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RESEARCH MEMORANDUM

A COMPARISON OF FLIGHT MEASUREMENTS WITH CALCULATIONS OF THE HORIZONTAL-TAIL ROOT BENDING MOMENTS FOR A JET-POWERED BOMBER AIRPLANE

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NATIONAL ADVISORY COMMITTEE
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SUMMARY

A comparison is made between the incremental aerodynamic root bending moments on the horizontal tail of a jet-powered bomber airplane measured during a flight investigation in the Mach number range from 0.40 to 0.73 and the bending moments calculated by using available theoretical methods in conjunction with measured loads, elevator positions, and elevator and stabilizer twists. The measured and calculated bending moments associated with the additional load showed good agreement whereas the bending moments due to deflecting the elevator were not predicted as well by the theory. The procedure followed in the analysis did not allow the zero-lift bending moment resulting from a varying downwash angle over the tail to be determined; however, the results did indicate that the shape of the downwash distribution along the tail span which existed at the start of a maneuver was not altered during the maneuver.

INTRODUCTION

The structural design of horizontal-tail surfaces involves as a primary step the determination of the aerodynamic tail load required to balance the airplane under specified flight conditions. In order to obtain the shears, moments, and torques across the tail span, these aerodynamic loads are usually distributed across the span in accordance with strip theory with account being taken of the tail chords, control angles, and any built-in twist. Effects of tail surface flexibility and spanwise variations in downwash are usually neglected unless these effects are either suspected of being large or are known from wind-tunnel tests.

A recent tail-loads investigation conducted with a jet-powered bomber airplane offered a limited amount of data from which the magnitude of the effects of flexibility and downwash variation could be studied. In the investigation, simultaneous measurements were made in flight of tail root shear and root bending moment, elevator position, elevator twist, and stabilizer twist. Pressure measurements over the tail were not made and a procedure was therefore adopted for calculating the spanwise distribution of air load using measured root shears and bending moments, elevator position, and elevator and stabilizer twists in conjunction with lifting-line theory.

The present report contains a discussion of the procedure used to analyze the flight measurements and to compute the root bending moments for comparison with the flight measurements. The information presented herein supplements the data previously given in references 1 and 2.

SYMBOLS

q dynamic pressure, lb/sq ft

M Mach number

N aerodynamic horizontal-tail shear, lb

B aerodynamic horizontal-tail bending moment, in-lb

δ_e elevator position measured at root of elevator, positive down, deg

θ_e twist of elevator tip with respect to elevator root, positive when trailing edge at tip is down more than trailing edge at root, deg

θ_s twist of stabilizer tip with respect to stabilizer root, nose-up twist is positive, deg

Δ when used in conjunction with any of above symbols indicates increments

APPARATUS AND TESTS

Airplane

The jet-powered bomber airplane (B-45A) has unswept wing and tail surfaces with 12° of geometric dihedral in the horizontal tail. Power is provided by four jet engines, two being housed in a single nacelle on each wing. A three-view drawing of the test airplane is shown in figure 1 and pertinent geometric characteristics are given in table I.

Weight of the airplane during the test flights was approximately 60,000 pounds and the center of gravity was located at approximately 28 percent of the mean aerodynamic chord.

Instrumentation

Standard NACA recording instruments were installed in the airplane to obtain measurements of airspeed, altitude, control positions, linear accelerations at the airplane center of gravity and at the tail, angular velocities, and angular accelerations. Strain-gage bridges were employed to measure shears and bending moments and the output from the strain gages was recorded on an 18-channel oscillograph. A 1/10-second time pulse was used to correlate the records of all recording instruments.

The airspeed head was located on a boom at the tip of the left wing and extended approximately one local chord length ahead of the wing leading edge. The results of a flight calibration of the airspeed system for position error and an analysis of available data for a similar installation indicated a Mach number error of less than ±0.01 throughout the test range.

Structural loads and bending moments on the tail surfaces were measured by electrical strain-gage bridges mounted on the spars near the root. A calibration of the strain-gage installation was performed by the method outlined in reference 3.

Twist of the stabilizer was measured by an installation inside the tail structure consisting of a twist bar, anchored near the root of the tail and extending outboard to the tip, and a specially designed fitting on which was mounted a strain-gage bridge. Twisting of the tail produced bending strains on this fitting which were picked up by the strain-gage bridge and recorded on the 18-channel oscillograph.

Twist of the elevator was considered to be the difference in readings of the elevator root position and the elevator tip position as indicated by control position transmitters located at the root and tip.

Flight Tests

The data used in the present analysis were obtained from measurements made in push-over—pull-up maneuvers made with varying degrees of abruptness and covering the Mach number range from 0.40 to 0.73 at an altitude of approximately 20,000 feet. Additional data were provided from measurements made in wind-up turns during which the increase in normal acceleration was gradual. The turn maneuvers covered approximately the same Mach number range as the abrupt maneuvers but at an altitude closer to 22,500 feet. No appreciable change in airspeed or altitude occurred during any of these maneuvers. At the start of each maneuver the airplane was in the clean condition and in trimmed steady flight.

METHOD OF ANALYSIS

Flight Data

The data are presented as aerodynamic loads and bending moments and were obtained from the strain-gage measurements by the addition of the inertia loads and moments computed by multiplying the dead-weight shear and bending moment of the tail outboard of the strain-gage station (18 inches from the center line of the airplane) by the measured accelerations at the tail. The contribution to the total aerodynamic bending moment of elevator position, elevator and stabilizer twist, and change in tail angle of attack was determined by an essentially graphical procedure. The first step in applying the procedure was the selection of time intervals during a maneuver where a sufficient number of the quantities to be evaluated remained nearly constant so that those which continued to vary could be evaluated by cross-plotting. The measured data were first reduced to incremental form before analysis because the magnitude of the measurements at the start of each maneuver could not be determined. An alternate method of analysis which could have been used and which should yield results comparable to the graphical method would be to assume the form of an expression relating the variable quantities to the measured bending moment and then apply a least-squares treatment to the data in this form to obtain the appropriate constants.

