NASA TM-87631

NASA Technical Memorandum 87631

NASA-TM-87631 19860005849

PREDICTION OF WING AEROELASTIC EFFECTS ON AIRCRAFT LIFT AND PITCHING MOMENT CHARACTERISTICS

CLINTON V. ECKSTROM

NOVEMBER 1985

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

PREDICTION OF WING AEROELASTIC EFFECTS ON AIRCRAFT LIFT AND PITCHING MOMENT CHARACTERISTICS

Clinton V. Eckstrom
NASA Langley Research Center
Hampton, VA

ABSTRACT

The distribution of flight loads on an aircraft structure determines the lift and pitching moment characteristics of the aircraft. When the load distribution changes due to the aeroelastic response of the structure, the lift and pitching moment characteristics also change. Some estimate of the effect of aeroelasticity on stability and control characteristics, particularly lift and pitching moment, is required for use in aircraft simulation models for evaluation of flight characteristics. This presentation outlines a procedure to incorporate aeroelastic effects into lift and pitching moment data from wind tunnel tests. Results are presented which were obtained from applying this procedure to an aircraft with a very flexible transport-type research wing. The procedure described is generally applicable to all types of aircraft.

STATEMENT OF PROBLEM

Given: Wind tunnel measurements of stability and control characteristics for a rigid model with a cruise shape wing

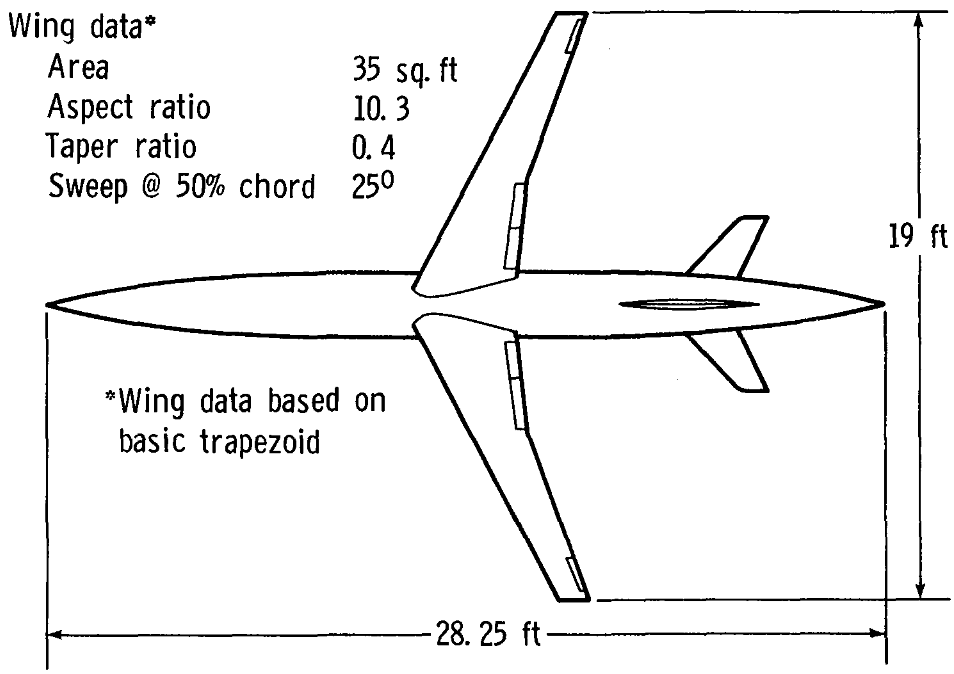
Needed: Stability and control characteristics for an aircraft with a flexible wing starting in the fabrication shape

Approach: Perform static aeroelastic analysis to predict effects of shape change (cruise to fab) and effects of flexibility (dynamic pressure) then use results to modify wind tunnel data

Designing a transport type wing for maximum efficiency at cruise flight conditions results in the definition of a specific wing cruise shape (planform, airfoil shapes, twist, etc.). Usually all wind tunnel test data available for evaluation of performance and stability and control characteristics will have been obtained from a relatively rigid model built to this desired cruise shape. However, most full scale transport type wings will have some degree of flexibility which will cause the wing shape to be a function of the aerodynamic load distribution and magnitude. Therefore a static aeroelastic analysis must be performed to define a fabrication shape such that the full scale wing will deform to the desired cruise shape when it is subjected to the cruise aerodynamic loading.

For the problem described herein the given information included the wind tunnel measurements for a rigid model with a cruise shape wing (ref. 1) and the fabrication shape for the full scale wing (ref. 2). What was needed was a prediction of the performance and stability and control characteristics of the full scale aircraft with a flexible wing starting in the fabrication shape. The approach was to use a static aeroelastic analysis procedure (ref. 3) to calculate the performance and stability and control characteristics of the aircraft with both a rigid cruise shape wing and a rigid fabrication shape wing and also to perform the same calculations for the aircraft with a flexible fabrication shape wing. The next step was to determine the differences in stability and control characteristics between the rigid cruise shape and the rigid fabrication shape and the changes due to flexibility (aeroelastic effects) (defined as a function of flight dynamic pressure). These changes were then applied to the wind tunnel measured data as increments or as ratios to give a prediction of the stability and control characteristics for the flexible flight vehicle using a procedure similar to that of reference 4. The information presented herein is for the lift and pitching moment characteristics at a Mach number of 0.80 although the calculations were performed for a range of Mach numbers.

