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Current Flight Test Experience Related to Structural Divergence of Forward-Swept Wings

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ABSTRACT

Flight testing the X-29A forward-swept-wing aircraft has required development of new flight test techniques to accomplish subcritical extrapolations to the actual structural divergence dynamic pressure of the aircraft. This paper provides current experience related to applying these techniques to analysis of flight data from the forward-swept wing in order to assess the applicability of these techniques to flight test data. The measurements required, maneuvers flown, and flight test conditions are described. Supporting analytical predictions for the techniques are described and the results using flight data are compared to these predictions. Use of the results during envelope expansion and the resulting modifications to the techniques are discussed. Some of the analysis challenges that occurred are addressed and some preliminary conclusions and recommendations are made relative to the usefulness of these techniques in the flight test environment.

NOMENCLATURE

℄	centerline
c	chord, percent
FDMS	flight deflection measurement system
FLEXSTAB	system of computer programs for aerodynamic analysis of flexible aircraft
g	normal loading factor, acceleration due to gravity
LED	light-emitting diode
MCC	manual camber control
NASTRAN	NASA finite element computer program for structural analysis
$\bar{q}$	dynamic pressure
q_{div}	divergence dynamic pressure
ws	wing station
α	angle of attack
λ	load or twist/unit angle of attack

INTRODUCTION

The X-29A technology demonstrator aircraft (fig. 1) is the first modern aircraft design to effectively exploit the aerodynamic performance advantages of the forward-swept wing. The major disadvantage of previous uses of forward-swept wings was the large weight penalty paid to provide sufficient stiffness to prevent structural divergence within the flight envelope. Through the use of aeroelastically tailored composite wing skins, this substantial disadvantage has been overcome. By moving the effective elastic axis of the wing forward and by exploiting the high stiffness-to-weight ratio of composite materials, the streamwise twist increase due to load along the wing span has been minimized, and the resulting structural divergence critical speed is well outside the flight envelope.

Because the X-29A flight test program is the first flight test of a high-performance forward-swept-wing configuration, new techniques are being developed to measure the structural divergence characteristics of the wing. The forward sweep of the wing results in an increasing twist increment to the local angle of attack along the span as the wing loads up. The resulting load distribution demonstrates a wingtip load amplification as dynamic pressure rises, rather than the customary load relief of aft-swept wings. The forward-swept wing, therefore, has an increasing lift curve slope as dynamic pressure increases. This is certainly an aerodynamic advantage, but it also causes the divergence phenomenon. The question is how to quantify this phenomenon to assure that the critical structural divergence speed is, in fact, outside the flight envelope.

The chosen flight test technique must provide data for flight safety during envelope expansion as well as obtain adequate data to allow validation of the design with respect to structural divergence. A method for monitoring and extrapolating data to determine the actual flight structural divergence boundary is required. Wind tunnel tests of a generic forward-swept-wing model were performed at the NASA Langley Research Center. Application of the Southwell subcritical extrapolation method to the wind tunnel data was successfully demonstrated (Ricketts and Doggett, 1980).

One of the concerns about structural divergence of the X-29A is that static divergence is not likely to be the limiting factor in envelope expansion. Another phenomenon, the coupling of the wing first bending mode with the rigid body pitch mode, is predicted to occur at lower speeds than static divergence (Chipman and others, 1984). However, frequency trends for this dynamic divergence are highly nonlinear, allowing only point-to-point clearances as speed is increased. The wing first bending frequency drops toward the pitch rigid body frequency, but the nonlinearity of the frequency trend prevents extrapolation to the actual divergence speed at speeds well below the divergence speed. Thus, comparisons between actual and theoretical predictions of the divergence speed cannot be made.

Likewise, the phase and gain margins for the control system become unacceptably small as the divergence speed is approached, and controllability becomes a problem. These effects are also nonlinear, requiring a point-to-point clearance approach. If the Southwell method can be used successfully with flight data, the resulting comparison between the design divergence speed and the flight data extrapolation of the divergence speed can be used to provide an independent indication of whether the aircraft limits are actually closer than expected to the flight envelope boundaries.

The flight test challenge is to apply the Southwell method to flight data to provide a reliable extrapolation to the actual structural divergence speed boundary during the envelope expansion program. Furthermore, the method ought to provide reliable results that can be used in comparisons with the predicted divergence speed in order to validate the methods used during the design process to assure that the divergence speed is outside the flight envelope.

