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DYNAMIC STRUCTURAL AEROELASTIC STABILITY TESTING OF THE XV-15 TILT ROTOR RESEARCH AIRCRAFT

by

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ABSTRACT

For the past 20 years, a significant effort has been made to understand and predict the structural aeroelastic stability characteristics of the tilt rotor concept. Beginning with the rotor-pylon oscillation of the XV-3 aircraft, the problem was identified and then subjected to a series of theoretical studies, plus model and full-scale wind tunnel tests. From this data base, methods were developed to predict the structural aeroelastic stability characteristics of the XV-15 Tilt Rotor Research Aircraft. This paper examines the predicted aeroelastic characteristics in light of the major parameters effecting rotor-pylon-wing stability; describes flight test techniques used to obtain XV-15 aeroelastic stability; presents a summary of flight test results; compares the flight test results to the predicted values; and presents a limited comparison of wind tunnel results, flight test results, and their correlation with predicted values.

1. BACKGROUND - PROBLEM IDENTIFICATION

The XV-3 Tilt Rotor Aircraft, shown in Fig. 1, identified a problem of possible rotor-pylon-wing instability during maneuvers in the airplane mode. During the 1962 NASA Ames 40- by 80-Foot Wind Tunnel test of the XV-3 aircraft, a sustained rotor-pylon oscillation was encountered. An extensive program of analyses and model testing was begun to investigate the low frequency rotor-pylon oscillation phenomenon, and the results are reported in Refs. 1 and 2. The objectives of these investigations were to provide a physical understanding of rotor-pylon stability, and to establish means of assuring stable configurations for the XV-3 and future tilt rotor VTOL designs. The sustained oscillation (decreased damping) was generated by destabilizing rotor forces that, at high inflow angles, could become significant in determining the coupled rotor-pylon stability. Figure 2 illustrates the forces acting on a rotor and pylon system during steady pitching motion. A complete description of this phenomenon is described in Ref. 1, but, in brief, the destabilizing moment is generated by the H forces that add to produce a hub shear force in the direction of the pylon pitching rate. The destabilizing moment is directly proportional to blade inertia, the number of blades, mast length, airspeed, and is inversely proportional to rotor radius squared. The results of these analytical and model testing programs defined the major parameters that can affect rotor-pylon-wing stability. These major parameters, and their affects on aeroelastic stability, are outlined in Table 1.

TABLE 1. MAJOR PARAMETERS AFFECTING ROTOR-PYLON-WING AEROELASTIC STABILITY

Parameter	Affect	Comments
High pylon mounting stiffness	Stabilizing	Increasing the pylon stiffness increases the frequency of the pylon oscillation so that the rotor cannot follow, and the rotor mode of oscillation remains highly damped.
Swashplate/ pylon coupling	Destabilizing	Rotor controls must be isolated from pylon motion to prevent destabilizing forces that are generated when the rotor plane is disturbed.
Delta three control	Destabilizing	The use of negative delta three control reduces maneuvering induced rotor flapping, but has a destabilizing effect on rotor-pylon-wing stability
Rotor elastic flapping restraint	Stabilizing	Spring restraint on rotor flapping produces a stabilizing effect.
Wing mode effects	Destabilizing	Wing beam and torsional degrees-of-freedom produce a destabilizing effect by lowering the pylon stiffness and consequently the pylon natural frequency.
Increasing airspeed	Destabilizing	Increasing airspeed is destabilizing because it is accompanied by increasing destabilizing rotor forces at high in-flow angles.
Increasing rotor thrust	Stabilizing	Increasing rotor thrust has a stabilizing effect because it has the effect of increasing pylon stiffness.
Increasing rotor rpm	Destabilizing	Increasing rotor rpm is destabilizing because the increase in rotor angular momentum produces an increase in processional moments resulting in greater rotor destabilizing forces.

2. PREDICTED XV-15 STRUCTURAL AEROELASTIC STABILITY

The technology base derived from the earlier analytical and model testing programs made it possible to predict the structural aeroelastic stability of the XV-15 Rotor Research Aircraft with a high degree of confidence. The validity of these predictions were then evaluated by additional model and full-scale tests. The results of these tests are presented and discussed in a later section of this paper.

The XV-15 predictions produced by the Bell Helicopter Company were based on a linear analysis (BHC Proprotor Stability Analysis, DYN4), and a nonlinear analysis (BHC Proprotor Aerolastic Analysis, DYN5) techniques. The DYN4 and DYN5 analysis techniques are described in Ref. 3. The DYN5 program is an expanded version of a math model and computer program developed for the Air Force Flight Dynamic Laboratory and is described in Ref. 4.

The XV-15 predictions produced by the NASA-Ames Research Center are presented in Ref. 5, and updated predictions are presented in Ref. 6.

The predicted rotor-pylon-wing stability characteristics of the XV-15 in airplane mode are presented in the root locust format in Figs. 3, 4, 5, and 6. Bell predictions for the symmetric and asymmetric modes are presented in Fig. 3 and 4, respectively. The NASA-Ames predictions for the symmetric and asymmetric modes are presented in Figs. 5 and 6, respectively. They both show:

1. Low frequency, highly damped rotor modes.

2. High frequency, lightly damped pylon modes.

3. Low frequency, lightly damped wing modes.

These predictions are also compared to flight test results as a function of damping ratio (ζ) and airspeed.

Differences in the predicted damping levels for the various modes may result from differences in the analysis techniques. These differences are listed in Table 2.

TABLE 2. ANALYSIS DIFFERENCES

Bell Helicopter (linear analysis)	Government
Wing motion	
Discrete masses, inertias and springs which are coupled to match the 6 fundamental wing modes and pylon pitch and yaw modes	NASTRAN mode shapes (all six components)
Rotor blade lag motion	
Purely inplane, rigid body rotation about offset hinge with spring that represents first in-plane cyclic mode	Coupled inplane/out-of-plane bending modes of elastic blade
Rotor aerodynamics	
Analytical integration over rotor disk, using single lift-curve slope value (corrected for compressibility) (ideally twisted blade @ 3/4 radius)	Numerical integration over disk, using lift-curve slope based on local angle-of-attack and Mach number
Axial flow and high inflow only	Applicable to conversion and helicopter mode flight also
Rotor dynamics	
No blade torsion dynamics	Coupled blade bending and torsion
Pitch/lag coupling calculated from separate analysis	Pitch/lag coupling calculated automatically

3. AIRCRAFT DESCRIPTION

The XV-15 aircraft is powered by two Lycoming T-53 turboshaft engines, which have been uprated and modified for both vertical and horizontal operation. The three-blade proprotors are 7.62 m (25 ft) in diameter, and the blade twist is 45° from root to tip. The rotors are gimbal-mounted to the hub with an elastomeric spring for flapping restraint. The wing span is 9.75 m (32 ft) from spinner to spinner, and the aircraft is 12.8 m (42 ft) long, excluding the instrumentation boom. Aircraft dimensions are shown on the three-view drawing in Fig. 7. Wing loading is 3687 n/m^2 (77 lbs/ft^2), and disc loading at the design gross weight of 13,000 lbs. is 632 n/m^2 (13.2 lbs/ft^2). The XV-15 carries 669 kg (1,475 lbs) of fuel, which allows a research flight of about 1 hour. It is equipped with LW-3B rocket seats which provide a 0-altitude/0-airspeed recovery capability for the crew.

The key design features and the reason for selection in the XV-15 design are listed in Table 3.