AIRCRAFT USED AS EXAMPLE PROBLEM

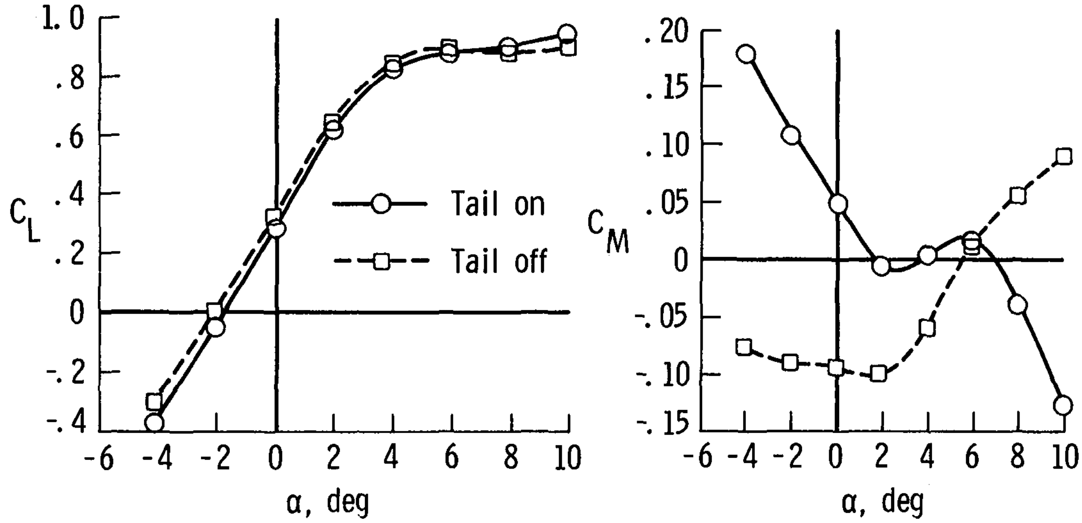


The procedure described herein was applied to a research wing mounted on a drone vehicle. The size and general arrangement of the research wing and drone vehicle is shown in the above figure. The fuselage shown is a modified Firebee II target drone vehicle. The research wing was designed for a 2.5-g maneuver load at a gross vehicle weight of 2500 pounds. The wing structural strength and stiffness were determined using an integrated design procedure which included the wing load reduction benefits of active control systems for maneuver and gust load alleviation and the stiffness reduction benefits of an active control system for flutter suppression (ref. 2). Therefore the wing is probably quite flexible in comparison to most transport type wings in use today. For advanced designs such as this the effects of flexibility on stability and control characteristics is a subject of general interest.

LIFT AND PITCHING MOMENT COEFFICIENT DATA FROM WIND TUNNEL TEST

Model with rigid cruise shape wing

M = 0.80

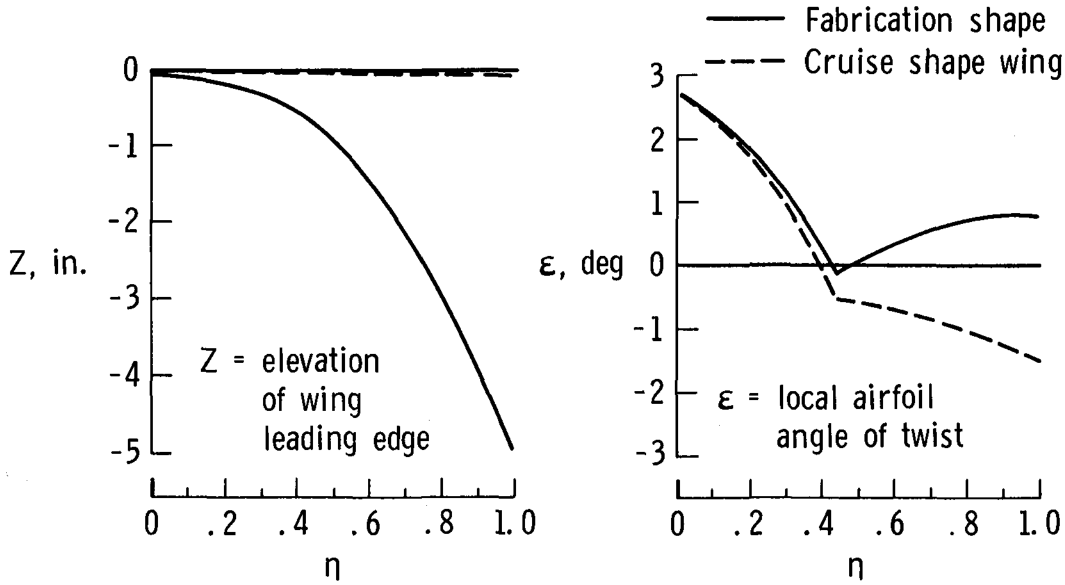


The lift and pitching moment coefficient data from a wind tunnel test of a model with a rigid cruise shape wing (ref. 1) are shown in this figure. Data are presented for tests performed at a Mach number of 0.80 with the model in both the tail on and tail off configurations.

For the lift coefficient data on the left the slight difference between the two sets of data results from the lift on the tail. Note that the lift on the tail is downward until an angle of attack of 6 degrees has been reached. The circles and squares represent actual test data points whereas the solid and dashed lines represent equations which were fit to the test data points. The equations were used to define a set of pseudo "wind tunnel" results with data every 0.5 degrees angle of attack for use in subsequent analyses.

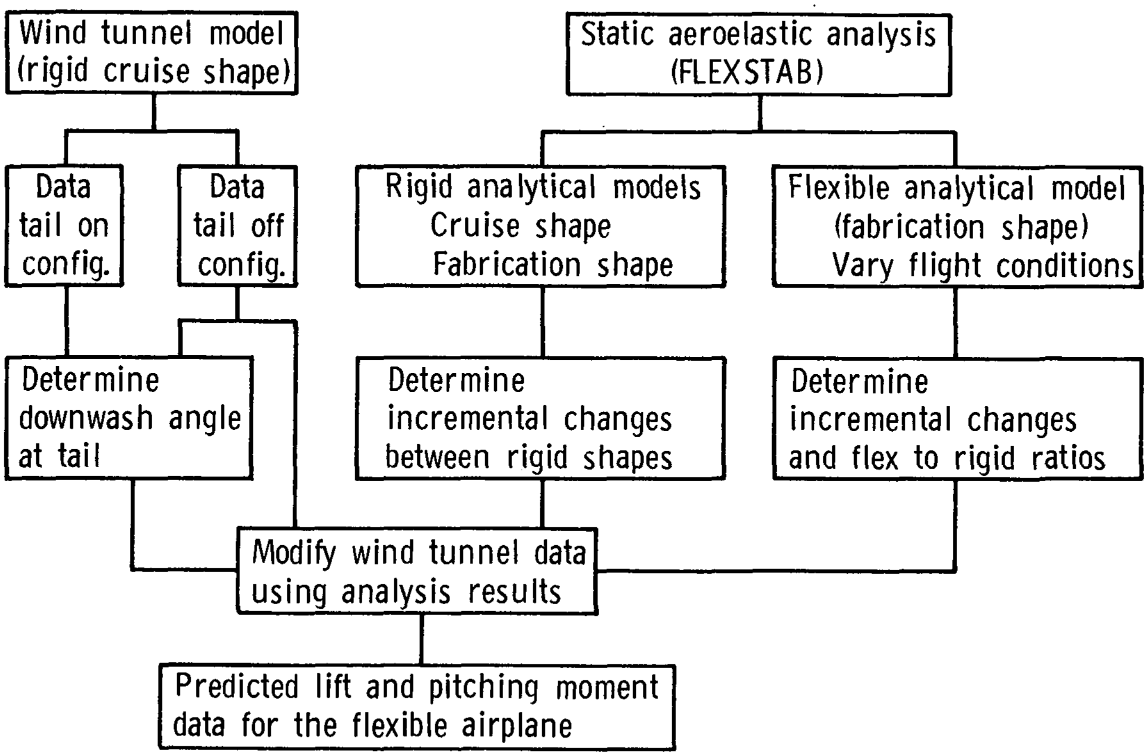
For the pitching moment coefficient data on the right the difference between data for the tail on and tail off configurations is considerably greater. The difference is the lift on the tail acting on the moment arm between the tail center of pressure and the vehicle center of gravity. Note that the two curves cross at about 6 degrees angle of attack indicating that the lift on the tail changes from negative to positive which is in agreement with the lift coefficient data on the left side of the figure.