The problem with using the Southwell method is that the flight data are obtained at dynamic pressures well below the divergence dynamic pressure. The wind tunnel data were available at conditions relatively near the actual divergence speed. None of the flight data is at conditions that can be considered near the actual divergence speed. In fact, the extent of the extrapolation is quite large (fig. 2). The accuracy of flight test measurements is not much better than in the wind tunnel, and control of the test conditions is certainly more difficult. Considerable effort is required to improve the chances of successful application of the Southwell technique. The highest quality flight data are needed, an analytical assessment of the characteristics of the data is required, and very careful and thorough flight data analysis techniques must be used.

The purpose of the current activity on the X-29A is to evaluate the use of subcritical divergence prediction techniques using flight data. The scope of the work includes subsonic, transonic, and supersonic evaluations based on comparison of flight data results and analytical predictions. This report will describe the techniques used and the lessons learned by applying the subcritical extrapolation method to transonic data.

INSTRUMENTATION

Strain gages calibrated to provide shear, bending moment, and torque measurements at several locations on the X-29A (fig. 3) are used to provide data for the structural divergence flight tests. Although all load measurements on the wing are available for analysis, the principal load measurement used for divergence is the wing root bending moment. This measurement is the most accurate one available on the wing and is also thought to be the best measure of the loads that produce the structural divergence phenomenon. In other words, the streamwise twisting of the wing is likely to be proportional to the wing root bending moment.

Perhaps the most direct measurement of structural divergence is the aeroelastic streamwise twist per unit angle-of-attack increment along the span due to increasing dynamic pressure. Measurement of the wingtip twist provides the best measurement of the local angle-of-attack changes along the wing span due to aeroelasticity. To measure the wing twist during flight maneuvers, an electro-optical flight deflection measurement system (FDMS) was installed early in the flight test program. The wing box twist can be calculated from wing deflection measurements made at streamwise measurement stations on the wing. Figure 4 is a functional diagram of the FDMS. The FDMS as installed on the X-29A consists of a control unit, a target driver, twelve infrared light-emitting diode (LED) targets and two receivers. The control unit interfaces with the aircraft pulse code modulation (PCM) data system and also commands the operation of the target driver and receivers. The surface-mounted LED targets serve as active location markers and are momentarily energized one at a time by the target driver beginning with target number 1 and ending with target number 12. This cycle is repeated 12 1/2 times/sec. The light image from the energized LED is focused by the receiver's cylindrical lens as a line cutting perpendicularly across its linear photodiode array. This output from the photodiode array in the receiver is the signal that is converted by the control unit into a displacement data sample. Because of vertical field-of-view restrictions, one receiver monitors the inboard six targets while the other receiver monitors the outboard six targets. Figure 5 shows the layout of the FDMS on the X-29A. Wingtip twist is calculated from the displacements of the forward and aft tip targets. Sample displacement data are shown in figure 6.

STATIC AEROELASTIC ANALYSIS

A static aeroelastic analysis of the X-29A is being performed to support the flight tests. A NASTRAN structural model (fig. 7) consisting of seven separate substructures is assembled using the NASTRAN substructuring technique, and a FLEXSTAB aerodynamic model (fig. 8) is used for the analysis, with modifications to represent the wind-tunnel-derived aerodynamics. The NASTRAN model is used to provide structural flexibility data to FLEXSTAB for the aerodynamic stability and control analysis. The FLEXSTAB program computes the pressure distribution and structural deflections for trimmed flight conditions corresponding to the actual flight conditions. The pressure data are integrated at the various load measurement stations to provide analytical shear, bending moment, and torque values for comparison with the flight data. Streamwise twist values are computed from the deflection data at the FDMS measurement stations on the wing. The FLEXSTAB analysis is also run at theoretical conditions corresponding to dynamic pressures above the flight envelope values, corresponding to "altitudes" below sea level (fig. 9). The analysis is performed for conditions very near the divergence dynamic pressure. This allows comparisons to be made between extrapolations from FLEXSTAB analyses at dynamic pressures corresponding to actual flight conditions and extrapolations from FLEXSTAB analyses at dynamic pressures near the predicted divergence dynamic pressure.