The XV-15 flight control system includes exciter actuators in the right-hand flaperon and right-hand collective control systems to excite the modes shown in Fig. 8. Inflight structural aeroelastic stability investigations used the flaperon exciter actuator to excite the wing beam and torsional symmetrical, and

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TABLE 3. KEY XV-15 DESIGN FEATURES

Design Featu	Reason for Selection
Torsionally stiff wing and stiff pylon-to-wing attachment	Ample stability margin at low technical risk
Forward-swept wing planform	Ample clearance (12 degrees) for flapping in severe maneuvers and gust encounters
Gimbaled, stiff-inplane, over-mass-balanced proprotor	Proprotor loads not sensitive to flapping
	Air and ground resonance problems avoided
	Blade pitch-flap-lag instabilities and stall flutter problems avoided
Large tail volume, H configuration	Good damping of Dutch roll and short-period flight modes

asymmetrical bending modes. The collective exciter actuator was used to excite the wing chord symmetric and asymmetric bending modes. Inflight use of these exciter actuators are shown and discussed in the following section.

4. FLIGHT TEST TECHNIQUES

Structural aeroelastic stability flight test evaluations were conducted at the contractor's Flight Research Facility in Arlington, Texas, and at the NASA Dryden Flight Research Center at Edwards AFB, California. These tests were conducted within the limits listed below:

1. Design gross weight of 5900 kg (13,000 lbs) and a neutral C.G. location.
2. At density altitudes of 1,500, 3,000, and 4,600 meters (5,000, 10,000, and 15,000 feet).
3. In airplane mode (pylons down and locked) within the true airspeed range of 170 to 296 knots.
4. At two rotor speeds of 98% (589 rpm) and 86% (517 rpm).

The XV-15 aircraft was predicted to have low frequency, lightly damped wing beam, chord and torsion bending modes. The three techniques used to excite these modes are:

1. Atmospheric turbulence.
2. Exciter frequency sweeps.
3. Exciter frequency dwell/decay.

Strain gages, mounted on the left and right wing, measured the beam, chord, and torsional bending response of the wing to the exciting force. The left & right gages were combined in a sum/difference network to separate the symmetric and asymmetric modes.

In the first technique, the aircraft was flown in moderate turbulence that provided a broad band excitation force. Continuous time history records of the wing gages were taken while the aircraft was flown in trimmed level flight in turbulence. The digital time history of the wing beam, chord, and torsional bending data were then analyzed to determine the natural (or resonant) frequencies of the wing structural modes, and to calculate the associated structural damping ratio for each mode. The method used to analyze this data is the Random Decrement Signatures (RANDOMDEC) program described in Ref. 7.

In the second technique, the aircraft was flown in trimmed level flight while a constant amplitude automatic frequency sweep from 1 to 10 Hz. was performed with either the flaperon or the collective exciter. Again, continuous time history records were taken during the frequency sweeps. The data were analyzed off-line using the RANDOMDEC program and/or a modal analysis technique developed by the Grumman Corporation.

The third method used the frequency dwell/decay technique. In this technique, the pilot flew the aircraft in trimmed level flight or descending wind-milling (power off) flight, and the copilot tuned the selected exciter to the desired frequency and amplitude as dictated by the on-line monitoring in the ground control room. Once the exciter was tuned to the desired wing bending mode, it was turned on and the mode excited at a constant amplitude and constant frequency. Once the desired mode was excited, the exciter was turned off, and the excitation decay was qualitatively evaluated in the control room before the test was repeated. These decays were later analyzed off-line using an interactive computer program to obtain frequency and damping values. This interactive program is discussed in Ref. 8 and described in detail in Bell Helicopter Company Report 299-099-898.

Figures 9 through 12 present examples of the dwell and decay technique for the symmetric and asymmetric modes, with and without the sum and difference on-line analysis technique. For example, Fig. 9 presents a frequency dwell at 3.3 Hz., and a decay response of the symmetric wing beam bending mode without using the sum-and-difference technique. As shown, both the right and left beam bending modes are excited. The right wing beam bending load is higher than the left, because the flaperon exciter is operating on the right wing only. From these traces, it is difficult to determine if the symmetric or asymmetric beam bending mode is excited.

Figure 10 is the same frequency dwell/decay record using the sum and difference technique. Comparison of the amplitude of the two traces makes it apparent that the symmetric wing mode has been excited. The positive damping of the symmetric wing beam bending mode is easily recognized by the shape of the decay envelope in Fig. 9 or 10. The sum and difference was only used to identify the wing bending mode. The dwell-and-decay technique worked very well on the beam bending mode for three reasons. First, the damping level is positive, but low, making it easy to excite the load. Second, the ambient noise level was low (nonturbulent flight conditions), and the signal-to-noise ratio is high without abusing the structure with excessively high exciter input forces. Third, the symmetric natural frequency of 3.4 Hz. was sufficiently separated from the asymmetric natural frequency of 6.7 Hz. to prevent coupling of the two modes.

An example of coupled symmetric and asymmetric response is shown in Figs. 11 and 12. Figure 11 presents a frequency dwell/decay record of the symmetrical wing torsion mode. Both the left and right wing loads have a "beat" type response caused by the coupling of the symmetric and asymmetric modes which have a natural frequency of 7.7 and 8.2, respectively, and are very close to the 1 per revolution frequency of the rotor which is 8.6 Hz. Figure 14 presents the same dwell/decay record using the sum and difference technique. Again, the sum and difference technique is used to identify which mode is excited, but the damping level is not easily recognized because of the "beat" type response that still exists in the "sum" trace.

The dwell and decay technique was the primary tool used to measure the aeroelastic stability of the XV-15 aircraft. Its advantages are:

1. It provides a point-by-point evaluation of the aeroelastic modes.

2. It provides, in most cases, the opportunity to qualitatively evaluate the damping level at each point.

3. Final calculations of natural frequency and damping are relatively easy using the analysis technique described in Ref. 8.

4. It is easy to abort a test (turn off exciter) if a problem is encountered.

Its disadvantages are:

1. It is time consuming to do a point-by-point evaluation.

2. It requires nonturbulent atmospheric conditions.

3. It requires extensive ground-to-air-to-ground coordination.

4. It was difficult to excite the desired symmetric or asymmetric modes because the flaperon and collective exciter actuators were mounted only on the right wing and right rotor. In the future, the exciters should be incorporated on both rotors and wings.

Data obtained by flying in moderate turbulence using the RANDOMDEC analysis method compared very well with data from the dwell/decay technique as shown in Ref. 8. The advantages of this method are:

1. Tests can be conducted in turbulent air.

2. It is time efficient in that data for all modes are collected simultaneously.

3. Very little ground-to-air-to-ground coordination is required.

4. It may identify an overlooked resonant frequency.

Its disadvantages are:

1. It does not provide an on-line point-by-point evaluation of individual aeroelastic modes.

2. Without this point-by-point evaluation capability, it is not as easy to detect stability augmentation/airframe coupling as was encountered during evaluations of the asymmetric wing beam bending mode. (This problem is discussed in Test Results section of this paper.)

. If a problem is encountered, it is more difficult to abort the test, as it is harder to "turn off" the turbulence than it is to turn off the exciter in the dwell/decay technique.

4. It is difficult to get the right amount of turbulence at the higher altitudes.

5. The data is more difficult to analyze, because of the multiple mode content of the data.

The automatic frequency sweep technique was only used occasionally during these tests. Data obtained using the RANDOMDEC analysis compared favorably with other data, but the disadvantages of the technique outweighed the advantages. Its advantages are.

1. It can help to identify overlooked resonant frequencies in the range of the frequency sweep, 1 to 10 Hz.

2. Tests can be aborted easily if a problem is encountered.

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Its disadvantages are:

1. Tests must be flown in nonturbulent atmospheric conditions.
2. It is time consuming, because it requires a point-by-point data collection process.
3. It does not provide a good point-by-point evaluation of individual modes.
4. Control system/airframe coupling is not easily recognized.
5. It requires considerable ground-to-air-to-ground coordination.
6. The data is difficult to analyze because of the multiple mode content of the data.