The graphical procedure which was used for analyzing the data will now be described in detail. A typical set of data in incremental form for a push-over—pull-up maneuver made at an altitude of 20,000 feet and a Mach number of 0.71 is shown in figure 2. Similar information from other maneuvers covering the Mach number range from 0.40 to 0.73 at 20,000 feet was used in the analysis.

From an inspection of figure 2 it can be seen that in the interval of time between 0.4 and 1.0 second the elevator is held at a constant angle while the airplane is pitching and therefore changing the tail angle of attack. The change in incremental tail lift and bending moment experienced during this period of time is therefore proportional to this angle-of-attack change at the tail. A center of pressure of the air load distribution associated with an angle-of-attack change on the untwisted tail surface (the additional load) can be determined from the slope of the curve of the bending moment plotted against load at constant elevator angle. Figure 3 shows, for a number of push-over—pull-up maneuvers, the incremental load and bending moment at various times with respect to the load and bending moment when the constant elevator position was first attained, from which the center of pressure of the additional load was obtained.

Referring again to the time history in figure 2 it can be seen that in the time interval from 0 to 0.2 second the elevator was being deflected and this caused a variation of the load and bending-moment increment over the tail surface. In this short period of time, however, the airplane has not yet responded as is evidenced by the constant value of pitching velocity and normal acceleration at the center of gravity. Therefore, the increment in load and bending moment experienced by the tail was primarily a result of the elevator deflection. The increment in tail load and corresponding bending-moment increment were read from time histories at the various Mach numbers covered by the flight tests. A plot of all the data obtained in this manner for the available maneuvers is shown in figure 4. The center of pressure of the tail load due to deflecting the elevator is given by the slope of the solid line through the data.

Because of the flexibility of the elevator structure on the test airplane, the elevator positions that are responsible for the measured loads and bending moments shown in figure 4 are a combination of both the elevator root deflection and the twist along the elevator span. If the twist is assumed to vary linearly along the elevator span, an average elevator position will be obtained which is equal to the elevator root deflection corrected for one-half the twist measured at the elevator tip.

Theoretical Data

A number of theoretical load distributions were computed for the horizontal tail of the test airplane. From these calculations comparisons could be made with the experimental results in order to gain some idea as to the adequacy of existing methods for calculating tail root bending moments. A matrix method similar to that outlined in reference 4 was employed to calculate the additional-aerodynamic-load distribution on the tail surface with the untwisted elevator in the neutral position. Zero-lift aerodynamic-load distributions were then calculated for the tail of the test airplane for the following cases:

(1) Unit elevator deflection (no twist)

(2) Unit linear elevator twist

(3) Unit linear stabilizer twist

The additional-load distribution gives a bending moment which is proportional to the tail load since in theory it has a fixed center of pressure. The zero-lift distributions give bending moments which are proportional to the various twists and the dynamic pressure.

The increment in aerodynamic bending moment can accordingly be expressed as the sum of the individual contributions by the following equation:

$$\Delta B = K_1 \Delta N + K_2 \Delta \delta_e q + K_3 \Delta \theta_e q + K_4 \Delta \theta_s q$$

Integration of the computed load distributions resulted in the following values for the numerical constants in the above equation:

For the additional load, based on a lift-curve slope $dc_l/d\alpha$ of 0.11 per radian . . . . $K_1 = 101.4$
For unit elevator deflection in degrees and an assumed elevator effectiveness $d\alpha/d\delta_e$ of 0.66 . . . . $K_2 = -30$
For linear twist of the elevator in degrees . . . . $K_3 = 45$
For linear twist of the stabilizer in degrees . . . . $K_4 = 124$

The numerical constants tabulated above have been adjusted to refer to the strain-gage station so that direct comparisons could be made with the bending moments measured at that station. The values of the lift-curve slope and elevator effectiveness indicated above are the theoretical two-dimensional values.

DISCUSSION

Abrupt Maneuvers

The additional-load center of pressure measured in flight and shown in figure 3 was approximately 100 inches outboard of the strain-gage station for Mach numbers up to 0.71. The center-of-pressure location for the additional load as obtained from the lifting-line-theory calculations, 101.4 inches outboard of the strain-gage station, is also shown in figure 3. Good agreement is seen to exist between the experimental and predicted centers of pressure for the low and medium Mach number runs. However, it may also be noted from observation of figure 3 for $M = 0.73$ that the measured center of load is slightly farther outboard than indicated by the theory.

It is to be expected that the elevator, which on the test airplane is not a full-span control but extends over approximately 75 percent of the horizontal-tail span, will cause a shift in the overall center of load as well as in the magnitude of the load when deflected. Furthermore, the elevator structure is relatively flexible and under the influence of air loads will be distorted along its span and will assume an effective position which is different from the root position. The center of pressure of the load due to elevator deflection and twist as determined from the measured incremental bending moments and corresponding incremental shears associated with deflecting the elevator is shown in figure 4 to be 80 inches outboard of the strain-gage station or approximately 20 inches inboard of the center of pressure of the additional load. Also shown in figure 4 for comparison is the calculated center of pressure of the load due to deflecting the elevator. The calculated values, based on the theoretical span load distributions and the measured elevator positions and twists, give a center of pressure of 92 inches outboard of the strain-gage station. Thus, the calculations predict an inboard center-of-pressure shift of approximately 8 inches due to deflecting the elevator from the neutral position whereas the flight measurements indicated an inboard shift of approximately 20 inches. It will be remembered, however, that the assumption of linear elevator twist was used in the calculations because the angle of twist was measured only at the tip of the elevator. If the twist were considered to vary across the elevator span in a different manner from the assumed-linear-twist distribution, the calculated center-of-pressure shift due to elevator twist could be brought closer into agreement with the measured center of pressure.