AIRCRAFT CONFIGURATION AND FLIGHT TEST CONDITIONS

The standard mode of operation of the X-29A control system is known as normal digital mode, with automatic camber control (ND/ACC). This mode controls the flap position as a function of normal load factor such that the flaps deflect more trailing edge down during increasing load factor maneuvers. In order to obtain the necessary load coefficient data for the divergence extrapolations, wing loads and deflections must be a function of angle-of-attack changes only. Therefore, a special flight test mode has been designed, called manual camber control (MCC), to allow operation of the X-29A at constant camber settings during maneuvering flight. The difference in wing loads is shown in figure 10. In the MCC mode, the camber setting can also be set at the same value for flight test points from very low to very high dynamic pressure values. To achieve this while preventing the trim loads on the canard surfaces from becoming large, canard protection logic is incorporated into the control system. This essentially limits operation in MCC mode to only two or three camber settings at each flight condition. The camber settings available at transonic flight conditions (either zero flap angle or trailing edge up flap angles of 5° or 10°) are not ideal for collecting aerodynamic data. However, without the MCC mode, it would be extremely difficult to obtain the necessary data for the divergence investigation.

Load coefficient and twist data are obtained during angle-of-attack sweep maneuvers, both pushover-pullups and windup turns, in order to obtain data over the widest possible angle-of-attack range. The maneuvers are performed at several altitudes at each Mach number of interest (fig. 11). From each maneuver, the slope of the data with respect to angle of attack is obtained for use in the extrapolation. All flight data presented are from Mach 0.90 maneuvers.

SUBCRITICAL EXTRAPOLATION METHOD

The purpose of subcritical divergence prediction techniques is to extrapolate the static aeroelastic characteristics of the configuration to the critical dynamic pressure at which the aeroelastic effects become infinite. When the dynamic pressure is at the critical value, the slightest disturbance results in essentially instantaneous and catastrophic overload of the aircraft structure. The aerodynamic load coefficients with respect to angle of attack are infinite at the critical condition.

Therefore, the first step in the process of using the subcritical extrapolation technique is to determine the values of the twist or load per unit angle-of-attack change at each flight condition. These values are called λ. This is done at several constant dynamic pressure conditions and the resulting data are extrapolated to the critical dynamic pressure. The values of λ are the linear least squares slopes obtained by plotting the twist or load data as a function of angle of attack.

This is a simple matter if the data are linear with respect to angle of attack within the angle of attack range of interest. The data are actually almost linear, varying slightly with angle of attack (fig. 12). Since the extrapolation is dependent on the subtle changes in λ due to static aeroelasticity, the choice of an appropriate angle-of-attack range for each maneuver and flight condition becomes important.

There is a lack of agreement between the FLEXSTAB root bending moment and tip twist divergence indicators when the analysis is performed using dynamic pressures within the flight envelope (fig. 13). These data provide some indication of what to expect from the actual flight measurement results. The flight data for root bending moment coefficient and tip twist do not extrapolate to the same value of divergence dynamic pressure, but disagree considerably (fig. 14). Such disagreement leads to the use of a combination of techniques to accomplish the envelope expansion process.

An example of how small errors in the determination of λ values lead to larger errors in the extrapolation to the divergence speed is shown in figure 15. If the errors are in the same direction and have the same percent magnitude, the divergence speed is not changed. However, if the magnitude or direction of the errors disagree, larger errors occur in the divergence speed than are present in the λ values. This is a characteristic of all extrapolation methods. The typical quality of flight data measurements leads to the possibility of rather large errors in λ values and even larger errors in the extrapolated divergence speed. The choice of which measurement to use as an indicator of the divergence instability is important because different measurements result in different divergence speed predictions, as shown in the FLEXSTAB analysis where measurement errors do not exist.

USE OF SOUTHWELL RESULTS FOR ENVELOPE EXPANSION

Because of the disagreement in Southwell extrapolation results, the envelope expansion program consists of a combination of the Southwell results with point-to-point clearances. Plots of λ values as a function of dynamic pressure are prepared to allow tracking of trends with respect to the trends from the FLEXSTAB analysis (fig. 16). This presentation of the data allows judgments to be made about the likely value of λ at the next dynamic pressure point, even though the data cannot be reliably extrapolated to the critical divergence speed. As long as the values of λ do not increase considerably more than expected from one dynamic pressure point to the next higher point, the envelope expansion can proceed as planned. As more data are obtained at higher dynamic pressures, the reliability of the extrapolation of a particular measurement generally improves. However, because the critical dynamic pressure values obtained from a variety of measurements do not agree, these values cannot establish an actual flight-derived divergence speed limit.

ANALYSIS CHALLENGES

Some of the factors which make the subcritical extrapolation analysis of flight data challenging are discussed in this section. Because the data are used in an extrapolation process, small variations that are ordinarily ignored can become significant. Efforts to minimize the effect of these variations are described.