COMPARISONS OF WING DROOP AND TWIST DISTRIBUTIONS FOR CRUISE AND FABRICATION SHAPE WINGS



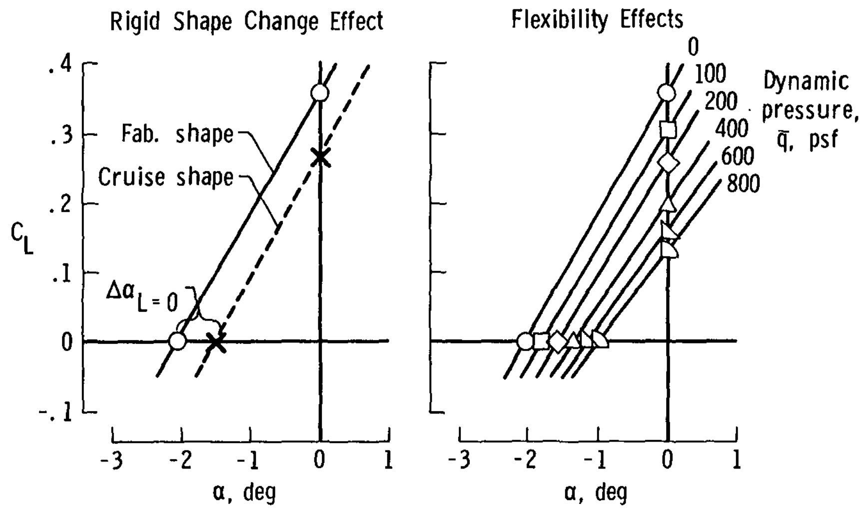
This figure presents a comparison of the wing leading edge elevation (droop) and spanwise twist distributions for the cruise and fabrication shape wings. As shown by the figure on the left, the leading edge of the cruise shape wing is a straight line with a very slight downward slope toward the wing tip. The leading edge of the fabrication shape wing droops downward considerably from the cruise shape wing to compensate for the upward bending that will occur due to the lifting aerodynamic loads experienced at the cruise flight conditions ($M = 0.80$, $C_L = .53$, $q = 127$ psf). The wing twist distribution for the cruise shape wing, shown on the figure at the right, was selected for aerodynamic efficiency reasons relative to spanwise lift distribution and wing tip stall. The fabrication shape wing has a reduced negative twist distribution to compensate for the negative twisting which will occur as a result of bending when the flexible fabrication shape wing is subjected to the aerodynamic loads associated with the cruise flight conditions.

FLOW CHART SHOWING ANALYSIS PROCEDURE



This flow chart outlines the tasks and the procedures for obtaining the predicted lift and pitching moment characteristics for a flexible aircraft. The wind tunnel test data for the tail-on and tail-off aircraft configurations referred to on the left side of the chart have already been presented. The static aeroelastic analyses referred to on the right side of the chart were performed using the Flexible Airplane Analysis Computer Program called FLEXSTAB (reference 3). As noted on the chart, static aeroelastic analyses are required for: (1) rigid analytical models at both the design cruise shape and the fabrication shape, and (2) a flexible analytical model (initially at the fabrication shape) subjected to various levels of flight dynamic pressure. The results from these analyses are used to define incremental changes in lift and pitching moment between the two rigid shapes and for the variations of flight dynamic pressure for the flexible model. The incremental changes are used either directly, or as ratios, to modify the measured wind tunnel data.

STATIC AEROELASTIC ANALYSIS OF LIFT CHARACTERISTICS



A comparison of the calculated lift coefficients for the rigid cruise-shape wing and the rigid fabrication-shape wing are shown on the figure on the left. The difference in angle of attack at zero lift (C_L=0) for the two curves is the incremental value that will be used in modifying the measured wind tunnel lift coefficients to those expected for the rigid fabrication shape wing. Note that for these two rigid wing shapes there is a shift in angle of attack for zero lift but no change in lift curve slope.

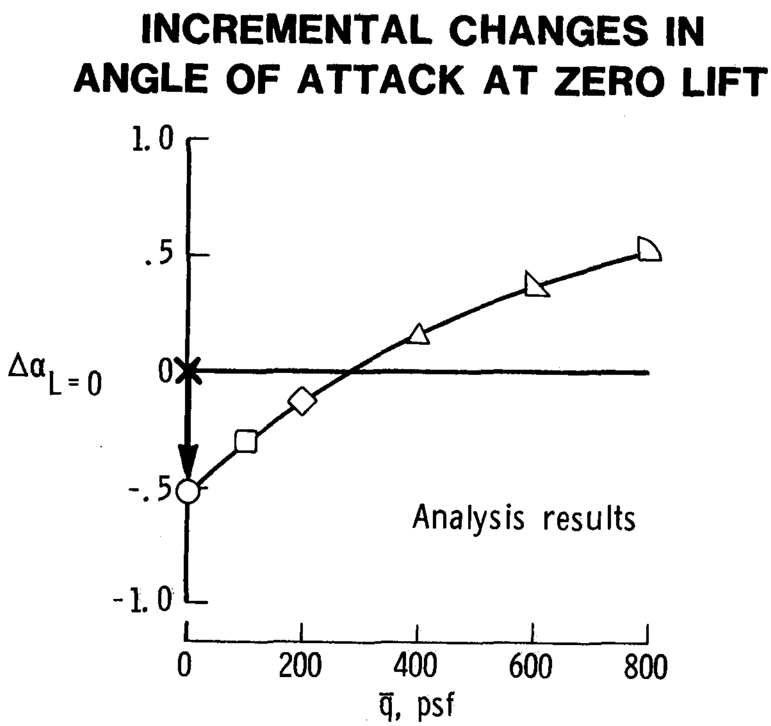
The next step is to calculate the lift coefficient slope and intercept values for the flexible wing. The linear aerodynamic equations used in the static aeroelastic analysis program are of the form:

$$\{C_p\} = [A] \left\{\alpha \{1\} + \{\alpha_c\}\Big|_{(\alpha=0)} + \{\alpha_F\} \right\}$$

where α_F can be calculated from the deflection of the structure given by:

