YF-16 FLIGHT FLUTTER TEST PROCEDURES

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SUMMARY

The procedures used for flight flutter testing of the YF-16 lightweight fighter prototype are described. The Random Decrement technique was incorporated to augment the initial plan to use only the pilot pulse approach. With Random Decrement, subcritical damping of the structural modes is extracted from the turbulence-induced random vibrations of the structure. Hence, the method bypasses the requirement for an excitation system needed in the conventional approaches. Damping is obtained from the Randomdec Signature of each mode. The Randomdec Signature is analogous to the transient response to an initial displacement. To obtain a Randomdec Signature, one collects and averages a number of segments of the random response of the mode. Expeditious flutter clearance of the YF-16 was accomplished, marking the first known application of the technique to a full-scale test article. Although the Random Decrement apparatus used was lacking in completeness, it produced damping on check problems which were consistent with values from conventional methods. For the YF-16, it was possible to identify and track most of the modes of interest for each of the configurations tested. Good quantitative damping was obtained for the lower surface modes. Most of the higher modes were detectable and at least a qualitative evaluation of the damping was possible. Most of the testing was done at the more critical low altitudes where the random excitation is high. Due to equipment limitations, only one channel could be monitored on a real time basis. Therefore, most of the analysis was accomplished on a postflight basis. Damping values obtained substantiate the adequacy of the flutter margin of safety.

To confirm the structural modes which were being excited, a spectral analysis of each channel was performed using the AFFTC Time/Data 1923/50 Time Series Analyzer.

The inflight test procedure included the careful monitoring of strip charts, three axis pulses, rolls and pullups.

Conclusions are that, for the YF-16, the procedures used, including Random Decrement, were a satisfactory alternate to more costly conventional test procedures.

INTRODUCTION

A vital step in an aircraft development program is the substantiation of freedom from flutter by means of flight flutter tests. Since flutter clearance is a pacing item for expanding the speed envelope, the need for accurate, rapid and low cost means to forecast flutter is widely recognized. Because flight flutter tests have been costly and time consuming, there have been continuing efforts by industry (Reference 1) and government agencies (Reference 2) to upgrade their procedures. As indicated by a recent survey (Reference 3), most current methods require onboard forced excitation, usually sinusoidal, to excite the structural modes. Damping is then obtained by a variety of methods including from decay records from the well-known "shake and stop" technique. The incorporation of high speed digital computers into the data acquisition and reduction operations has resulted in some significant advances in the state of the art. The methods, however, still tend to be both expensive and time consuming. The excitation system itself is usually a costly item.

Alternatives to methods requiring forced excitation have been advanced. These methods utilize inflight or wind tunnel turbulence as the excitation source. In one approach, PSD analyses of the response signals are made and damping is obtained from the frequency and bandwidth associated with each peak in the PSD plot. The PSD approach is more widely used in Europe at this time.

The Random Decrement approach, the application of which is to be discussed herein, is a second alternate to forced excitation methods. The method was invented by H. A. Cole, Jr., and is fully documented (Reference 4 and 5). The Random Decrement method is basically an ensemble averaging of the turbulence-induced random vibrations of the test article. As is illustrated in Figure 1, Cole advocates triggering each data sample at a constant level, Y_t. Assuming linear superposition, the time history of each sample can be regarded as the combined solution from (1) an initial step displacement, (2) an initial velocity and (3) a random forcing function. Note that the Figure 1(c) sample represents the response to the same initial displacement as Figure 1(b), a different initial velocity with the opposite sign, and a different random forcing function. It can be reasoned intuitively that when a large number of samples are averaged, only the response to the constant initial displacement will remain because the average of responses due to the alternating initial velocities and the random forcing functions will tend to zero. Thus, it is seen that the ensemble average converges toward the transient response to an initial step. For a constant trigger level, the ensemble average (Randomdec Signature) will be constant even if the amplitude of the forcing function varies. If the ensemble average is made up of samples with initial positive slopes only, then the resulting trace represents the transient response to a combined step and initial velocity. Under these conditions the Randomdec Signature would vary with the intensity of the forcing function, thus minimizing the use of the signature trace as a failure detector. However, the damping as determined from the decay rate of the signature trace would be valid. A rigorous mathematical derivation of Random Decrement is given in Reference 6. Included are descriptions of other triggering procedures and automated methods of analyzing the Randomdec Signature to obtain damping.

The main objective of this paper is to present the results of the application of a simplified flutter test technique to a flight article. It is hoped that these results will be of use to others who may be considering new methods and/or improvements for similar techniques.

BACKGROUND

The YF-16 is a lightweight fighter prototype whose high performance credits include supersonic sea-level capability. A top and side view of the airplane is shown in Figure 2. The design features a thin (4%) aluminum wing with leading-edge maneuver flaps and trailing-edge flaperons. The all-movable horizontal tail and the conventional fin-rudder vertical tail have graphite composite skins. Although flutter and aeroelastic considerations had a considerable impact on the design, cost and schedule constraints on the prototype programs dictated a flutter prevention program which minimized flight flutter tests. In the initial planning, flight flutter tests were to be conducted with pilot pulses. The austere flight flutter test program was to be supported by comprehensive analyses and a complete 1/4 scale flexible model to be tested in the NASA Langley 16-Foot Transonic Tunnel. A twenty percent margin of safety was to be utilized for design.

It was during early tests of the YF-16 1/4-scale model components that General Dynamics was first exposed to the Random Decrement concept. NASA LRC tunnel personnel had assembled a Random Decrement analyzer and were using it to monitor the tunnel tests. Although the single-channel instrument limited the extent of on-line monitoring, the capability to extract quantitative damping was demonstrated. An example of the damping of one mode at successive speed increments is shown in Figure 3. NASA LRC had also indicated (see Figure 4) satisfactory agreement between Random Decrement and PSD methods on predicting the flutter speed of an SST wing model.

Following the exposure to Random Decrement at the tunnel test, General Dynamics assembled a Random Decrement analyzer analogous to the NASA equipment and undertook a further evaluation of its capability. An investigation was made on an electric analog computer model of a simple two-degree of freedom system illustrated in Figure 5. The electric model is analogous to a model in a wind tunnel or an airplane in flight and subcritical damping can be determined by the "shake and stop" procedure. Using the Random Decrement analyzer, damping was also obtained with the model being excited by sea-level simulated atmospheric turbulence. As shown in Figure 5, consistent damping and flutter speeds were obtained by the two methods. The damping obtained by the Random Decrement analyzer did not vary significantly with excitation levels higher by a factor of two.

An additional limited evaluation was made using F-111 taped flight flutter test data. Wing tip vanes were used for excitation on the F-111 program; consequently, generally good wing damping records had been obtained. The general observation was that good damping agreement was observed for modes with high ambient response levels and, conversely, poor agreement was shown when the ambient excitation level was low. It was observed that, in cases of low ambient excitation levels, the damping as evaluated by the Random Decrement analyzer was lower than that from the forced excitation.

Following the somewhat cursory evaluation described above, it was decided to implement Random Decrement for the YF-16 flight flutter test program. Some apparent basic limitations of the method were recognized. However, it was felt that realistic damping could be obtained for all modes that were excited by the ambient environment. Separation problems when mode frequencies are close were expected but this problem plagues all methods. In addition, the capability to analyze rapidly any unexpected vibratory phenomenon was highly desirable.

PROCEDURE

The four airplane configurations which were tested are shown in Figure 6. The 1400 liter (370 gallon) external tank loading was tested full, empty and at two intermediate fuel levels. The onboard flutter instrumentation is shown in Figure 7. Included are two accelerometers in each wing tip, one in each horizontal tail tip and one in the vertical tail tip. The output of each transducer was telemetered to the ground and also recorded onboard on magnetic tape. Each telemetered item was displayed on an analog recorder. Variable band-pass filters were used on the accelerometer signals to narrow the response to the frequency range of interest. Any six channels could also be patched to the Random Decrement analyzer for analysis individually.

The test procedure included a slow acceleration to the test point while the strip charts were carefully monitored. Speed was stabilized for 30 to 60 seconds to accumulate data for Random Decrement analysis. Then the pilot would pulse the controls about all three axes, roll 360° in each direction and do a symmetric pullup.

The test procedure was augmented with Random Decrement as follows. The stabilized period at each test point was sufficient to obtain damping only of one selected mode. Since only one Random Decrement analyzer was available, analysis of additional modes could only be accomplished on a rotating basis at the expense of a longer stabilized period. In general, this was not done because the need was not apparent. Instead, all channels were carefully analyzed on a postflight basis.