As an illustration of the agreement between the measurements and calculations with regard to root bending moments, the measured incremental bending moments which were shown in figure 2 are repeated in figure 5 together with the bending moments calculated neglecting elevator position and twist and stabilizer twist and merely multiplying the measured shear by the additional-load center of pressure as computed from lifting-line theory. The difference between the measured and computed bending moments shown in figure 5, except for the contribution due to stabilizer twist which was small in magnitude, are the bending moments due to deflecting the elevator. These differences in bending moment plotted against the increment in average elevator position are indicated by the solid line in figure 6. When calculations for the bending moments due to elevator position and twist and stabilizer twist were made and added to the bending moments caused by the additional load, the difference between the measured and calculated bending moments was reduced as shown by the dashed line in figure 6.

Gradual Turn Maneuvers

The gradual wind-up turns performed during the investigation differ from the push-over—pull-ups in that they are a quasi-static maneuver with negligible pitching acceleration and have an associated effective elevator position of just that needed to produce the tail load required for longitudinal balance of the airplane. Although the method of analysis used for the abrupt maneuvers cannot be extended to the gradual turn maneuvers, it will be shown that the results previously obtained from the pull-ups will predict the measured bending moments in the gradual maneuvers. Figure 7 shows a comparison of the bending moments measured in a gradual turn maneuver made at $M = 0.71$ with the bending moments obtained by making use of the coefficient for linear stabilizer twist from lifting-line theory, the bending-moment increment due to average elevator angle found from analysis of the abrupt maneuvers, and the experimentally determined center of pressure of the additional load. The appropriate factors when multiplied by the average elevator positions, stabilizer twist, and root shear measured in the gradual turns result in the bending moments shown by the solid line in figure 7. The dashed line in figure 7 represents the bending moment associated only with the additional load, neglecting the effects of elevator position and twist and stabilizer twist. The comparisons shown in this figure for the computed and measured bending moments are typical of the results found for the gradual maneuvers performed at other Mach numbers.

Effects of Downwash

Because only the incremental shears and bending moments were accurately measured, the zero-lift bending moment resulting from varying downwash over the tail semispan could not be found, and the analysis was limited to the determination of the effect on the bending moments of a change in the variation of spanwise downwash. The agreement which has already been shown to exist between experimental and computed incremental bending moments was effected without consideration being given to a contribution from a downwash variation across the tail semispan. In view of the consistency of these results for both the abrupt and gradual maneuvers over the range of Mach numbers covered, indications are that the shape of the downwash distribution along the tail semispan does not change during these maneuvers a sufficient amount to influence the bending-moment results.

Reference to figure 1 shows that the tail of the test airplane is well above the wing wake at low angles of attack and although the tail extends outboard beyond the location of the jet engines in the wings, the dihedral places it above the wake from the engines. For this configuration then, and considering the angle-of-attack range covered in normal flight altitudes, the downwash effects on the bending moment would be expected to be minimized.

CONCLUDING REMARKS

The results of an analysis of the horizontal-tail root aerodynamic bending moments for a jet-powered bomber airplane measured in flight indicate that the additional-load center of pressure can be predicted quite accurately by available methods at Mach numbers from 0.40 to 0.71. The measured center of pressure at $M = 0.73$, however, was slightly outboard of the calculated center of pressure.

For the test airplane, which has a partial-span elevator, there was a center-of-pressure shift due to deflecting the elevator. This change in the center of load was due to both elevator position and elevator twist. The bending moments calculated from the theoretical component load distributions and the measured elevator position and twist agreed only qualitatively with the measured bending moments.

The bending-moment coefficients which were determined from the pushover—pull-up maneuvers when multiplied by the shear, the elevator position and twist, and the stabilizer twist measured in gradual turn maneuvers were found to predict accurately the bending moments measured in the gradual maneuvers.

The results of the analysis indicated that there were no effects on the root bending moments of a change in the downwash distribution across the semispan of the tail during any of the maneuvers considered. This conclusion might not be applicable to configurations which differ radically from that of the test airplane, in which case it would be desirable to have experimental downwash results for the particular model under consideration.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., April 27, 1954.

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2. Cooney, T. V.: The Vertical-Tail Loads Measured During a Flight Investigation on a Jet-Powered Bomber Airplane. NACA RM L52G21, 1952.

3. Skopinski, T. H., Aiken, William S., Jr., and Huston, Wilber B.: Calibration of Strain-Gage Installations in Aircraft Structures for the Measurements of Flight Loads. NACA TN 2993, 1953.