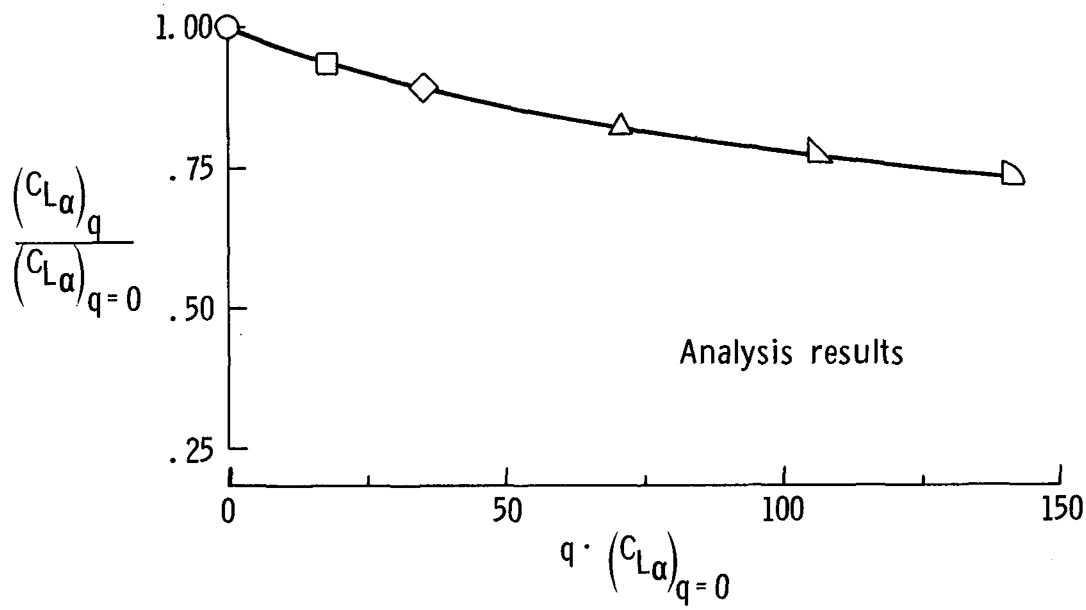
$$\{\delta_F\} = q\ [K]^{-1}\ [S]\ \{C_p\}$$

The static aeroelastic program integrates the resulting pressure distributions to give corresponding lift and pitching moment coefficient slope and intercept values for the flexible wing as shown by the figure on the right above. The results for the flexible wing are different from those for the rigid wing shapes in that there is a change in both the intercept values and the lift curve slopes as flight dynamic pressure is changed. These changes in lift curve slope occur because the wing twist distribution for the flexible wing is a function of wing loading which in turn is a function of aircraft angle of attack for any given flight dynamic pressure. Note that the data shown on the left for the rigid fabrication shape wing is the same as the data shown on the right for a dynamic pressure of zero, i.e., the rigid case. The results shown above are summarized in the next two figures.



The incremental changes in angle of attack at zero lift, as shown above, are needed as one of the inputs for modifying the measured wind tunnel data to account for the wing rigid shape change (shown at zero flight dynamic pressure) and for the aeroelastic effects which are a function of flight dynamic pressure. (These data were obtained from the previous figure at $C_L=0$). Note that the incremental changes for the rigid shape change and the flexibility effects are opposite in sign. The fabrication shape wing has zero lift at a lower angle of attack than the cruise shape wing because, as shown earlier, the fabrication shape wing has less negative twist along the span than does the cruise shape wing. However as the flight dynamic pressure is increased, the aft swept flexible wing will bend upwards at the tip resulting in an effectively decreasing local angle of attack along the span.

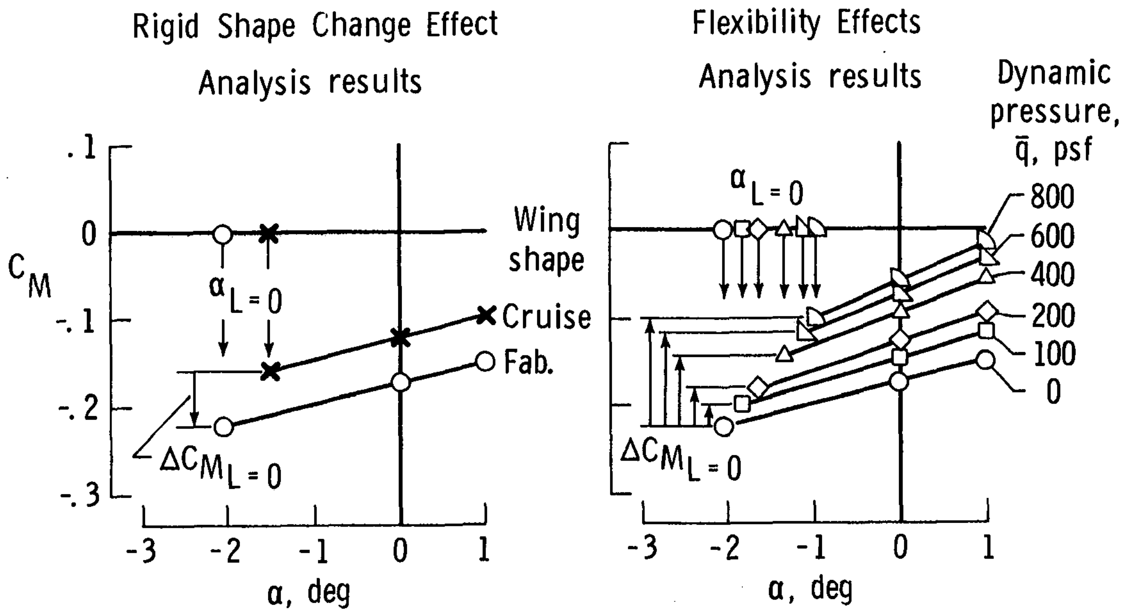
RATIO OF FLEXIBLE TO RIGID LIFT CURVE SLOPES



This figure presents the ratio of the flexible to rigid lift curve slopes as a function of dynamic pressure multiplied by the lift curve slope at zero dynamic pressure (rigid fabrication shape). The data are from the static aeroelastic analysis results for the flexible wing which were shown earlier. The flexible to rigid lift curve slope ratios defined by this curve are used to modify the values of the measured wind tunnel lift curve slopes, which change as angle of attack changes, particularly at the higher angles of attack. When either the flight dynamic pressure or the wind tunnel lift curve slope is small the correction to the slope will be small. In this way the shallow lift curve slope increments near maximum lift receive only a very small correction whereas those portions of the lift curve with the highest slopes will get the largest corrections.

The next several figures present results of the static aeroelastic analysis of changes in pitching moment.

