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A THEORETICAL STUDY OF THE EFFECT OF PIVOT LOCATION ON THE AERODYNAMIC-CENTER MOVEMENT OF VARIABLE-SWEEP WINGS IN INCOMPRESSIBLE FLOW

by John E. Lamar

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SUMMARY

Theoretical studies of aerodynamic-center movement have been conducted for a series of variable-sweep wings in incompressible flow, which have unbroken leading and trailing edges and a skewed tip in the high-sweep positions. Some comparisons of theoretical results with experimental results are made to validate the theoretical method. The low-sweep outer panels and corresponding pivot locations, selected to be used with each high-sweep wing having the same tip skew angle, are determined from two parameters: the ratio of low- to high-sweep wing span and the fraction of high-sweep normal chord at which the pivot is specified to be located.

These studies indicate that for a given low sweep of the outer panel, the spanwise location of the pivot required to give a zero aerodynamic-center movement in going from high sweep to low sweep of the outer panel seems to be essentially linearly related to the ratio of low- to high-sweep wing span in such a way that as the value of the span increase parameter becomes larger the pivot must move outboard. Furthermore, the lower the sweep of the outer panel, the farther outboard the pivot location must be.

INTRODUCTION

One of the major problems facing the designer of variable-sweep-wing airplanes is the high trim drag and poor maneuverability that may occur with increasing wing sweep due to excessive stability being generated. This excessive stability is associated with a rearward movement of the aerodynamic center. Early variable-sweep-wing airplanes incorporated wing translation in combination with wing sweep in order to minimize the aerodynamic-center variation and, consequently, the resulting problems. Subsequent research (for example, refs. 1 and 2) indicated that by placing the pivot outboard of the plane of symmetry and providing a proper size relationship between the resulting fixed and movable wing panels, the aerodynamic-center shift could be greatly reduced without the use of translation. Many configurations based on this concept have been studied at the Langley Research Center and some of the configurations are described in references 3 and 4. Recently, the subsonic lifting surface theory of Multhopp with certain modifications has been programed for a high-speed computer to allow rapid calculations of the aerodynamic characteristics of composite planforms (ref. 5) and has been extended to cover variable-sweep wings. An example of the use of the program for variable-sweep wings is presented in reference 6.

The purpose of the present paper is to illustrate the way in which the lifting surface computer program can be used to select a pivot point which minimizes the aerodynamic-center shift and to present design charts for several selected high-speed planforms.

SYMBOLS

A	aspect ratio of high-sweep wing at $\Lambda = 72^{\circ}$, b^2/S
b	span
C_L	lift coefficient
C_m	pitching-moment coefficient about $\bar{c}/4$
ΔC_p	incremental pressure coefficient due to angle of attack, $\dfrac{\text{Pressure}_{\text{upper surface}} - \text{Pressure}_{\text{lower surface}}}{\text{Free-stream dynamic pressure}}$
$\bar{c}$	mean geometric chord of reference wing (see fig. 1)
c_r	root chord at $\Lambda = 72^{\circ}$ (see fig. 1)
c_t	tip chord at $\Lambda = 20^{\circ}$ (see fig. 1)
M	Mach number
R_b	span increase parameter, $\dfrac{b_{\text{low sweep}}}{b_{\Lambda=72^{\circ}}}$
S	total area of high-sweep wing
T	fraction of chord normal to high-sweep leading edge
T_p	fraction of chord normal to high-sweep leading edge at which pivot is located

x longitudinal distance from wing apex (positive aft)

x_{ac} chordwise distance, in fractions of $\bar{c}$, from leading edge of $\bar{c}$ to aerodynamic center (positive aft), $-\frac{\partial C_m}{\partial C_L} + \frac{1}{4}$ (see fig. 1)

Δx_{ac} aerodynamic-center movement with change in wing sweep from $\Lambda = 72^o$ to $\Lambda = 26^o$ at $M = 0$

y_p spanwise distance from plane of symmetry to pivot

Λ leading-edge sweep angle of wing outer panel, deg

λ taper ratio, c_t/c_r

METHOD OF ANALYSIS

The theoretical approach employed for the prediction of the subsonic aerodynamic center of variable-sweep wings is basically that taken by Multhopp in reference 7. However, some improvements and extensions have been made to the method as discussed in reference 5, and this improved version (in electronic computer program form) is used in making the present calculations. The computer program has been applied to wings with variable sweep and the results were compared with experimental data in references 5 and 6; reasonable agreement was found.

Additional comparisons of theory with experiment are presented herein to give further confirmation to this approach. These present comparisons involve two variable-sweep wings (fig. 2) which exemplify a wide variation in spanwise pivot location, that is, from the plane of symmetry (refs. 8 and 9) to a more outboard location (ref. 10). The experimental aerodynamic-center values for the wing with the inboard pivot were obtained with little effort, but those for the wing with the outboard pivot were difficult to determine from the original data figure; therefore, an enlargement of the figure had to be used. However, even with the enlargement, the aerodynamic center for the wing in the 75^o sweep position had to be obtained by averaging the slope of the C_m—C_L curve over the lift range from -0.15 to 0.15 because of the nonlinearity in the data around zero lift. If the lift range had been smaller, the aerodynamic center found by experiment would have been in even better agreement with that obtained by theory.

Comparison of the theoretical and experimental data indicates that the theory does predict reasonably well the aerodynamic center at the different sweep angles for both pivot locations. (The experimental data for the wing with the pivot at the plane of symmetry included the effects of a body for which the theory did not account.) The comparison illustrates both the importance of pivot location and that the theoretical method is sufficiently accurate to use in selecting an appropriate pivot location and planform during preliminary design of a variable-sweep wing.

All the theoretical computations were made with eight chordwise control points at each of 23 spanwise stations and at a Mach number of zero. This pattern of control points is adequate to give acceptable values of aerodynamic center for the planforms examined, although reference 5 states that the control-point pattern should depend upon the aspect ratio of the individual configuration (which in this study changes with wing sweep) to be considered. However, for the class of wings investigated herein, the aforementioned combination of control points give, in general, good results and eliminate the time needed to determine the required combination of control points for each configuration. Inasmuch as the intent of this report is to present the results of a study of the subsonic aerodynamic-center movement with sweep for various pivot locations, a Mach number of zero was selected because this Mach number can be used as well as any other subsonic Mach number. Using any other subsonic Mach number could lead to some different individual values of Δx_{ac} but the trend of the movements would be the same.

With the theoretical approach to be used for the prediction of the aerodynamic center established as being suitable and some computer parameters selected, a method was sought by which an arbitrary pivot location could be specified from a minimum of pertinent geometric parameters. A geometric analysis given in the Supplement to reference 5 has indicated that only three parameters are needed for determining a pivot location and these result from the design considerations shown in figures 1 and 3. The parameters are as follows:

(1) The change in the outer-panel wing sweep angle from a high-sweep position, where the leading and trailing edges are unbroken and the tip is skewed, to a low-sweep position, where the tip is streamwise (This angle corresponds to the tip skew angle and it is used to specify the sweep range in ref. 5.)

(2) The increase in span that the wing in the low-sweep streamwise-tip position is to have relative to the high-sweep position

(3) The fore and aft movement of the wing outer panel relative to the fixed portion of the wing due to decreasing the outer-panel sweep

Since all the wings studied herein have the same change in outer-panel sweep angle, only the other two parameters are discussed.

The increase in span is specified as a ratio of low- to high-sweep wing span and is therefore called herein the span increase parameter R_b. This parameter determines the line of all pivot points (locus) that give the same amount of span increase for the low-sweep streamwise-tip position and the identical high-sweep planform. The longitudinal position of the low-sweep outer panel is fixed by use of the parameter T, which represents the fraction of the chord normal to the high-sweep leading edge where the pivot location is desired. At the intersection of the locus of all pivot points which gives a certain desired span increase and the line of points having the specified fraction of normal chord T, the pivot location is found.

This procedure for determining a pivot location has been programed (Langley computer program A1591) and is given in the Supplement to reference 5 for high-sweep wings with unbroken leading and trailing edges, skewed tips, and no inboard chord-extensions. (See fig. 3 for an example.)

The reference wing used for each wing series in the theoretical studies of wing pivot location is the outer panel extended to the root when $\Lambda = 20^{o}$ and the fraction of normal chord T is 0.25. (See fig. 1.)

RESULTS AND DISCUSSION

Since the high-sweep planform is the only common planform in each wing series, the results are discussed in terms of decreasing rather than increasing sweep. Some typical aerodynamic-center movements which result from reducing the sweep of the outer panel of the high-sweep wing by using different pivot locations are presented in figure 4 for a wing with an aspect ratio of 2, a taper ratio of 0.10, and, like all the other wings studied herein, a high-sweep leading-edge angle of 72^{o} (fig. 4(a)). These pivot locations selected by the two parameters give low-sweep wings that look like cranked tips for the lower values of R_b and the more conventional variable-sweep wings at the higher values of R_b.

Figure 4(b) presents the aerodynamic-center variation with sweep for various values of the span increase parameter R_b and of the fraction of normal chord T_p. From the figure it can be seen that for the high values of span increase parameter, which are of primary interest for variable-sweep-wing airplanes, the undesirable forward shift of aerodynamic center with decreasing sweep is greatest at low sweep angles. Because of this characteristic, it may be desirable to limit the forward wing position to a higher sweep angle. Therefore, in the remainder of the data figures a value of R_b based on $\Lambda = 26^{o}$ rather than on $\Lambda = 20^{o}$ is used. However, the pivot locations already determined which give a streamwise wing tip at $\Lambda = 20^{o}$ are retained for application.