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TABLE I

GEOMETRIC CHARACTERISTICS OF THE AIRPLANE

Wing:	
Airfoil section at root	NACA 66_2-215
Airfoil section at tip	NACA 66_1-212
Area, sq ft	1175.2
Span, in.	1068
Chord at root, in.	225
Chord at tip, in.	93
Dihedral, deg	1
Incidence at root, deg	3
Incidence at tip, deg	1/2
Mean aerodynamic chord, in.	168
Vertical tail:	
Airfoil section at root	NACA 65_1-012
Airfoil section at tip	NACA 65-010
Area of portion extending above horizontal tail, sq ft	108
Rudder and tab area, sq ft	29
Fin offset, deg	0
Chord at attachment to horizontal tail, in.	145
Chord at tip, in.	64
Span extending above horizontal tail, in.	150
Horizontal tail:	
Airfoil section at root	NACA 65_1-012
Airfoil section at tip	NACA 65-010
Total area, sq ft	288
Elevator and tab area, sq ft	68
Span, in.	526
Chord at root, in.	123
Chord at tip, in.	36
Dihedral, deg	12
Aspect ratio	6.7
Taper ratio	0.29

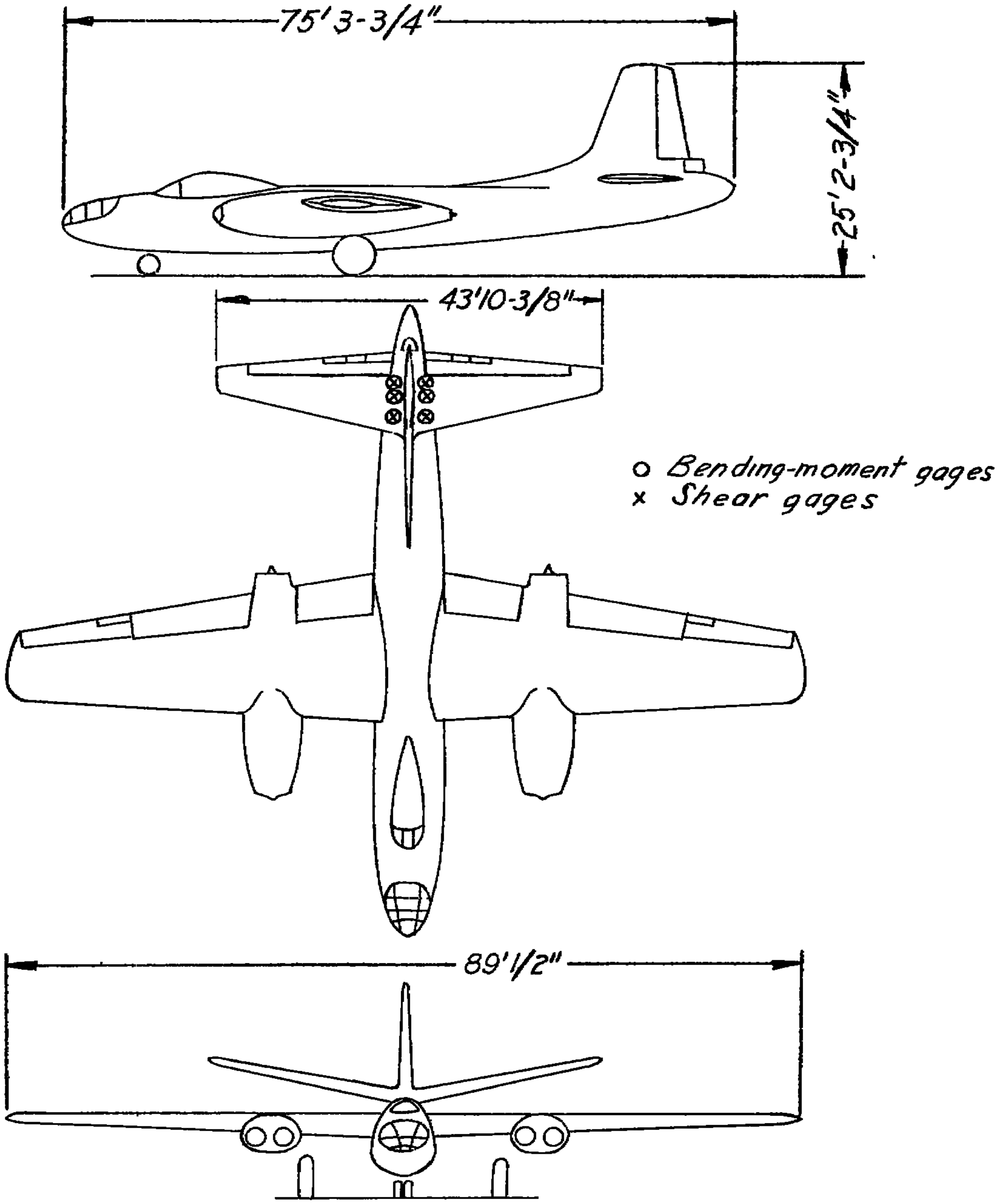

Figure 1.- Three-view drawing of test airplane.