CHANGE IN PITCHING MOMENT AT ZERO LIFT



Changing the wind tunnel measured pitching moment coefficient curve to account for wing shape changes is a two step process. The first step is to establish the incremental changes in pitching moment at zero lift as shown here. The left side of this figure presents pitching moment coefficients as a function of angle of attack as determined from the analytical models for the rigid cruise shape wing and the rigid fabrication shape wing. The incremental change in pitching moment at zero lift resulting from going from the cruise shape wing to the fabrication shape wing is:

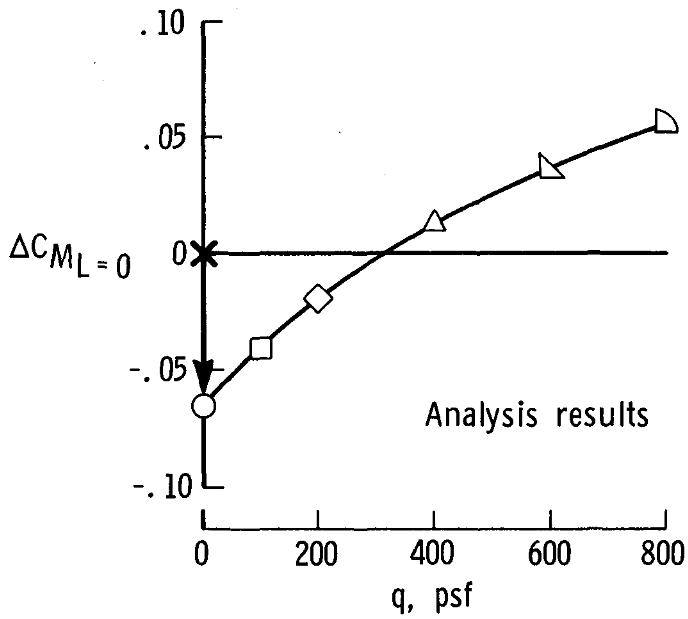
$$\Delta C_{m_{L=0}} = (C_{m_{L=0}})_{FAB} - (C_{m_{L=0}})_{CRUISE}$$

The incremental value of pitching moment coefficient at zero lift is applied to the wind tunnel data as the first step in determining a new pitching moment coefficient curve for the fabrication shape wing.

The right side of the figure presents similar results for the flexible wing starting in the fabrication shape for several values of flight dynamic pressure. The values for incremental changes in pitching moment at zero lift are shown referenced to the value of pitching moment at zero lift determined at zero dynamic pressure which is the same data point as shown on the left side of the figure for the rigid fabrication shape wing.

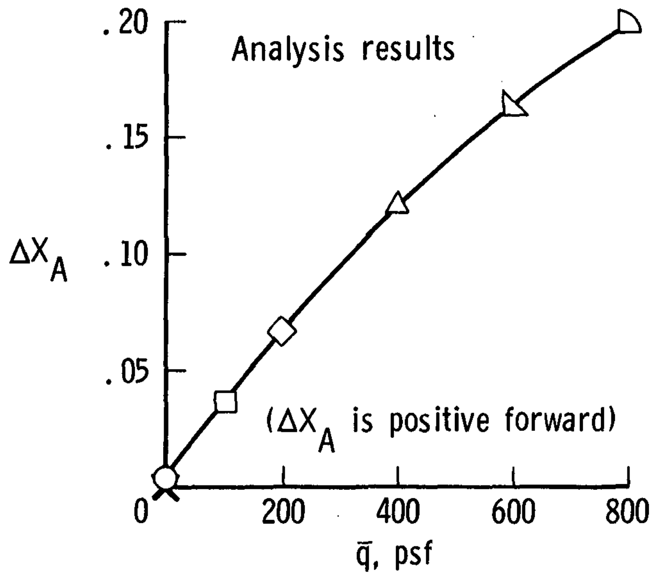
The next figure presents a summary of the incremental changes in pitching moment coefficient at zero lift conditions.

INCREMENTAL CHANGES IN PITCHING MOMENT AT ZERO LIFT



The incremental changes in pitching moment are presented here as a function of dynamic pressure to show the relationship between the increment for changing from the rigid cruise shape wing to the rigid fabrication shape wing (at zero dynamic pressure) and the increments for the flexible fabrication shape wing. Note that the increment between rigid shapes is opposite in sign to the increments due to flexibility.

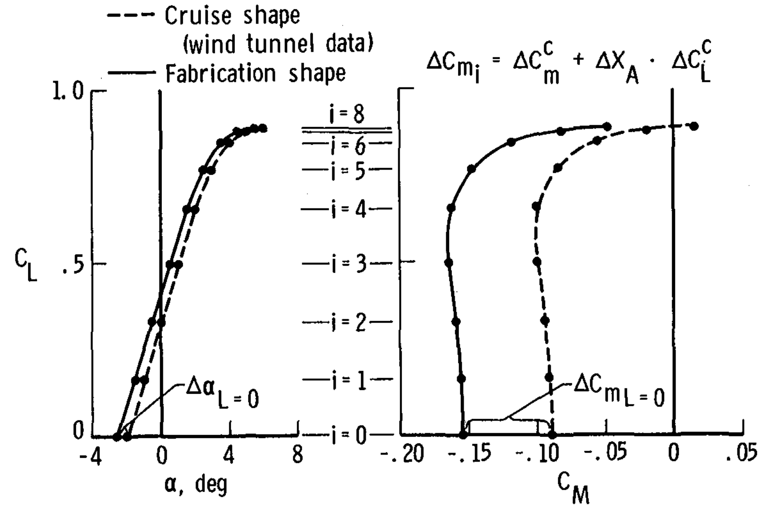
INCREMENTAL CHANGES IN AERODYNAMIC CENTER LOCATION



As mentioned previously, changing the wind tunnel measured pitching moment coefficient curve to account for wing shape changes is a two step process. The first step was to establish the incremental changes in pitching moment at zero lift as shown on the previous two figures. The second step is to change the slopes of the pitching moment coefficient curves because of changes in aerodynamic center positions between the different wing shapes. The above figure presents the incremental changes in aerodynamic center location as a function of flight dynamic pressure with the incremental change resulting from going from the rigid cruise shape to the rigid fabrication shape being shown at a dynamic pressure of zero. These data were obtained directly from the static aeroelastic analysis results without additional computations. As can be seen the incremental change in aerodynamic center location due to changing from the rigid cruise shape wing to the rigid fabrication shape wing is very small in comparison to the changes due to flexibility as dynamic pressure is increased.

The next figure shows how the analysis results are used to modify the wind tunnel measured data for the tail off aircraft configuration.