The parameter $\dfrac{y_p}{(b/2)_{\Lambda=72^{o}}}$ also presented in figure 4(c) is the fractional distance from the plane of symmetry to the pivot required to give a streamwise tip at $\Lambda = 20^{o}$ rather than at $\Lambda = 26^{o}$ used in the investigation. Therefore, the values for this parameter obtained by cross-plotting are slightly in error because one of the constraints employed in determining these values (i.e., the wing tip being streamwise) is no longer valid.

Similar graphs of aerodynamic-center movement with sweep and pivot location are presented in figures 5 to 8 for high-sweep wing planforms of aspect ratios 1.5, 2.5, and 3.0 at a taper ratio of 0.10 and of aspect ratio 2.0 at a taper ratio of 0.25. For all planforms, increasing the value of R_b from 1 initially produces a rearward movement of the aerodynamic center in going from the high-sweep to the low-sweep position. This movement is followed, for all planforms, by an eventual forward location of the aerodynamic center in the low-sweep position which is caused by the longitudinal load adjustment that occurs when the outer panel is in a sweptforward position. (See fig. 9.) The outer panel in the low wing-sweep ($\Lambda = 30^{\circ}$) position produces more of the total loading for a given lift coefficient than does the same panel in the high-sweep ($\Lambda = 72^{\circ}$) position simply due to the larger lift-curve slope that exists for wings with low sweep. Therefore, when the value of R_b is low and the longitudinal placement of the outer panel at low sweep angles does not differ significantly from the high-sweep position, it is not surprising that the aerodynamic center in low sweep is behind the aerodynamic center in high sweep.

As more and more of the wing becomes a part of the outer panel (at the higher value of R_b), more of the total loading is consequently developed on the low-sweep panel. Also, the longitudinal placement of the outer panel in the low-sweep position on the fixed wing no longer approximates the high-sweep position but will be ahead of it. The combination of these two features of variable-sweep wings now results in the aerodynamic center in low sweep being ahead of the aerodynamic center in high sweep.

The importance of the parameter T_p can be partially visualized at a constant value of the R_b for any of the wings in figures 4 to 8 by realizing that the longitudinal position of the outer panel relative to the fixed portion of the wing varies significantly with T_p. In addition to this direct physical effect, the change in the division of lift between the fixed and rotating panels with varying sweep is also a function of T_p.

The consequences of these two effects of pivot location T_p are evident in figure 4(b). The direct geometric effect can be seen in that, for any given sweep angle and value of R_b, the aerodynamic center always moves forward as the pivot is moved inboard (increasing values of T_p). For small values of R_b (1.2, for example), the division of lift between the fixed and rotating panels causes, in general, a rearward movement of the aerodynamic center as the sweep angle of the outer panel is decreased. However, for large values of R_b (2.0, for example), the trend is generally toward a forward movement of the aerodynamic center with decreasing sweep of the outer panel below $\Lambda = 40^{\circ}$. Pivot locations which result in small values of R_b might be of interest as a longitudinal control to offset the rearward movement of the aerodynamic center with

Mach number for fixed wings (ref. 6), whereas pivot locations which result in large values of R_b are more typical of variable-sweep-wing airplanes.

The geometric conditions which cause a zero aerodynamic-center movement in going from high sweep to low sweep are plotted in figure 10. From figure 10(b), it can be seen that for a given low-sweep angle and high-sweep aspect ratio, the pivot location is required to move outboard in an essentially linear manner with increasing values of the span increase parameter R_b in order that $\Delta x_{ac} = 0$. As an example, for a variable-sweep wing having a high-sweep aspect ratio of 2 and a low sweep angle of 26°, the pivot is located at 31.5 percent of the high-sweep semispan when $R_b = 1.575$ and at 40 percent of the high-sweep semispan when $R_b = 1.8$. Figure 10(b) shows that the y_p movement between the two R_b values is well approximated by a straight line.

A more outboard pivot location would be required in going from a zero aerodynamic-center movement at $\Lambda = 35^{\circ}$ to a zero movement at $\Lambda = 20^{\circ}$ with the same high-sweep wing and span increase. This characteristic results from the condition that if the same pivot location were maintained which gave the zero aerodynamic-center movement at $\Lambda = 35^{\circ}$ when the sweep was decreased to $\Lambda = 20^{\circ}$, the aerodynamic center would probably move ahead of the high-sweep aerodynamic center. Therefore, in order that the aerodynamic-center movement could be brought back to zero, the pivot is required to be more outboard so that the longitidunal placement of the outer wing panel on the fixed wing is not as far forward.

The effect of increasing the taper ratio from 0.10 to 0.25 at a constant high-sweep aspect ratio of 2 (fig. 10(a)) is to require a larger value of R_b for any given value of T_p. When this is translated into spanwise location of the pivot (using figs. 10(a) and 8(a)), the taper-ratio effect is determined to be a slight shift in y_p of not more than 3 percent of the semispan or about the difference between the straight-line approximation of the data and the data scatter (fig. 10(b)) for the different high-sweep aspect-ratio planforms at $\Lambda = 26^{\circ}$.

CONCLUSIONS

From results of theoretical aerodynamic-center-movement studies conducted for a series of high-sweep planforms in incompressible flow, the following conclusions were reached:

(1) Proper selection of the pivot location for a variable-sweep wing can result in a zero aerodynamic-center movement between the high- and low-sweep positions. For example, a variable-sweep wing having a high-sweep aspect ratio of 2 with a low sweep angle of 26° and a low-sweep span 1.8 times the high-sweep span should have the pivot at approximately 40 percent of the high-sweep semispan.

(2) The spanwise pivot location required to give the zero aerodynamic-center movement between the high- and low-sweep positions is essentially linearly related to the ratio of low- to high-sweep wing spans and must be farther outboard as the span ratio gets larger or the design low sweep angle is decreased.

(3) The effect of increasing the taper ratio from 0.10 to 0.25 on the spanwise location of the pivot for zero aerodynamic-center movement between the high- and low-sweep positions is not more than 3 percent of the high-sweep semispan or about the difference between the straight-line approximation of the data and the data scatter for the different high-sweep aspect-ratio planforms at a sweep angle of 26°.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., March 15, 1968,
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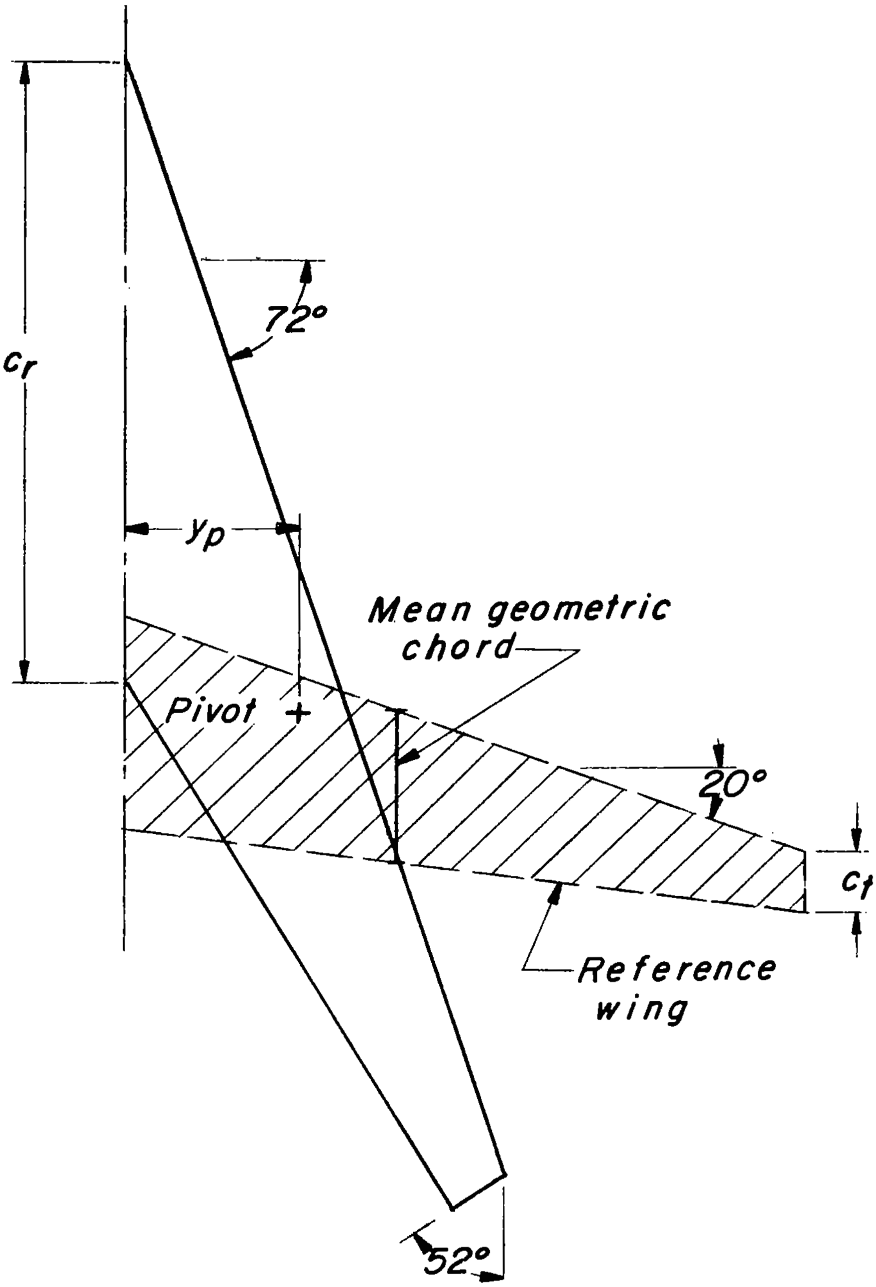


Figure 1.- Typical planform showing the reference wing and chord which are defined for the pivot at $T_p = 0.25$.

