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AN EXPLORATORY AERODYNAMIC AND STRUCTURAL INVESTIGATION OF ALL-FLEXIBLE PARAWINGS

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SUMMARY

A theoretical investigation was made of the aerodynamic and structural aspects of all-flexible parawings. These wings are characterized by large amounts of spanwise camber. Consequently, planar lifting surface theory is inadequate for predicting the aerodynamic load distribution on the canopy. An aerodynamic method was developed through the use of slender-body theory to account for the principal nonplanar effects. The method considers sections in the plane normal to the root chord to be circular arcs which may translate and dilate with distance along the root chord. The method yields spanwise and chordwise distributions of loading, the distribution of suction along the leading edge and the induced drag. Various static equilibrium models were examined for the purpose of determining the canopy tension distribution and rigging line loads. The methods were applied to a single- and a twin-keel parawing for which data on inflated shape, overall aerodynamic loads, and line loads were obtained by the Langley Research Center, NASA. Comparisons with these load data were made using the measured canopy shapes.

Systematic calculations on conical parawings indicate that spanwise camber increases the lift-curve slope considerably and has a favorable effect on the ratio of normal force to induced drag. These calculations indicate that if a parawing could be rigged closer to a conical shape so that the entire leading edge could be operated close to luffing, a significant increase in lift-drag ratio could be achieved. Comparisons with lift and drag data for single- and twin-keel parawings indicate reasonably good agreement and show that the induced drag constitutes most of the total drag. Line load comparisons illustrate the proper behavior for the analytical structural models, but indicate that the models are not sufficiently detailed to be predictive in nature.

INTRODUCTION

Because the all-flexible parawing is completely stowable, it has received much attention for applications such as aerial delivery schemes, parachute jumping, and space capsule recovery where this property is of prime importance (refs. 1-3). In contrast to the rigid boom parawing, however, its stowability feature has made it more difficult to specify the aerodynamic shape of the inflated parawing and to develop rational aerodynamic and structural theories of the device. Accordingly, almost all progress to date in developing all-flexible parawings has been through experimental means. It is the purpose of this report to present some exploratory work aimed at obtaining insight into the aerodynamic and structural problems of all-flexible parawings.

It was recognized before the present investigation started that no substantial theoretical progress could be made unless good measurements of all-flexible parawing shapes were made to guide the analysis. Accordingly, measurements were made at Langley Research Center in the 7- by 10-Foot Wind Tunnel using stereoscopic photography to determine the inflated shapes of a single-keel and a twin-keel all-flexible parawing. These measured shapes have been utilized together with a specially developed nonplanar slender-wing lifting-surface theory to obtain approximate aerodynamic loadings on the parawings. In this manner the necessary aerodynamic loadings for a preliminary structural analysis have been obtained.

In the present report, the aerodynamic theory developed for all-flexible parawings is presented first. Next, the theory is utilized to describe the aerodynamic characteristics of idealized all-flexible parawings and to assess the importance of various factors in their aerodynamic efficiency. The measured shapes are presented, and are then used together with the theory to estimate the lift and drag characteristics of the single-keel and twin-keel parawings. Finally, results on predicted and measured line loads are presented.

LIST OF SYMBOLS

a	radius of circle in ζ_3 or ζ_4 plane
a_n	complex coefficients in Laurent series for $W_2(\zeta_4)$
$A\!\!\!R$	aspect ratio
A_n	real part of c_n
B_n	imaginary part of c_n
c_r	root chord of inflated parawing
C_D	drag coefficient, D/qS_R
C_{D_i}	induced-drag coefficient, D_i/qS_R
C_{D_o}	friction drag coefficient, nondimensionalized by qS_R
C_L	lift coefficient, L/qS_R
C_s	suction-force coefficient, S/qS_R
C_{T_k}	keel-line tension coefficient, T_k/qS_R
C_{T_ℓ}	leading-edge line tension coefficient, T_ℓ/qS_R
C_X	chord-force coefficient, X/qS_R
C_Y	lateral-force coefficient on half of the canopy, Y/qS_R
C_Z	normal-force coefficient, Z/qS_R
C_X', C_Y', C_Z'	components of C_X, C_Y, and C_Z due to differential pressure loading on canopy

$(\Delta C_X)_s$ $(\Delta C_Y)_s$ $(\Delta C_Z)_s$ $(\Delta C_{D_i})_s$	components of C_X, C_Y, C_Z, and C_{D_i}, respectively, due to leading-edge suction
$(\Delta C_X)_v$ $(\Delta C_Z)_v$ $(\Delta C_{D_i})_v$	components of C_X, C_Z, and C_{D_i}, respectively, associated with vortex lift
C_{11}	coefficient of ζ^{-1} term in Laurent series for $W_1(\zeta)$
C_{12}	coefficient of ζ^{-1} term in Laurent series for $W_2(\zeta)$
$d\ell$	element of length lying in canopy surface cut out by plane parallel to x-axis, fig. 2(a)
$D_o, C_o, C_1, \ldots$	complex coefficients in Laurent series for $W(\zeta)$, eq. (72)
D	total drag
D_i	induced drag of canopy
e	distance between top of canopy and x_1-axis, measured parallel to z-axis, positive downward
e'	distance between top of canopy and x-axis, measured parallel to z-axis, positive downward
$\vec{e}_x$	unit vector along x-axis
e_1, e_2	values of e associated with contours C_1 and C_2, respectively, fig. 2(b)
e_1', e_2'	values of e' associated with contours C_1 and C_2, respectively, fig. 2(b)
f	circular arc camber in crossflow plane, defined in fig. 1
h	rigging line length, figs. 14 and 17
h_k	keel length of theoretical wing canopy flat pattern, measured from theoretical apex to trailing edge of the plane of symmetry

I_1, I_2, I_3, I_4	definite integrals given by eq. (93)
$J(k)$	definite integral given by eq. (99)
k	$\sqrt{f/2r}$
K	ratio of lift-curve slope of segment of circular cone to that of the uncambered wing corresponding to its chord plane, eq. (139) or eq. (140)
ℓ	$s/2$
L	lift of canopy
M_y	moment of canopy about y-axis
M_z	moment of canopy about z-axis
n	summation index
$\vec{n}$	unit vector normal to canopy
$\vec{n}_1$	unit upward vector perpendicular to canopy at right-hand leading edge
$\vec{n}_2$	unit normal tangent to canopy and normal to right-hand leading edge, directed away from canopy
p	local static pressure
p_∞	free-stream static pressure
Δp	pressure difference across the canopy
P	pressure coefficient, $(p - p_\infty)/q$
ΔP	$P_\ell - P_u$, wing loading
P_ℓ	pressure coefficient for lower wing surface
P_n, Q_n	coefficients in a Laurent series, eq. (50)
P_u	pressure coefficient for upper wing surface
q	free-stream dynamic pressure
$\vec{q}$	vector flow velocity
r	radius of curvature of circular arc in ζ_1 and ζ_2 planes

r_1, r_2	values of r associated with contours C_1 and C_2, respectively, fig. 2(b)
s	parawing local semispan
s_m	maximum semispan of conical parawing formed from surface of circular cone
S	leading-edge suction force associated with both leading edges
S_R	reference area, taken as flat canopy area unless otherwise indicated
T_k	keel rigging line tension
T_ℓ	leading-edge rigging line tension
u, v, w	perturbation velocities along x, y, and z axes, respectively
u_ℓ, w_ℓ	values of u and w on lower surface, respectively
u_u, w_u	values of u and w on upper surface, respectively
$(u_u)_{odd}$	$(u_u - u_\ell)/2$
v_r, v_ϕ	radial and tangential perturbation velocity components in yz plane
v_{r_1}, v_{ϕ_1}	radial and tangential perturbation velocity components on circular arc in ζ_1 plane associated with ϕ_1
v_{r_2}, v_{ϕ_2}	radial and tangential perturbation velocity components on circular arc in ζ_2 plane associated with ϕ_2
V_∞	free-stream velocity
$(w_u)_{odd}$	$(w_u - w_\ell)/2$
w_1	velocity component along z-axis associated with ϕ_1
w_2	velocity component along z-axis associated with ϕ_2
$W(\zeta)$	complex potential for total flow
$W_1(\zeta_1)$	complex potential for circular arc translating upward at unit velocity with fluid stationary at infinity