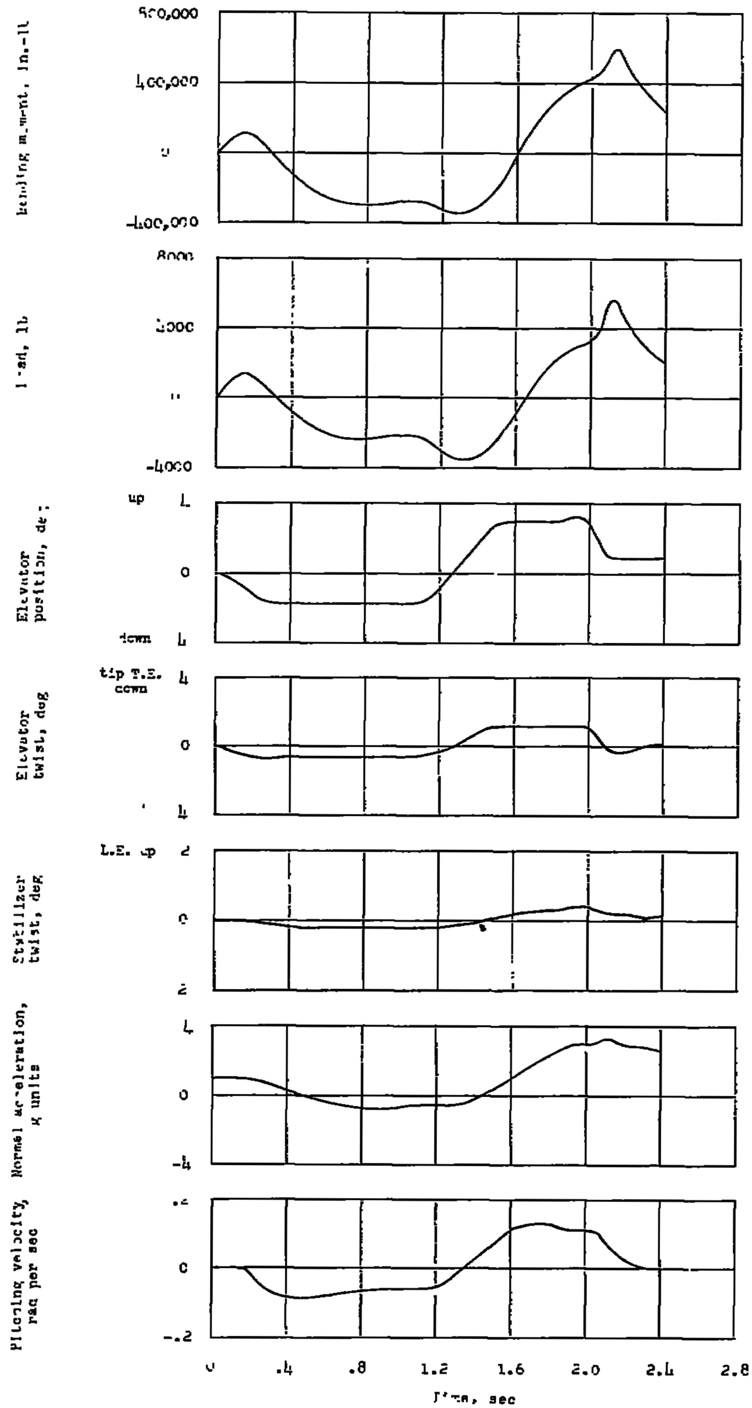

Figure 2.- Variation with time of the incremental values of various quantities measured during a push-over—pull-up maneuver made at 20,000 feet and M = 0.71.