The on-line and postflight Random Decrement analysis was carried out with the system illustrated in Figure 8. The random output signal was first run through a band-pass filter to isolate a mode before going through the analyzer. The heart of the system is the Hewlett-Packard Model 5480B Signal Analyzer which performed the function of acquiring each data sample and displaying an updated average continuously on an oscilloscope. Programming on this computer is hardwired to panel-mounted push-button controls which enable program START, STOP and MEMORY CLEAR commands. This feature proved to be of considerable operational utility since analysis could be rapidly updated to reflect a change in flight condition or to examine a different measurement location. The ability to switch in and display the random waveform on the scope was very valuable with regard to setting the trigger level for sampling. After triggering, the system reads each data sample at 1000 intervals. The analyzer may be somewhat less than optimum in that it is triggered by positive slope crossings only. As previously mentioned, the analysis time for each damping record usually varied from 30 seconds to a minute depending on the excitation level and the frequency of the mode. Generally, the damping trace was observed to converge after about 25 to 40 samples were acquired. An item which greatly facilitated the postflight data analysis was the conveniently located magnetic tape unit with start, stop and rewind controls operated by the Random Decrement analyzer operator. The reason is that setting optimum trigger levels and locating resonant frequencies can require many passes through the magnetic tape.

The procedure for setting up the analyzer was to first observe the random signal on the oscilloscope to determine existence of periodic motion. The time scale was varied on the CRT display to cover the desired range of frequencies. Obvious aides in detecting specific frequencies were the calculated vibration frequencies, the ground vibration test results, and a frequency spectral analysis described at the end of this section. The variable band-pass filters were adjusted to focus on a specific desired frequency. The trigger level was adjusted by observing the filtered signal on the oscilloscope and triggering at the maximum level possible that would still allow the accumulation of a satisfactory number of data samples within the test period.

The frequency detection portion of this process could be started while the airplane was in transit to the test area or otherwise preparing for the test run. The trigger setting was done after the airplane reached the test speed. With a little experience this could be done fairly quickly. The only time difficulty was experienced was when the turbulence level varied greatly during the test period. Moderate to heavy turbulence was preferred because the setup was easier and a shorter time period was required to accumulate a sufficient number of data samples. In extremely smooth air, the low structural amplitude caused problems in obtaining sufficient data samples and led to some loss of confidence in the accuracy of the results.

A spectral analysis of each data channel was performed to confirm that all structural modes which were responsive to the random excitation were in fact being identified and tracked by the Random Decrement Analyzer. The analysis was performed using the AFFTC Time/Data 1923/50 Time Series Analyzer. This analysis produced the conventional power vs frequency chart and provided graphic confirmation of the frequency content of the response.

OVERALL RESULTS

The flutter free envelopes which were demonstrated are shown in Figure 9. It is noted that the cleared envelopes were those required for prototype evaluations and the design envelopes are somewhat larger. Although full envelope capability is indicated by analysis, model tests and flight flutter test results, the prototype program's tight schedule did not call for full clearance. All subsonic points for each configuration were accomplished on one flight. Generally, two points per flight were accomplished in the low supersonic region. Only one test point per flight was accomplished at the high supersonic speeds to allow a complete postflight evaluation before proceeding to the next test point. The flight flutter test program was planned as part of an integrated program in which considerable data in other disciplines was acquired before the envelope expansion was completed. The flutter test program was completed on schedule with the maximum test dynamic pressure of 103 000 N/m^2 (2150 psf) being reached approximately three months after the first flight.

As expected based on analysis and model test results, the flight flutter test program was accomplished expeditiously and without any major problems. One specific flight test incident occurred which had not been anticipated. Early in the flight test program, a gain sensitive oscillation of the nominal 6.5 Hz antisymmetric wing mode became apparent due to a coupling with the flight control stability augmentation system. The instability is reviewed in detail in a separate paper (Reference 7) and only the highlights will be discussed here. The oscillation was first encountered at approximately .85M at 6096 m (20 000 feet) where insufficient control system interaction analyses had been accomplished. Most of the control system interaction analyses had been accomplished at 1.2M where flutter margins were a minimum and no problem was indicated. The actual problem occurred where the roll effectiveness of the flaperons was the highest. The problem was quickly identified and a fix worked out consisting of a notch filter in the roll feedback loop and realignment of gains in the command and feedback loops. It is worth mentioning that the YF-16's fly-by-wire control system made quick implementation of the fix possible.

Random Decrement was very useful in further defining the region of instability which is shown in Figure 10. The region was actually traversed with reduced roll gains before the final fix was incorporated. As will subsequently be shown, the Random Decrement results show a significant difference between the mode's characteristics with reduced gains and with the notch filter installed. The difference is due to the phase shift which the filter introduces.

Overall, Random Decrement demonstrated that most of the modes of interest were excited by the random environment and solid damping is indicated throughout the flight envelope. A review of the damping records obtained is presented in the following section.

DAMPING

The quality of the damping obtained is described in Table I for the basic configuration with and without tip missiles. The table indicates the modes of each surface that were most easily detected. In general, these are the first two wing modes and the fundamental tail modes. The higher modes, including some in addition to the ones in Table I, were usually detectable but the quality of the decay record was poor or erratic. The fundamental horizontal tail mode was detectable but highly damped. The higher horizontal tail modes were apparently very highly damped also. A complete set of decay records for a missiles-on test point is shown in Figures 11 and 12. Mode identification corresponds to that given in Table I. Plots of damping versus Mach number for the missiles-on fundamental wing symmetric, wing antisymmetric, and vertical tail modes are shown in Figure 13. Corresponding decay records are shown in Figures 14 and 15. Note that the frequencies of the two wing modes are relatively close and some difficulty was experienced in separating the responses. The problem was overcome by adding the signals from corresponding transducers on opposite sides to emphasize the symmetric response and subtracting to emphasize the antisymmetric response. The process is illustrated in Figure 16. A simple network of isolation resistors was used to combine the output of two discriminators. The outputs were summed to get the symmetric response. The phase of one discriminator was reversed to obtain the antisymmetric response. No attempt was made to correct for the slight difference in sensitivity of the accelerometers involved.

The basic wing modes for the configurations with pylon-mounted external stores were detected at approximately the same frequencies listed above and exhibited similar damping characteristics. The carriage of the external stores well inboard (at 27 percent of the exposed semispan) accounts for the small effect on the basic wing frequencies. For the external store configurations, the fundamental store pitch and yaw frequencies were also detected and their decay records extracted. Typical examples of external store decay records are shown in Figure 17 for the airplane with empty 1400 liter (370 gallon) tanks.

Some further examples of the results obtained with Random Decrement are in connection with the oscillation of the antisymmetric mode. Shown in Figure 18 is a comparison of the damping at .9M and 1520 m (5000 feet), before and after the notch filter was added. Before the notch filter was added, the motion of the mode was sustained although of extremely low magnitude for the applicable gain setting. Shown in Figure 18(a) are the individual decay records from opposite wing tips and the decay records obtained after adding and subtracting the wing tip response. It is noted that even though the antisymmetric mode appears to dominate the individual responses, a good damping record was obtained for the symmetric mode. Shown in Figure 18(b) are the corresponding records after the filter was added. Note that even though the numerical value of the feedback loop gain was close to the "before filter" value, positive damping is shown for the antisymmetric mode. As previously mentioned, the difference is apparently due to the favorable phase shift from the filter.

All of the results hereto shown were for relatively low altitude levels where the ambient excitation levels were generally high and damping of each of the principal structural modes was obtained. Early in the test program, some horizontal tail and vertical tail data was obtained at higher altitudes. Although the ambient response levels were lower than at low altitude, no difficulty was encountered in obtaining consistent damping at 6096 m (20 000 feet) and 9144 m (30 000 feet). Damping records for the fundamental tail modes at 1520 m (5000 feet), 6096 m (20 000 feet), and 9144 m (30 000 feet) are shown in Figure 19. The damping at the higher altitude is noticeably lower. The question arises as to whether the damping is lower due to lower density or to inaccuracies associated with the lower excitation levels. In the case of the fundamental tail modes, it is believed that sufficient excitation was provided from wing downwash, etc., so that the high altitude damping is realistic. The high altitude damping for the higher modes is believed to be more questionable.

CONCLUSIONS

Application of Random Decrement to the flight flutter tests of the YF-16 has led to the following evaluation of the technique:

1. The frequency and damping of most of the predominant structural modes can be obtained.
2. The quality of the damping depends on the excitation level, the damping level, and the accumulation of a sufficient number of samples, usually 25-40.
3. The lower structural modes are more easily detected and good quality damping can be expected for these modes.
4. The higher structural modes can usually be detected but damping values tend to be more qualitative than quantitative.
5. Separation of symmetric and antisymmetric modes of nearly the same frequency was possible.

6. As used, the Random Decrement analysis relied heavily on postflight analysis because of the single analyzer available.

7. The method has the obvious limitation of not being able to detect a particular mode if it is not excited. Also, closely spaced modes cause analysis problems.

8. Some of the limitations mentioned here can be overcome with improved facilities and analysis techniques.

For the YF-16, the results from the Random Decrement analysis substantiate the predicted flutter margins of safety. Hence, Random Decrement was a meaningful addition to the flight flutter test procedure and served as a satisfactory alternate to more costly conventional techniques. The principal result was that quantitative damping was obtained which would not have been possible for this airplane with the pilot pulse technique.