$W_1'(\zeta_4)$	complex potential for flow about a fixed circle with center at the origin with unit free-stream directed along the negative z-axis
$W_2(\zeta_4)$	complex potential in ζ_4 plane for flow which in the ζ_1 plane yields a circular arc dilating at unit velocity with the flow velocity zero at infinity
x,y,z	axis system with origin at leading edge of parawing with positive x rearward along the root chord, positive y laterally to the right facing forward, and positive z vertically up
x',y',z'	axis system used in canopy shape measurement tests, with origin at the rigging line confluence point. x' is parallel to the keel chord, positive aft; z' is positive up; and y' is positive to right facing forward in tunnel
x_1,y_1,z_1	axis system with origin at leading edge of parawing with positive x_1 rearward in streamwise direction, positive y_1 laterally to right facing forward, and positive z_1 vertical upward
X	chordwise force directed along x-axis
Y	lateral force on half of the canopy, directed along y-axis
Z	normal force on canopy in direction of z-axis
α	angle between free-stream velocity and root chord direction
α_{ideal}	angle of attack for conical parawing at which the leading-edge suction is zero
$\alpha_k,\beta_k,\gamma_k$	direction cosines of vectors representing the keel line tension, positive downward
$\alpha_\ell,\beta_\ell,\gamma_\ell$	direction cosines of vectors representing the leading-edge line tension, positive downward
α_o	angle of zero lift of segment of a circular cone
α_7	"angle of attack" for a single-keel parawing, defined as the angle between the number 7 keel line and the vertical direction
α_8	"angle of attack" for twin-keel parawing, defined as the angle between the projection of number 8 keel line onto vertical plane of symmetry and the vertical direction
β	polar angle in ζ_3 plane, fig. 4

ζ	complex variable, $y + iz$
ζ_1	$y_1 + iz_1$
ζ_2	$\zeta_1 + i(e + f)$
ζ_3	$\frac{\zeta_2}{2} + \frac{1}{2}\left(\zeta_2^2 - 4\ell^2\right)^{1/2}$
ζ_4	$\zeta_3 - \frac{if}{2}$
η	fraction of semispan
θ	polar angle in ζ_4 plane, fig. 4
λ_1	$-\left(\frac{dr}{dx} + \frac{de}{dx}\right)$
λ_2	$+\frac{dr}{dx}$
λ_3	$xV_\infty \cos \alpha + zV_\infty \sin \alpha$
ν	coordinate in $\vec{\nu}$ direction
$\vec{\nu}$	unit vector normal to canopy contour lying in crossflow plane
$\sigma_x, \sigma_y, \sigma_z$	components in the x, y, and z directions, respectively, of canopy tension per unit width
$\vec{\tau}$	unit vector tangent to canopy contour lying in crossflow plane
ϕ	polar angle of points on canopy surface in yz plane, fig. 2(b)
ϕ_o	$\Phi/V_\infty \cos \alpha$
ϕ_1	velocity potential for circular arc translating upward at unit velocity
$(\phi_1)_{odd}$	$\left(\phi_{1_u} - \phi_{1_\ell}\right)/2$
ϕ_2	velocity potential for expanding circular arc with unit radial velocity
$(\phi_2)_{odd}$	$\left(\phi_{2_u} - \phi_{2_\ell}\right)/2$
Φ	velocity potential for complete flow past parawing

Subscripts

ee	associated with $(de/dx)^2$
ef	associated with $\frac{de}{dx}\,\frac{df}{dx}$
er	associated with $\frac{de}{dx}\,\frac{dr}{dx}$
2e	associated with d^2e/dx^2
rf	associated with $\frac{dr}{dx}\,\frac{df}{dx}$
rr	associated with $(dr/dx)^2$
2r	associated with d^2r/dx^2

AERODYNAMIC THEORY

Preliminary Considerations

As part of a general investigation of the structural and aerodynamic characteristics of all-flexible parawings, it is desired to develop an aerodynamic theory that will predict the detailed load distribution on such wings. None of the existing planar lifting-surface theories is applicable to all-flexible parawings because the canopies of such wings are not even approximately planar. Since the rigging lines from the wing tips slant inward toward the vertical plane of symmetry, the canopy must be nearly vertical near the tips. Accordingly, the rigging method of all-flexible parawings effectively provides the wing with end plates which preclude the use of planar lifting-surface theory if accurate predictions are desired.

No nonplanar lifting-surface theory exists which is applicable to all-flexible parawings with the accuracy of linearized wing theory. However, it appears possible to develop a slender-wing nonplanar lifting-surface theory that will account for the principal nonplanar effects of canopy shape. The principal assumption used in the analysis is that the shape of the canopy in any crossflow plane can be approximated in the mean by a circular arc. The circular arcs will vary chordwise in span, camber ratio, and vertical location of the center of curvature. The variation of these quantities with chordwise distance in the cases considered in this report is obtained from measurement, but in other cases may have to be obtained by other means. The aerodynamic theory will be complete in that loading distributions as well as gross forces and moments will be obtained.

A line joining the wing leading edge and trailing edge in the vertical plane of symmetry is defined as the root chord of the parawing (fig. 1). The apex of the wing is taken as the origin of the wing axis system with x taken positive rearward, along the root chord, and y and z as shown in the figure. The free-stream velocity V_∞ is in the vertical plane of symmetry for the present analysis, and the x-axis is inclined at the angle α to V_∞. For the purposes of the analysis, crossflow planes are considered perpendicular to the x-axis. In these crossflow planes, the canopy shape is assumed to be representable by a circular arc. The circular arc is described by three quantities which vary with x. Besides the camber, f, and the local semispan, s, there is the distance e between the top of the canopy and the x_1-axis, measured in the z direction.

The crossflow planes have been set up normal to the root chord rather than normal to the free-stream direction so that the canopy shape for a rigid canopy will not change with angle of attack. Also, the local crossflow section of maximum span will be farther aft than if the crossflow planes are taken normal to the free-stream direction. Since slender-body theory usually predicts negative lift on sections of decreasing span in the downstream direction, the present choice of crossflow planes will tend to reduce the extent of regions of negative lift on the rear of the parawing.