5. FLIGHT TEST RESULTS

The results of the structural aeroelastic stability tests conducted with the XV-15 Tilt Rotor Research Aircraft are summarized in Fig. 13. Natural frequency and damping ratio data is plotted as a function of calibrated airspeed.

The predicted natural frequencies of the six primary wing bending modes agree very well with those measured in flight as shown in Table 4. Both Bell Helicopter Company and NASA Ames used the NASA NASTRAN program to predict mode natural frequencies. NASA Ames and Bell Helicopter predicted curves of aeroelastic structural damping levels (as a function of airspeed) are also presented in Fig. 13. The largest discrepancy between the two prediction techniques is seen in the symmetric and asymmetric wing beam bending modes. The NASA Ames prediction appears to be correlated with the symmetric beam bending mode, whereas the Bell prediction has better correlation with the asymmetric beam bending mode. But the point of greatest interest in these predictions is the airspeed where the damping ratio approaches zero: neither of these prediction techniques have been tested in this area as airspeeds to date have not approached the stability boundary limits. Data presented in Fig. 13 represents data up to the maximum speed obtainable in level flight with maximum continuous power at 86% (517 rpm) rotor speed.

TABLE 4. COMPARISON OF PREDICTED AND MEASURED XV-15 WING MODE NATURAL FREQUENCIES

Wing Bending Modes	Natural Frequency Hz Predicted	Measured
Symmetric beam bending	3.1	3.3 to 3.4
Asymmetric beam bending	5.7	6.1 to 6.7
Symmetric chord bending	5.9	6.3 to 7.6
Asymmetric chord bending	5.7/8.1*	7.5 to 9.2
Symmetric torsional bending	7.[illegible]	7.5 to 8.6
Asymmetric torsional bending	7.[illegible]	7.1 to 9.3

*First NASTRAN model did not include a wing/fuselage shear tie member. Inclusion of this member increased stiffness and frequency.

The next point of interest is the large variation in measured damping ratios for a given mode and flight condition. The symmetric wing beam bending mode has the least amount of scatter. This is caused by two factors. First, it has low damping level and is easily excited by the flaperon. Second, its natural frequency (3.4 Hz.) is significantly lower than the other modes, and the absence of mode coupling makes it easier to analyze (see Figs. 9 and 10). Other modes, specifically the symmetric wing chord bending mode, have a high damping level at the airspeeds tested, and the modes are difficult to excite with only a right-hand exciter system. The greater the scatter in the data, the more difficult it is to detect trends in the data.

The third point of interest on this summary plot is the coupling of the roll stability and control augmentation system (SCAS) with the asymmetric wing beam bending mode. Coupling of the roll SCAS caused the oscillation to continue after the flaperon exciter was turned off, giving the appearance of low damping, see Fig. 14. Checks made with the roll SCAS turned off produced significantly higher levels of damping. Its permanent solution was the incorporation of a "notched" filter in the roll SCAS to prevent coupling at the natural frequency of 6.0 Hz.

6. COMPARISON OF WIND TUNNEL FLIGHT TEST RESULTS

Over the past 20 years, a significant theoretical and model testing effort has been made to understand and to predict the structural aeroelastic stability characteristics of the tilt rotor concept. Using only one mode, the symmetric wing beam bending mode, an attempt is made to show correlation between ground and flight test results. This mode was selected because it had a low predicted damping level, and therefore, it is used most often by those conducting model tests to evaluate prediction methods. Figure 15 is a composite photograph showing four major ground tests conducted prior to the flight tests. These tests are:

Fig. 15A - Wind tunnel test of the 1/5 scale semispan wing

Fig. 15B - Wind tunnel test of the full scale semispan wing

Fig. 15C - Wind tunnel tests of the 1/5 scale XV-15 aircraft

Fig. 15D - Wind tunnel test of the XV-15 aircraft

Figure 16 presents data from each of these tests with a comparison to flight test results. In general, there appears to be fairly good agreement between ground and flight tests results, with the model tests tending to be optimistic. Figure 17 presents the same data on a single plot and includes Bell Helicopter Company and NASA Ames prediction curves. The ground test results tend to confirm the Bell predictions, whereas the flight test results tend to confirm the NASA Ames predictions. It must, however, be pointed out again that it is this mode, the wing beam mode, where the greatest difference was noted between the two prediction techniques. Comparison with the ground tests results to the Bell prediction curve indicates that the Bell prediction methods are conservative. Flight test results have not been conducted at high enough speeds to determine if the NASA Ames curve is also conservative.

7. CONCLUSIONS

1. Within the airspeeds tested, the XV-15 is free of structural aeroelastic instabilities.

2. Resonant frequencies can be reliably predicted using the NASTRAN method.

3. The aeroelastic testing indicating that the theoretical and model testing effort resulted in prediction methods that are, in general, conservative and adequate for future development of the tilt rotor concept.

4. Flight test techniques need to be refined to lower the risk to the aircrew, decrease the time required for data collection, and permit better excitation of selected structural modes. (Exciters should be installed on both wings and rotors.)

5. Postflight off-line data analysis method should be refined, and if possible, moved to on-line data processing system.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation to Messrs. J. Bilger and R. Marr of the Bell Helicopter Company for the efforts in the collection and analysis of data used in this paper The author would also like to express his appreciation to Dr. J. Leung, of the NASA Ames Research Center, for his assistance in the reprocessing and analysis of selected data.

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Fig. 1. XV-3.

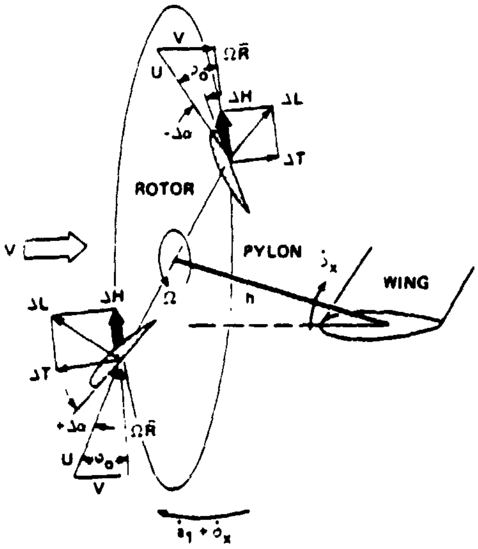

Fig. 2. Rotor tip path plane schematic showing origin of destabilizing forces.