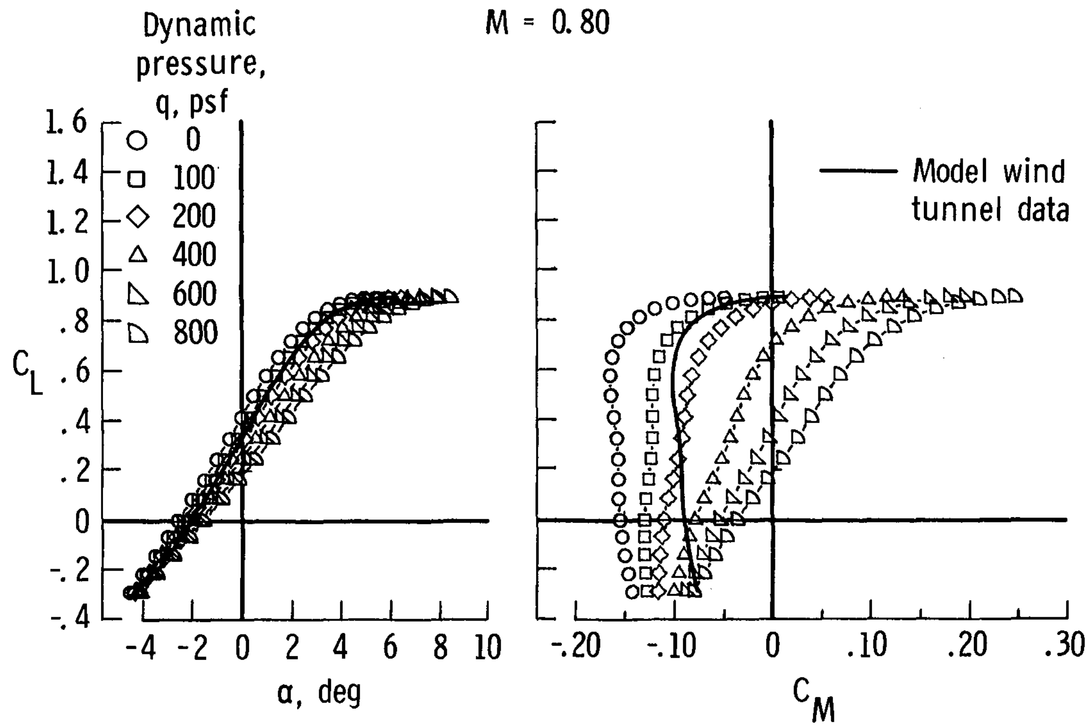
USE ANALYSIS RESULTS $\Delta\alpha_{L=0}$, $\Delta C_{m_{L=0}}$, AND ΔX_A TO MODIFY WIND TUNNEL DATA



Lift coefficient as a function of angle of attack and pitching moment coefficient as a function of lift coefficient are presented to illustrate the first few of several steps in obtaining modified wind tunnel data. The dashed lines represent wind tunnel data for the tail off model configuration. Each data point along the dashed line represents one of the pseudo "wind tunnel" data points available at every 0.5 degrees angle of attack with the exception that the data point at $C_L = 0$ is an interpolated value. Each of these data points also represents a step in the modification process as defined by the i=0 to i=8 notation in the center of the figure. The solid lines are results as determined for the rigid fabrication shape wing. For lift coefficient versus angle of attack the new data for the rigid fabrication shape wing is simply the measured wind tunnel data (cruise shape wing) shifted over on the angle of attack axis at each data point by the increment of angle of attack at zero lift determined by analysis. This means that each segment between data points on the new curve has exactly the same slope as the original wind tunnel data.

Determining the pitching moment coefficient for the rigid fabrication shape wing is a two step process. The first step is to shift the initial value for pitching moment at zero lift (at i=0) by the incremental change in pitching moment at zero lift as determined by analysis. The second step is to determine the new value of slope for the pitching moment curve as shown by the equation at the top of the figure. The new curve slope for each step, i, along the curve is equal to the slope of the original wind tunnel data plus the product of the incremental change in aerodynamic center, ΔX_A, times the incremental change in lift coefficient for each step. As was shown earlier, there was only a very small change in aerodynamic center in going from the rigid cruise shape wing to the rigid fabrication shape wing, therefore each of the steps along the two pitching moment curves are nearly parallel. The data shown are for values of lift starting at zero and going positive. The same procedure, starting at zero lift, is used to determine data for the fabrication shape for negative values of lift coefficient.

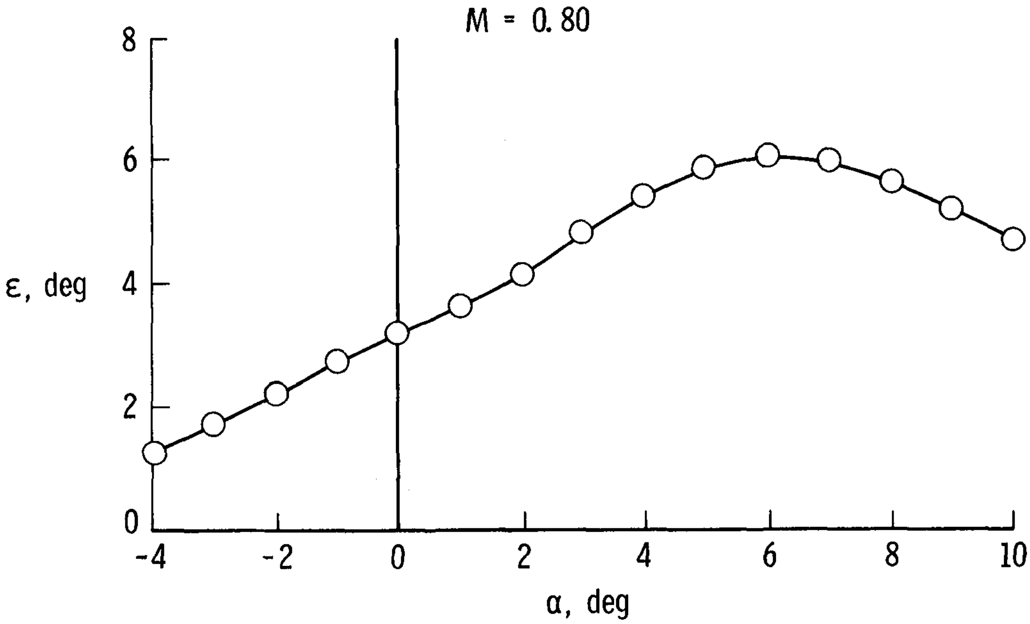
ANALYSIS RESULTS FOR THE FLEXIBLE AIRPLANE - TAIL OFF



Lift and pitching moment coefficient results for the flexible airplane in the tail off configuration are presented in this figure. Pitching moment is again presented as a function of lift coefficient to show, for the flexible airplane, how the large changes in aerodynamic center affect the slopes of the pitching moment curves. Data for both lift coefficients and pitching moment coefficents are presented for lift coefficient values both greater and less than zero. The plots also show the wind tunnel data for reference purposes. The left side of the figure shows how the incremental changes in angle of attack at zero lift coefficient and the changes in lift curve slope with dynamic pressure affect lift coefficient data. The right side of the figure shows how the pitching moment coefficient changes with the rigid shape change and with increasing dynamic pressure for the flexible wing.