Determination of the λ values at a particular flight condition is difficult because both Mach number and dynamic pressure vary during the maneuver. Usually the average Mach number is close to the target Mach number. Variations in Mach number during the maneuver are usually small (about 3 percent or less). However, in the transonic range, even those small variations can have some effect on the value of λ. Matching the target dynamic pressure during a given maneuver is not too critical because the value of λ will be used with respect to the average dynamic pressure during that particular maneuver. However, variations in dynamic pressure during the maneuver can have a variety of effects on the resulting value of λ, depending on how the dynamic pressure varies with respect to variations in angle of attack during the maneuver. Some of these effects depend on how the value of λ is computed from the load measurement.

There are two ways to obtain λ values (fig. 17). The first is to plot the measurement as a function of angle of attack and obtain the slope. This slope is the λ value. The Southwell analysis requires that the λ value be divided by the average dynamic pressure of the maneuver to obtain a $\lambda/\bar{q}$ value. The second way to obtain λ values is to normalize the measurement by dynamic pressure at each time point throughout the maneuver by dividing by the dynamic pressure at the instant when the measurement was obtained. The slope of the normalized measurement as a function of angle of attack is then the $\lambda/\bar{q}$ value. To obtain the value of λ, multiply the slope by the average dynamic pressure of the maneuver. The second method is preferred because it minimizes the errors caused by variations of dynamic pressure during the maneuver.

The instantaneous values of λ and $\lambda/\bar{q}$ are higher when the dynamic pressure is higher, even during the same maneuver. This leads to nonlinear plots of load and load/$\bar{q}$ as a function of angle of attack. The effect is greater on the load as a function of angle of attack plots. Therefore, a better result is obtained by taking the slope of the load/$\bar{q}$ as a function of angle of attack plot. This is the method used to reduce the load measurements. In fact, the measurements used are actually the aerodynamic load coefficients, which are normalized for both dynamic pressure and the geometry at a particular load measurement station.

Another factor in determination of the value of λ for a particular dynamic pressure is that the value of λ varies with angle of attack. Even at moderate angles of attack representing the typical linear range of aerodynamics, these variations are present. This leads to obtaining different values of λ for pushover-pullups and windup turns, because the angle-of-attack ranges for the two maneuver types are different. When the data from these two maneuver types are compared using a common angle-of-attack range, the values show better agreement.

As the flight test progresses from lower dynamic pressure test points to higher dynamic pressure test points, the trim angle of attack and the range of angle of attack available within the load limits decreases. This is a factor in the question of what angle-of-attack range is best to use at each test point. The wind tunnel data can aid in pointing out the "linear" portion of the angle-of-attack range for a rigid model. The extrapolation to the divergence speed may be affected by the choice of angle-of-attack range. If the same normal load factor range (for example, 1.5 to 3.0 *g*) is used at all dynamic pressures, the results may be different than if the same angle-of-attack range (for example, 3.0° to 6.0°) is used. Perhaps the most appropriate range to use is one that brackets the 1-*g* trim condition likely at the divergence dynamic pressure. Unfortunately, this is a very low angle-of-attack condition, below 0 *g* at most flight conditions, and is also outside the "linear" wind tunnel angle-of-attack range. The current data reflect use of the widest possible "linear" angle-of-attack range for each maneuver. This probably leads to lower quality extrapolation results but provides more data for a given measurement as a function of angle-of-attack plot from which to determine λ values.

CONCLUDING REMARKS

The X-29A program provides data to allow preliminary evaluation of the Southwell subcritical extrapolation technique using flight measurements. The basic application of the subcritical extrapolation technique is being refined to make the technique more reliable for envelope expansion use. Many of the challenging problems are being identified by attempting to apply subcritical extrapolation techniques to flight data which are for flight conditions far removed from the critical flight condition.

More refined analysis of the data should be performed to allow a definitive comparison to the divergence dynamic pressure predicted by the design data. Examination of data at 1.2 and 0.8 Mach should be completed to evaluate the technique at supersonic and subsonic conditions.

Recommendations for future flight test applications of subcritical methods can be made as a result of this program on the X-29A. High-quality measurements of all parameters that participate in the extrapolation, particularly angle of attack, dynamic pressure, loads, and deflections, are required to provide the necessary sensitivity to obtain reliable results. A predictive database should be available to use for point-by-point tracking of the critical parameters to assist in identification of any adverse trends in the flight data. Finally, some planning effort is required to correctly identify the parameters most likely to represent the phenomenon of interest for use in any subcritical extrapolation method.