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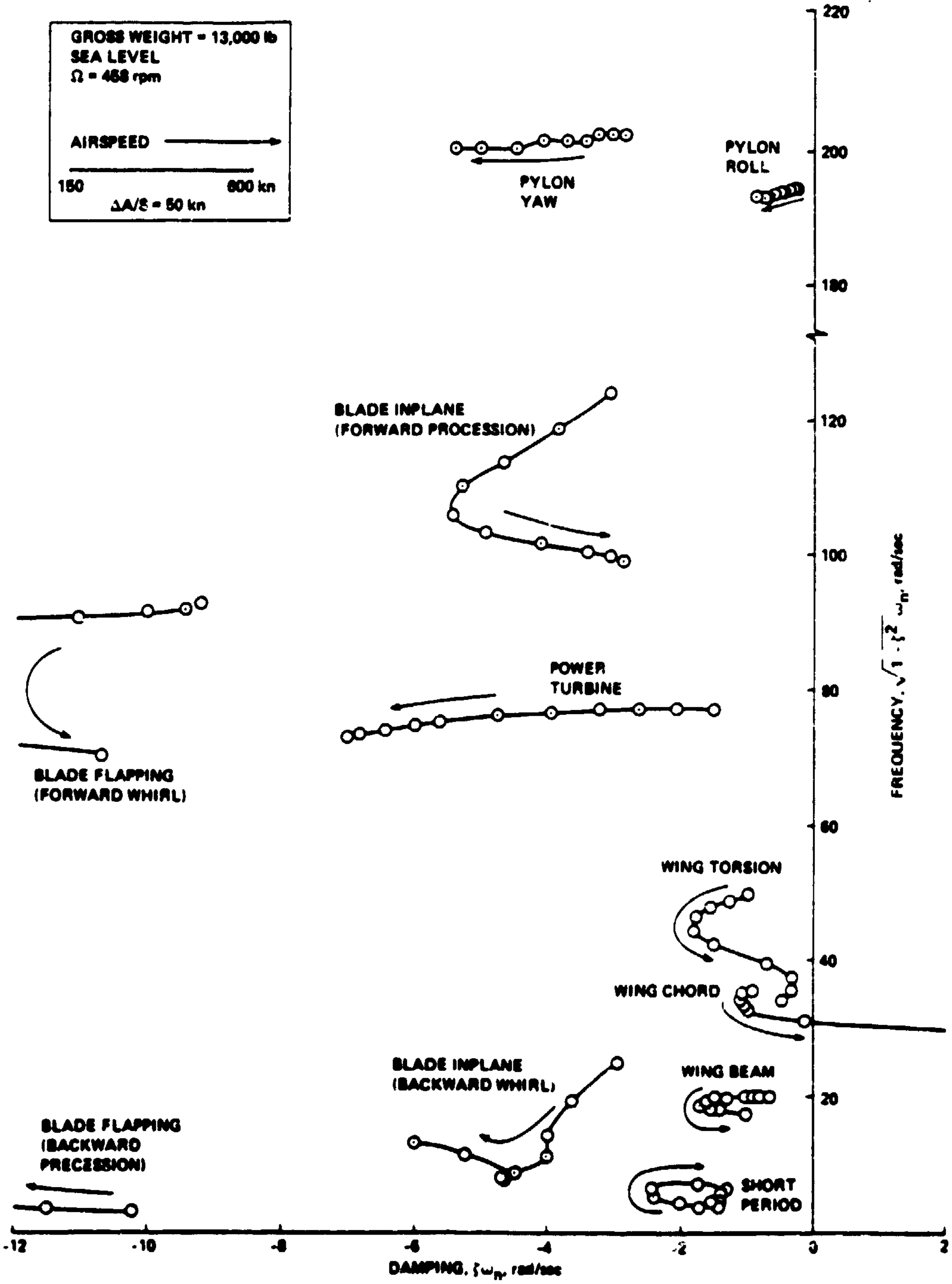

Fig. 3. Bell stability predictions of the XV-15 symmetric rotor-pylon-wing modes.

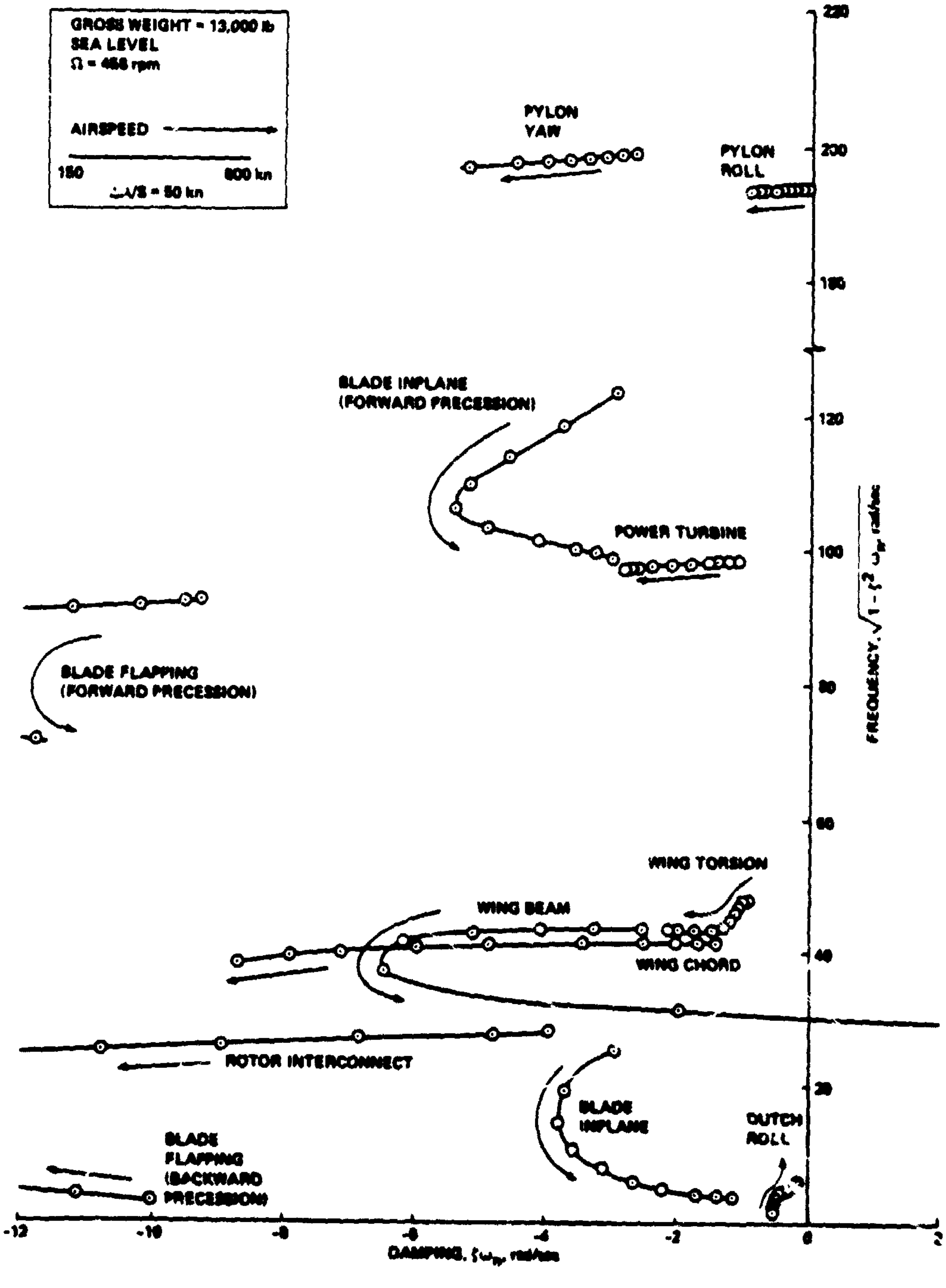

Fig. 4. Bell stability predictions of the XV-15 asymmetric rotor-pylon-wing modes.

