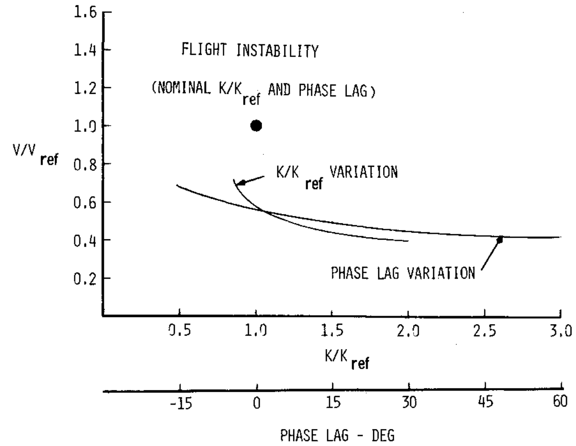

Fig. 11 Missiles-on instability trends for gain and phase-lag variations.

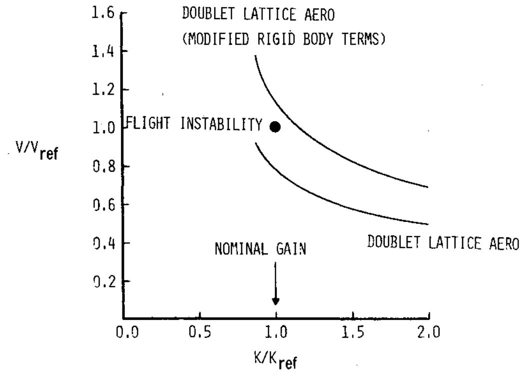

Fig. 12 Missiles-off instability trend with gain.

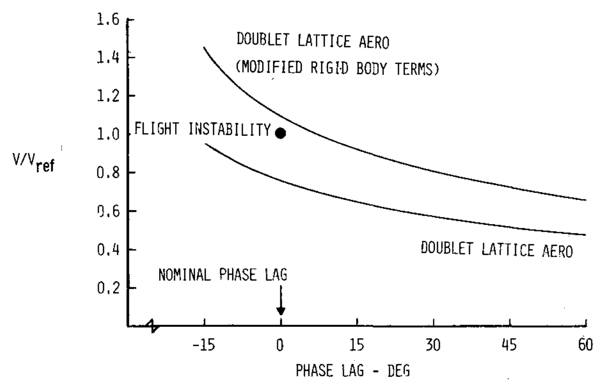

Fig. 13 Missiles-off instability trend with phase lag.

Variations were made from the nominal gain and phase to check the sensitivity of this instability speed to these parameters. Figure 11 shows that the missiles-on instability speed is more sensitive to gain increases than phase lag.

The second YF-16 instability occurred without the tip missiles. Again the motion was antisymmetric, but the frequency dropped to 3.5 Hz (well below the frequency of the first elastic mode but above the rigid-body roll frequency). Figures 12 and 13 show the analysis results for gain and phase variations for the missiles-off instability. On these figures the flight-test point is also shown (for nominal control system gain and phase). The predictions using the doublet lattice aerodynamics are conservative. If the rigid-body unsteady aerodynamic terms are modified to match steady-state wind-tunnel data, the instability speed predictions are slightly unconservative. The analysis does not include additional phase lag (12 deg at 3.5 Hz) observed in the test data[15] for the actuators. This additional phase lag would make the analysis conservative.

Variations of the damping and natural frequency of the roll-rate sensor were investigated for the missiles-on[7] and missiles-off[16] configurations to determine the effects on stability. For the analyses discussed above, a damping of 0.6 (ratio of damping to critical damping) and a natural frequency of 50 Hz were used for the nominal roll-rate sensor. Stability analyses with a 30-Hz sensor natural frequency (damping remaining at 0.6) show a destabilizing effect for both the missiles-on and missiles-off configurations. Use of the measured sensor response rather than the calculated values destabilized the missiles-on configuration and slightly stabilized the missiles-off configurations.

ASE Testing

Aeroservoelastic analyses can be substantiated by a wide variety of ground and flight tests. Each segment of the analysis, i.e., flight control system dynamics, structural dynamics, and aerodynamics must be verified individually to insure a safe, flightworthy vehicle. A lack of correlation in any segment can completely negate the ASE analysis results.