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Ricketts, Rodney H. and Robert V. Doggett, Jr., *Wind-Tunnel Experiments on Divergence of Forward-Swept Wings*, NASA TP-1685, 1980.

Chipman, Richard, Frank Rauch, Melvyn Rimer, and Benigno Muñiz, *Body-Freedom Flutter of a 1/2-Scale Forward-Swept-Wing Model, an Experimental and Analytical Study*, NASA CR-172324, 1984.

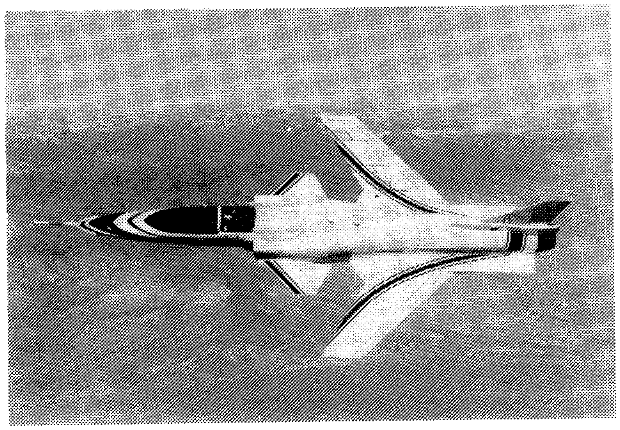

Figure 1. X-29A forward-swept wing technology demonstrator aircraft.

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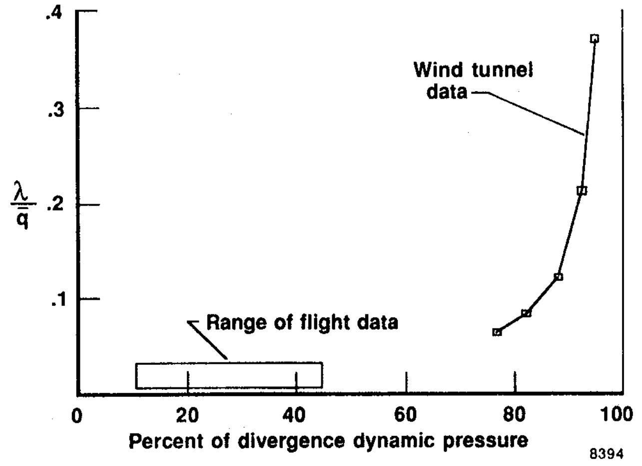

Figure 2. Contrast between wind tunnel and flight data.

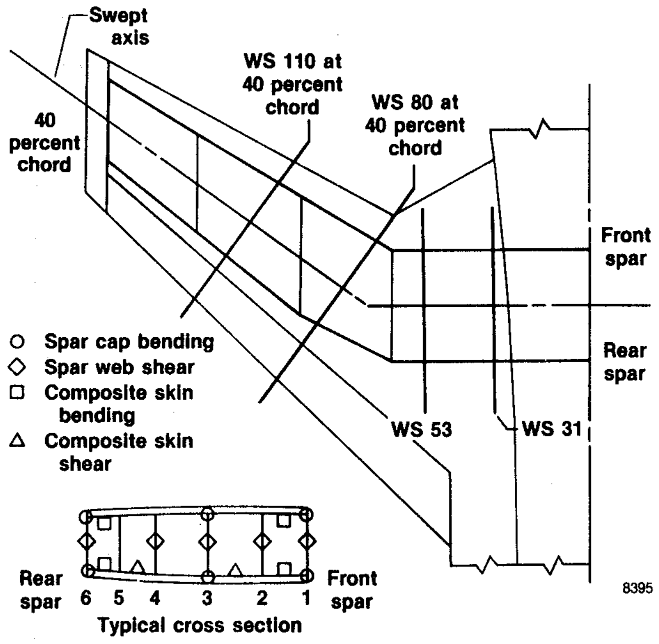

Figure 3. X-29A wing load measurements.