FUTURE PLANS

Full scale development of the production F-16 is now in progress. The flutter prevention plan is the same as followed for the prototype YF-16 including a twenty percent margin of safety for design. Planned flight flutter tests will use procedures similar to those described in this paper. The flutter test equipment is being expanded to provide two-channel capability through acquisition of a second Hewlett-Packard Model 5480B Signal Analyzer.

All flutter test data on the YF-16 was both recorded on onboard tape and transmitted via telemetry to the ground receiving station using FM/FM techniques. The F-16 full scale development test aircraft will be equipped with the AFFTC Automatic Test Instrumentation System (ATIS). This is a high rate (up to 512K bits/sec) PCM system. The existing Random Decrement analysis system uses analog input; therefore, digital-to-analog conversion will be required. Experimental confirmation of the sampling rates necessary in order to produce an acceptable damping record has been accomplished. It has been determined that an absolute minimum of four samples per cycle of response is required.

SYMBOLS

A,B	points at which response crosses specified reference amplitude, Y_t
f	frequency, Hz
f_F	flutter frequency, Hz
f_o	frequency of selected response mode, Hz
Δf	band width of response mode at half-power point, Hz
g	damping coefficient
K_h	translational spring constant, dynes/cm
K_α	rotational spring constant, dyne cm/rad
M	Mach number
q	dynamic pressure, N/m^2
t	time, sec
V	airspeed, knots
V_F	flutter speed, knots
V_1,V_2	equivalent initial velocity at points A and B
x_n	half-amplitude of nth cycle of exponential decay curve
x_o	half-amplitude of initial cycle of exponential decay curve
Y_t	reference amplitude of response
γ	viscous damping ratio

REFERENCES

1. Baird, E. F., and Clark, W. B.: Recent Developments in Flight Flutter Testing in the United States. Presented at 34th Meeting of the AGARD Structures and Materials Panel, April 1972, AGARD Report 596

2. Houbolt, J. C.: Subcritical Flutter Testing and System Identification. NASA CR-132480, August 1974

3. Rosenbaum, Robert: Survey of Aircraft Subcritical Flight Flutter Testing Methods. NASA CR-132479, August 1974

4. Cole, Henry A., Jr.: Method and Apparatus for Measuring Damping Characteristics of a Structure. United States Patent No. 3,620,069, 16 November 1971

5. Cole, H. A., Jr.: On-Line Failure Detection and Damping Measurements of Aerospace Structures by Random Decrement Signatures. NASA CR-2205, March 1973

6. Chang, C.S.: Study of Dynamic Characteristics of Aeroelastic Systems Utilizing Randomdec Signatures. NASA CR-132563

7. Peloubet, R. P., Jr.: YF-16 Active-Control-System/Structural Dynamics Interaction Instability. Presented at 16th AIAA/ASME/SAE Structures, Structures Dynamics and Materials Conference, May 1975

TABLE I PRIMARY STRUCTURAL FREQUENCIES

	SYMMETRIC		ANTISYMMETRIC	
	FREQUENCY (Hz)		FREQUENCY (Hz)	
A. MISSILES ON				
WING				
1ST BEND.	4.9	GOOD DECAY	8.0	GOOD DECAY
MISSILE PITCH	6.7	GOOD DECAY	6.4	GOOD DECAY
2ND BEND.	21.7	FAIR DECAY	22.0	FAIR DECAY
TORSION-FLAPERON ROT.	38.4	FAIR DECAY	36.6	FAIR DECAY
HORIZONTAL TAIL				
1ST BEND.	25.2	HIGH DAMPING	25.7	HIGH DAMPING
2ND BEND.	50.1	NOT DETECTED	51.2	NOT DETECTED
PITCH	95.6	HIGH DAMPING	97.1	HIGH DAMPING
VERTICAL TAIL				
1ST BEND.			15.2	GOOD DECAY
2ND BEND.			39.0	POOR DECAY
RUDDER ROTATION			56.5	NOT DETECTED
B. MISSILES OFF				
WING				
1ST BEND.	8.5	GOOD DECAY	10.9	FAIR DECAY
LAUNCHER PITCH	17.2	POOR DECAY	17.4	FAIR DECAY
2ND BEND.	29.7	GOOD DECAY	32.0	FAIR DECAY
TORSION-FLAPERON ROT.	39.6	POOR DECAY	40.8	POOR DECAY