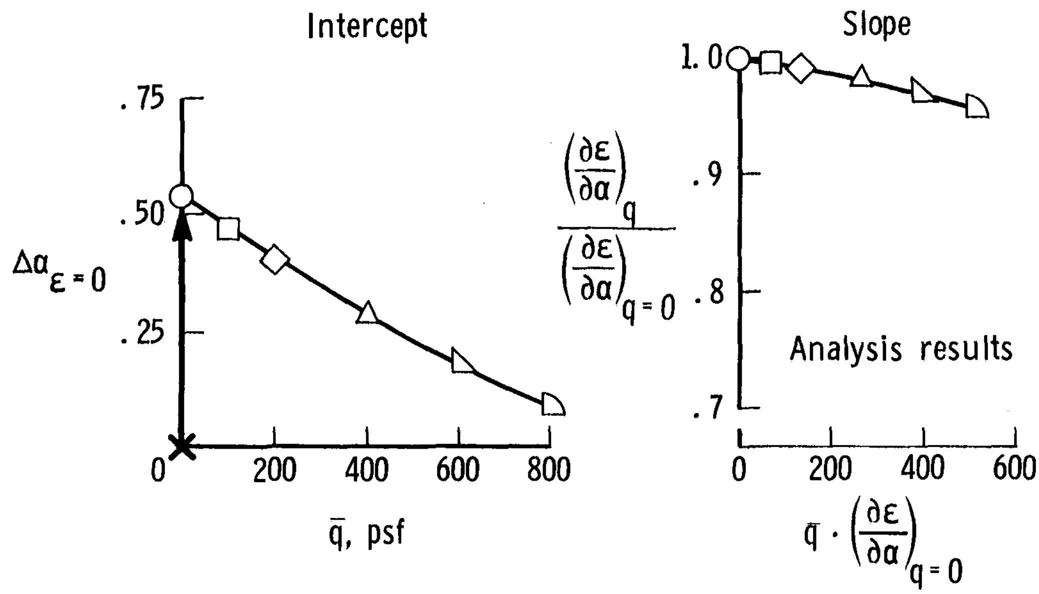
DOWNWASH AT THE HORIZONTAL TAIL

(From wind tunnel data)



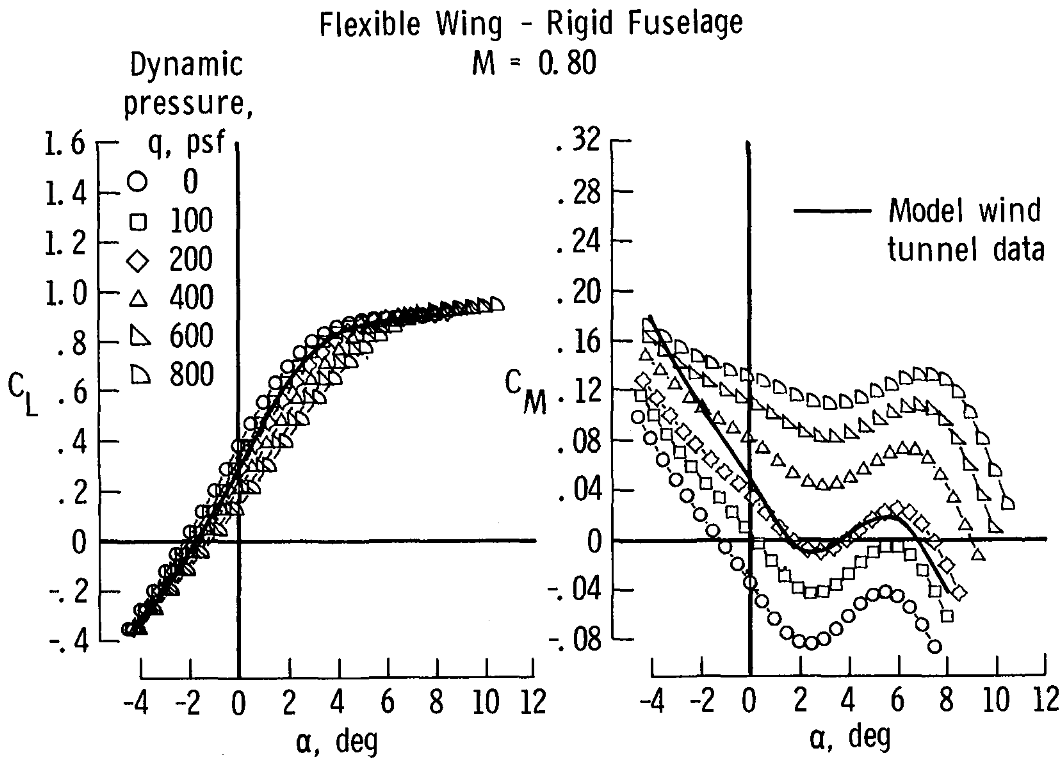
Predictions of wing aeroelastic effects on lift and pitching moment characteristics were also made for the tail-on aircraft configuration. A description of the procedure (reference 4) used to determine these effects is beyond the scope of this presentation but results generated during the investigation are presented in the remaining figures. This figure presents the flow downwash angle at the horizontal tail as derived from measured wind tunnel data. The flow downwash angle at the horizontal tail is also affected by the rigid and flexible wing shape changes. These effects, which will be estimated using the static aeroelastic analysis, primarily result in shifting the curve along the horizontal axis but there are also some moderate slope changes that result from wing flexibility.