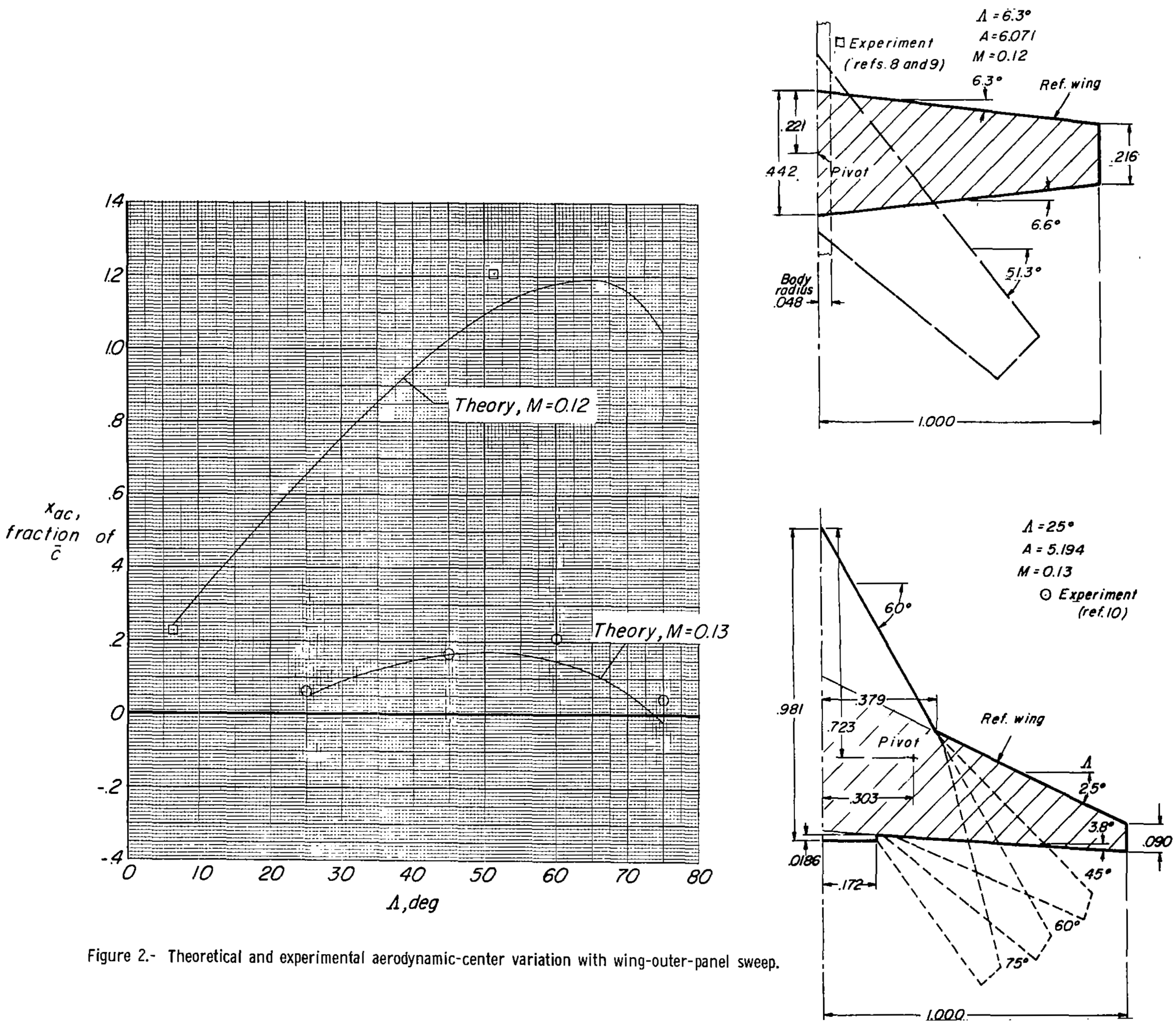


Figure 2.- Theoretical and experimental aerodynamic-center variation with wing-outer-panel sweep.

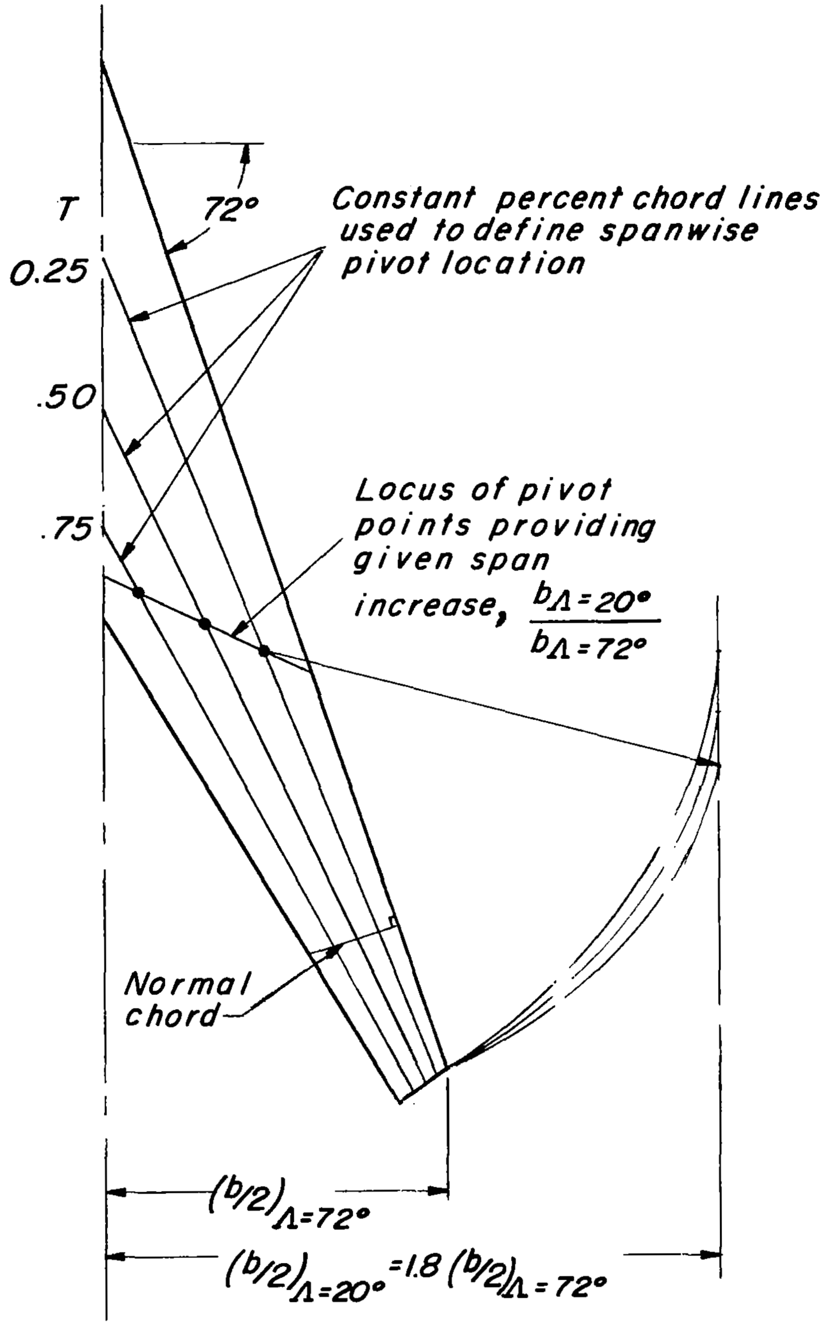
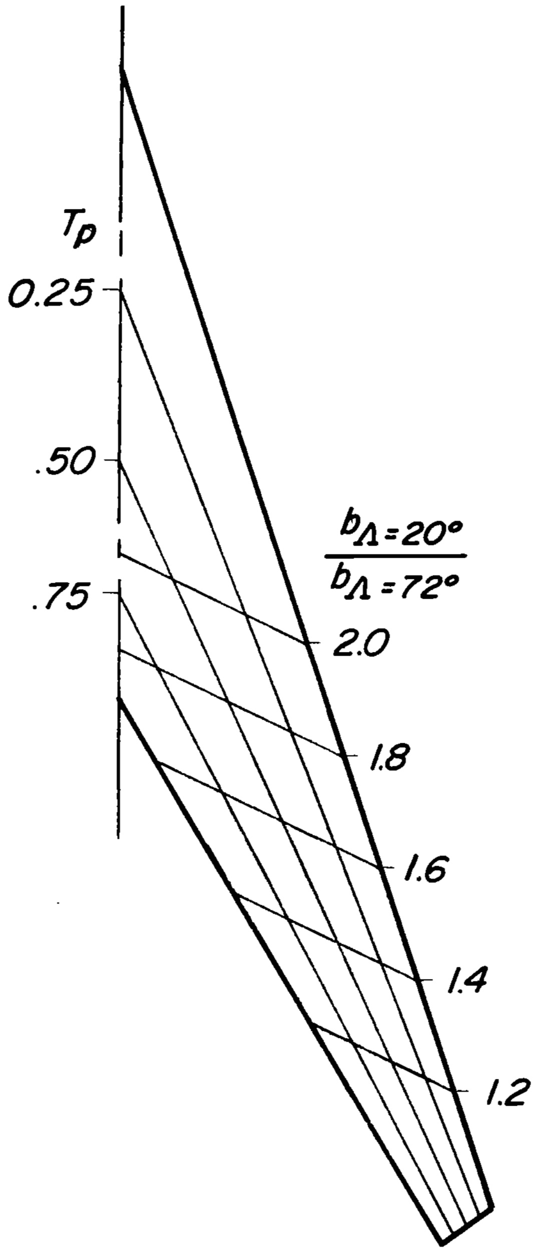
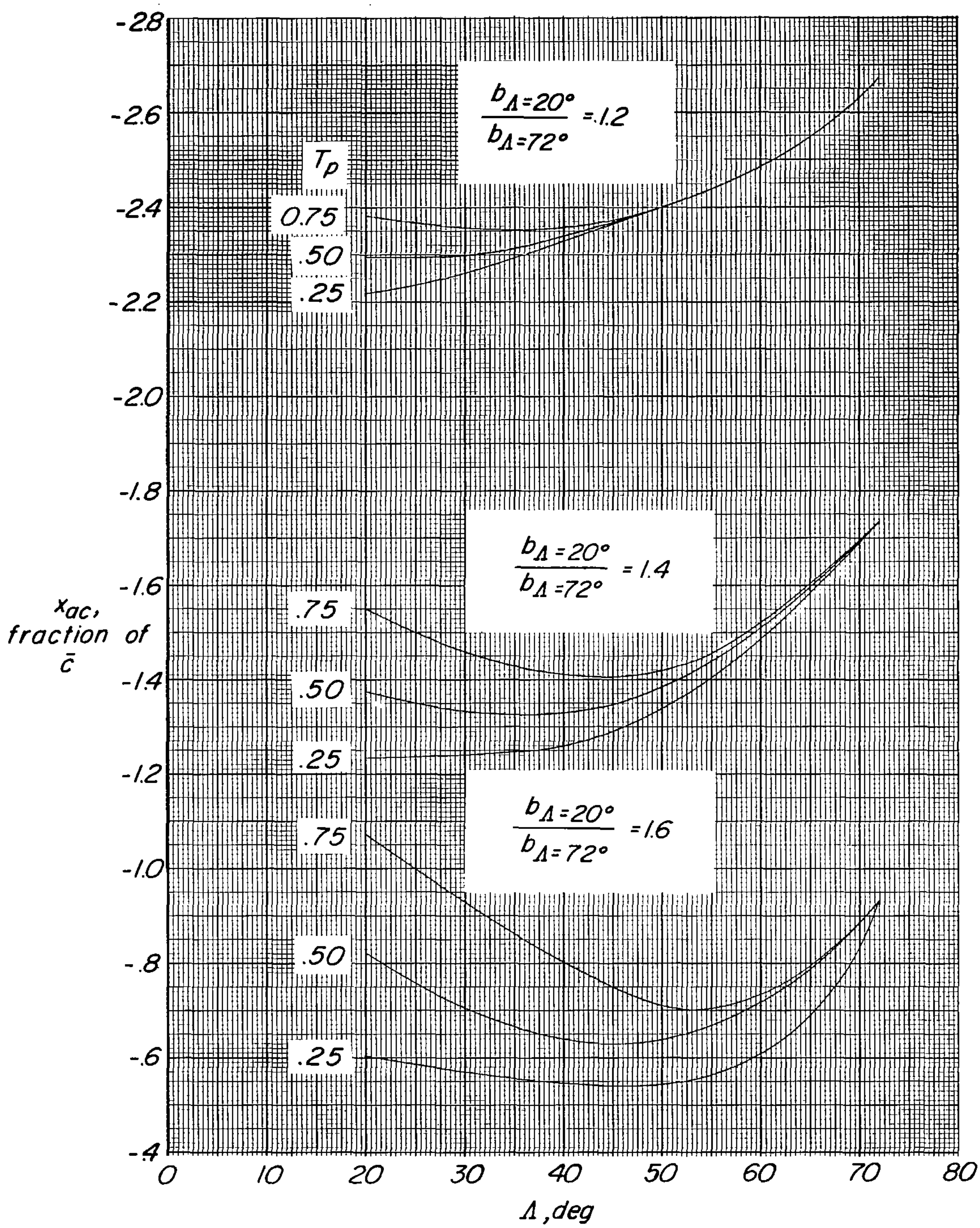