Boundary Conditions

Consider the two contours C_1 and C_2 lying in the canopy in crossflow planes dx apart as shown in figure 2(a). Let $\vec{\tau}$ and $\vec{\nu}$ be unit vectors tangent to and perpendicular to the contour C_1, respectively at some point. Consider a plane parallel to the x-axis and containing $\vec{\nu}$. This plane intersects the body surface between C_1 and C_2 along an element $d\ell$. Let $\vec{n}$ be normal to $\vec{\tau}$ and $d\ell$ so that it is the unit normal to the surface. If Φ is the entire velocity potential and if the unit vector along the x-axis is $\vec{e}_x$, then the velocity vector $\vec{q}$ is

$$\vec{q} = \frac{\partial\Phi}{\partial x}\vec{e}_x + \frac{\partial\Phi}{\partial\nu}\vec{\nu} + \frac{\partial\Phi}{\partial\tau}\vec{\tau} \tag{1}$$

The tangency condition is

$$\vec{q} \cdot \vec{n} = 0 \tag{2}$$

or

$$\frac{\partial\Phi}{\partial x}\cos\,(\vec{e}_x,\vec{n}) + \frac{\partial\Phi}{\partial\nu}\cos\,(\vec{\nu},\vec{n}) = 0 \tag{3}$$

It is noted that $\vec{\nu}$, $d\ell$, and dx are coplanar by construction, lying in a plane normal to $\vec{\tau}$. Since $\vec{n}$ also lies in this plane, $\vec{n}$, $\vec{\nu}$, $d\ell$, and dx are coplanar, with $\vec{n}$ and $\vec{\nu}$ perpendicular to $d\ell$ and dx, respectively. If we make the small angle assumption for $d\nu/dx$, we have

$$\left.\begin{aligned}\cos\,(\vec{e}_x,\vec{n}) &= -\frac{d\nu}{dx}\\ \cos\,(\vec{\nu},\vec{n}) &= 1\end{aligned}\right\} \tag{4}$$

Thus the boundary condition becomes

$$\frac{\partial\Phi/d\nu}{\partial\Phi/dx} = \frac{d\nu}{dx} \tag{5}$$

We can write on the basis of small perturbation velocities

$$\frac{\partial\Phi}{\partial\nu} = (V_\infty \cos\alpha)\frac{d\nu}{dx} \tag{6}$$

It is desirable to relate the tangency condition to the geometric parameters of the canopy shape. For this purpose consider a fixed crossflow plane through which the wing is passing. Let the contours C_1 and C_2 as seen in the fixed crossflow plane be circular arcs as shown in figure 2(b) where the traces of the x- and x_1-axes are shown. Then

$$-\Delta\nu = OA + AB \tag{7}$$

$$\left.\begin{aligned} OA &= r_1 - r_2 \\ AB &= \left[(r_2 + e_2') - (r_1 + e_1')\right] \sin \phi \end{aligned}\right\} \qquad (8)$$

$$-\Delta\nu = +(r_2 - r_1)(-1 + \sin \phi) + (e_2' - e_1') \sin \phi$$

or with $dr = r_2 - r_1$ and $de' = e_2 - e_1$, we obtain

$$\frac{d\nu}{dx} = + \frac{dr}{dx} - \sin \phi \left(\frac{dr}{dx} + \frac{de'}{dx}\right) = \frac{dr}{dx} - \sin \phi \left(\frac{dr}{dx} + \frac{de}{dx} - \tan \alpha\right) \qquad (9)$$

The change from e' to e is desirable for computational purposes because of the way the canopy shape is measured in the wind tunnel.

This boundary condition suggests two potential problems that must be solved. The first term dr/dx is the boundary condition for an expanding circular arc. For a translating arc the velocity normal to the arc varies as $\sin \phi$ so that the second term of equation (9) describes the boundary condition of a translating arc. Let ϕ_1 be the potential function for a translating arc with the normal velocity equal to $\sin \phi$ and no velocity at infinity. Let ϕ_2 be the crossflow potential function for an expanding arc with unit normal velocity and no velocity at infinity. Thus, the boundary conditions are, from figure 3,

$$\left.\begin{aligned} &\frac{\partial \phi_1}{\partial \nu} = \sin \phi \quad \text{on the arc} \\ &\frac{\partial \phi_1}{\partial y}, \frac{\partial \phi_1}{\partial z} \rightarrow 0 \quad \text{as} \quad y,z \rightarrow \infty \end{aligned}\right\} \qquad (10)$$

$$\left.\begin{aligned} &\frac{\partial \phi_2}{\partial \nu} = 1 \quad \text{on the arc} \\ &\frac{\partial \phi_2}{\partial y}, \frac{\partial \phi_2}{\partial z} \rightarrow 0 \quad \text{as} \quad y,z \rightarrow \infty \end{aligned}\right\} \qquad (11)$$

We can construct the total potential function as follows.

$$\Phi = xV_\infty \cos \alpha + zV_\infty \sin \alpha - \left(\frac{dr}{dx} + \frac{de}{dx}\right) V_\infty \cos \alpha \, \phi_1 + V_\infty \cos \alpha \frac{dr}{dx} \phi_2 \tag{12}$$

To verify the boundary condition on the body, differentiate equation (12) with respect to ν.

$$\frac{\partial \Phi}{\partial \nu} = \frac{\partial z}{\partial \nu} V_\infty \sin \alpha - V_\infty \cos \alpha \left(\frac{dr}{dx} + \frac{de}{dx}\right) \sin \phi + V_\infty \cos \alpha \frac{dr}{dx} \tag{13}$$

On the body $\partial z/\partial \nu$ is $\sin \phi$ so that

$$\frac{\partial \Phi}{\partial \nu} = V_\infty \cos \alpha \left[\frac{dr}{dx} - \left(\frac{dr}{dx} + \frac{de}{dx} - \tan \alpha\right) \sin \phi\right] \tag{14}$$

Using equation (9), we obtain

$$\frac{\partial \Phi}{\partial \nu} = V_\infty \cos \alpha \frac{d\nu}{dx} \tag{15}$$

a result fulfilling the boundary condition, equation (6). The only other condition that the potential must fulfill is that it must give the parallel flow at infinity. Since ϕ_1 and ϕ_2 yield no velocities at infinity, it can be seen from equation (12) that $\partial \Phi/\partial x$ and $\partial \Phi/\partial z$ have the proper behavior at infinity.

Pressure Coefficient

Let u, v, and w be the perturbation velocities along the x, y, and z axes, respectively, such that

$$\left.\begin{aligned} \frac{\partial \Phi}{\partial x} &= V_\infty \cos \alpha + u \\ \frac{\partial \Phi}{\partial y} &= v \\ \frac{\partial \Phi}{\partial z} &= V_\infty \sin \alpha + w \end{aligned}\right\} \tag{16}$$

Then from reference 4, p. 48, the pressure coefficient for zero yaw angle is given by

$$P = \frac{-2(u + \alpha w)}{V_\infty} - \frac{(v^2 + w^2)}{V_\infty{}^2} \tag{17}$$

With regard to the square terms, it is easier to evaluate the sum by means of the following equality

$$(v^2 + w^2) = (v_r^2 + v_\phi^2) \tag{18}$$

where

$$\left.\begin{aligned} v_r &= \frac{\partial}{\partial r}(\Phi - xV_\infty \cos\alpha - zV_\infty \sin\alpha) \\ v_\phi &= \frac{1}{r}\frac{\partial}{\partial\phi}(\Phi - xV_\infty \cos\alpha - zV_\infty \sin\alpha) \end{aligned}\right\} \tag{19}$$

Carrying out the operation to obtain the velocity components, we find that

$$\frac{u}{V_\infty \cos\alpha} = -\phi_1 \frac{d}{dx}\left(\frac{dr}{dx} + \frac{de}{dx}\right) - \left(\frac{dr}{dx} + \frac{de}{dx}\right)\frac{\partial\phi_1}{\partial x} + \phi_2 \frac{d^2r}{dx^2} + \frac{dr}{dx}\frac{\partial\phi_2}{\partial x} \tag{20}$$

$$\frac{w}{V_\infty \cos\alpha} = -\left(\frac{dr}{dx} + \frac{de}{dx}\right)\frac{\partial\phi_1}{\partial z} + \frac{dr}{dx}\frac{\partial\phi_2}{\partial z} \tag{21}$$

and on the canopy

$$\frac{v_r}{V_\infty \cos\alpha} = -\left(\frac{dr}{dx} + \frac{de}{dx}\right)\sin\phi + \frac{dr}{dx} \tag{22}$$

$$\frac{v_\phi}{V_\infty \cos\alpha} = -\frac{1}{r}\left(\frac{dr}{dx} + \frac{de}{dx}\right)\frac{\partial\phi_1}{\partial\phi} + \frac{1}{r}\frac{dr}{dx}\frac{\partial\phi_2}{\partial\phi} \tag{23}$$

It is noted that the pressure coefficient depends not only on dr/dx and de/dx, but also on $d^2(r + e)/dx^2$.