CHANGES IN DOWNWASH AT TAIL



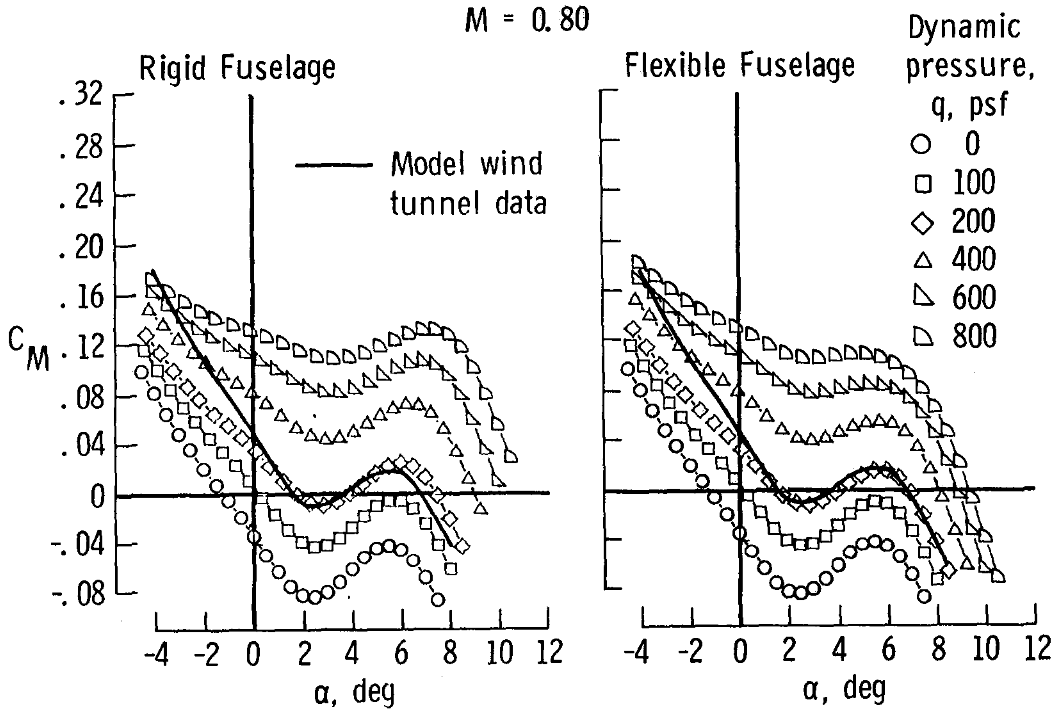
Changing the wing shape also has an effect on the flow downwash angle at the horizontal tail location as shown by the above figure. The changes occur to both the angle of attack at which the downwash angle is zero (intercept) and the rate of change of downwash angle with change in angle of attack (slope). As can be seen from the curve for the intercept the incremental change resulting from going from the rigid cruise shape wing to the rigid fabrication shape wing (shown at dynamic pressure of zero) is larger in the positive direction than the negative increment for the flexible wing at a dynamic pressure of 800 psf. The changes in slope as a function of flight dynamic pressure are very small. Note that the symbols used for the right half of the figure correspond to the dynamic pressure values used on the left half of the figure.

ANALYSIS RESULTS FOR THE TAIL ON AIRCRAFT CONFIGURATION



This figure presents results for the airplane with a flexible wing but a rigid fuselage in the tail on configuration, i.e., where the tail effects have been added as a part of the computation process. Note also that the pitching moment coefficient data is now presented as a function of angle of attack which is the normal method of presentation. The wind tunnel measured data for the rigid cruise shape wing is again included for reference purposes. The data for lift coefficient looks very similar to that for the tail off configuration as the lift on the tail does not significantly change the total lift. The effect of the tail on pitching moment is very significant as can be seen. Note that the reversal in the pitching moment curve between two and six degrees angle of attack smoothes out considerably at the higher dynamic pressure flight conditions.

EFFECT OF FUSELAGE FLEXIBILITY ON PITCHING MOMENT COEFFICIENT



Comparisons of pitching moment coefficients predicted for the airplane with a flexible wing in the tail on configuration are presented in this figure for calculations which both neglected and included fuselage flexibility. Fuselage flexibility affects the angle of attack at the tail and therefore affects the contribution of the tail to the pitching moment coefficient. Although the fuselage flexibility effect is small, it is still noticeable, particularly for the higher angles of attack and dynamic pressures.

CONCLUDING REMARKS

- Wind tunnel measurements of aircraft stability and control characteristics are usually made on a model with a rigid cruise shape wing
- Because of flexibility, the wing for a full scale aircraft may be built to a fabrication shape which accounts for the deformation expected at cruise flight conditions
- Stability and control characteristics for the full scale aircraft should match wind tunnel data at cruise but may be significantly different at off-design flight conditions
- A procedure is presented for using static aeroelastic analysis results to modify measured wind tunnel data to account for going from the cruise to the fabrication shape wing and for aeroelastic effects
- Example results for lift and pitching moment characteristics for a transport type wing are presented

REFERENCES

1. Byrdsong, Thomas A.; and Brooks, Cuyler W., Jr.: Wind-Tunnel Investigation of Longitudinal and Lateral-Directional Stability and Control Characteristics of a 0.237-Scale Model of a Remotely Piloted Research Vehicle With a Thick High-Aspect-Ratio Supercritical Wing, NASA TM-81790, July 1980.

2. Staff of Boeing Wichita Company: Integrated Design of a High Aspect Ratio Research Wing With an Active Control System for Flight Tests on a BQM-34F Drone Vehicle, NASA CR-166108, June 1979.

3. Hink, G. R.; Snow, R. N.; Bhatia, K. G.; Maier, R. E.; Bills, G. R.; Henderson, D. M.; Bailey, D. C.; Dornfield, G. M.; and Dauria, P. V.: A Method For Predicting the Stability and Control Characteristics of an Elastic Airplane. Volume II FLEXSTAB 1.02.00 Users Manual, NASA Contract NAS2-5006, NASA CR-114713, Oct. 1974.

4. Letsinger, G. R.; and Lewis, G. E.: AFTI-F-111 Stability and Control Report, Revision D, The Boeing Company, Document No. D365-10041-1, August 1983.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-87631		

4. Title and Subtitle	5. Report Date
Prediction of Wing Aeroelastic Effects on Aircraft Lift and Pitching Moment Characteristics	November 1985
	6. Performing Organization Code 505-63-21-04
7. Author(s) Clinton V. Eckstrom	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665-5225	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Presented at the Aircraft Flight Loads Technology Transfer Conference, Naval Air Systems Command, Washington, DC, October 16-17, 1985.

16. Abstract

The distribution of flight loads on an aircraft structure determines the lift and pitching moment characteristics of the aircraft. When the load distribution changes due to the aeroelastic response of the structure, the lift and pitching moment characteristics also change. Some estimate of the effect of aeroelasticity on stability and control characteristics, particularly lift and pitching moment, is required for use in aircraft simulation models for evaluation of flight characteristics. This presentation outlines a procedure to incorporate aeroelastic effects into lift and pitching moment data from wind tunnel tests. Results are presented which were obtained from applying this procedure to an aircraft with a very flexible transport-type research wing. The procedure described is generally applicable to all types of aircraft.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Aeroelastic Stability and Control Lift and Pitching Moment	Unclassified - Unlimited Subject Category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	21	A02

For sale by the National Technical Information Service, Springfield, Virginia 22161