Figure 3.- Effect of fraction of normal chord parameter on the longitudinal placement of the outer panels on the fixed portion of the wing at a constant value of the span increase parameter.



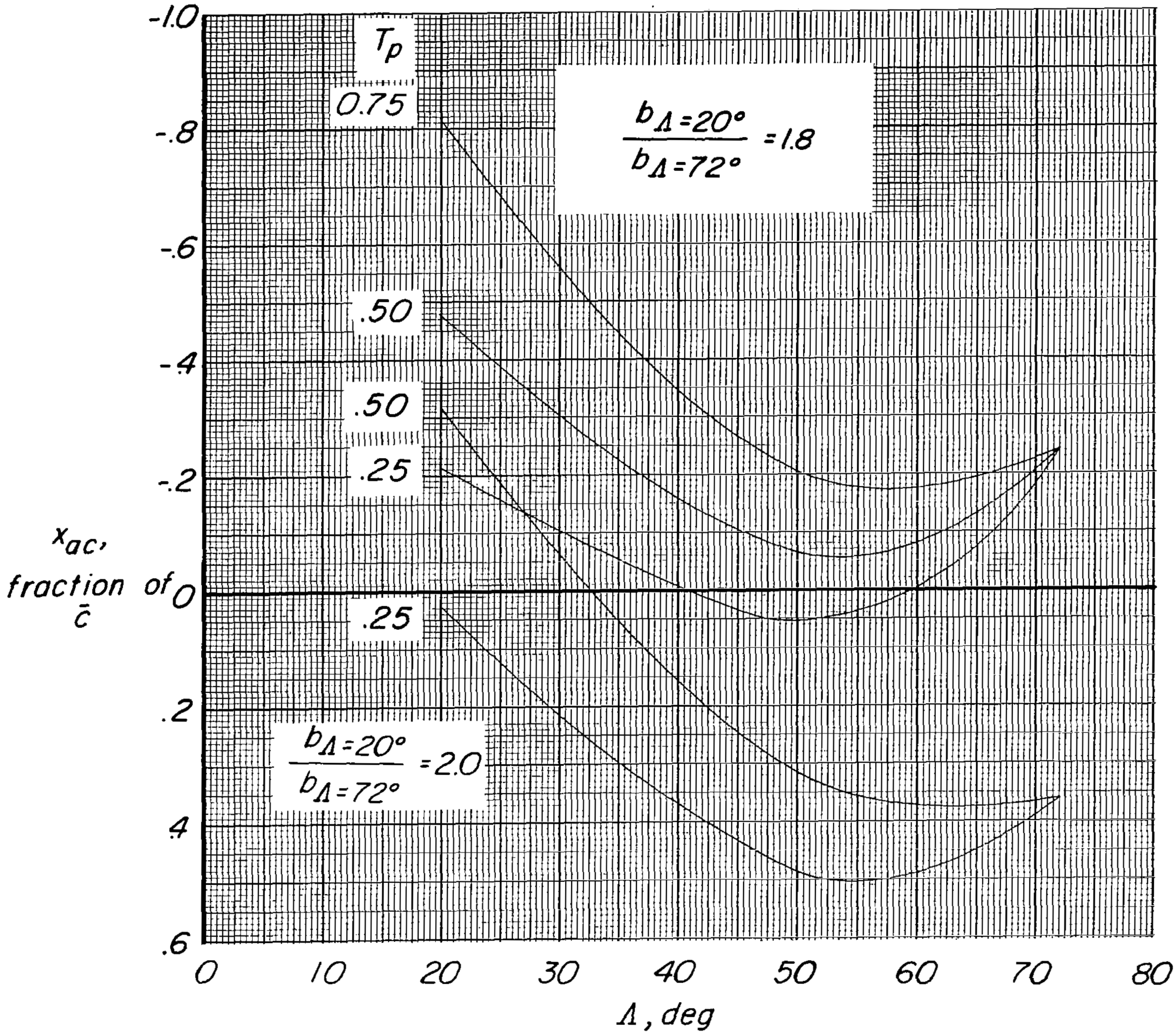
(a) Planform used in computations.

Figure 4.- Effect of outer-panel sweep on the aerodynamic center for different low-sweep wings having the same high-sweep wing with $A = 2$ and $\lambda = 0.10$ at $M = 0$.



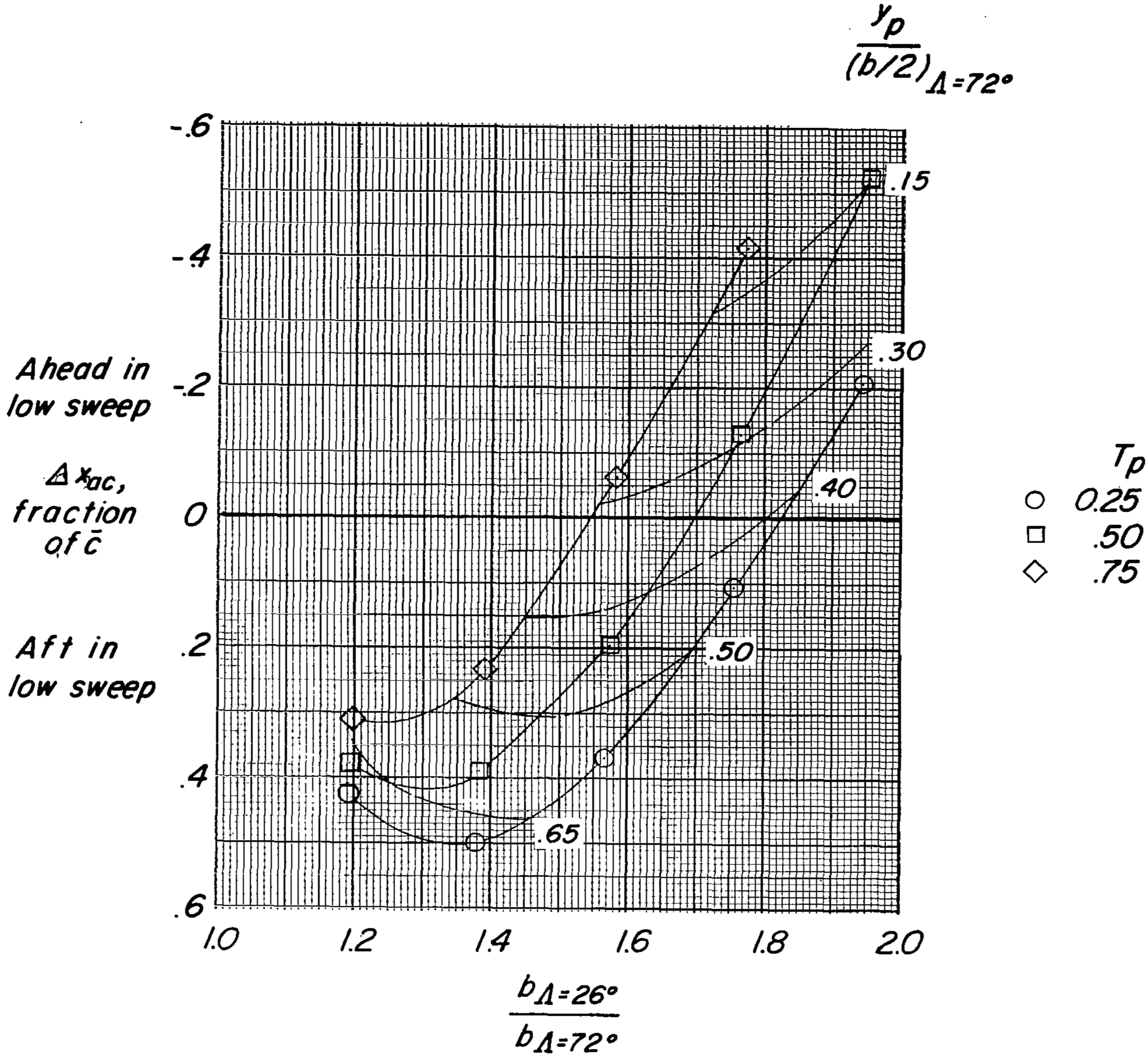
(b) Variation of aerodynamic center with sweep angle.