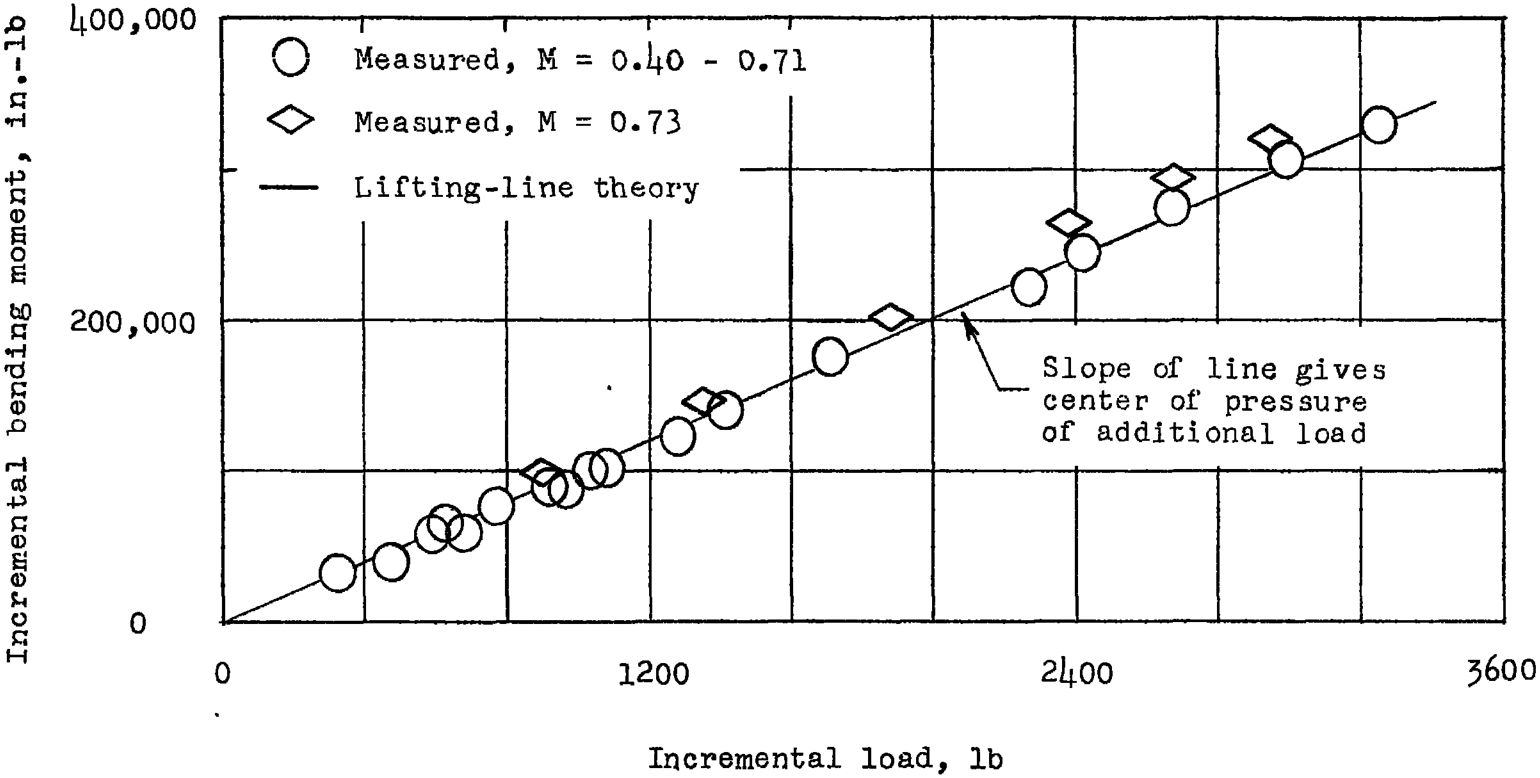

Figure 3.- Incremental load and corresponding incremental bending moment associated with change in tail angle of attack and constant elevator position. Data from various runs at 20,000 feet covering Mach number range from 0.40 to 0.73.

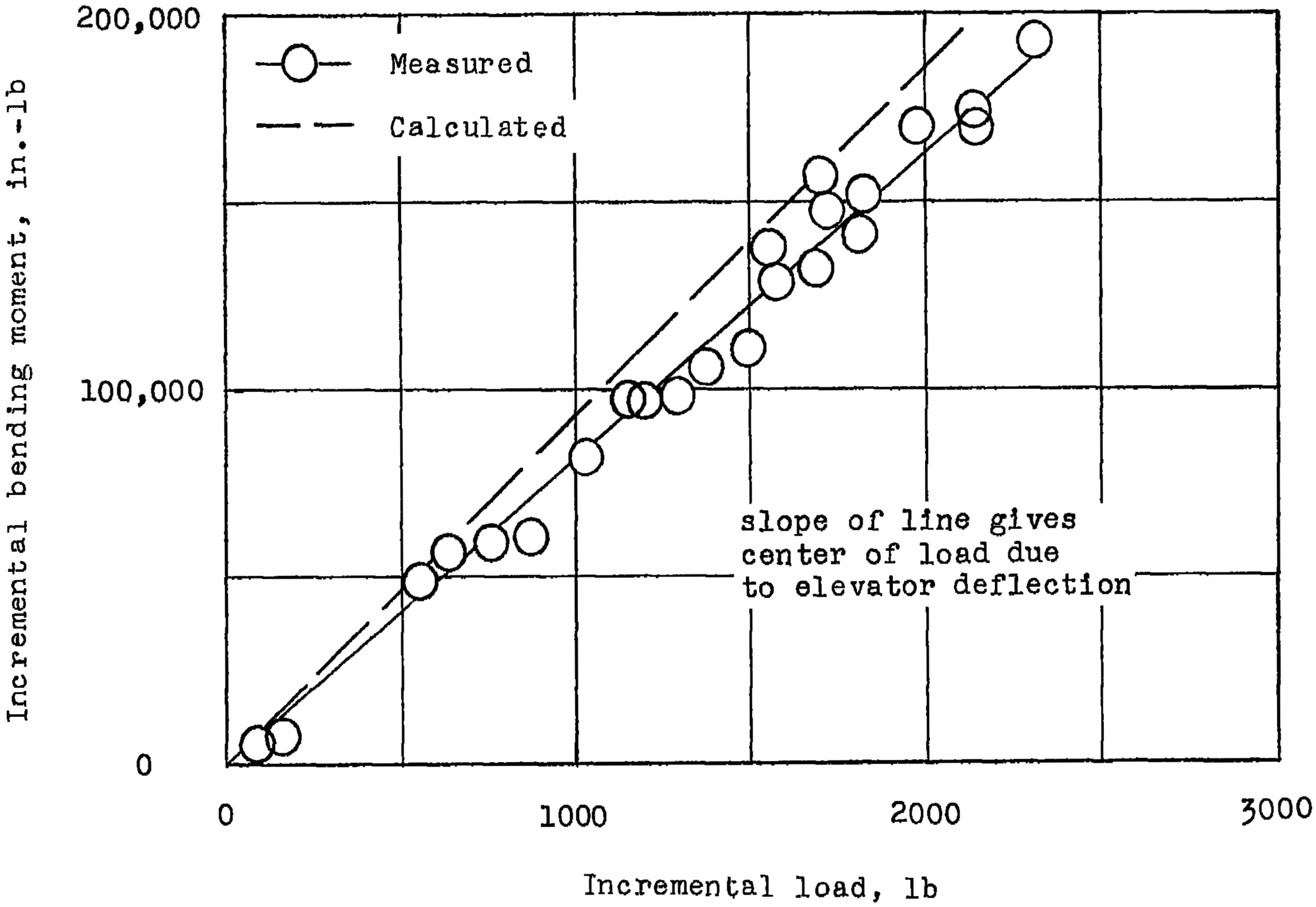

Figure 4.- Incremental load and corresponding incremental bending moment associated with deflecting the elevator. Data from various runs at 20,000 feet covering Mach number range from 0.40 to 0.73.