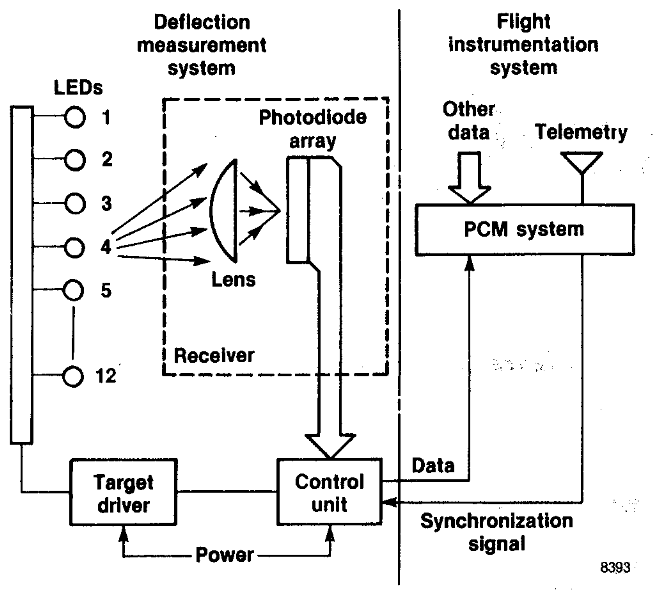

Figure 4. X-29A FDMS functional diagram.

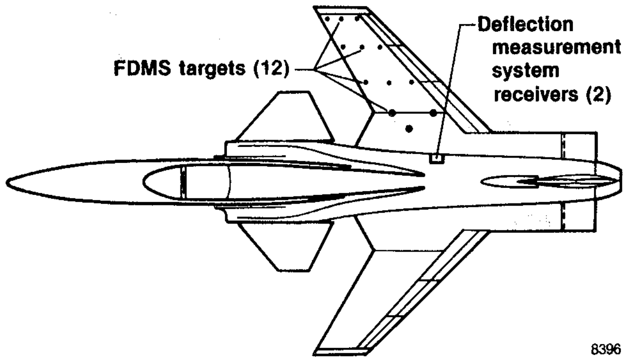

Figure 5. X-29A FDMS installation of targets and receivers.

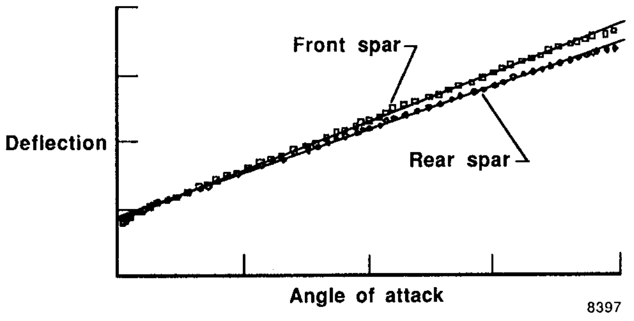

Figure 6. Wingtip deflection.

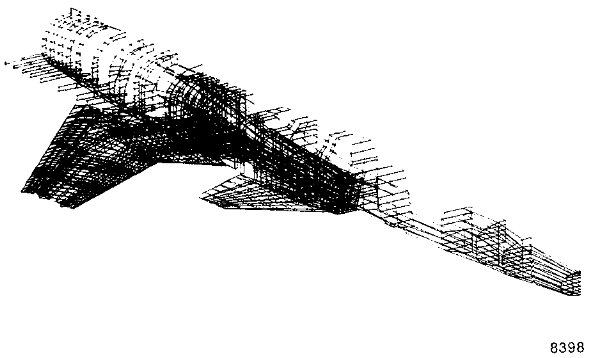

Figure 7. X-29A NASTRAN model.

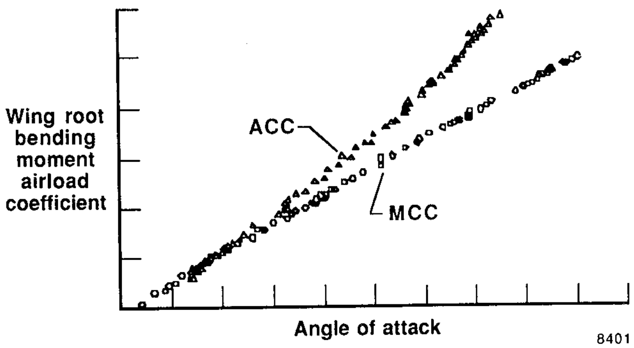

Figure 10. Contrast between ACC and MCC windup turns.

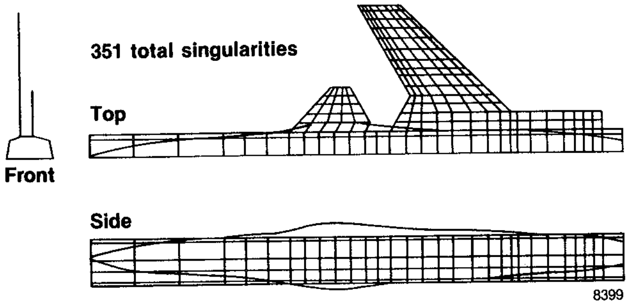

Figure 8. X-29A FLEXSTAB aerodynamic model.