Figure 4.- Continued.



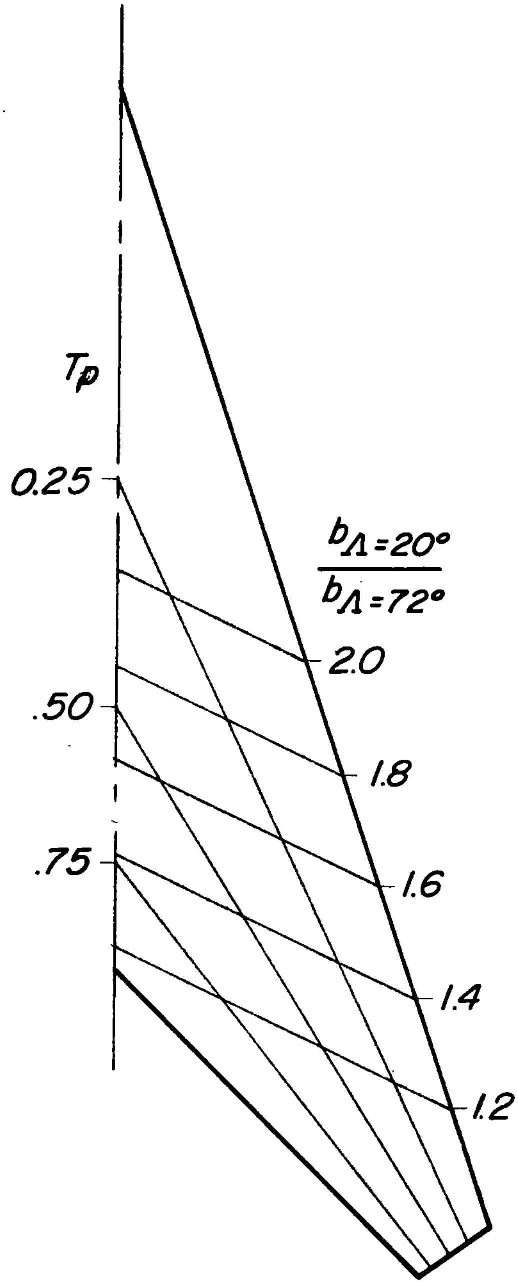
(b) Concluded.

Figure 4.- Continued.



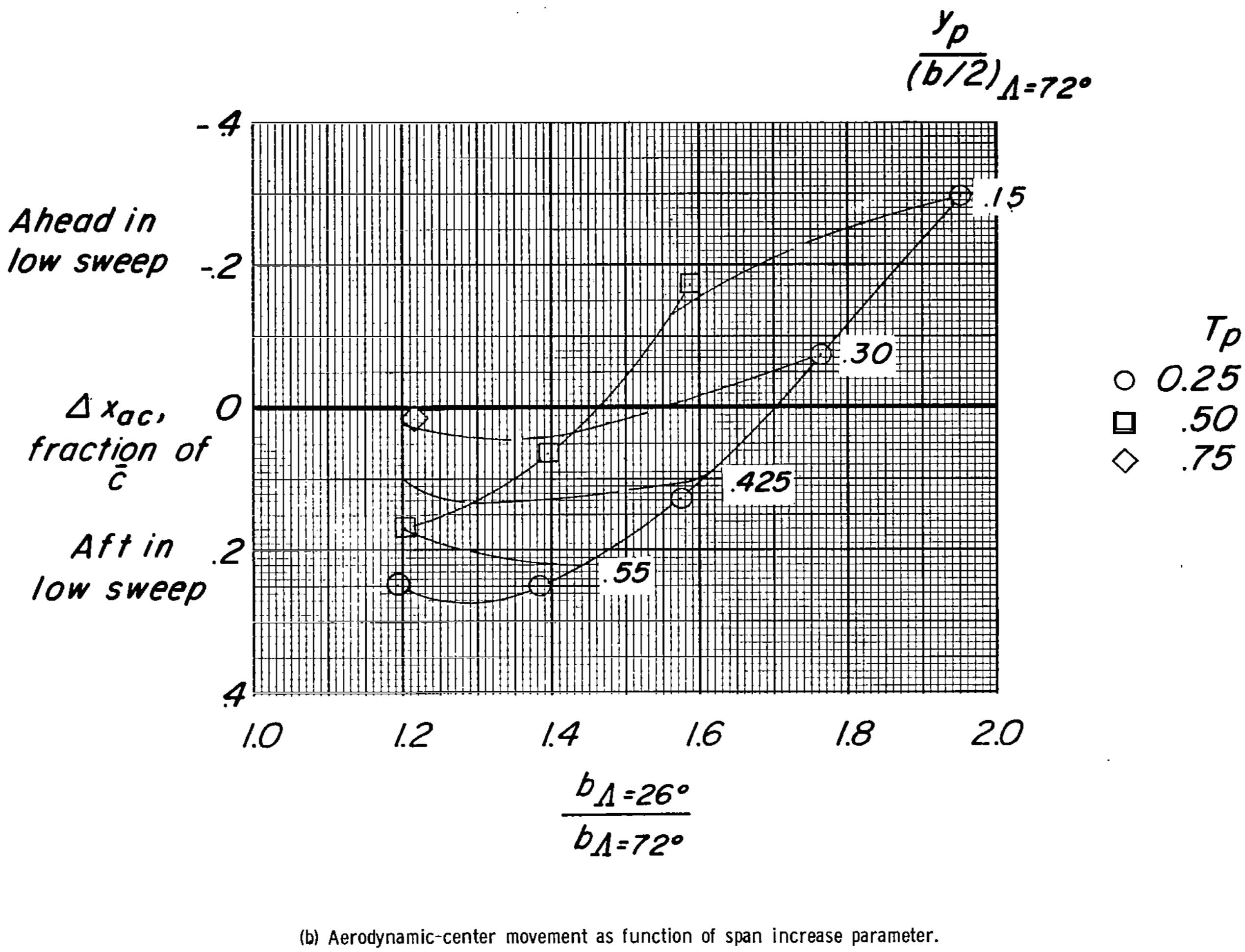
(c) Aerodynamic-center movement as function of span increase parameter.

Figure 4.- Concluded.



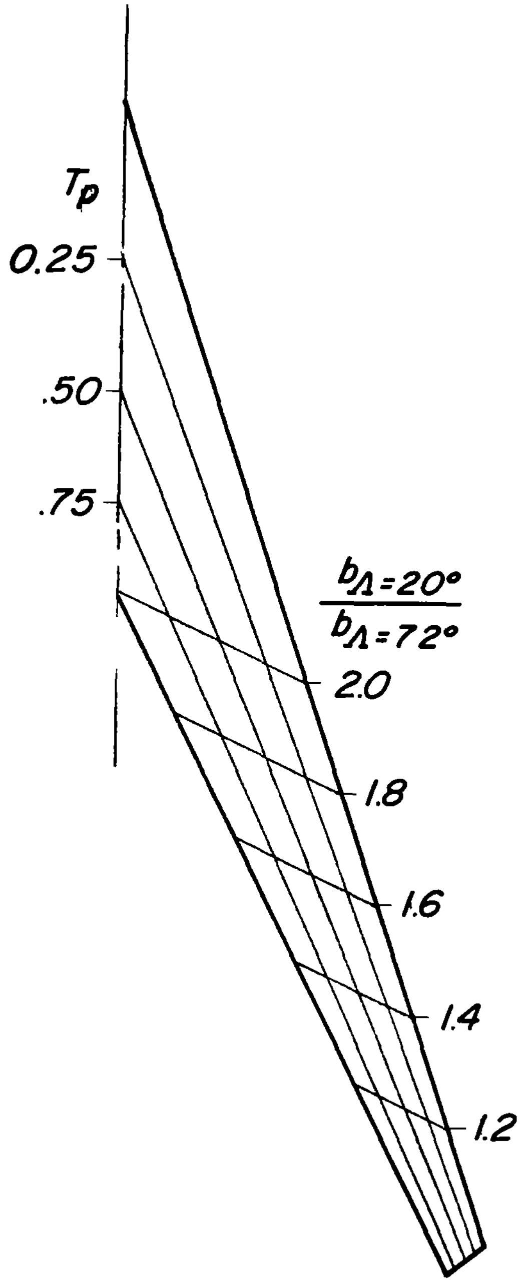
(a) Planform used in computations.