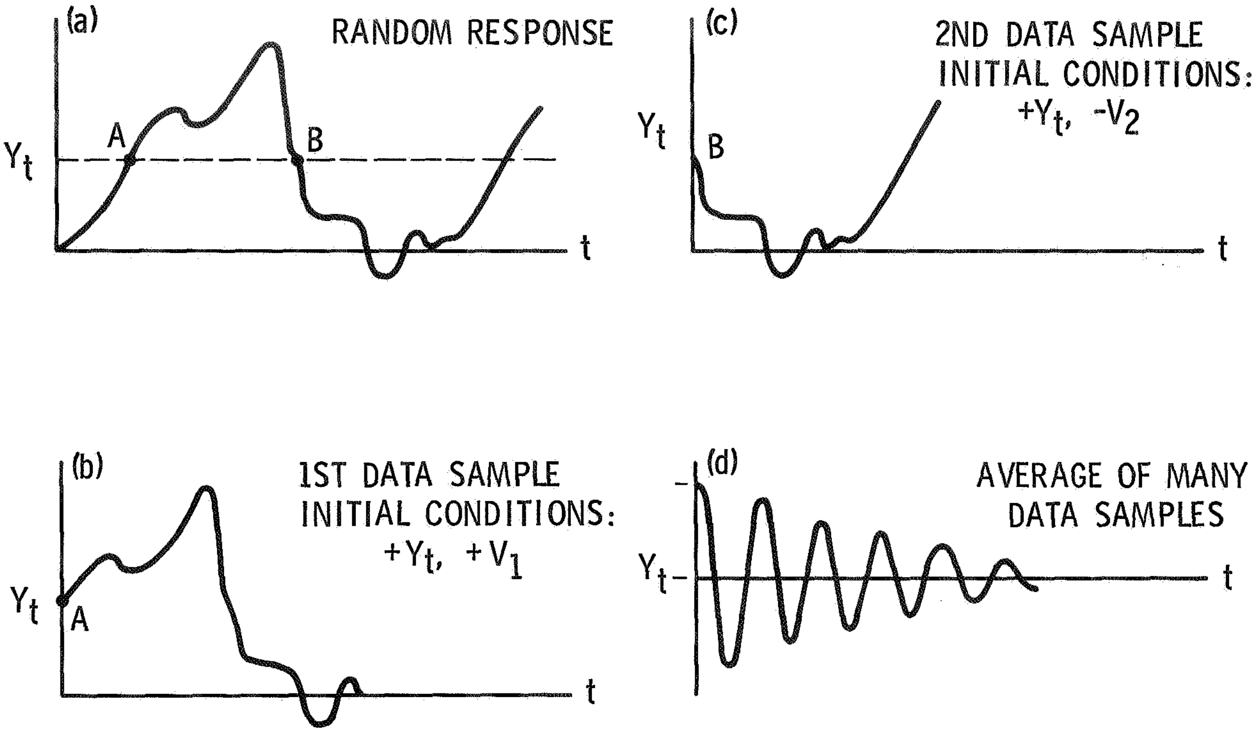

Figure 1 Random Decrement Concept

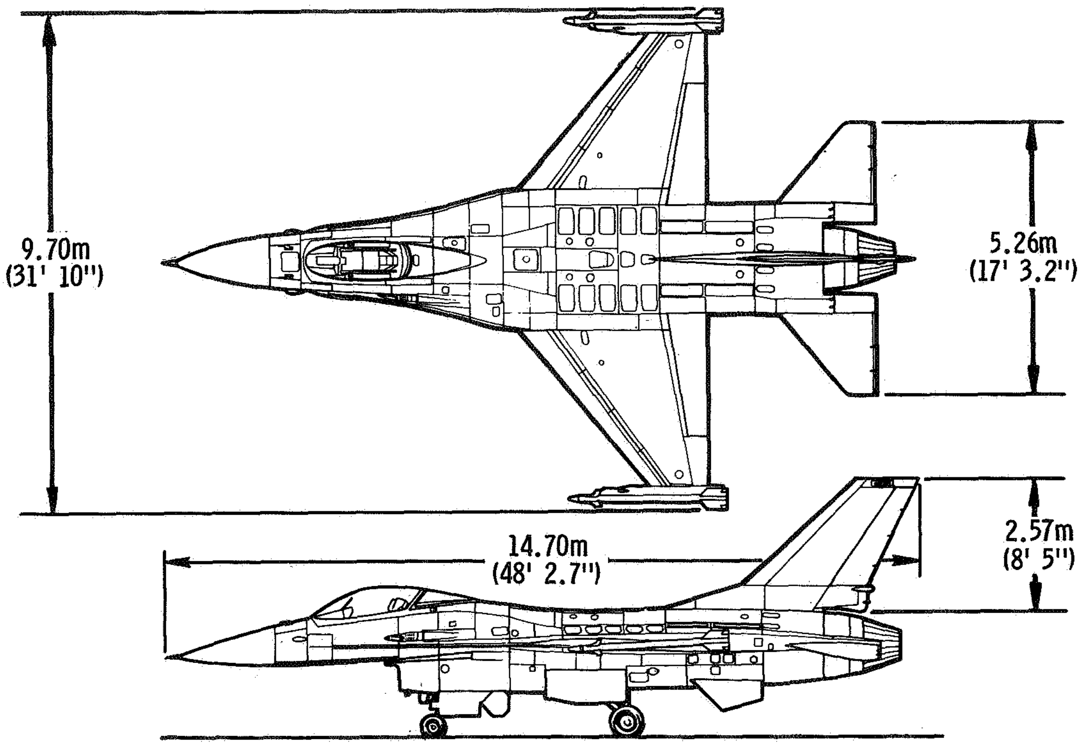

Figure 2 YF-16 Airplane

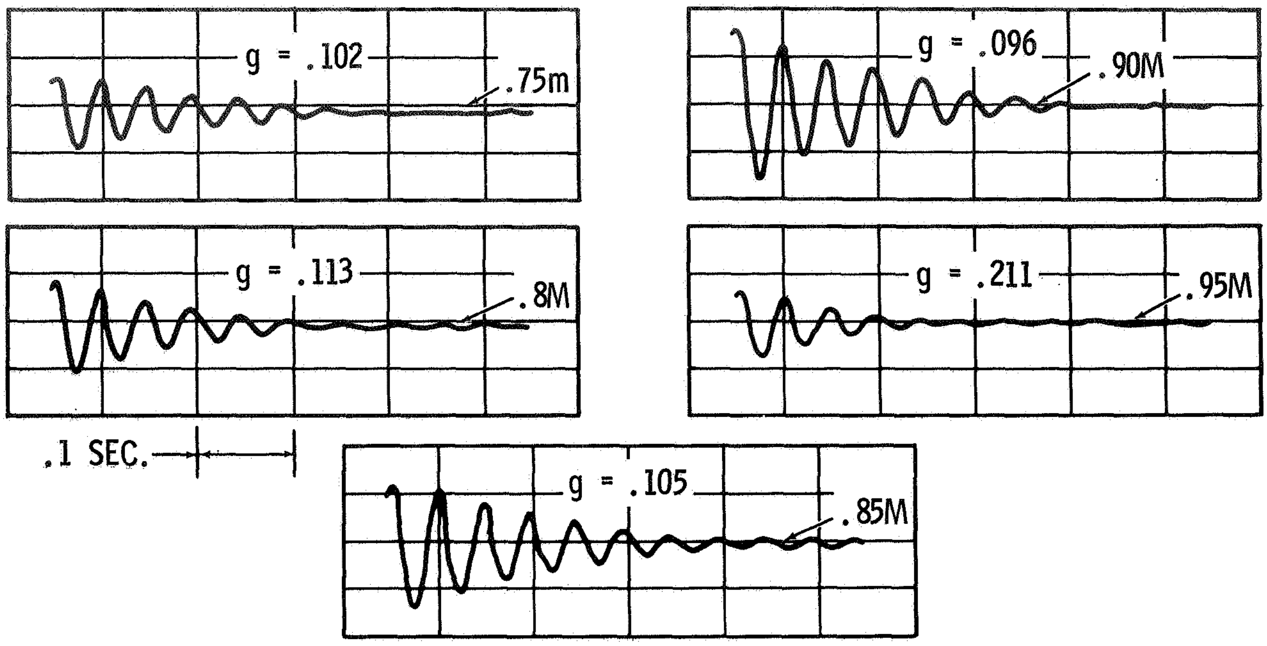

Figure 3 Model Pylon Damping

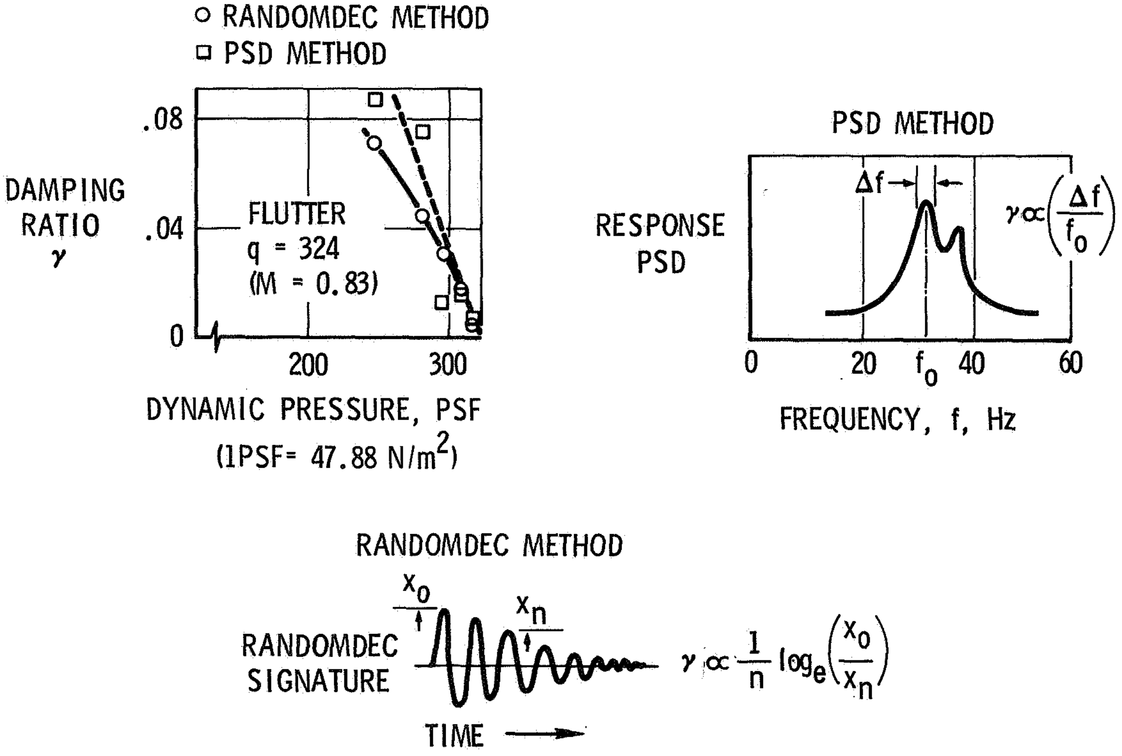

Figure 4 SST Model Damping