Individual components within the flight control system are usually bench tested to verify predicted frequency response characteristics. Environmental conditions, variations due to manufacturing tolerances, and changes due to wear often complicate the interpretation of these test results. For example, a typical large aircraft stability augmentation system actuator experienced the following variations due to wear and temperature: 16-deg. phase angle and 1.3-dB magnitude due to wear; 8-deg. phase angle and -0.2-dB magnitude due to temperature (both at 10 Hz).

Once the various components have been tested individually, they are assembled on the aircraft or an "iron-bird" flight control system simulation for additional testing. Open-loop, end-to-end (sensor to control surface) frequency response tests are conducted and correlated with predictions. Often a component near one end, e.g., a sensor or a surface, is omitted from the test. These tests are done at several amplitudes and over a wide range of frequencies.[15] Because of nonlinearities and limits encountered during these tests, the correlation between the linear predicted frequency response and the test data is less than straightforward. Care must be taken that the linear analysis includes structural flexibility similar to the test article, including the type of aircraft support. Reference 15 presents comparisons between experimental and analytical open-loop frequency response data. For the YF-16 three levels of excitation were used. The aircraft was supported on a soft suspension system that simulated the free-free (in-flight) boundary conditions of the structural math model. Since modern flight control systems commonly use multiple feedback paths, each loop must be investigated independently during these open-loop, end-to-end frequency response tests.

Closed-loop ground tests should also be conducted with the objective of correlating with analysis results. System stability should be determined with and without notch filters, where possible.[17] Each loop or combination of loops should be investigated and correlated with predictions. Engineering judgment is needed to assess the importance of closed-loop ground tests in determining effects of gain scheduling with flight parameters, gain changes with flap settings, landing gear position, etc., and possible flight control system single-failure modes. As in the open-loop tests, the vehicle's structural dynamic characteristics during the test must agree with the analysis configuration. Aircraft support, possible critical store loadings, fuel loadings, etc., should be selected to permit validation of the mathematical model used for flight predictions. Once the analysis is validated, the entire range of variations, such as external stores and fuel loading, can be investigated analytically. Ground tests that close a single control system loop with a simplified representation of the aerodynamics are of limited value and contribute virtually nothing to the correlation with analyses.[17]

The structural dynamics section of an ASE analysis is usually verified by the Ground Vibration Test (GVT). By exciting the structure with shakers and measuring the response at several locations on the vehicle, sufficient data are obtained to confirm or improve upon the dynamic mathematical model of the structure. Several techniques employing single shakers, multiple shakers, random inputs, sinusoidal inputs, constant-frequency dwell and stop, Fourier analysis, etc., are available, but the ultimate objective is to correlate with and substantiate the structural dynamics analysis. During the GVT, flight control sensor output should be recorded as part of the modal survey.[15] Because these sensors are intentionally located in regions of little structural response, conventional GVT techniques for measuring mode shapes are usually inadequate for determining sensor outputs. Additional correlation with the structural math model can also be achieved during static proof load or structural influence coefficient tests.

For the purposes of correlating with ASE analyses, the open-and closed-loop ground tests can be done most efficiently in conjunction with the Ground Vibration Test. The same GVT techniques used to determine modal damping can be applied with the control system on. Thus, the stabilizing or destabilizing effects of each combination of control system feedback loops can be determined and compared to analyses.

The final aircraft ground test that substantiates the ASE analysis is the taxi test. Analysis of taxi-test results on an instrumented aircraft can add valuable insight into possible significant aeroservoelastic effects. Taxi tests with variable control system gains, augmentation systems on and off, or variations in other parameters that may affect ASE stability can safely add confidence to the first flight configuration of a new or highly modified vehicle. In addition, since analyses are usually of insufficient detail to include local structural flexibilities, such as the sensor attachments or the servo/actuator interface, adverse servoelastic interactions beyond the scope of the analyses may be identified during the taxi test.