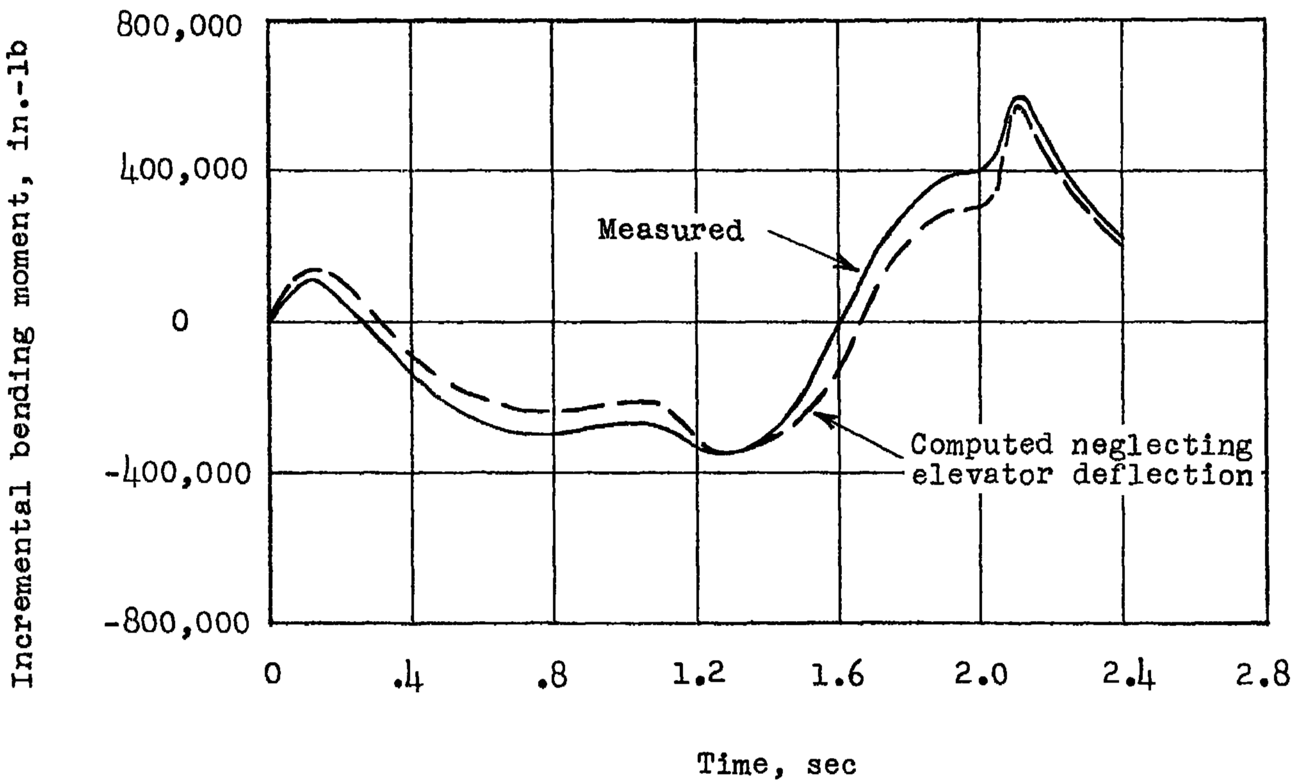

Figure 5.- Time history of measured incremental bending moment for a push-over—pull-up maneuver showing the effect of neglecting the elevator position and computing the bending moment from the additional-load center of pressure only.