Solution for Translating Circular Arc

Complex potential.- It is desired to obtain the potential for a translating arc with unit upward velocity with the flow stationary at infinity. The arc is shown in figure 1(a), together with its dimensions and its position with respect to the x, y, z coordinate system. The potential is obtained in several steps, as illustrated in figure 4. We start with the known potential for a circle with its center at the origin with downward flow parallel to the z-axis at unit speed in the far field (fig. 4(d)).

$$W_1'(\zeta_4) = i\left(\zeta_4 - \frac{a^2}{\zeta_4}\right) \tag{24}$$

This potential can be transformed through the planes $\zeta_4 \rightarrow \zeta_3 \rightarrow \zeta_2 \rightarrow \zeta_1$ to obtain a flow past the translating arc in the ζ_1 plane with the velocity at infinity unchanging. The first transformation simply shifts the origin of the circle up onto the imaginary axis.

$$\zeta_3 = \zeta_4 + \frac{if}{2} \tag{25}$$

The second transformation is the Joukowski transformation which carries a circle with the center offset on the imaginary axis into a circular arc.

$$\zeta_2 = \zeta_3 + \frac{\ell^2}{\zeta_3} \tag{26}$$

or

$$\zeta_3 = \frac{\zeta_2}{2} + \frac{1}{2}\sqrt{\zeta_2^2 - 4\ell^2} \tag{27}$$

where we have used the positive sign on the square root. The last transformation merely changes the vertical position of the circular arc.

$$\zeta_1 = \zeta_2 - i(e + f) \tag{28}$$

By simply making the appropriate transformations in the complex potential, we obtain the flows in the several planes since the contours are streamlines and the flow velocity at infinity is unaltered. Accordingly,

$$W_1'(\zeta_3) = i\left[\zeta_3 - \frac{if}{2} - \frac{a^2}{\zeta_3 - \frac{if}{2}}\right] \tag{29}$$

$$W_1'(\zeta_2) = i\left[\frac{\zeta_2}{2} - \frac{if}{2} + \frac{1}{2}\sqrt{\zeta_2^2 - 4\ell^2} - \frac{a^2}{\frac{\zeta_2}{2} - \frac{if}{2} + \frac{1}{2}\sqrt{\zeta_2^2 - 4\ell^2}}\right] \tag{30}$$

$$\begin{aligned} W_1'(\zeta_1) = i\Bigg[&\frac{\zeta_1}{2} + \frac{ie}{2} + \frac{1}{2}\sqrt{\left[\zeta_1 + i(e + f)\right]^2 - 4\ell^2} \\ &- \frac{a^2}{\frac{\zeta_1}{2} + \frac{ie}{2} + \frac{1}{2}\sqrt{\left[\zeta_1 + i(e + f)\right]^2 - 4\ell^2}}\Bigg] \end{aligned} \tag{31}$$

The complex potential for the upward moving arc is now obtained by imposing a flow given by $-i\zeta_1$ which makes the velocity at infinity zero and imparts a uniform upward velocity to the circular arc. The final complex potential in the ζ_1 plane is thus

$$W_1(\zeta_1) = W_1'(\zeta_1) - i\zeta_1 \tag{32}$$

This complex function $W_1(\zeta_1)$ is now transformed back to the ζ_4 plane, resulting in the following simple form, correct except for a constant.

$$W_1(\zeta_4) = -i\left[\frac{a^2}{\zeta_4} + \frac{\ell^2}{\zeta_4 + \frac{if}{2}}\right] \tag{33}$$

Velocity components.- With the complex potential for the terms known, it is possible to obtain the velocity components. The following scheme is used.

$$\left(v_{r_1} - iv_{\phi_1}\right)e^{-i\phi} = \frac{dW_1}{d\zeta_1} = \frac{dW_1}{d\zeta_4}\,\frac{d\zeta_4}{d\zeta_3}\,\frac{d\zeta_3}{d\zeta_2}\,\frac{d\zeta_2}{d\zeta_1} \tag{34}$$

Carrying out the operations yields the following results on the contour

$$\left.\begin{aligned}
&\frac{dW_1}{d\zeta_4} = i\left[e^{-2i\theta} + \frac{(1 - k^2)}{(e^{i\theta} + ik)^2}\right]; \quad k^2 = \frac{f}{2r} \\
&\frac{d\zeta_4}{d\zeta_3} = 1 \\
&\frac{d\zeta_3}{d\zeta_2} = \frac{(e^{i\theta} + ik)^2}{2ie^{i\theta}(\sin\theta + k)} \\
&\frac{d\zeta_2}{d\zeta_1} = 1
\end{aligned}\right\} \tag{35}$$

where θ is the polar angle in the ζ_3 plane (fig. 4). In order to separate the velocity components into components which are symmetric and antisymmetric with respect to the top and bottom surfaces of the wing, we must express the results in terms of some angle other than θ. An appropriate angle is β, the polar angle in the ζ_3 plane (fig. 4). Use of equation (25) yields the following relationships

$$\left.\begin{aligned}
\sin\theta &= -k\cos^2\beta + \sin\beta\sqrt{1 - k^2\cos^2\beta} \\
\cos\theta &= \cos\beta\left[k\sin\beta + \sqrt{1 - k^2\cos^2\beta}\right]
\end{aligned}\right\} \tag{36}$$

between θ and β. The equation of the circular arc in the ζ_2 plane in terms of β is

$$\zeta_2 = 2a\cos\beta\sqrt{1 - k^2\cos^2\beta} + 2aik\sin^2\beta \tag{37}$$

Accordingly, β and $-\beta$ yield corresponding points on the top and bottom of the circular arc.

With the use of equations (34), (35), and the following relationship

$$e^{i\phi} = \frac{ke^{2i\theta} + ie^{i\theta}}{e^{i\theta} + ik} \tag{38}$$

it can be shown that in terms of θ and ϕ

$$\left.\begin{aligned} v_{r_1} &= \sin\phi \\ v_{\phi_1} &= \frac{-\cos\theta}{\sin\theta + k}\left(1 + k^2 + 2k\sin\theta\right) + \cos\phi \end{aligned}\right\} \tag{39}$$

It is seen that v_{r_1} satisfies the boundary condition for the arc translating upward at unit velocity.

In order to bring out the symmetry properties of the velocity components, both velocities are given in terms of β with the help of equation (36) as follows:

$$\left.\begin{aligned} v_{r_1} &= 1 - 2k^2\cos^2\beta \\ v_{\phi_1} &= -\frac{\cos\beta}{\sin\beta}\left[1 + k^2(\sin^2\beta - \cos^2\beta)\right] \end{aligned}\right\} \tag{40}$$

It is seen that v_{r_1} is an even function of β and v_{ϕ_1} is an odd function of β.

The vertical velocity w_1 is also used in the loading equation

$$w_1 = v_{r_1}\sin\phi + v_{\phi_1}\cos\phi \tag{41}$$

Equation (41) can be expressed entirely in terms of β by use of equation (40) and the relationships

$$\left.\begin{aligned} \sin\phi &= 1 - 2k^2\cos^2\beta \\ \cos\phi &= 2k\cos\beta\sqrt{1 - k^2\cos^2\beta} \end{aligned}\right\} \tag{42}$$

with the result that

$$w_1 = 1 - \frac{2k\cos^2\beta}{\sin\beta}\left(k\sin\beta + \sqrt{1 - k^2\cos^2\beta}\right)^2 \tag{43}$$

Solution for Dilating Circular Arc

Complex potential.- The complex potential and velocities for a dilating arc can be obtained in a manner similar to that for a translating arc. The boundary conditions in the ζ_1 plane, figure 5(a), are that $\partial\phi/\partial\nu$ be unity on the arc and the velocity at infinity be zero. The flow external to a circular arc with an as yet undetermined normal velocity distribution in the ζ_4 plane can be transformed as before to a circular arc with a uniform normal velocity distribution. The specification of the normal velocity distribution in the ζ_4 plane is determined by the boundary conditions in the ζ_1 plane.