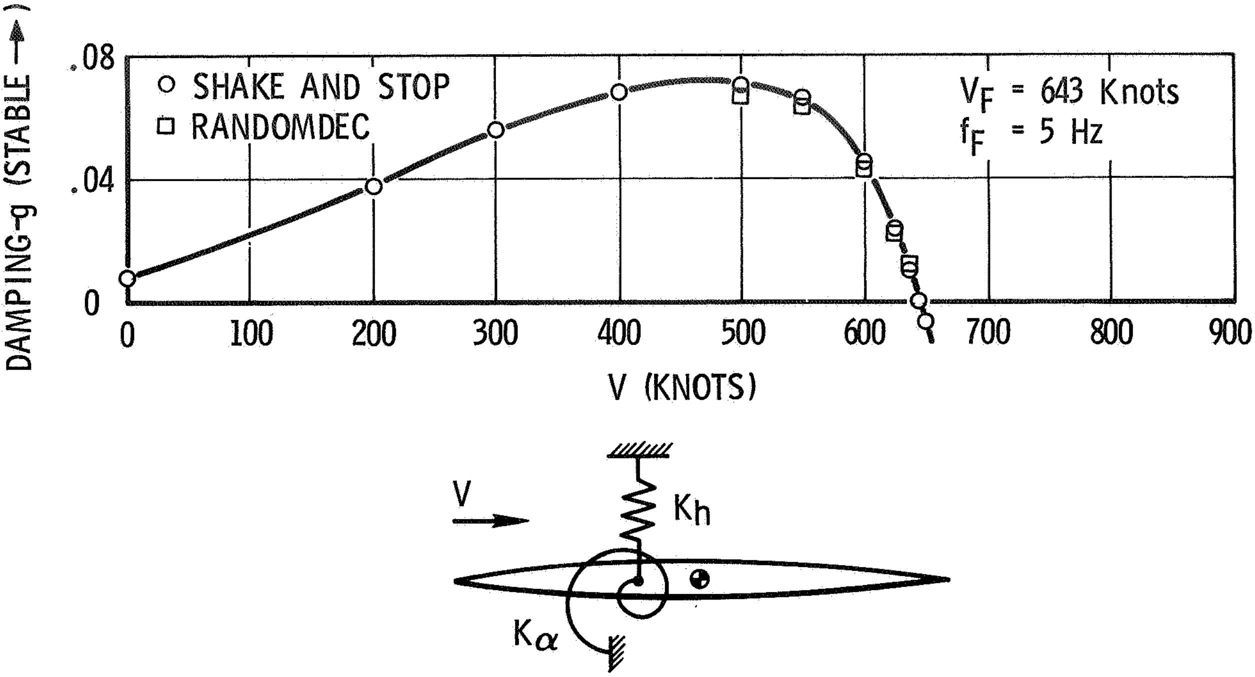

Figure 5 Analog Model Damping

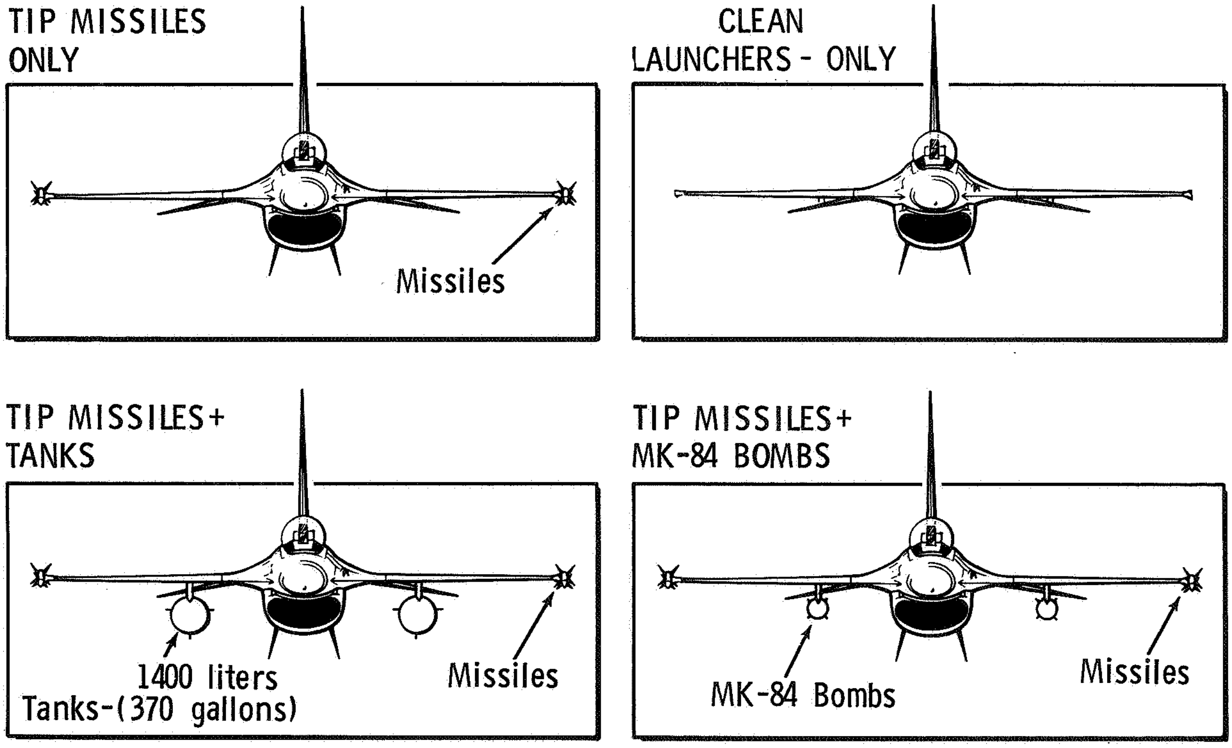

Figure 6 YF-16 Test Configurations

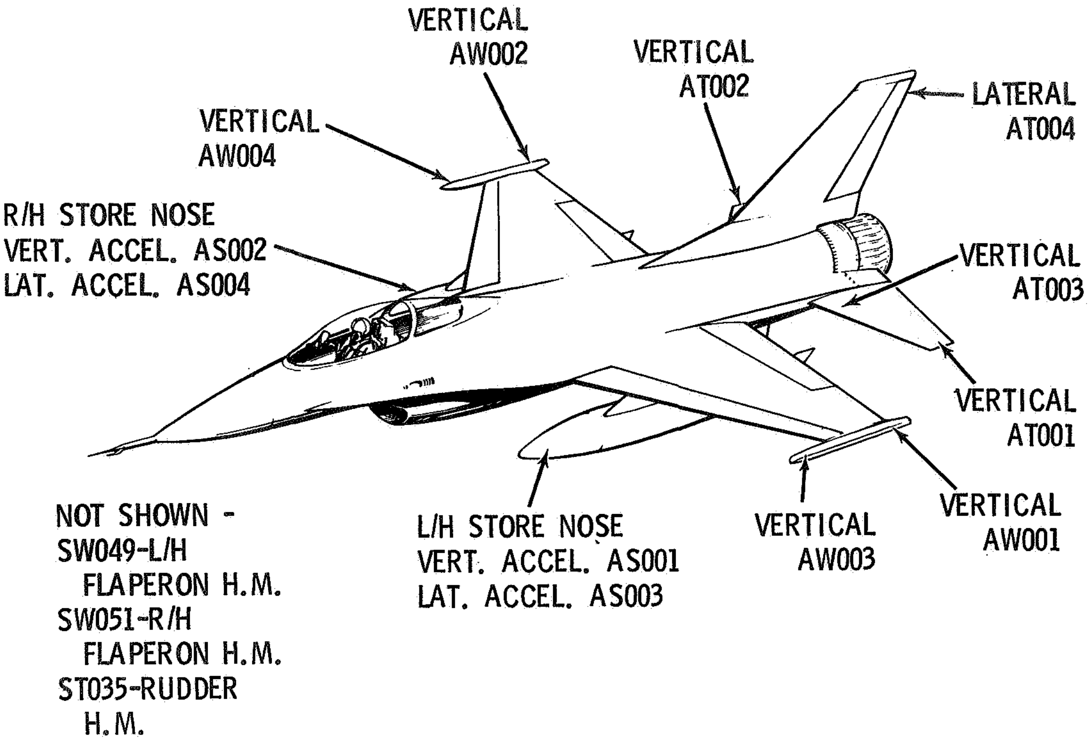

Figure 7 YF-16 Test Instrumentation

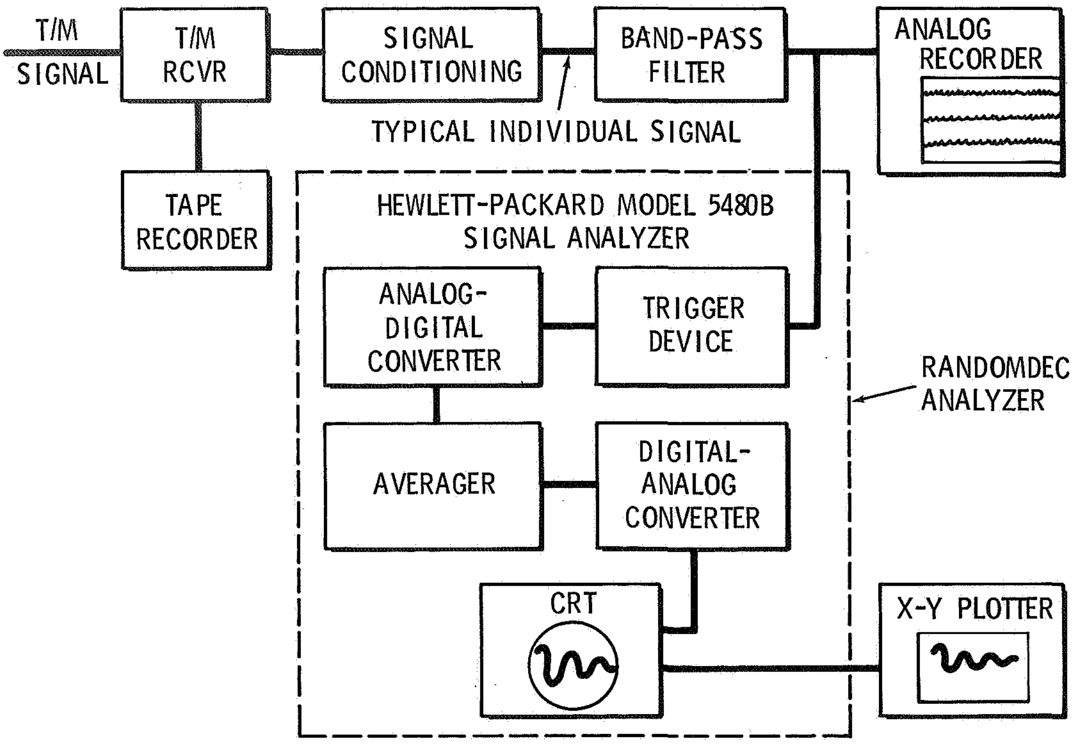