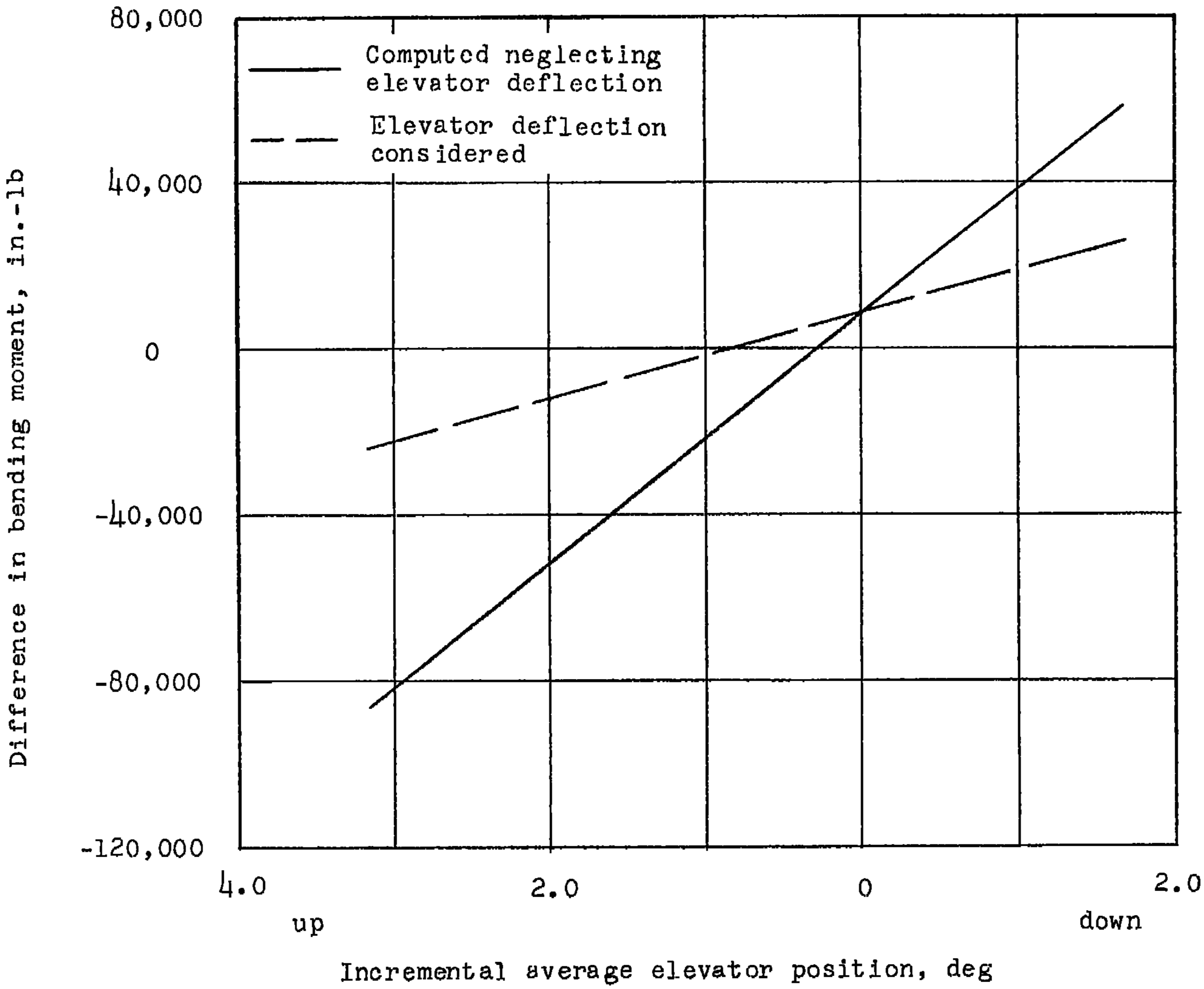

Figure 6.- Variation with incremental average elevator position of the difference between the measured and calculated bending moments.

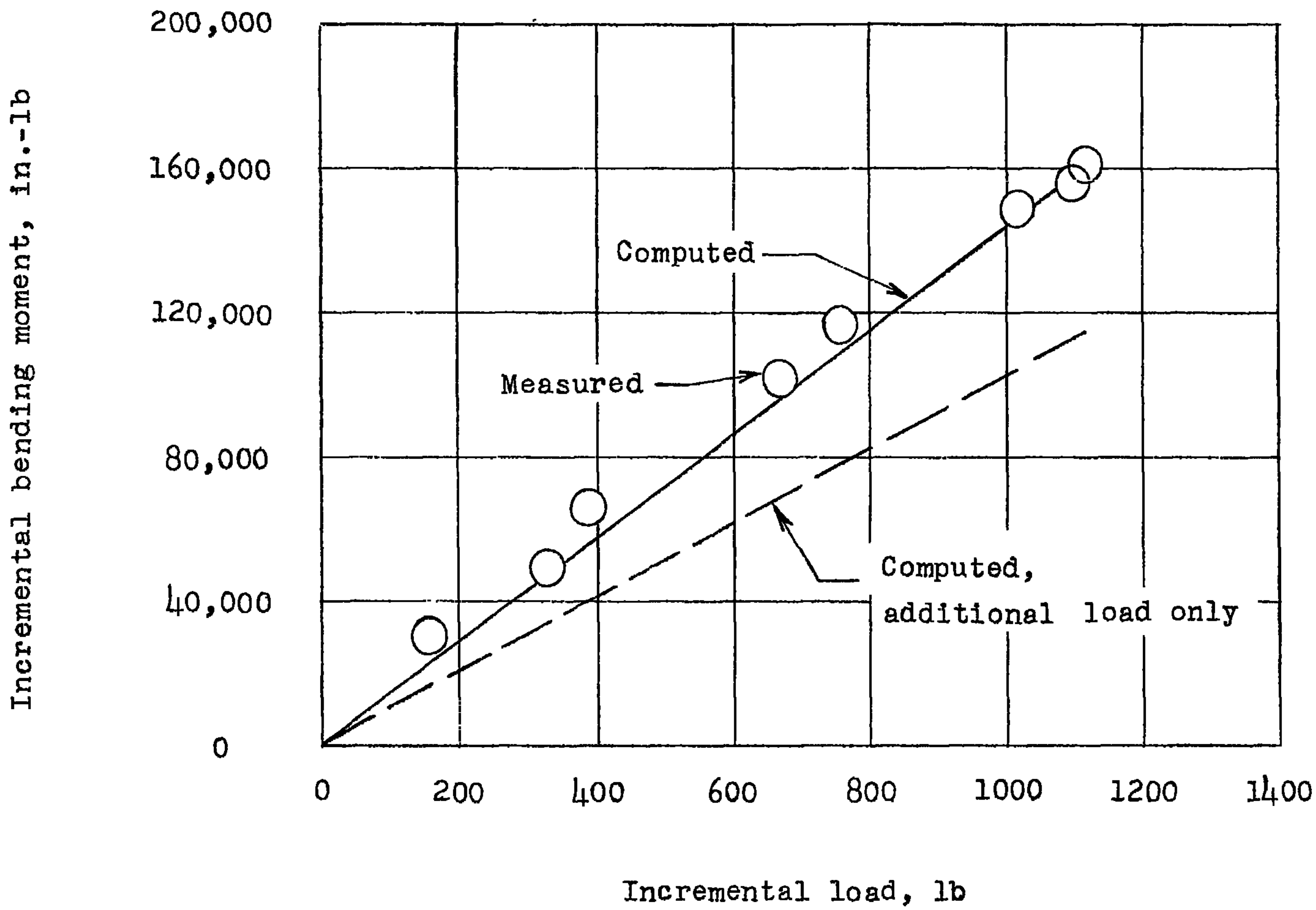

Figure 7.- Comparison of the measured incremental bending moment in a gradual turn maneuver made at 22,500 feet and $M = 0.71$ with the incremental bending moment computed using information obtained from analysis of push-over—pull-up maneuvers.

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