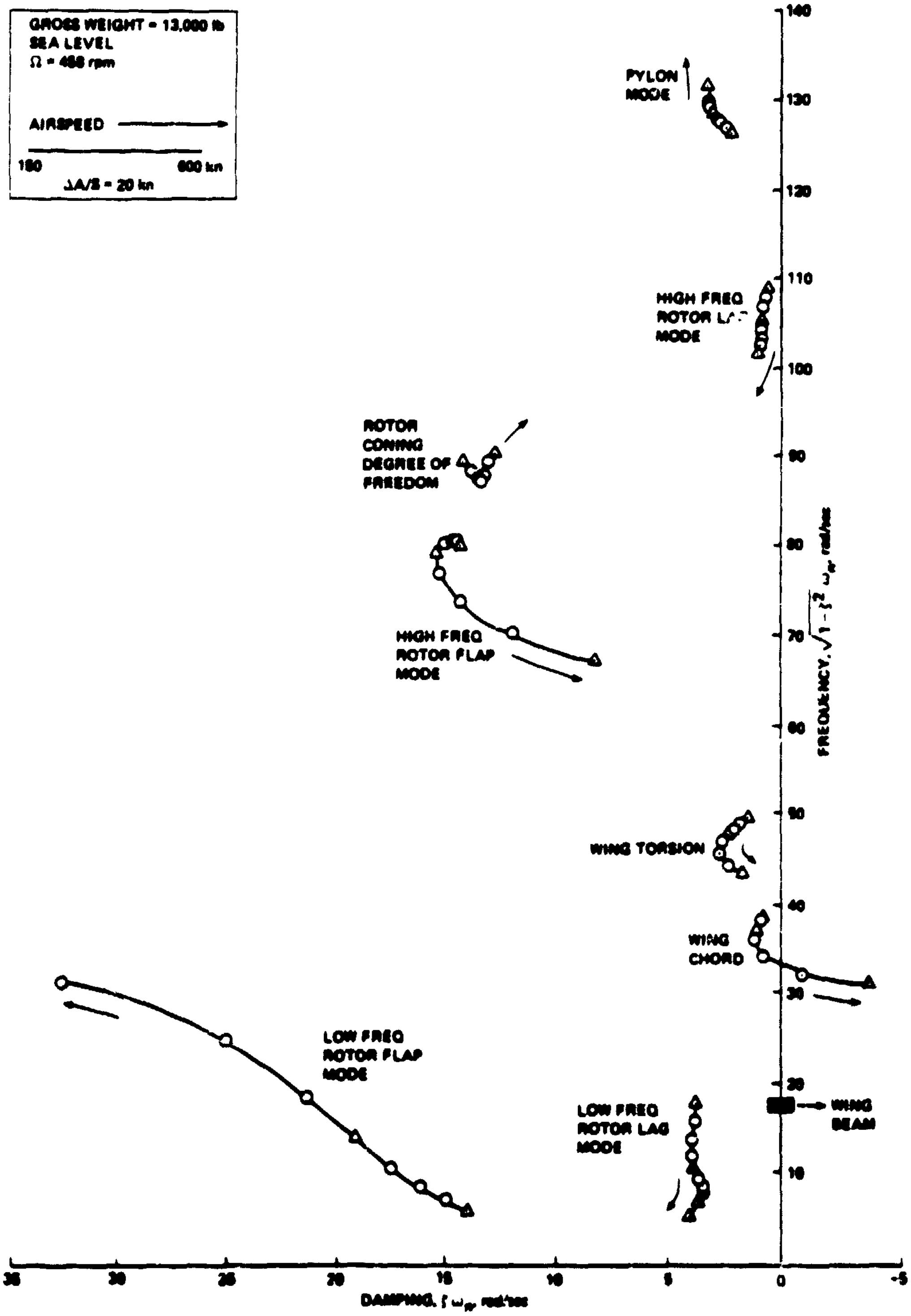

Fig. 5. NASA Ames stability predictions of the XV-15 symmetric rotor-pylor-wing modes.

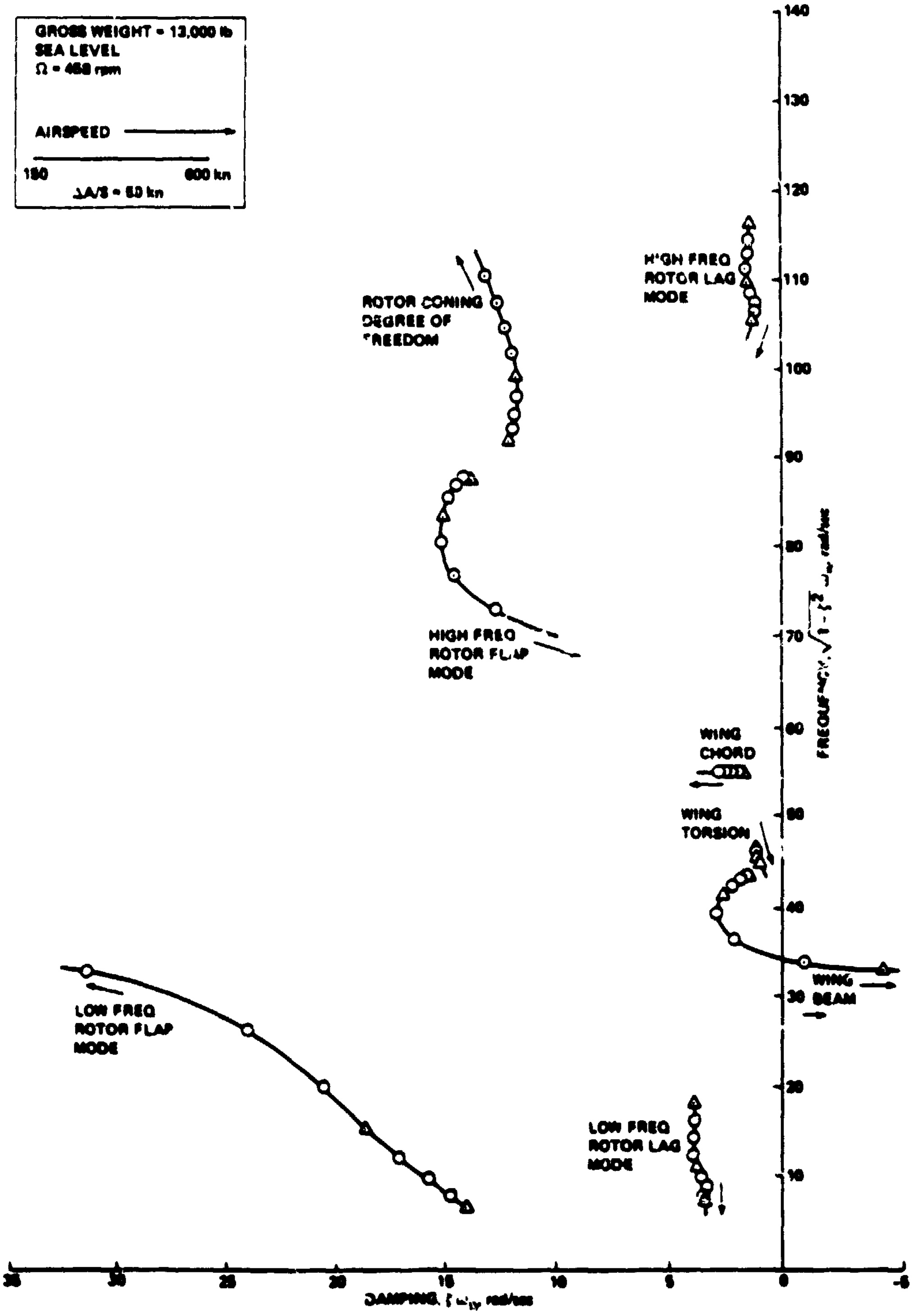

Fig. 6. NASA Ames stability predictions of the XV-15 asymmetric rotor-pylon-wing modes.

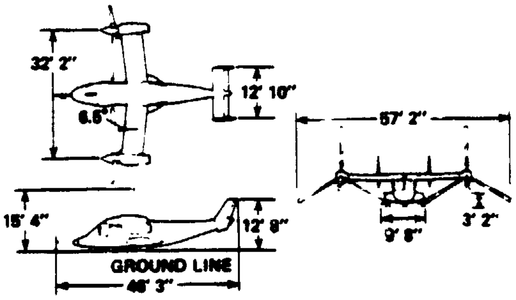

Fig. 7. XV-15 dimensions.