Figure 5.- Effect of outer-panel sweep on the aerodynamic center for different low-sweep wings having the same high-sweep wing with $A = 1.5$ and $\lambda = 0.10$ at $M = 0$.



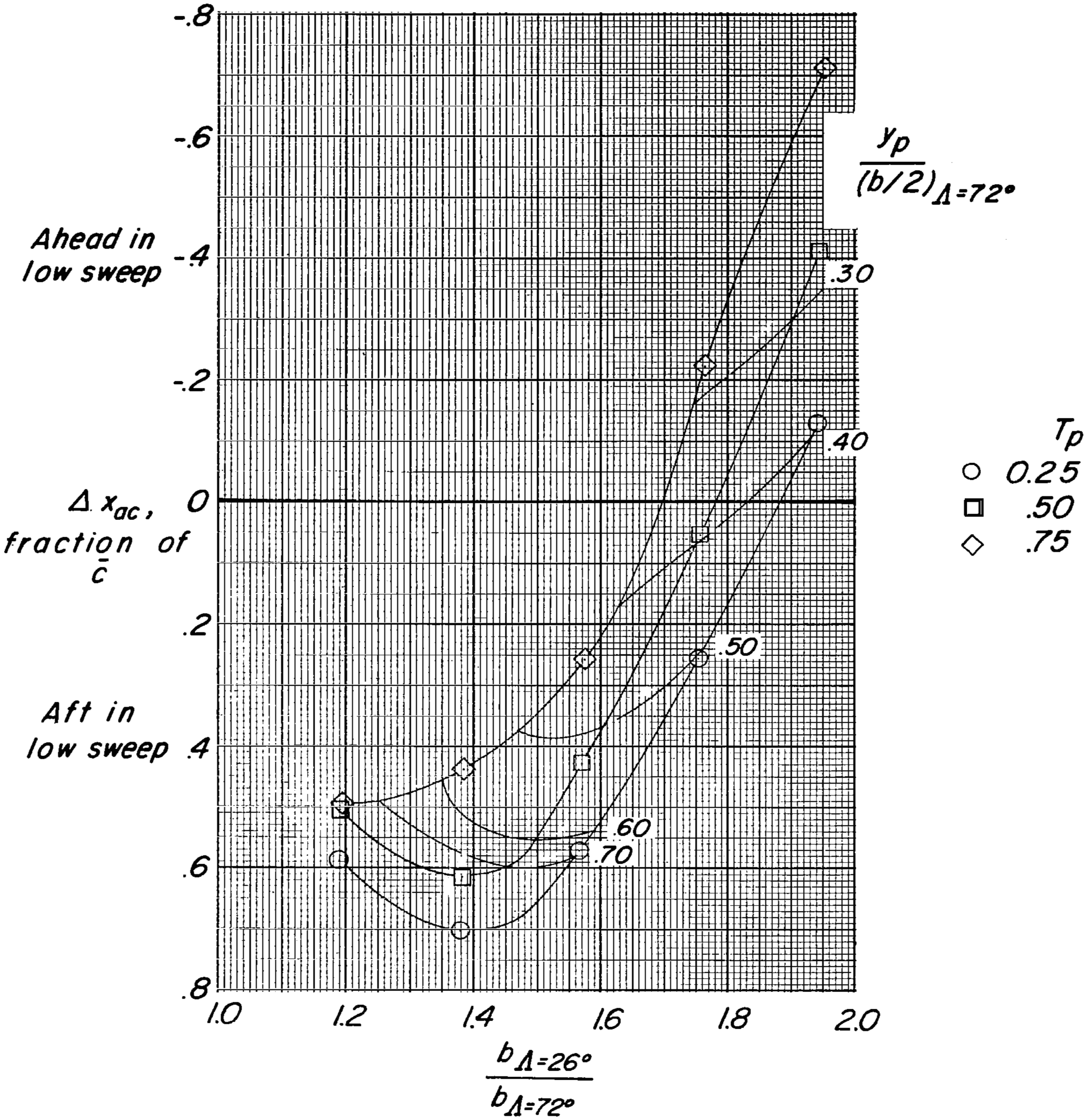
(b) Aerodynamic-center movement as function of span increase parameter.

Figure 5.- Concluded.



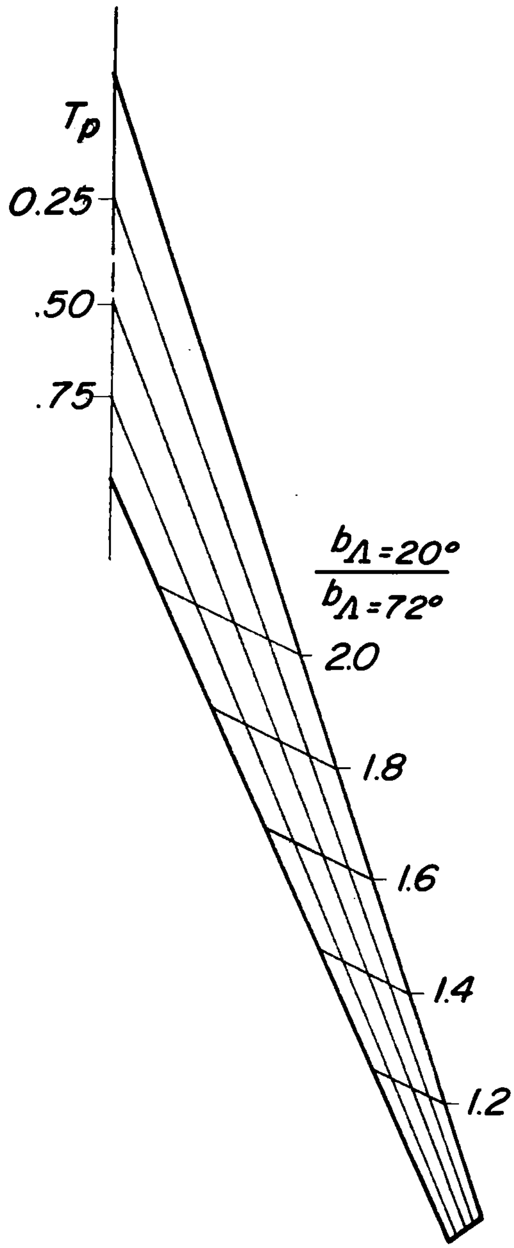
(a) Planform used in computations.

Figure 6.- Effect of outer-panel sweep on the aerodynamic center for different low-sweep wings having the same high-sweep wing with $A = 2.5$ and $\lambda = 0.10$ at $M = 0$.



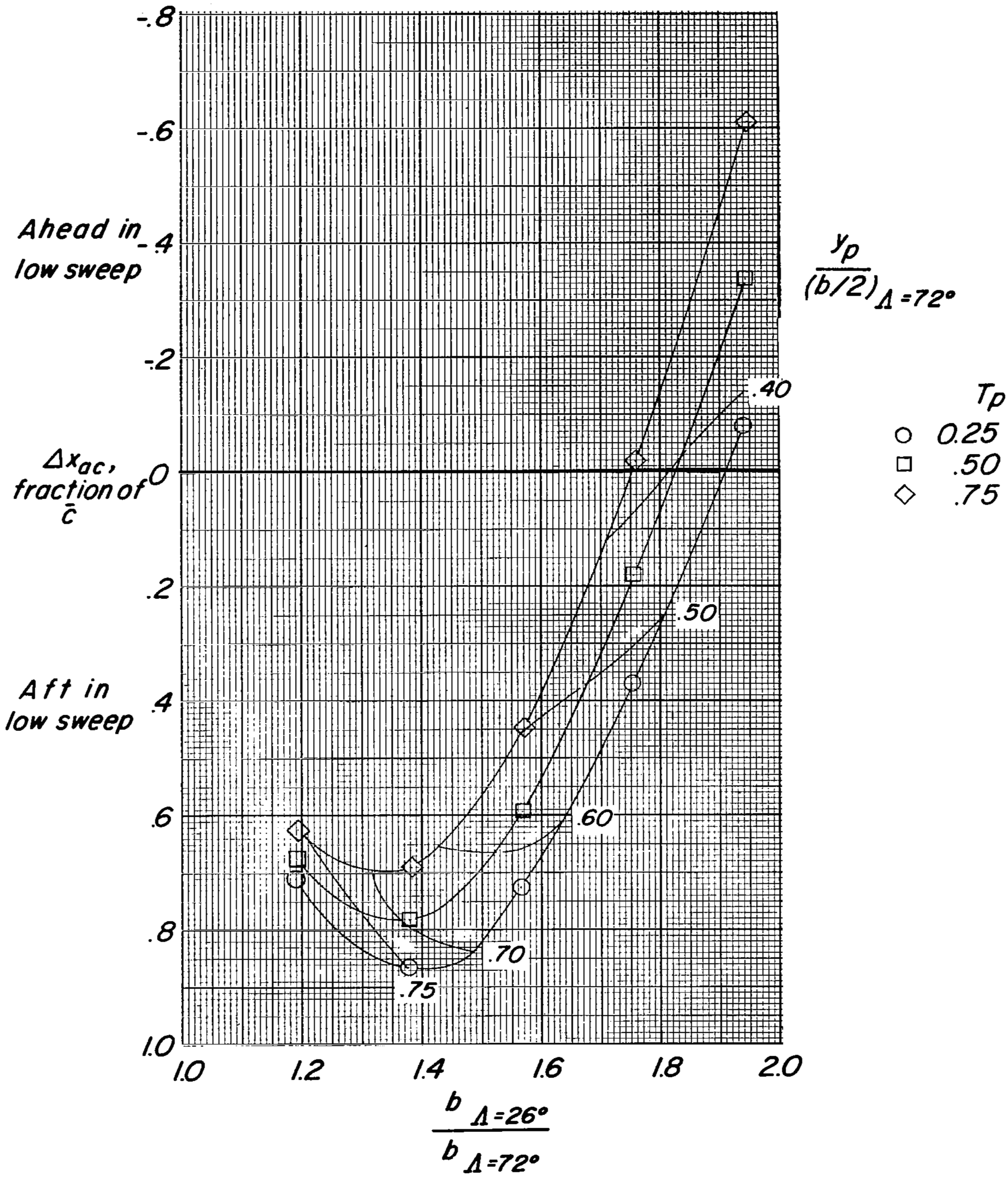
(b) Aerodynamic-center movement as function of span increase parameter.