The flow due to any distribution of normal velocity on the circle in the ζ_4 plane can be represented by a Laurent series

$$W_2(\zeta_4) = \sum_{n=1}^{\infty} \frac{a_n}{\zeta_4^n} \tag{44}$$

The problem is to determine the coefficients a_n which will satisfy the normal boundary condition in the ζ_1 plane; that is, unit normal velocity on the circular arc. We satisfy the boundary condition in the following way

$$\left(v_{r_2} - iv_{\phi_2}\right) e^{-i\phi} = \frac{dW_2}{d\zeta_1} = \frac{dW_2}{d\zeta_4} \frac{d\zeta_4}{d\zeta_3} \frac{d\zeta_3}{d\zeta_2} \frac{d\zeta_2}{d\zeta_1}$$

$$= \frac{-1}{1 - \frac{\ell^2}{\zeta_3^2}} \sum_{n=1}^{\infty} \frac{na_n}{\zeta_4^{n+1}} \tag{45}$$

Equation (45) is a Laurent series in ζ_4 valid over the complete interval $0 \leq \theta \leq 2\pi$. On the circle, we find that

$$\frac{e^{i\phi}\zeta_3^2}{\zeta_3^2 - \ell^2} = \frac{(ke^{i\theta} + i)(e^{i\theta} + ik)}{2i(\sin\theta + k)} \tag{46}$$

so that equation (45) becomes

$$\left(v_{r_2} - iv_{\phi_2}\right)_{\zeta_1 \text{arc}} = - \sum_{n=1}^{\infty} \frac{na_n}{a^{n+1}} e^{-i(n+1)\theta} \frac{(ke^{i\theta} + i)(e^{i\theta} + ik)}{2i(\sin\theta + k)} \tag{47}$$

or

$$\left(v_{r_2} - iv_{\phi_2}\right)_{\zeta_1 \text{arc}} (\sin\theta + k) = - \frac{1}{2} \sum_{n=1}^{\infty} \frac{na_n}{a^{n+1}} e^{-in\theta} (1 + 2k \sin\theta + k^2) \tag{48}$$

Defining

$$\frac{na_n}{a^{n+1}} = P_n + iQ_n \tag{49}$$

we get

$$\left(v_{r_2} - iv_{\phi_2}\right)_{\zeta_1 \text{arc}} (\sin\theta + k) = - \frac{1}{2} \sum_{n=1}^{\infty} (P_n + iQ_n) e^{-in\theta} (1 + 2k \sin\theta + k^2) \tag{50}$$

Since v_{r_2} is unity on the arc in the ζ_1 plane, we obtain for the real part of equation (50) after some manipulation

$$\frac{\sin\theta + k}{1 + 2k \sin\theta + k^2} = - \frac{1}{2} \sum_{n=1}^{\infty} (P_n \cos n\theta + Q_n \sin n\theta) \tag{51}$$

We have the known Fourier series

$$\frac{\sin\theta + k}{1 + 2k \sin\theta + k^2} = - \sum_{n=1}^{\infty} (-1)^n k^{2n-2} \left[k \cos 2n\theta + \sin (2n - 1)\theta\right]$$

$$0 \leq \theta \leq \pi; \ k < 1 \tag{52}$$

from which

$$\left.\begin{aligned} P_{2n} &= (2)(-1)^n k^{2n-1} \\ P_{2n-1} &= 0 \end{aligned}\right\} \quad n = 1,2,3,\ldots \tag{53}$$

$$\left.\begin{aligned} Q_{2n-1} &= (2)(-1)^n k^{2n-2} \\ Q_{2n} &= 0 \end{aligned}\right\} \tag{54}$$

Accordingly, the complex potential is

$$W_2(\zeta_4) = 2 \sum_{n=1}^{\infty} \frac{(-1)^n k^{2n-1} a^{2n+1}}{2n\zeta_4^{2n}} + 2i \sum_{n=1}^{\infty} \frac{(-1)^n k^{2n-1} a^{2n}}{(2n - 1)\zeta_4^{2n-1}} \tag{55}$$

The series can be rewritten as follows

$$W_2(\zeta_4) = - \frac{a}{k} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} \left(\frac{k^2a^2}{\zeta_4^2}\right)^n - 2i \frac{a}{k} \sum_{n=0}^{\infty} \frac{(-1)^n}{(2n + 1)} \left(\frac{ka}{\zeta_4}\right)^{2n+1} \tag{56}$$

From the known expansions for $\ln (1 + x)$ and $\tan^{-1} x$, we can sum the series

$$W_2(\zeta_4) = - \frac{2a}{k} \left\{\frac{1}{2} \ln \left(1 + \frac{k^2a^2}{\zeta_4^2}\right) + i \tan^{-1}\left(\frac{ka}{\zeta_4}\right)\right\} \tag{57}$$

The expression for W_2 can be further simplified to

$$W_2(\zeta_4) = - \frac{2a}{k} \ln \left(1 + \frac{ika}{\zeta_4}\right) \tag{58}$$

Velocity components.- The velocity components have been evaluated in the same manner as for the previous case. The results for the radial and tangential velocities on the arc are

$$\left.\begin{aligned} v_{r_2} &= \frac{\partial \phi_2}{\partial r} = 1 \\ v_{\phi_2} &= \frac{1}{r}\frac{\partial \phi_2}{\partial \phi} = -\frac{\cos\beta}{\sin\beta} \end{aligned}\right\} \tag{59}$$

It is noted that v_{r_2} is an even function of β while v_{ϕ_2} is an odd function analogous to the v_{r_1} and v_{ϕ_1} velocity components. We are also interested in w_2 for determining the wing loading

$$\begin{aligned} w_2 &= v_{r_2}\sin\phi + v_{\phi_2}\cos\phi \\ &= \sin\phi - \frac{\cos\beta}{\sin\beta}\cos\phi \end{aligned} \tag{60}$$

With the help of equation (42) the result for w_2 becomes

$$w_2 = 1 - \frac{2k^2\cos^2\beta}{\sin\beta}\left(k\sin\beta + \sqrt{1 - k^2\cos^2\beta}\right) \tag{61}$$

Wing Loading

The wing loading equations will now be determined with the help of equation (17). The loading is considerably simpler to obtain than the pressure distribution because the even terms in β do not contribute to the loading. Consider, for instance, the squares term, $v^2 + w^2$, in equation (17), or its equal, $v_r^2 + v_\phi^2$. From equations (40) and (59), it is clear that v_{r_1} and v_{r_2} are even in β. The quantities v_{ϕ_1} and v_{ϕ_2} are both odd in β by the same equations. Accordingly, the square term contributes nothing to the loading.