Static, dynamic, and aeroelastic wind-tunnel-model tests can also contribute to the verification and evaluation of the aeroservoelastic analyses. In the classical flutter design procedure, aeroelastic wind-tunnel models substantiate the unsteady aerodynamics. Similarly, in ASE design procedures the aerodynamics can be verified (at approximately steady-state conditions) by correlation with conventional force or pressure model wind-tunnel-test results. Dynamic stability and control model data (if available) can be compared directly with similar terms in the aeroservoelastic equations. Finally, correlation with flutter model results (active control system off) and with active control flutter model results (if such a model exists) provides additional confidence in the ASE analysis. To get the most meaningful data out of the tests, care must be taken to dynamically scale the model to the most severe aircraft flight condition and to conduct model scale analyses. Erroneous results can be derived from aeroelastic model test data if the correlation analyses (both airplane and model scale) are not conducted at matched-point conditions, i.e., assumed Mach numbers, speeds of sound, and flutter speeds consistently match.

The ultimate verification of ASE design and analysis procedures occurs during flight testing. In general, ASE considerations increase the complexity and amount of flight flutter testing that must be conducted to clear an aircraft configuration. For example, an aircraft with an autopilot and a stability augmentation system (that can safely be turned off in flight) could require four times as much data as conventional flight flutter tests to evaluate the ASE effects of each system independently[18] at each airspeed/altitude test point. Gain variations in the flight control system during flight flutter testing[17] can also add significantly to the test time.

Close Encounters

This section presents some typical examples of aircraft that have had close encounters of the aeroservoelastic kind. The list is by no means complete and very few cases are documented.

In 1948, an ASE instability was induced by the autopilot of a B-36. The sensor package had been located in the tail gunner's compartment and significant body bending motion had been picked up by the sensors. The solution was to move the sensor package to a position of relatively small body bending motion. Ironically, some 25 years later, a B-52 encountered an aeroelastic instability that was stabilized by its automatic flight control system.

A large bomber encountered a servoelastic instability on the ground during flight control system tests. Though ASE analyses of the vehicle indicated no problem, the aircraft was supported on jacks for these tests and the vehicle's structural dynamics were significantly different from the free-flight condition analyzed.

In spite of limited ASE analyses conducted on the YF-16, the aircraft experienced two separate ASE instabilities[7,14,16] during early flight tests. The ASE analyses were conducted at a high-Mach-number, low-altitude flight condition which was the most critical for classical flutter. However, based on control system effectiveness variations within the operating envelope, the most critical interaction occurred in the high subsonic Mach number regime, which was not an analysis flight condition. Later ASE analyses at the proper flight condition did correlate with the flight-test results.

Similarly, the YF-17 had two potential aeroservoelastic instabilities.[17] However, these instabilities were predicted and no unanticipated aeroservoelastic interactions were encountered during the flight test program. Parametric aeroservoelastic analyses of ground-test and flight-test interactions were done to select the final notch filters for the flight control system.

The Control Configured Vehicle Ride Control System (RCS)[19,20] tested on a B-52 encountered a servoelastic oscillation on the ground that illustrates an inadequacy inherent in aeroservoelastic analyses. Local structural vibrations such as those associated with bulkheads or support beams are too detailed to include in the aircraft structural dynamics mathematical model. On the B-52 RCS, the excitation of a person walking about in the crew compartment was sufficient to excite the local structure around the accelerometers that provided input to the RCS. By changing the accelerometer mounting, the oscillations were eliminated.

Another example of an aeroservoelastic instability that could not be adequately predicted by analyses occurred on a modified F-4.[21] During a sideslip maneuver in a gear-down, flaps-down configuration, a resonance in the pitch axis was encountered. The instability occurred at 23 Hz, which was close to both the flap rotation mode and the stabilator rotation mode frequencies. The instability mechanism was initiated by flap buffet which fed into a pitch-rate gyro located in the left wing root just forward of the flap. The resonance was sustained by the pitch-rate-gyro output driving the stabilator. The program was solved by additional filtering in the pitch axis.