Figure 8 Random Decrement Analyzer

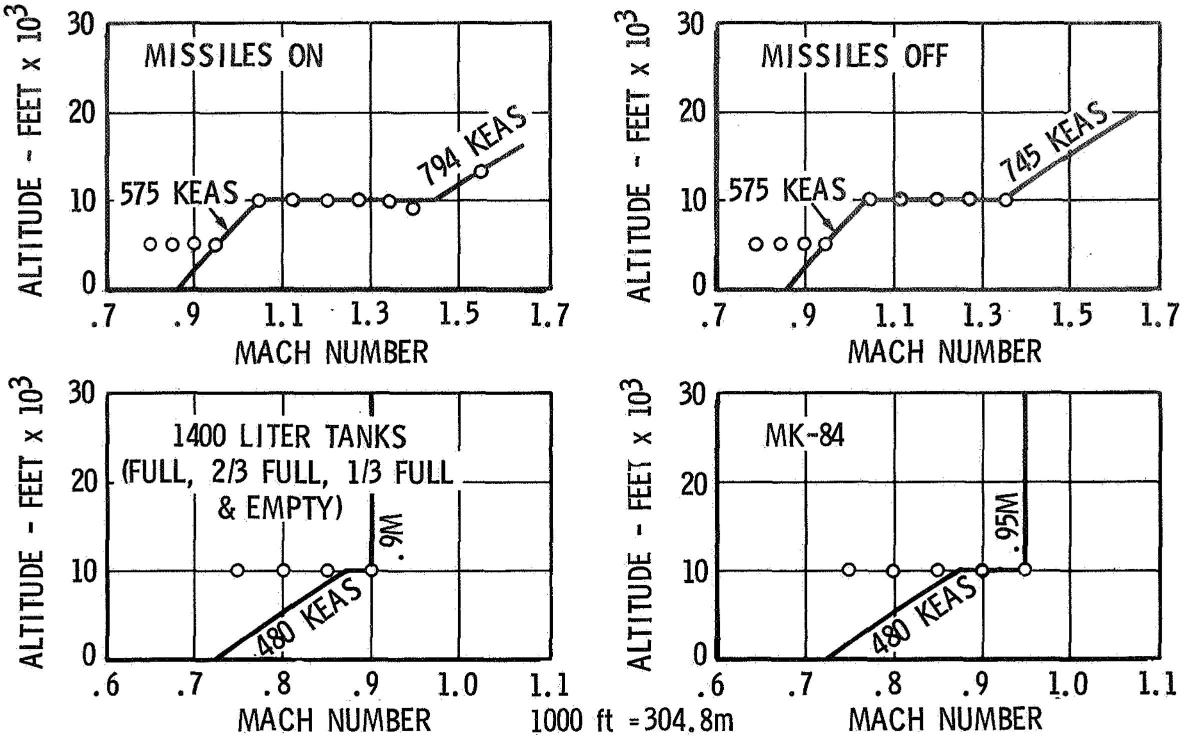

Figure 9 YF-16 Test Points

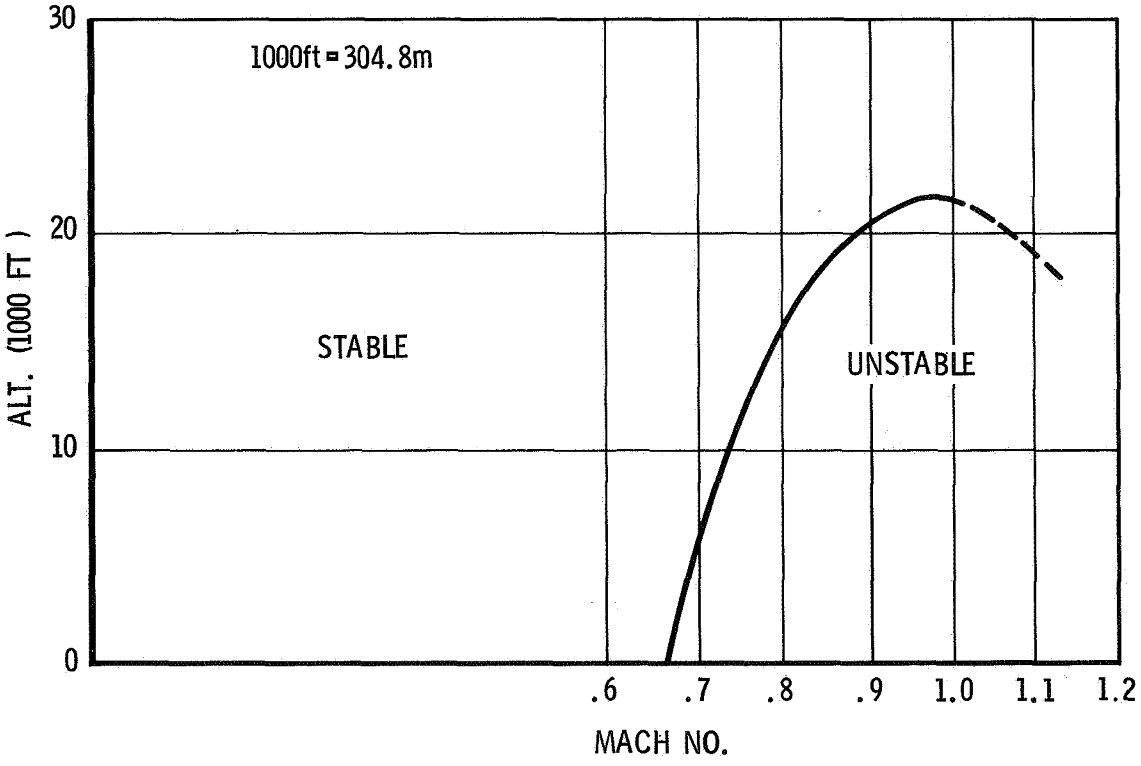

Figure 10 Control System Instability

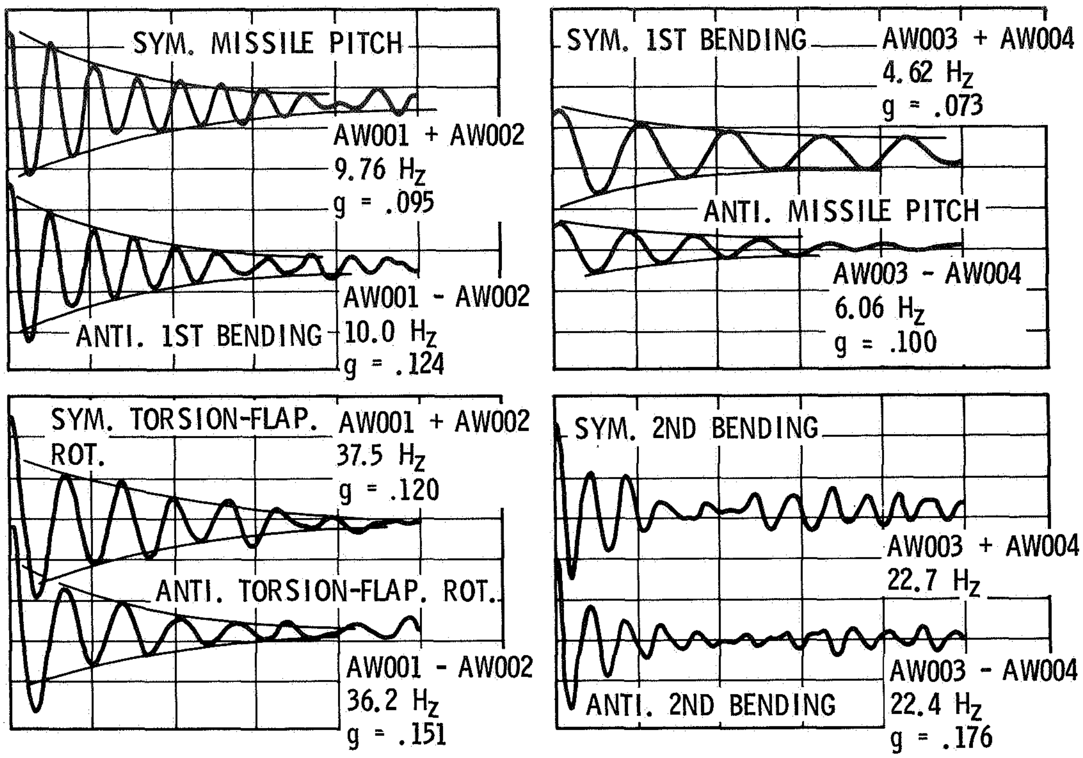

Figure 11 YF-16 Wing Decay Records - 1.34M, 3048m (10 000 Ft)