The loading is given with the help of equation (17) as

$$\Delta P = P_\ell - P_u = \frac{2(u_u - u_\ell)}{V_\infty} + \frac{2\alpha(w_u - w_\ell)}{V_\infty} \tag{62}$$

where the subscripts u and ℓ refer to corresponding points on the upper and lower surfaces respectively. Considering now only the parts of u and w odd in β, we have

$$\Delta P = 4\left(\frac{u_u}{V_\infty} + \frac{\alpha w_u}{V_\infty}\right)_{odd} \tag{63}$$

where the subscript odd applies to quantities of the upper surface. From equations (20) and (21) taking $\cos\alpha$ equal to unity

$$\frac{(u_u)_{odd}}{V_\infty} = -\frac{d^2}{dx^2}(e + r)(\phi_1)_{odd} - \frac{d}{dx}(e + r)\left.\frac{\partial\phi_1}{\partial x}\right|_{odd} + \frac{d^2r}{dx^2}\left.\phi_2\right|_{odd} + \frac{dr}{dx}\left.\frac{\partial\phi_2}{\partial x}\right|_{odd} \tag{64}$$

$$\frac{(w_u)_{odd}}{V_\infty} = -\frac{d}{dx}(e + r)\left.\frac{\partial\phi_1}{\partial z}\right|_{odd} + \frac{dr}{dx}\left.\frac{\partial\phi_2}{\partial z}\right|_{odd} \tag{65}$$

At the wing surface, we find the following results from equations (33) and (58) for the velocity potentials, from which the odd and even parts can readily be separated.

$$\phi_1 = rk\left[k - 2\sin\beta\sqrt{1 - k^2\cos^2\beta}\right] \tag{66}$$

$$\begin{aligned}\phi_2 &= -r\ln\left(\sqrt{1 - k^2\cos^2\beta} + k\sin\beta\right)\\ &= -2r\tanh^{-1}\left(\frac{k\sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\right) - r\ln(1 - k^2)\end{aligned} \tag{67}$$

The odd parts of the derivatives are found first by taking the derivatives of $W_1(\zeta)$ and $W_2(\zeta)$ with respect to x, determining the value of the resulting complex expressions at the canopy surface, and then extracting the real parts. These processes, which are quite lengthy, yield the following results.

$$\left.\frac{\partial\phi_1}{\partial x}\right|_{odd} = -\frac{k\sqrt{1 - k^2\cos^2\beta}}{\sin\beta}\left[2\cos^2\beta\,(1 + k^2 - 2k^2\cos^2\beta)\left(\frac{de'}{dx}\right) + (1 + 2k^2\cos^2\beta - 4k^4\cos^4\beta)\left(\frac{dr}{dx}\right) + \frac{1}{2k^2}\left(\frac{df}{dx}\right)\right] \tag{68}$$

$$\left.\frac{\partial \phi_2}{\partial x}\right|_{\text{odd}} = \frac{k\sqrt{1 - k^2\cos^2 \beta}}{2 \sin \beta} \left[-4 \cos^2 \beta \left(\frac{de'}{dx}\right) + \frac{2}{1 - k^2} \left(1 - 2 \cos^2 \beta \right.\right.$$

$$\left.\left. + 2k^2\cos^2 \beta\right) \left(\frac{dr}{dx}\right) - \frac{1}{k^2(1 - k^2)} \left(\frac{df}{dx}\right)\right] \tag{69}$$

It is noted that the three independent parameters specifying the shape have been taken to be r, e, and f together with their x derivatives. The total loading can then be written

$$\begin{aligned}
\Delta P = &+ 8r \frac{d^2e}{dx^2} k \sin \beta \sqrt{1 - k^2\cos^2 \beta} \\
&+ 4r \frac{d^2r}{dx^2} \left[2k \sin \beta \sqrt{1 - k^2\cos^2 \beta} - \ln \left(\frac{\sqrt{1 - k^2\cos^2 \beta} + k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta} - k \sin \beta}\right)\right] \\
&+ 8 \left(\frac{de}{dx}\right)^2 \frac{k \cos^2 \beta}{\sin \beta} \sqrt{1 - k^2\cos^2 \beta} \quad (1 + k^2 - 2k^2\cos^2 \beta) \\
&+ 4 \left(\frac{dr}{dx}\right)^2 \frac{k\sqrt{1 - k^2\cos^2 \beta}}{\sin \beta} \left[1 + \frac{1}{1 - k^2} - 2(1 - k^2)\cos^2 \beta - 4k^2\cos^4 \beta \right. \\
&\qquad \left. - \frac{\sin \beta}{k\sqrt{1 - k^2\cos^2 \beta}} \ln \left(\frac{\sqrt{1 - k^2\cos^2 \beta} + k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta} - k \sin \beta}\right)\right] \\
&+ 2 \left(\frac{de}{dx}\right) \left(\frac{df}{dx}\right) \frac{\sqrt{1 - k^2\cos^2 \beta}}{k \sin \beta} \\
&- 2 \left(\frac{dr}{dx}\right)\left(\frac{df}{dx}\right) \frac{k}{(1 - k^2)} \frac{\sqrt{1 - k^2\cos^2 \beta}}{\sin \beta} \\
&+ 4 \left(\frac{dr}{dx}\right)\left(\frac{de}{dx}\right) \frac{k\sqrt{1 - k^2\cos^2 \beta}}{\sin \beta} (1 + 4k^2\cos^2 \beta - 8k^2\cos^4 \beta);
\end{aligned}$$

$$0 \leq \beta \leq \pi \tag{70}$$

It is noted that the loading depends on the shape parameters dr/dx, de/dx, and df/dx as well as d^2r/dx^2, d^2e/dx^2, and α. There are a number of distinct types of loading associated with the seven characteristic terms in the foregoing result. All but those associated with d^2e/dx^2 and d^2r/dx^2 exhibit the usual square-root singularity at the edges of the wing. Integration of these pressure distributions spanwise across the canopy will yield the chordwise load distribution without any effects of leading-edge suction.

Normal Force and Moment Distributions

Quite simple results can be obtained for the chordwise normal-force and pitching-moment distributions despite the complicated wing loading equations. The complex potential for the total flow can be found by combining perturbation complex potentials with the free-stream complex potential. Thus

$$W(\zeta) = xV_\infty \cos\alpha - i\zeta \sin\alpha - V_\infty \cos\alpha \left(\frac{dr}{dx} + \frac{de}{dx}\right) W_1(\zeta)$$

$$+ V_\infty \cos\alpha \left(\frac{dr}{dx}\right) W_2(\zeta) \qquad (71)$$

The quantity $W(\zeta)$ can be expanded in a Laurent series

$$W(\zeta) = V_\infty \cos\alpha \left[D_o \ln\zeta + C_o + \sum_{n=1}^{\infty} \frac{C_n}{\zeta_n} \right] \qquad (72)$$

Herein ζ is the complex variable in the y,z coordinate system.

$$\zeta = y + iz = \zeta_1 - ix\tan\alpha \qquad (73)$$

The coefficients D_o and C_n are generally complex, and D_o is zero for the present case wherein the wing has no volume. If we express C_n as follows

$$C_n = A_n + iB_n \qquad (74)$$

then from equations (3-64) and (3-66), reference 4, we have for the normal force (Z) and the pitching-moment coefficient M_y

$$\frac{Z}{q} = 4\pi B_1(x) \qquad (75)$$

$$M_y + iM_z = 4\pi i x C_1(x) - 4\pi i \int_0^x C_1 \, dx \qquad (76)$$

where the values of Z and M_y are those for the wing canopy from its leading edge up to some chordwise distance x. A result of this nature yields the chordwise load distribution by differentiation. The chordwise loading includes the effects of leading-edge suction.