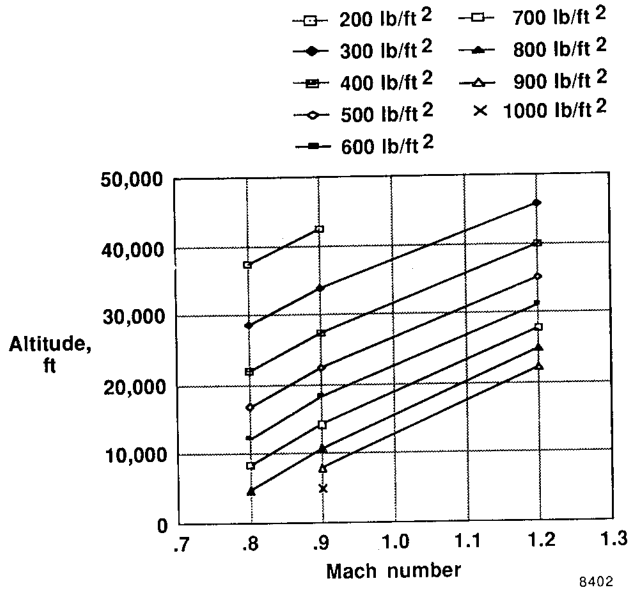

Figure 11. Test matrix for divergence.

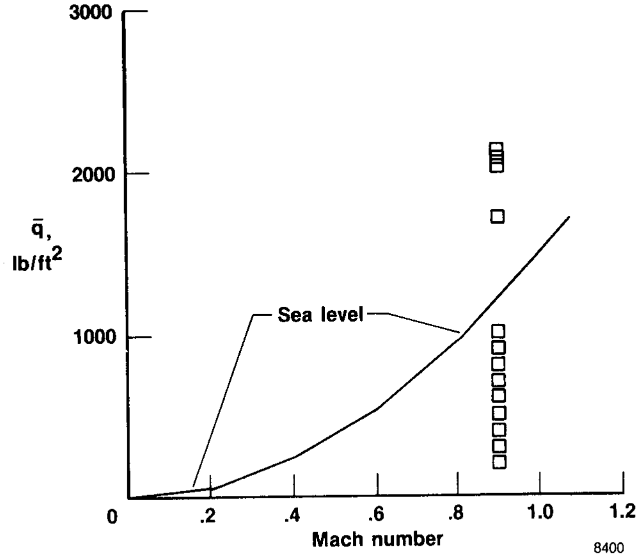

Figure 9. FLEXSTAB analysis conditions.

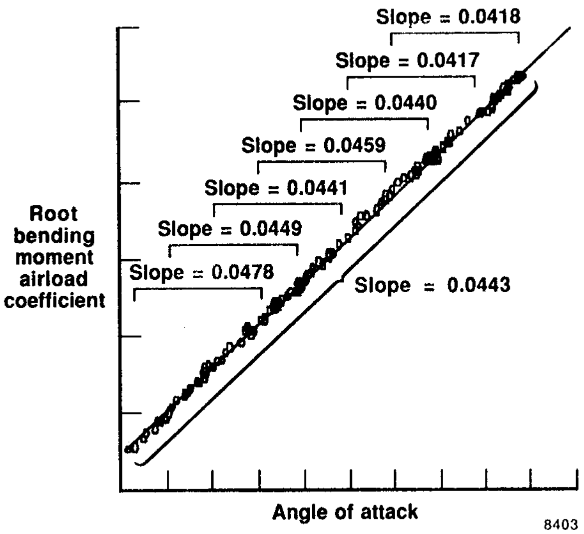

Figure 12. Determination of λ/ $\bar{q}$.

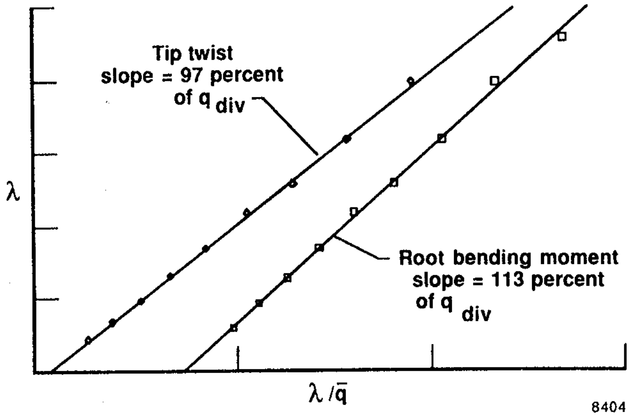

Figure 13. Southwell plot for FLEXSTAB at flight altitudes.