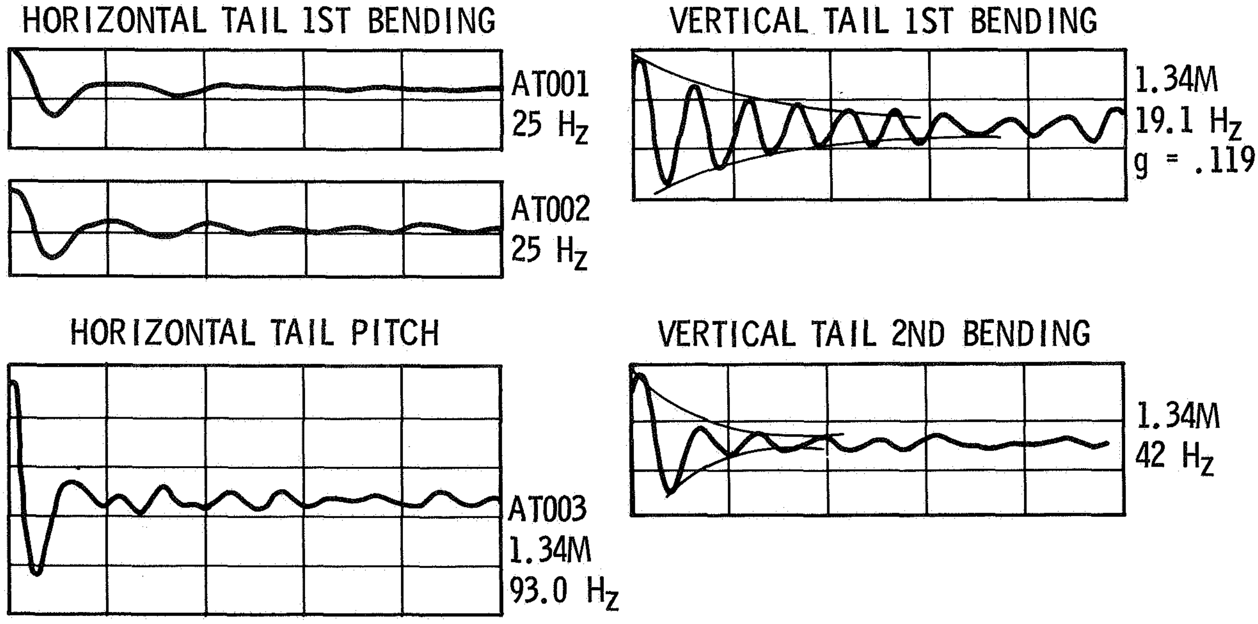

Figure 12 YF-16 Tail Decay Records - 1.34M, 3048m (10 000 Ft)