The coefficient C_1 for $W(\zeta)$ can be written from equation (71) as

$$C_1 = -V_\infty \cos\alpha\left(\frac{dr}{dx} + \frac{de}{dx}\right)C_{11} + V_\infty \cos\alpha\left(\frac{dr}{dx}\right)C_{12}$$

where C_{11} and C_{12} are the coefficients of ζ^{-1} in the Laurent expansions for $W_1(\zeta)$ and $W_2(\zeta)$, respectively. Since the series of transformations $\zeta_4 \rightarrow \zeta_3 \rightarrow \zeta_2 \rightarrow \zeta_1 \rightarrow \zeta$ are the identity transformations at infinity, the coefficients C_{11} and C_{12} are the same in all planes. Collecting together previous results from equations (33) and (58)

$$W_1(\zeta_4) = -i\left(\frac{a^2}{\zeta_4} + \frac{\ell^2}{\zeta_4 + \frac{if}{2}}\right) \tag{77}$$

$$W_2(\zeta_4) = -\frac{2a}{k}\ln\left(1 + \frac{ika}{\zeta_4}\right) \tag{78}$$

we can see by inspection that

$$C_{11} = -i(a^2 + \ell^2) \tag{79}$$

and

$$C_{12} = -2ia^2 \tag{80}$$

The assumption is now made that $\cos\alpha$ does not differ significantly from unity. These results lead directly to the equation for the normal force

$$\frac{Z}{q} = 4\pi\left[(a^2 + \ell^2)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - 2a^2\left(\frac{dr}{dx}\right)\right] \tag{81}$$

or

$$\frac{Z}{q} = \pi s^2\left(1 + \frac{1}{1 - k^2}\right)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - \frac{2\pi s^2}{1 - k^2}\left(\frac{dr}{dx}\right) \tag{82}$$

and for the pitching moment about the apex

$$\frac{M_y}{q} = 4\pi x\left[(a^2 + \ell^2)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - 2a^2\left(\frac{dr}{dx}\right)\right]$$

$$- 4\pi\int_0^x \left[(a^2 + \ell^2)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - 2a^2\left(\frac{dr}{dx}\right)\right] dx \qquad (83)$$

or

$$\frac{M_y}{q} = \pi s^2 x\left(1 + \frac{1}{1 - k^2}\right)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - \frac{2\pi s^2 x}{1 - k^2}\left(\frac{dr}{dx}\right)$$

$$- \pi\int_0^x \left[s^2\left(1 + \frac{1}{1 - k^2}\right)\left(\frac{dr}{dx} + \frac{de}{dx}\right) - \frac{2s^2}{1 - k^2}\left(\frac{dr}{dx}\right)\right] dx \qquad (84)$$

Induced Drag

For the present lifting surface which has no volume, the induced drag is given by equation (3-74) of reference 4, as

$$\frac{D_i}{q} = - \oint_C \Phi_o \frac{\partial \Phi_o}{\partial \nu} d\tau \qquad (85)$$

where C is a contour enclosing the base of the lifting surface in the rearmost crossflow plane, $\vec{\nu}$ is the outward normal in the crossflow plane, and $\vec{\tau}$ is the tangent. Now repeating equation (12)

$$\Phi = -V_\infty \cos\alpha\left(\frac{dr}{dx} + \frac{de}{dx}\right)\phi_1 + V_\infty \cos\alpha \frac{dr}{dx}\phi_2$$

$$+ xV_\infty \cos\alpha + zV_\infty \sin\alpha \qquad (86)$$

and making the assumption that $\cos\alpha$ is unity, we define the following quantities

$$\phi_o \equiv \frac{\Phi}{V_\infty \cos\alpha} \equiv \lambda_1\phi_1 + \lambda_2\phi_2 + \lambda_3 \qquad (87)$$

wherein

$$\lambda_1 \equiv -\left(\frac{dr}{dx} + \frac{de}{dx}\right)$$

$$\lambda_2 \equiv \frac{dr}{dx}$$

$$\lambda_3 \equiv x + z \tan \alpha$$

The values of ϕ_1 and ϕ_2 on the surface have odd and even parts, and since $\partial\phi/\partial\nu$ is an odd function of β, only the odd parts of ϕ_1 and ϕ_2 at the surface contribute to the induced drag. From equations (66) and (67), we find

$$(\phi_1)_{odd} = -2a \sin \beta \sqrt{1 - k^2\cos^2 \beta} \tag{88}$$

$$(\phi_2)_{odd} = -\frac{a}{k} \ln\left(\frac{k \sin \beta + \sqrt{1 - k^2\cos^2 \beta}}{-k \sin \beta + \sqrt{1 - k^2\cos^2 \beta}}\right) \tag{89}$$

or

$$= -\frac{2a}{k} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right)$$

On the wing surface

$$\frac{\partial\phi_1}{\partial r} = \sin \phi \tag{90}$$

$$\frac{\partial\phi_2}{\partial r} = 1 \tag{91}$$

Equation (85) for the drag can be written

$$\frac{D_i}{q} = \lambda_1^2 I_1 + \lambda_1\lambda_2(I_2 + I_3) + \lambda_2^2 I_4 \tag{92}$$

where

$$\left.\begin{aligned} I_1 &= -\oint_C \phi_1 \frac{\partial \phi_1}{\partial \nu}\, d\tau \\ I_2 &= -\oint \phi_1 \frac{\partial \phi_2}{\partial \nu}\, d\tau \\ I_3 = I_2 &= -\oint \phi_2 \frac{\partial \phi_1}{\partial \nu}\, d\tau \\ I_4 &= -\oint \phi_2 \frac{\partial \phi_2}{\partial \nu}\, d\tau \end{aligned}\right\} \tag{93}$$

$$\left.\begin{aligned} \sin\phi &= 1 - 2k^2\cos^2\beta \\ \cos\phi &= 2k\cos\beta\sqrt{1 - k^2\cos^2\beta} \\ d\tau = r\,d\phi &= \frac{4rk^2\cos\beta\sin\beta\,d\beta}{\cos\phi} = \frac{2rk\sin\beta\,d\beta}{\sqrt{1 - k^2\cos^2\beta}} \end{aligned}\right\} \tag{94}$$

The integrals can be evaluated as follows.

$$I_1 = -2\int_0^{\pi} \left(-2a\sin\beta\sqrt{1 - k^2\cos^2\beta}\right)\sin\phi\ \frac{(2rk\sin\beta)\,d\beta}{\sqrt{1 - k^2\cos^2\beta}}$$

$$= +\,8ark\int_0^{\pi} \sin^2\beta\,(1 - 2k^2\cos^2\beta)\,d\beta$$

Now

$$\int_0^{\pi} \sin^2\beta\,d\beta = \frac{\pi}{2}$$

and

$$\int_0^{\pi} \sin^2 \beta \cos^2 \beta = \int_0^{\pi} \sin^2 \beta \, d\beta - \int_0^{\pi} \sin^4 \beta \, d\beta = \frac{\pi}{2} - \frac{3\pi}{8} = \frac{\pi}{8}$$

Therefore,

$$I_1 = +8ark\left(\frac{\pi}{2} - k^2 \frac{\pi}{4}\right) = +2\pi ark\left(2 - k^2\right) \tag{95}$$

Also,

$$I_2 = -2\int_0^{\pi} \left(-2a \sin \beta \sqrt{1 - k^2\cos^2 \beta}\,\right) \frac{(2rk \sin \beta)\,d\beta}{\sqrt{1 - k^2\cos^2 \beta}}$$

$$= 8ark \int_0^{\pi} \sin^2 \beta \, d\beta$$

$$= 4\pi ark \tag{96}$$

Also

$$I_3 = -2\int_0^{\pi} \left[-\frac{2a}{k} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right)\right] (1 - 2k^2\cos^2 \beta) \frac{2rk \sin \beta \, d\beta}{\sqrt{1 - k^2\cos^2 \beta}}$$

$$= +\ 8ar \int_0^{\pi} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right) \frac{(1 - 2k^2\cos^2 \beta) \sin \beta \, d\beta}{\sqrt{1 - k^2\cos^2 \beta}}$$

$$= 4\pi ark \tag{97}$$

Finally,

$$I_4 = -2\int_0^{\pi} \left[-\frac{2a}{k} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right)\right] \frac{2rk \sin \beta \, d\beta}{\sqrt{1 - k^2\cos^2 \beta}}$$

$$= +\ \frac{8ar}{k} \int_0^{\pi} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right) \frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}} \, d\beta \tag{98}$$