A target drone, when equipped with a prototype infrared wing tip pod, encountered sustained constant-amplitude sinusoidal oscillations at high speeds. On some flights, these oscillations produced structural damage to the wing tip area. Because the vehicle's automatic flight control system had no wing control surfaces, ASE interaction was not initially considered to be a source of the problem. After further investigations, it was determined that a roll-rate gyro in the fuselage was sensing a wing tip pod pitching mode and commanding differential horizontal tail motions. Notch filters and control system gain reductions were used to solve the problem.

ASE Analysis and Design Requirements

Aeroservoelastic analysis and design requirements needed to predict and prevent adverse interaction between automatic flight control systems and the vehicle's structural dynamics are complicated by several key factors that may change throughout the aircraft's operating envelope. Since each ASE analysis is conducted at a discrete point within the operating envelope, in a fixed flight control system state, and for a unique aircraft configuration, conducting analyses that include all possible combinations of factors that may influence ASE stability is impractical. Thus, engineering judgment tempered with experience is needed to assess the following:

1) flight control system scheduled gain changes;
2) control surface effectiveness;
3) control system failure modes;
4) structural dynamics changes, e.g., store loadings, fuel variations, aircraft support conditions, etc.;
5) multiple and blended feedback paths within the flight control system;
6) control system nonlinearities and rate and power limits;
7) uncertainties in the structural, aerodynamic, and control system math models;
8) control system dynamics changes from aging, wear, manufacturing tolerances, and the environment.

Some guidance is provided by Air Force specifications[1,22] which are based on years of experience with both successful and not-so-successful aircraft designs. The structures specification[22] requires the design to meet the same flutter margins and damping requirements with the augmentation system on and off. In addition, at speeds up to the aircraft limit speed, a stable system with at least 6-dB gain margin ($\pm$) and at least ± 60 deg phase margin is required. The flight control specification[1] requires the design to meet several different gain and phase margins, depending upon mode frequency and airspeed. Attempts are being made to update and improve specification requirements to be consistent with the latest state of the art. Based on recent experience and current state-of-the-art analysis and testing techniques, a ± 6-dB gain margin and a ± 45-deg phase margin appear to be satisfactory to assure flight safety.[23] A unified approach based on the latest experience is presented in the next section. When less accurate methods are used, more stringent design requirements should be imposed.

Recommendations

A unified approach[2] is recommended to assure safety of flight and prevent possible adverse ASE interactions. This approach must be based on analyses, ground tests, and flight tests, but with different levels of effort depending on the specific application. In general, the unified approach should include:

1) Incorporation of the structural dynamics data into the control system design as early as possible;
2) Continual interaction between the structural dynamicists and the control system engineers throughout the design, development, and test phases;
3) Updating the math model on the basis of correlation with static, dynamic, aeroelastic, and aeroservoelastic wind-tunnel-model test data;
4) Conducting and continually updating aeroservoelastic analysis at the most critical conditions on the basis of eight factors at the beginning of the previous section;
5) Conducting and correlating open-loop and closed-loop ground tests on each system component and on the entire vehicle. Testing should include ground vibration tests and instrumented taxi tests;
6) Conducting and correlating flight tests to verify freedom from aeroservoelastic instabilities;

7) Establishing realistic gain and phase margin requirements based on the analyses and tests to be done.

Future needs include continued research to improve and evaluate unsteady aerodynamic methods for oscillating control surfaces. Emphasis should be placed on measuring aerodynamic pressures produced by oscillating control surfaces in transonic flow. Also, the development of more efficient test techniques and data analysis methods should be continued. Particular emphasis should be placed on the development of methods to modify or even formulate the aeroservoelastic analytical representation from test data. Research should be focused on eliminating future encounters of the aeroservoelastic kind.

References

[1] Townsend, J. L. and Raymond, E. T., "Background Information and User's Guide for MIL-F-9490," AFFDL-74-116, Jan. 1975.

[2] Barfield, A. F. and Felt, L. R., "Aeroservoelasticity—A Merging of Technologies," Society of Flight Test Engineers 7th Annual Symposium, Aug. 1976.

[3] Triplett, W. E., "Computer Programs for the Frequency Response Stability Evaluation of Servoaeroelastic Systems," McDonnell Aircraft Co. Rept. No. MDC A2888, May 1974.