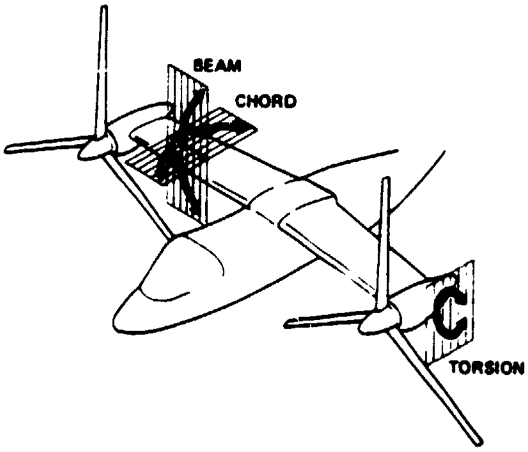

Fig. 8. XV-15 rotor/pylon/wing aeroelastic modes.

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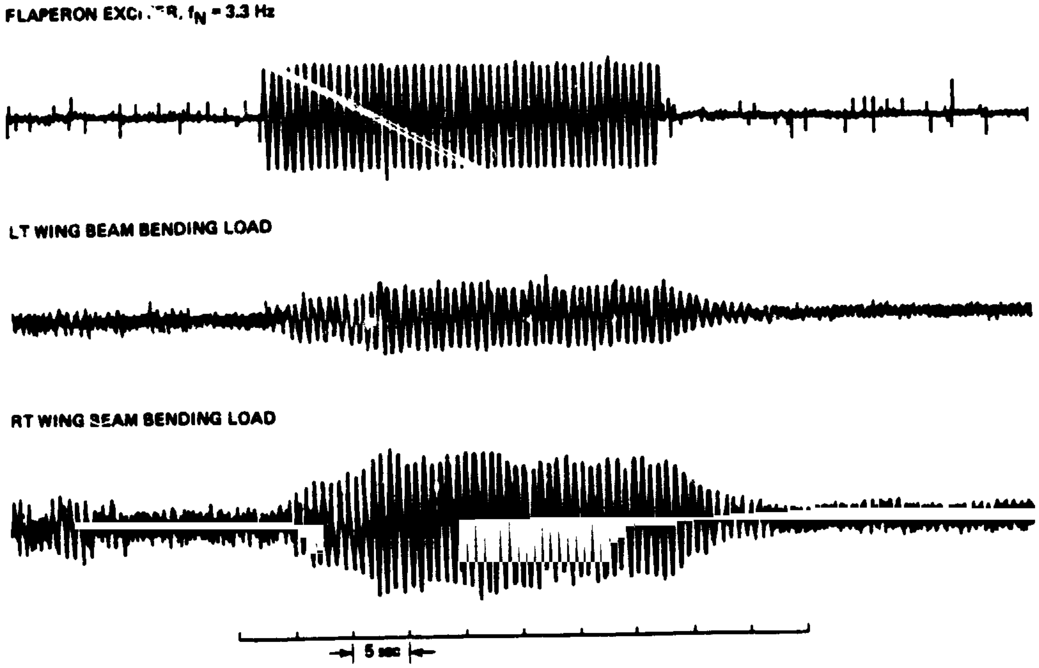

Fig. 9. Symmetric wing beam bending mode.

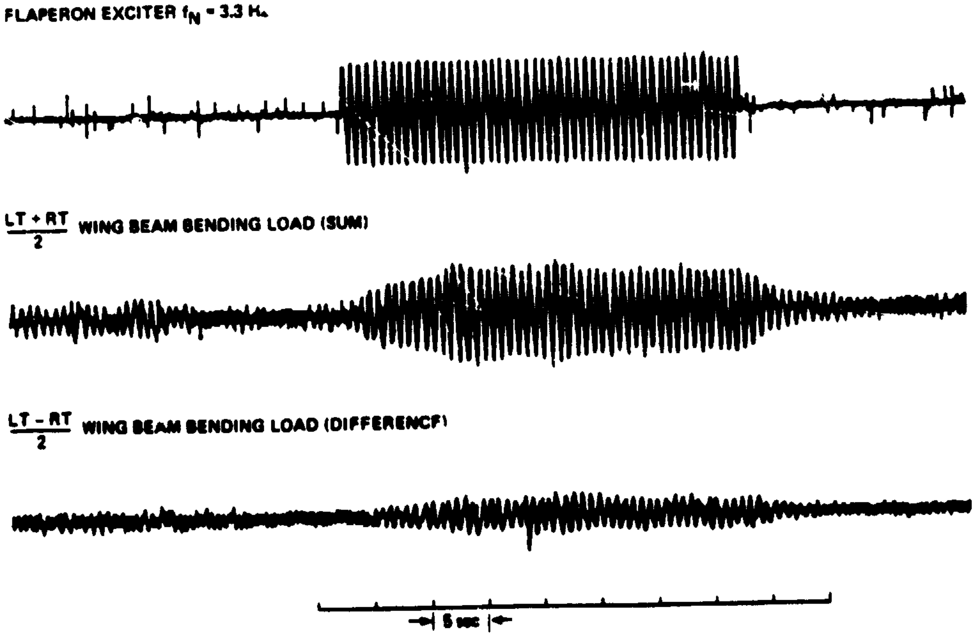

Fig. 10. Symmetric wing beam bending mode using the sum/difference technique.

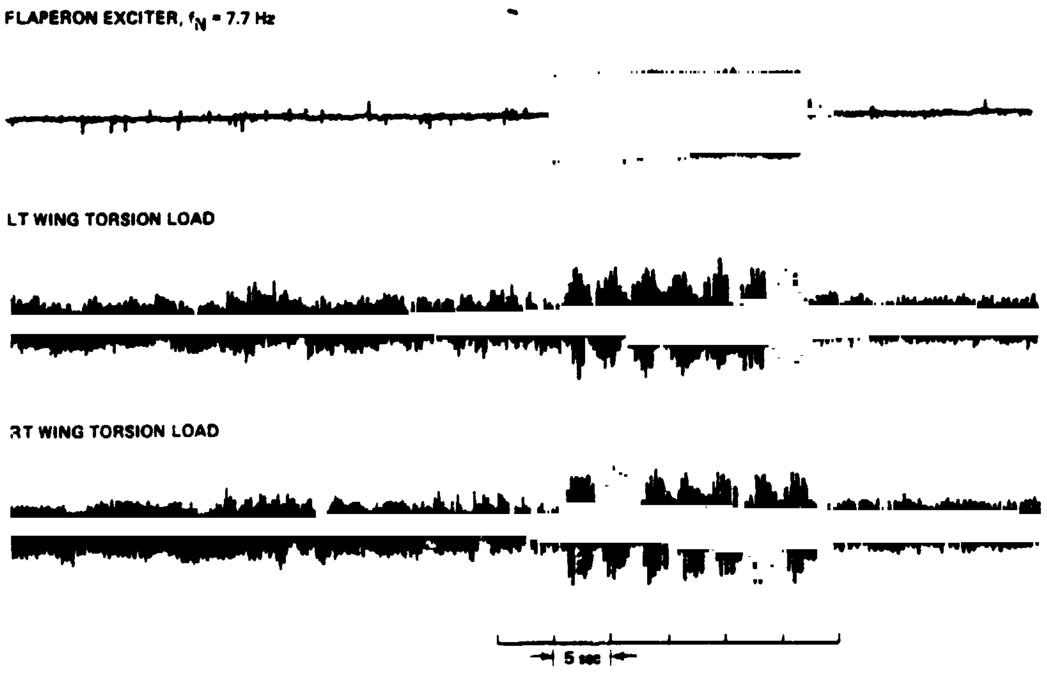

Fig. 11. Symmetric wing torsion mode.