Figure 6.- Concluded.



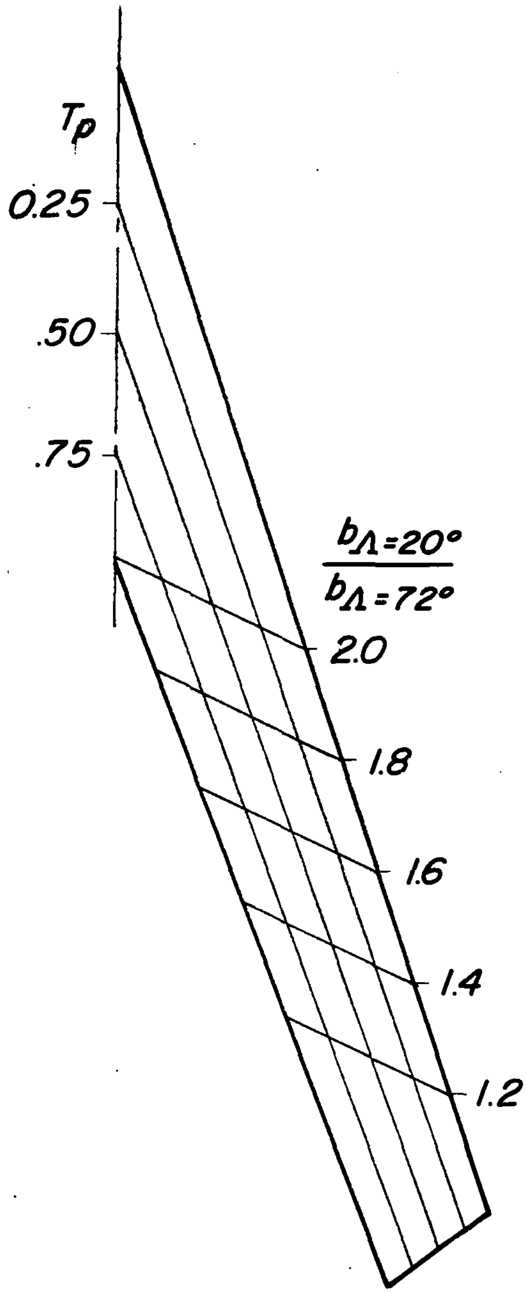
(a) Planform used in computations.

Figure 7.- Effect of outer-panel sweep on the aerodynamic center for different low-sweep wings having the same high-sweep wing with $A = 3.0$ and $\lambda = 0.10$ at $M = 0$.



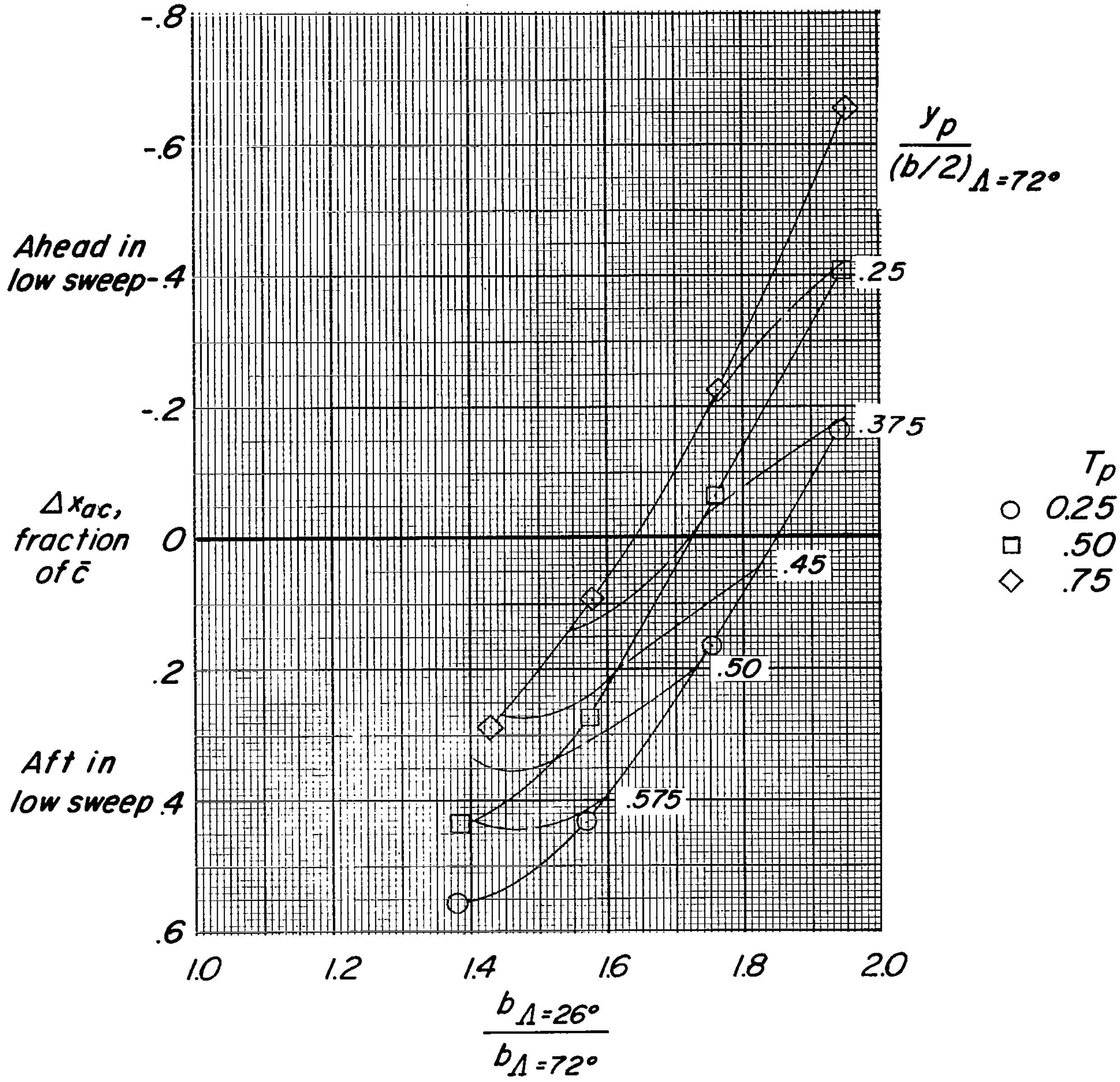
(b) Aerodynamic-center movement as function of span increase parameter.

Figure 7.- Concluded.



(a) Planform used in computations.

Figure 8.- Effect of outer-panel sweep on the aerodynamic center for different low-sweep wings having the same high-sweep wing with $A = 2.0$ and $\lambda = 0.25$ at $M = 0$.



(b) Aerodynamic-center movement as function of span increase parameter.

Figure 8.- Concluded.