[4] Lakin, G. C., "Flutter Suppresssion System Research Program, Phase II," The Boeing Co., D162-10402-1, Dec. 1970.

[5] Edwards, J. W., "Unsteady Aerodynamic Modeling and Active Aeroelastic Control," Dept. of Aeronautics and Astronautics, Stanford Univ., SUDAAR 504, Feb. 1977.

[6] Wilkinson, K., et al., "An Automated Procedure for Flutter and Strength Analysis and Optimization of Aerospace Vehicles," AFFDL-TR-75-137, Vols. 1 and 2, Dec. 1975.

[7] Noll, T. E. and Huttsell, L. J., "Control System/Airframe Interaction Analyses for the YF-16 Missile-On Configuration," AFFDL-TM-77-3-FBR, Mar. 1977.

[8] Nyquist, H., "Regeneration Theory," *Bell System Journal*, Vol. 2, Jan. 1932.

[9] Triplett, W. E., Kappus, H. F., and Landy, R. J., "Active Flutter Suppression Systems for Military Aircraft—A Feasibility Study," AFFDL-TR-72-116, Feb. 1973.

[10] Hwang, C., Winther, B. A., Noll, T. E., and Farmer, M. G., "Demonstration of Aircraft Wing/Store Flutter Suppression Systems," presented at the AGARD Structural Dynamics and Materials Panel, April 1978.

[11] Hwang, C., Winther, B. A., and Mills, G. R., "Demonstration of Active Wing/Store Flutter Suppression Systems," AFFDL-TR-78-65, June, 1978.

[12] Mikhailov, A. V., "Harmonic Analysis in the Theory of Automatic Control," *Automatika i Telemkhanika,* Moscow, 1938.

[13] Landahl, M. T., "Graphical Technique for Analyzing Marginally Stable Dynamic Systems," *Journal of Aircraft*, Vol. 1, Sept.-Oct. 1964, pp. 308-310.

[14] Peloubet, R. P., "YF-16 Active-Control-System/Structural Dynamics Interaction Instability," presented as Paper 75-823 at the AIAA/ASME/SAE 16th Structures Structural Dynamics and Materials Conference, Denver, Colo., May 27-29, 1975.

[15] Peloubet, R. P., et al., "Ground Vibration Testing of Fighter Aircraft with Active Control Systems," AFFDL-TR-76-110, Dec. 1976.

[16] Huttsell, L. J. and Noll, T. E., "Control System/Airframe Interaction Analyses for the YF-16 Missile-Off Configuration," AFFDL-TM-77-13-FBR, Aug. 1977.

[17] Arthurs, T. D. and Gallagher, J. T., "Interaction between Control Augmentation System and Airframe Dynamics on the YF-17," presented as Paper 75-824 at the AIAA/ASME/SAE 16th Structures, Structural Dynamics and Materials Conference, Denver, Colo., May 27-29, 1975.

[18] Kehoe, M. W., "NKC-135A Airborne Laser Laboratory (Cycle III) Flight Flutter Test Program," AFFTC-TR-77-45, Mar. 1978.

[19] Stockdale, C. R. and Poyneer, R. D., "Control Configured Vehicle Ride Control System (CCV RCS), B-52 Control System Analysis, Synthesis, and Design," AFFDL-TR-73-83, July 1973.

[20] Stockdale, C.R., Poyneer, R.D., Barfield, A.F., Stumpfl, S.C., Felt, L.R., and Earley, B.H., "Control Configured Vehicles Ride Control System Flight Test Results," AFFDL-TR-74-66, June 1975.

[21] Ettinger, R. C., Majoros, R. L., and Powell, C. W., "Air Force Evaluation of the Fly-by-Wire Portion of the Survivable Flight Control System Advanced Development Program," FTC-TR-73-32, Aug. 1973.

[22] "Military Specification Airplane Strength and Rigidity Flutter, Divergence, and Other Aeroelastic Instabilities," MIL-A-008870A (USAF), Mar. 31, 1971.

[23] Peloubet, R. P., Haller, R.L., Cunningham, A.M., Cwach, E.E., and Watts, D., "Application of Three Aeroservoelastic Stability Analysis Techniques," AFFDL-TR-76-89, Sept. 1976.