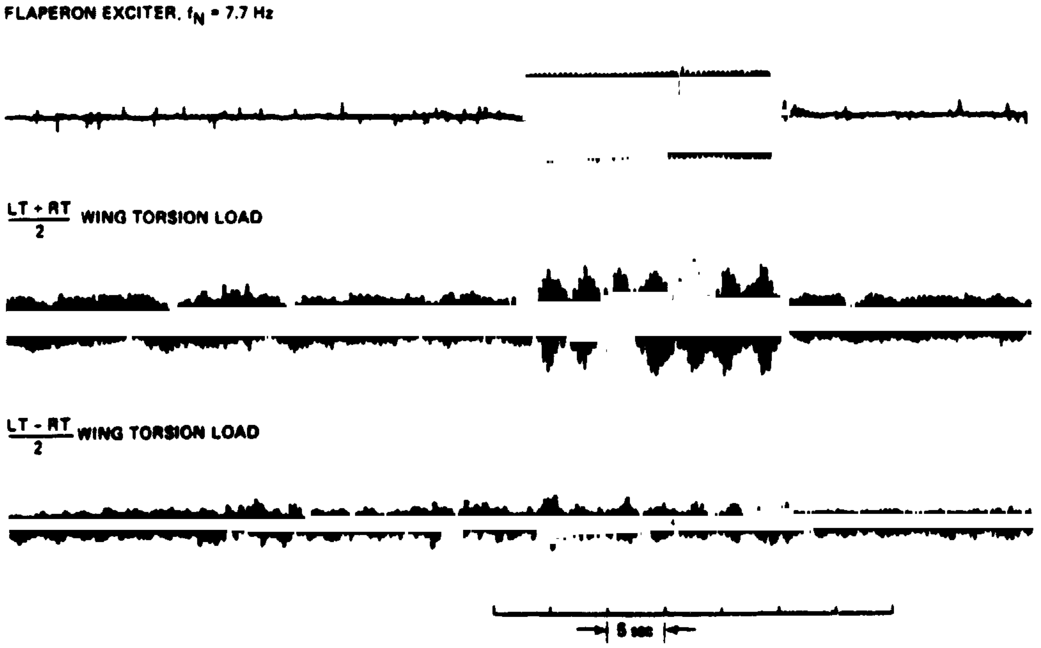

Fig. 12. Symmetric wing torsion mode using the sum/difference technique.

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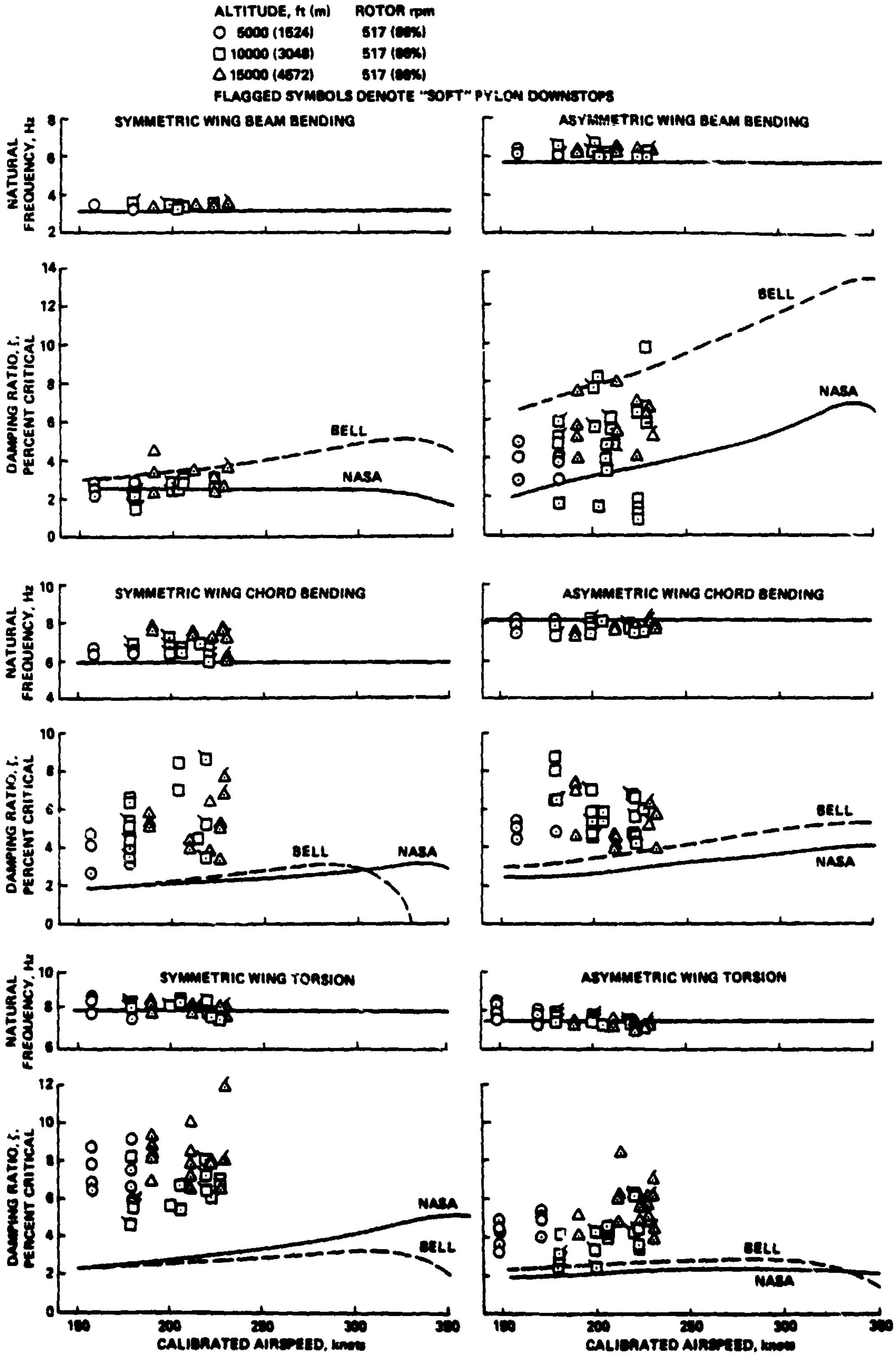

Fig. 13. Summary of aeroelastic stability data.

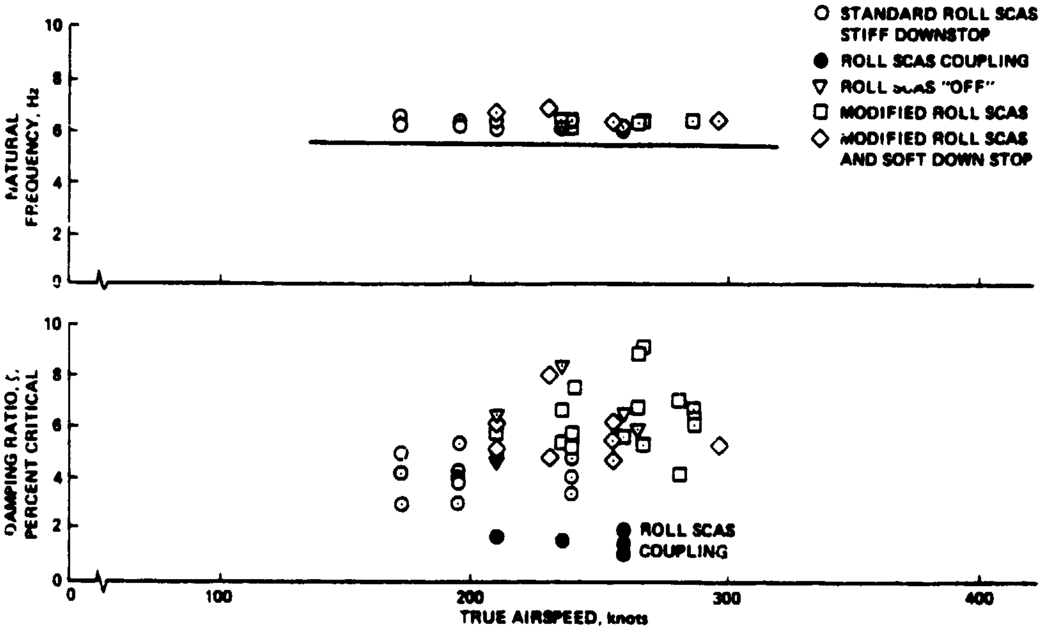

Fig. 14. Roll SCAS coupling.