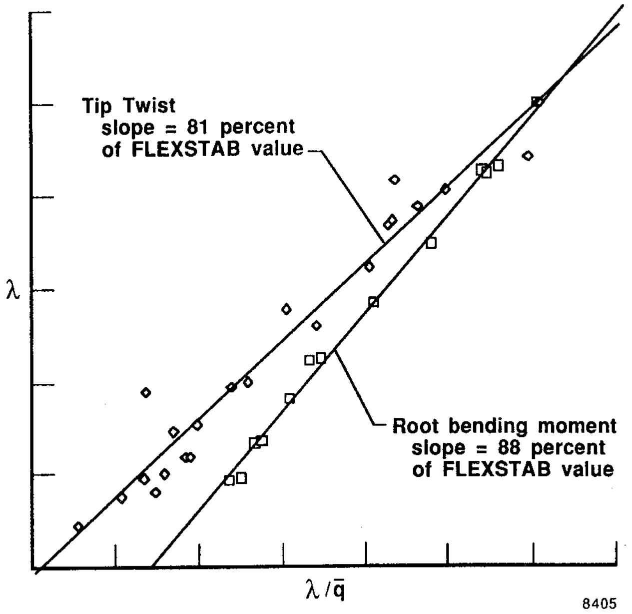

Figure 14. Southwell plot for flight data.

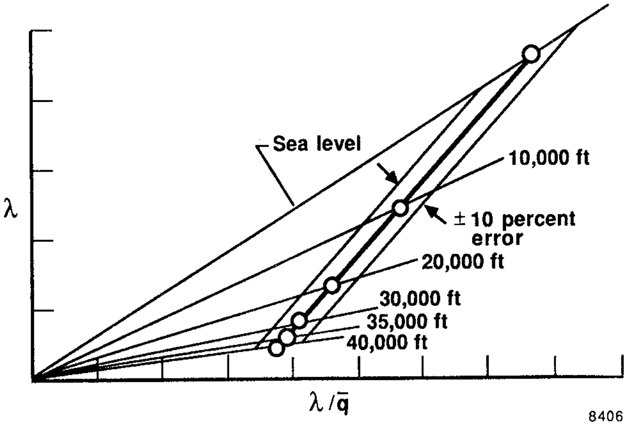

Figure 15. Effect of measurement errors.

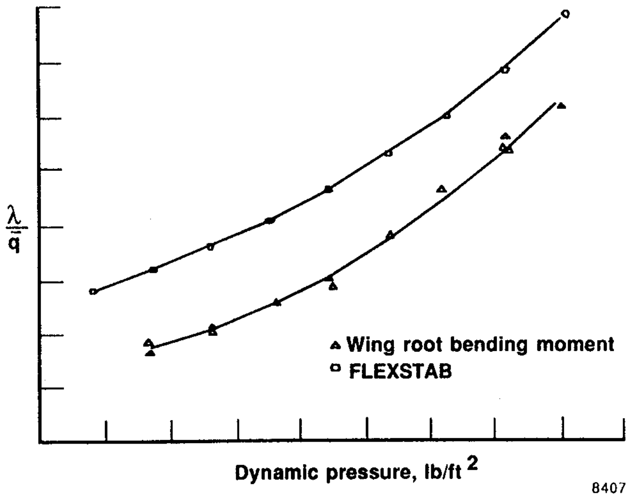

Figure 16. *$\lambda/\bar{q}$ trends.*

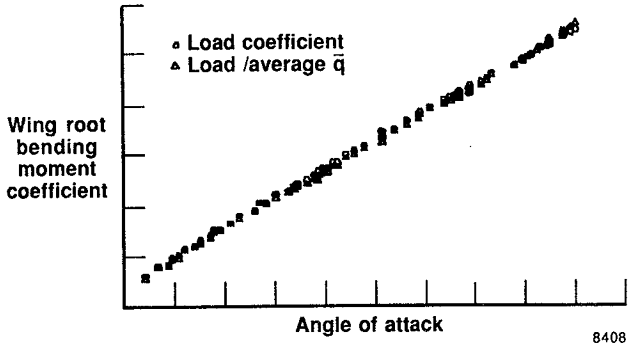

Figure 17. Two methods of computing λ: load or load coefficient vs angle of attack.

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17. Key Words (Suggested by Author(s))

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