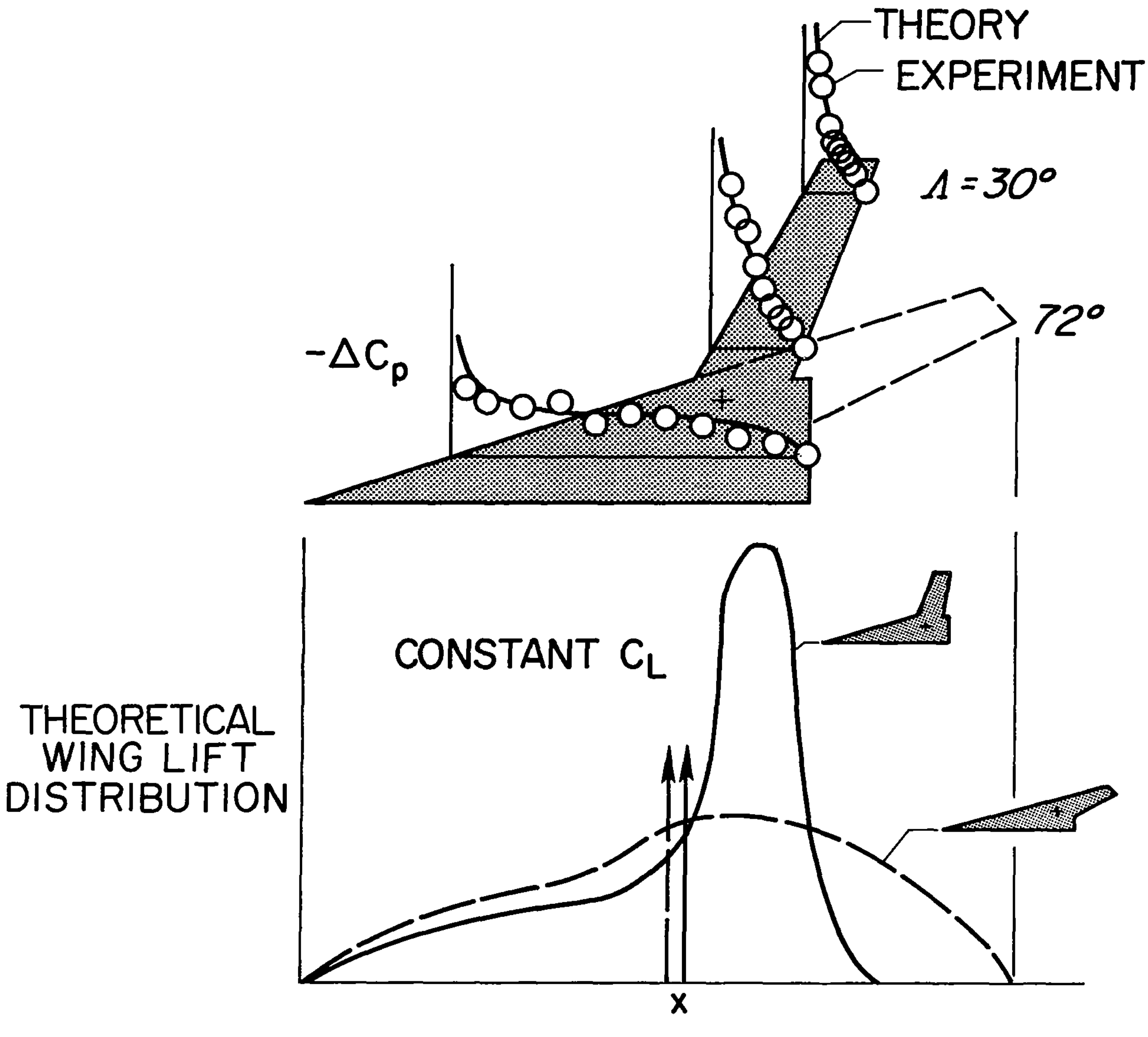
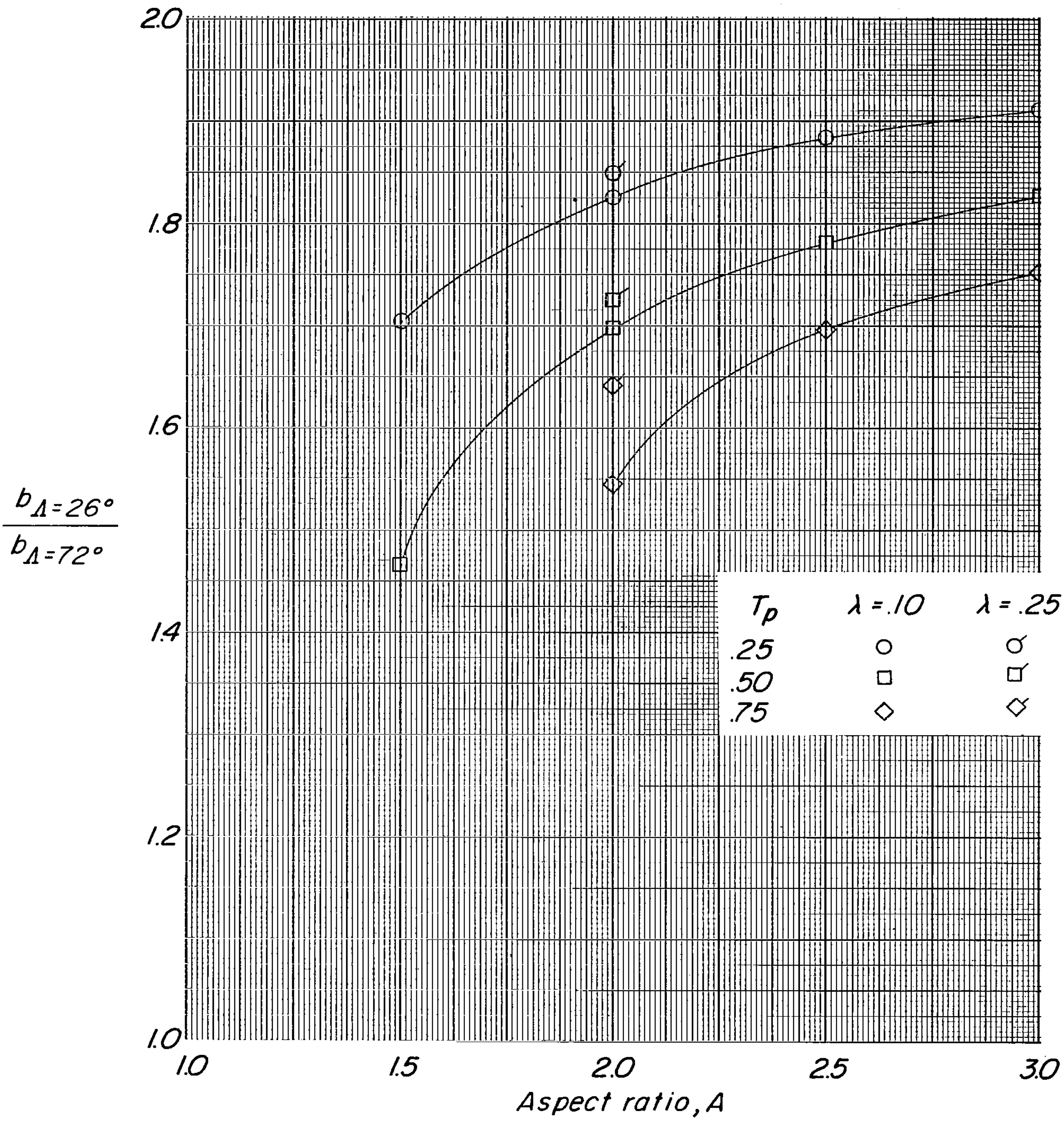
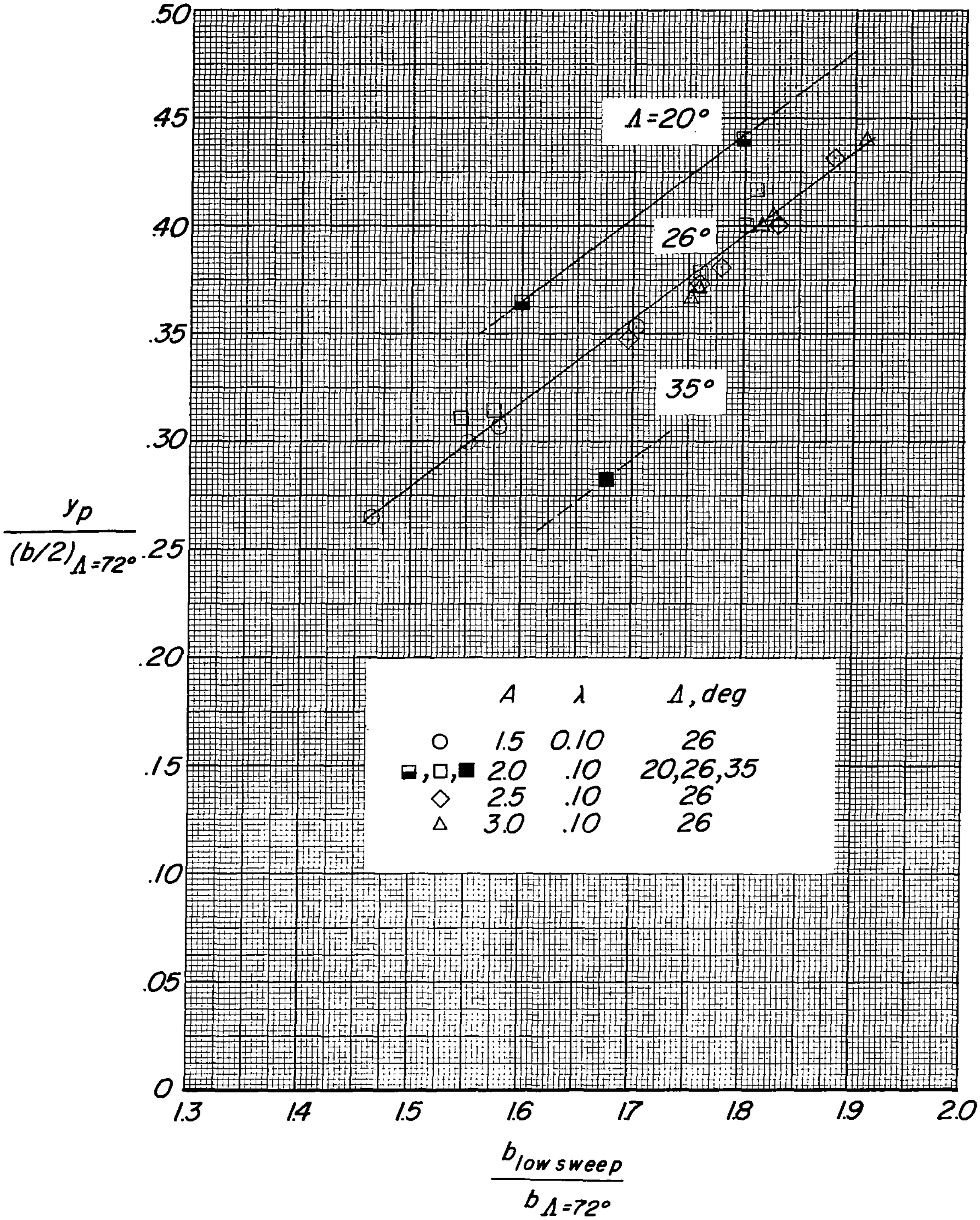


Figure 9.- Effect of sweep on load distribution. $M = 0.23$; $C_L = 0.12$.



(a) Effect of aspect ratio.

Figure 10.- Geometric conditions for zero aerodynamic-center movement.



(b) Effect of low- to high-sweep span ratio.

Figure 10.- Concluded.

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