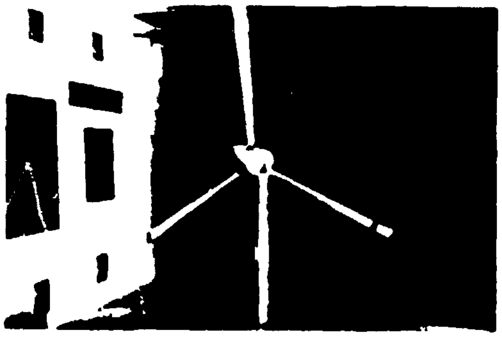

Fig. 15A. 1/5-scale semispan wing

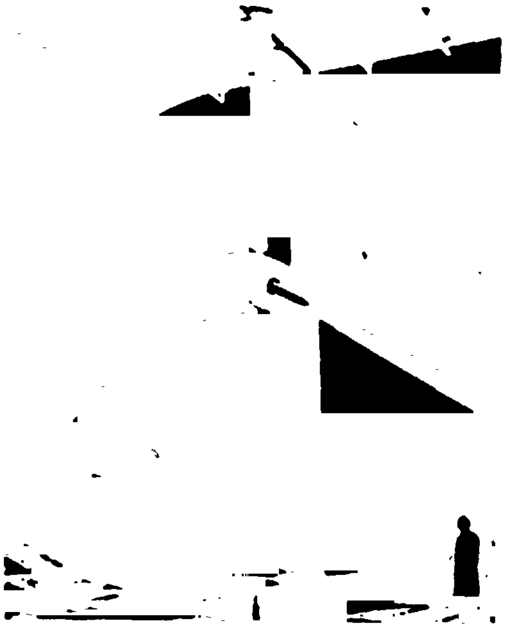

Fig. 15B. Full scale semispan wing

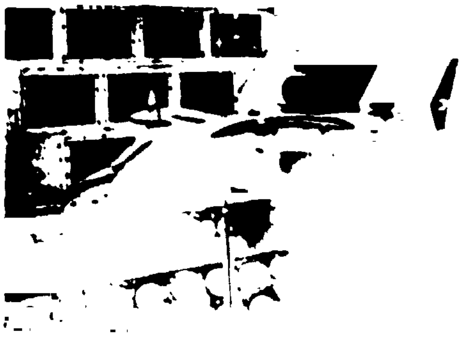

Fig. 15C. 1/5-scale aircraft model

Fig. 15D XV 15 aircraft

Fig. 15. Composite photo of 4 major ground tests.

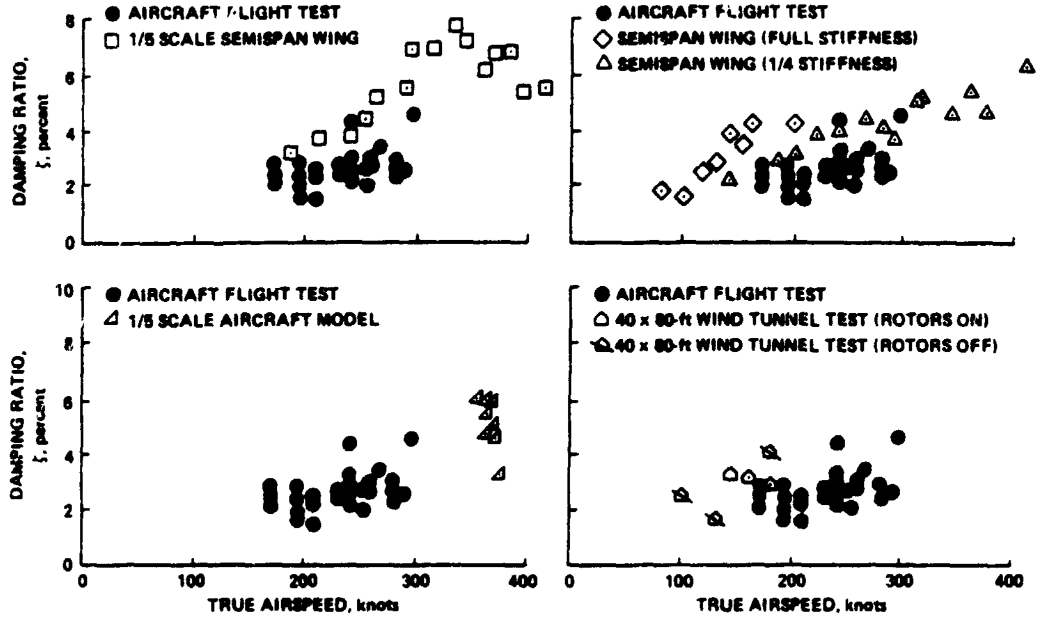

Fig. 16. Test data from 4 major tests.

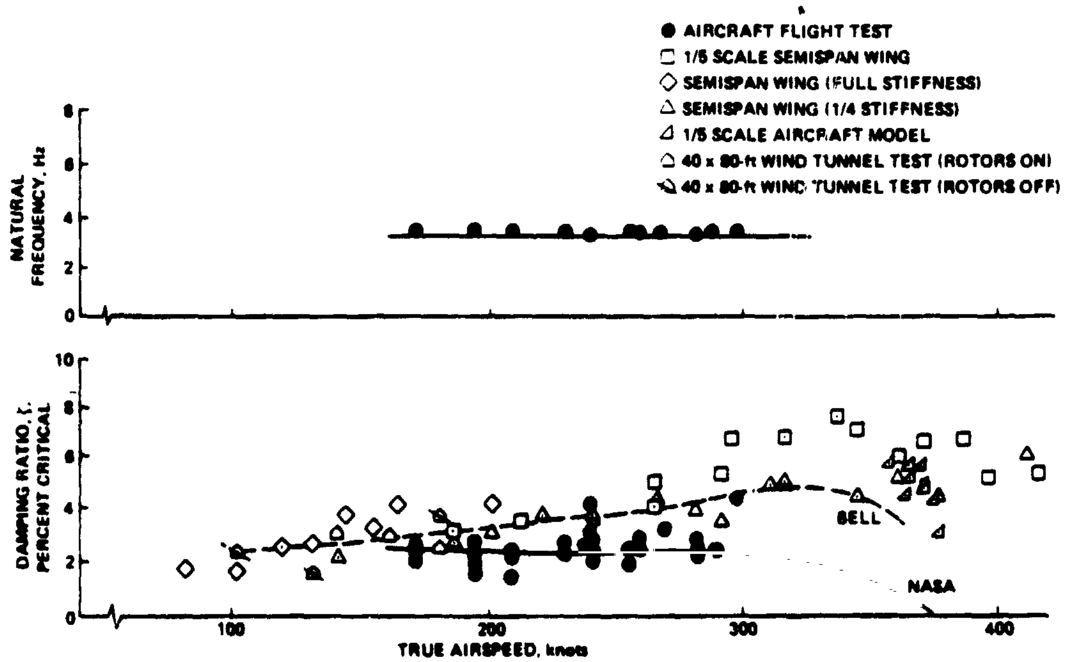

Fig. 17. Plot of all data from 4 major individual ground tests and flight tests.