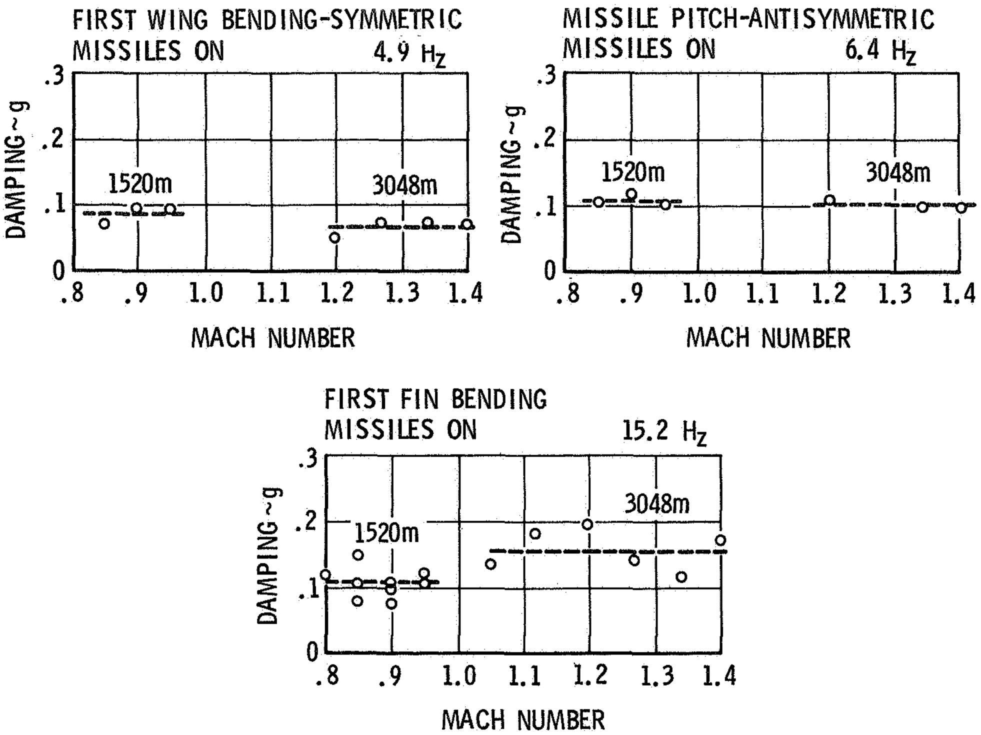

Figure 13 YF-16 Damping vs Mach Number

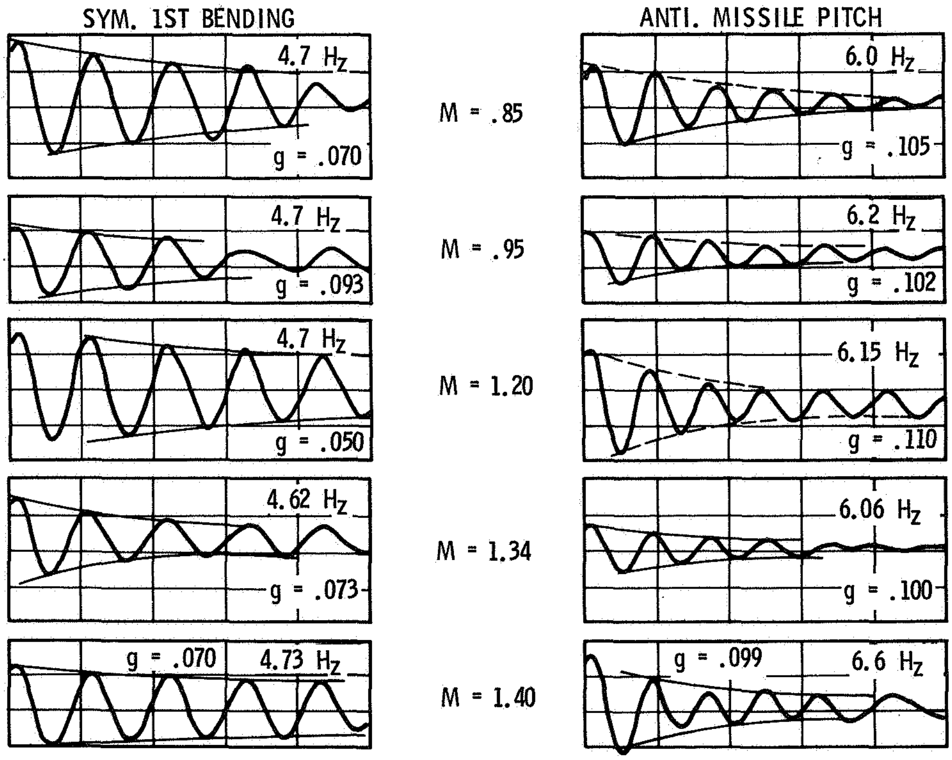

Figure 14 YF-16 Wing Decay Records

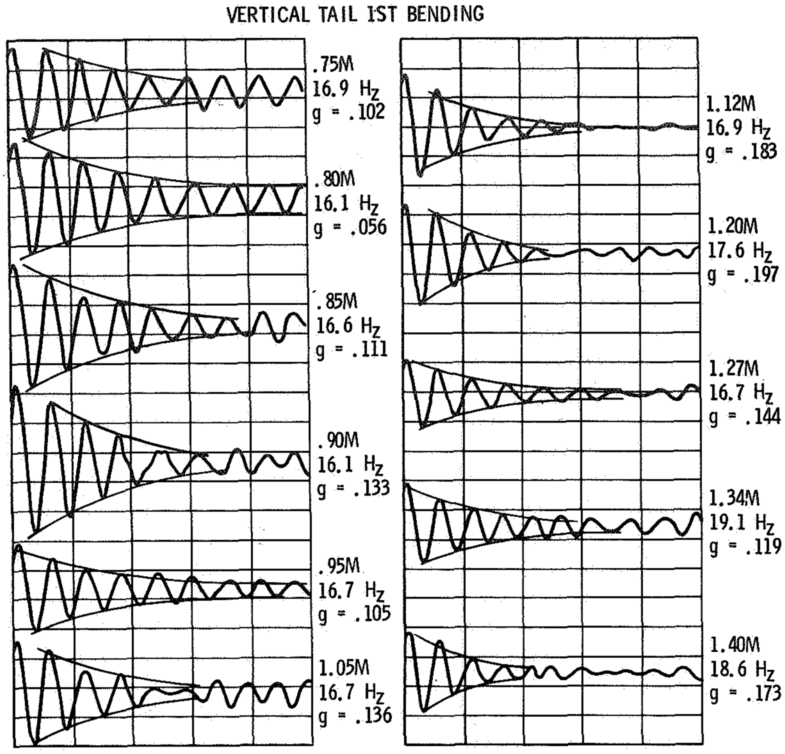

Figure 15 YF-16 Vertical Tail Decay Records

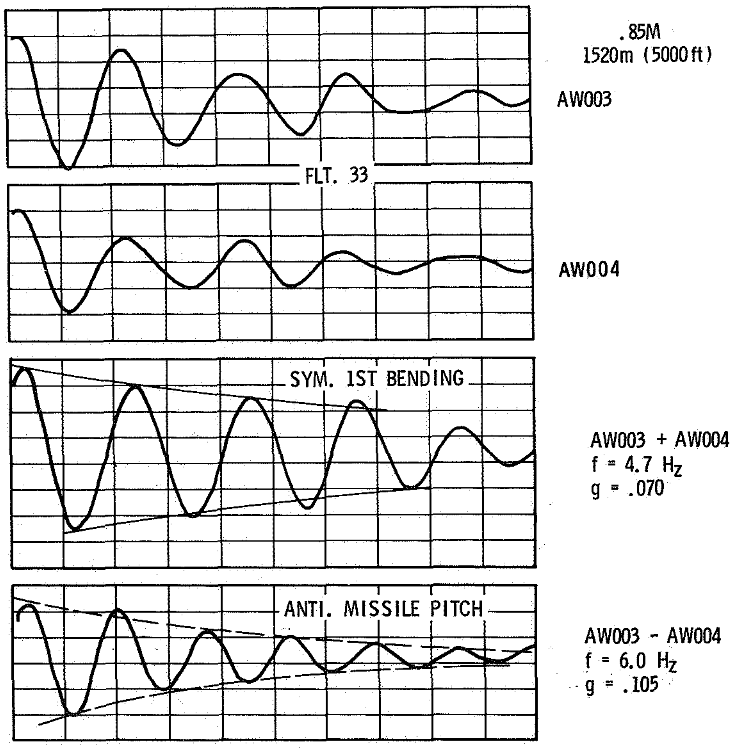

Figure 16 Symmetric and Antisymmetric Response

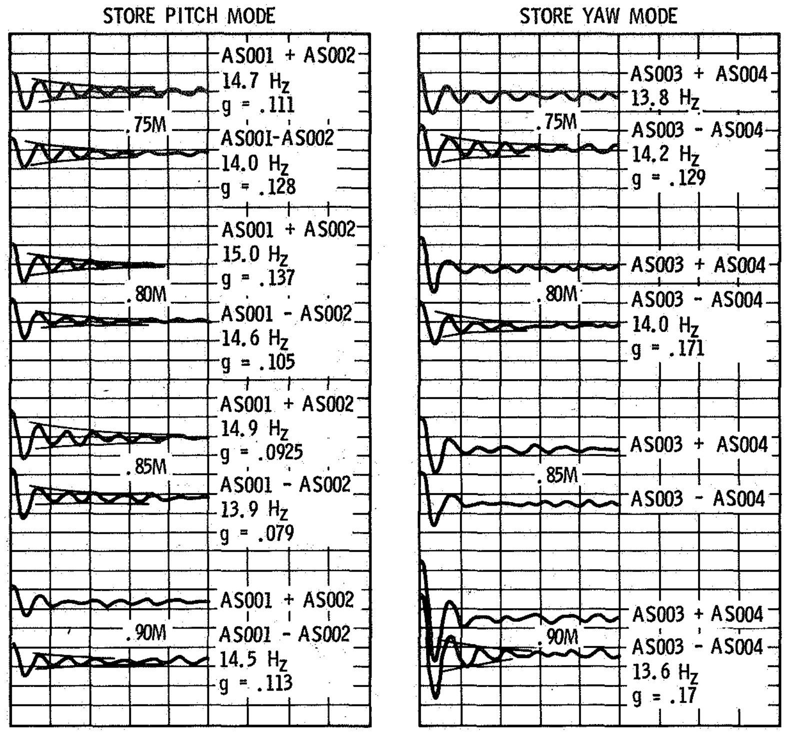

Figure 17 External Store Damping

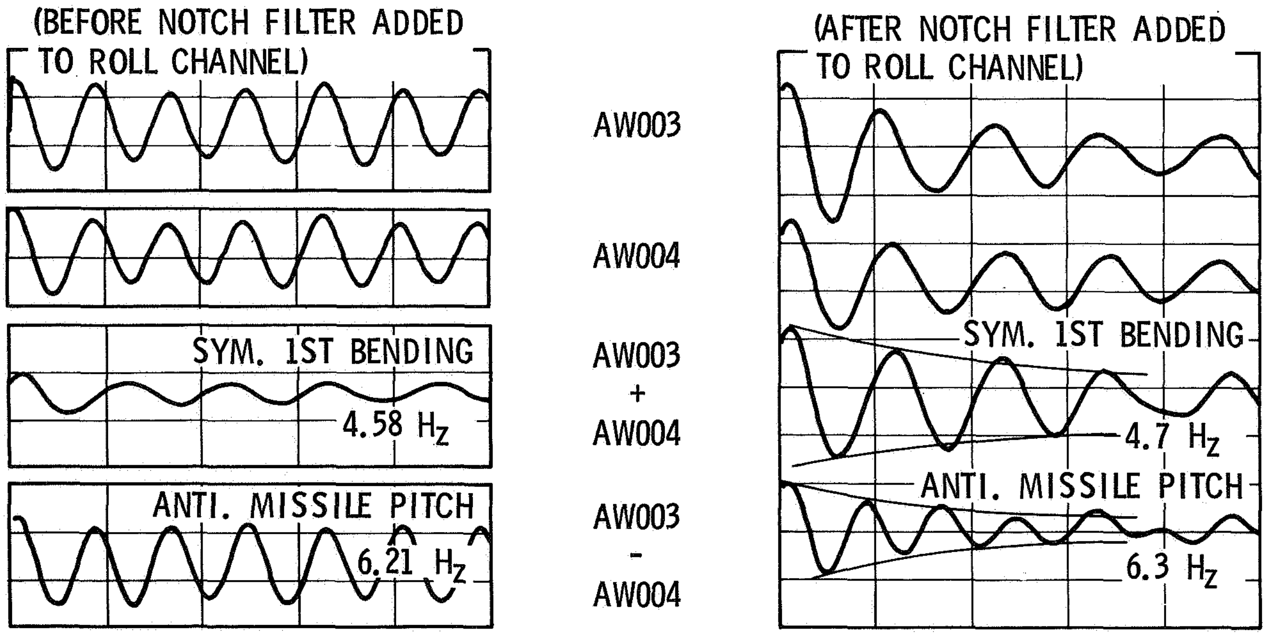

Figure 18 Effect of Notch Filter

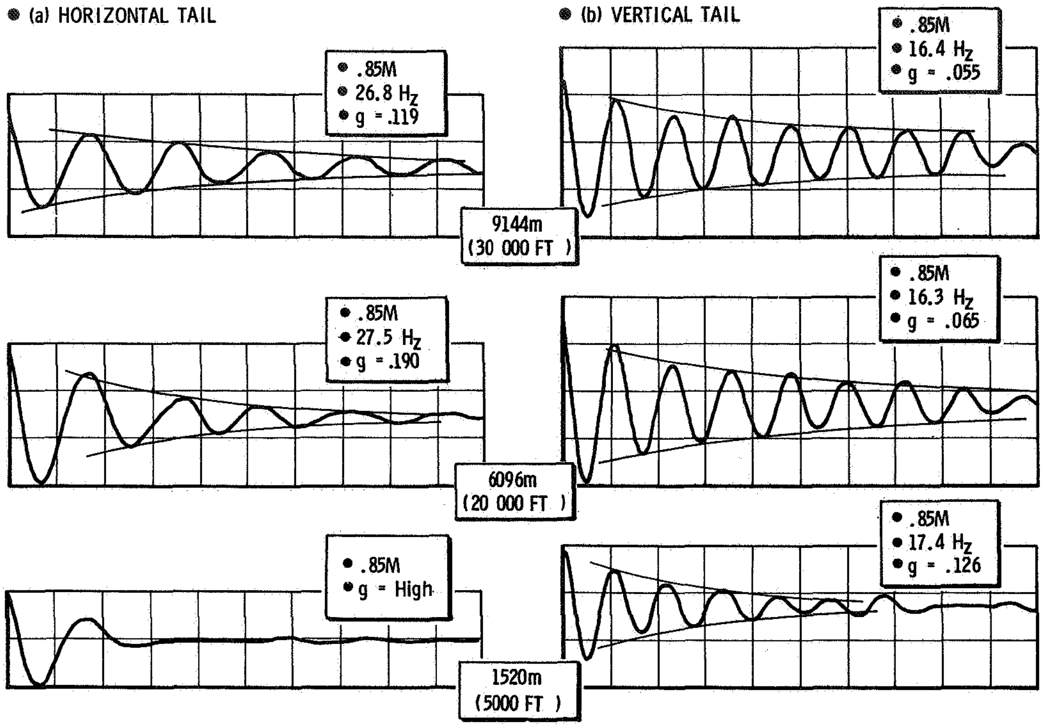

Figure 19 Tail Damping vs Altitude