The value of this integral is worked out in appendix A. With the notation

$$J(k) = \frac{1}{k^2}\int_0^{\pi} \tanh^{-1}\left(\frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\right) \frac{k \sin \beta}{\sqrt{1 - k^2\cos^2 \beta}}\, d\beta$$

$$= \frac{-\pi}{2k^2} \ln (1 - k^2) \tag{99}$$

we have

$$I_4 = 8arkJ(k) \tag{100}$$

From equation (92) the induced drag is found to be

$$\frac{D_i}{q} = 2\pi ark \left[\left(\frac{dr}{dx} + \frac{de}{dx}\right)^2 (2 - k^2) - 4\frac{dr}{dx}\left(\frac{dr}{dx} + \frac{de}{dx}\right) + \frac{4J}{\pi}\left(\frac{dr}{dx}\right)^2\right] \tag{101}$$

This result can be applied to the trailing edge of the nonplanar lifting surface to determine the induced drag. Such induced drag includes components associated with lift and with zero lift. For a cylindrical parawing dr/dx is zero, and if it is further at zero angle of attack, then de/dx is also zero. Accordingly, the induced drag given by equation (101) is zero, as it should be.

It is of interest to consider the ratio of normal force to induced drag as given by equations (82) and (101). From these results it is readily shown that

$$\frac{Z}{D_i} = \frac{2\left[\left(\frac{dr}{dx} + \frac{de}{dx}\right)(2 - k^2) - 2\frac{dr}{dx}\right]}{\left(\frac{dr}{dx} + \frac{de}{dx}\right)^2 (2 - k^2) - 4\frac{dr}{dx}\left(\frac{dr}{dx} + \frac{de}{dx}\right) + \frac{4J}{\pi}\left(\frac{dr}{dx}\right)^2} \tag{102}$$

For a flat plate at angle of attack α, it can be shown from equation (102) that

$$\frac{Z}{D_i} = \frac{2}{\alpha} \tag{103}$$

This is the well-known result of slender-body theory that the induced drag due to lift corresponds to a rearward inclination of the resultant force vector due to lift of $\alpha/2$.

Leading-Edge Suction and Vortex Lift

In the present case of a nonplanar lifting surface, the leading-edge suction forces can change the magnitude of the lift and drag as well as the side force of either panel. It is of interest to know how important the effect of leading-edge suction is on these aerodynamic quantities for nonplanar lifting-surface shapes typical of all-flexible parawings.

Leading-edge suction.- Usually an evaluation of the leading-edge suction is made by the method of Jones and Cohen, reference 5, which utilizes complex integration around a contour partially surrounding the edge. In the present case, a different method is utilized. The normal force as obtained from equation (82) includes the leading-edge suction force. We may determine the normal force without leading-edge suction by integrating the pressure distributions given by equation (70) over the lifting surface exclusive of contours around the leading edges. The difference in normal force for the two calculations is the component of leading-edge suction force in the normal-force direction. The leading-edge suction force is normal to the leading edge in a plane tangent to the lifting surface. Knowing the direction and the one component of the leading-edge suction, we can therefore determine its other components.

The integration of equation (70) to obtain the normal-force chordwise distribution without suction has been carried out for all seven terms of that equation. Introducing the following subscript notation

$$\left.\begin{array}{cccc} \dfrac{d^2e}{dx^2} \sim 2e & \dfrac{d^2r}{dx^2} \sim 2r & \left(\dfrac{de}{dx}\right)^2 \sim ee & \left(\dfrac{dr}{dx}\right)^2 \sim rr \\ \dfrac{de}{dx}\dfrac{df}{dx} \sim ef & \dfrac{dr}{dx}\dfrac{df}{dx} \sim rf & \dfrac{de}{dx}\dfrac{dr}{dx} \sim er & \end{array}\right\} \qquad (104)$$

we find the following result for the first component

$$\frac{dC_{Z_{2e}}}{dx} = \frac{1}{S_R}\int_{\phi_\ell}^{\phi_r} \Delta P_{2e} \sin\phi \; r \, d\phi$$

$$= \frac{16\,k^2r^2}{S_R} \; \frac{d^2e}{dx^2}\int_0^{\pi} \sin^2\beta(1 - 2k^2\cos^2\beta)d\beta$$

$$= \frac{4\pi r^2}{S_R} \; \frac{d^2e}{dx^2} k^2(2 - k^2) \tag{105}$$

The results for all seven components of the loading without suction are:

$$\frac{dC_{Z_{2e}}}{dx} = \frac{4\pi r^2}{S_R} \; \frac{d^2e}{dx^2} k^2(2 - k^2) \tag{106}$$

$$\frac{dC_{Z_{2r}}}{dx} = - \frac{4\pi r^2}{S_R} \; \frac{d^2r}{dx^2} k^4 \tag{107}$$

$$\frac{dC_{Z_{ee}}}{dx} = \frac{8\pi r}{S_R}\left(\frac{de}{dx}\right)^2 k^2(1 - k^2)^2 \tag{108}$$

$$\frac{dC_{Z_{rr}}}{dx} = \frac{8\pi r}{S_R}\left(\frac{dr}{dx}\right)^2 k^6 \tag{109}$$

$$\frac{dC_{Z_{ef}}}{dx} = \frac{4\pi r}{S_R}\left(\frac{de}{dx}\right)\left(\frac{df}{dx}\right)(1 - k^2) \tag{110}$$

$$\frac{dC_{Z_{rf}}}{dx} = - \frac{4\pi r}{S_R}\left(\frac{dr}{dx}\right)\left(\frac{df}{dx}\right) k^2 \tag{111}$$

$$\frac{dC_{Z_{re}}}{dx} = \frac{8\pi r}{S_R}\left(\frac{dr}{dx}\right)\left(\frac{de}{dx}\right) k^2(1 - 2k^2 + 2k^4) \tag{112}$$

where the induced drag associated with vortex lift $(\Delta C_{D_i})_v$ by analogy with equation (126) is

$$\begin{aligned}(\Delta C_{D_i})_v &= (\Delta C_Z)_v \sin\alpha + (\Delta C_X)_v \cos\alpha \\ &= C_s\left[\alpha\cos(n_1,z) + \cos(n_1,x)\right] \\ &= \frac{(\Delta C_Z)_s}{\cos(n_2,z)}\left[\alpha\cos(n_1,z) + \cos(n_1,x)\right] \qquad (132)\end{aligned}$$

Theory for Conical Parawings

While an all-flexible parawing is not conical, the qualitative effects of spanwise camber for a conical parawing are of interest to the extent they lead to an understanding of all-flexible parawings with large spanwise camber. Therefore, the foregoing theoretical results will be applied to a conical parawing to obtain closed algebraic results for the effects of spanwise camber.

The configuration type is illustrated in figure 6 with the straight leading edges lying in the x-y plane and all sections of the canopy in planes parallel to the y-z plane being circular arcs of uniform k. The canopy is thus part of a circular cone. For a canopy which is half of a right circular cone in particular, the cross sections are semicircular and $k = 0.707$.

For a conical canopy, the angle of attack of the chord plane is

$$\alpha = \frac{de}{dx} + \frac{df}{dx} \qquad (133)$$

so that

$$\frac{dr}{dx} + \frac{de}{dx} = \alpha + \frac{(1 - 2k^2)}{2k\sqrt{1 - k^2}}\frac{ds}{dx} \qquad (134)$$

where s is the local semispan.

Also,

$$\frac{dr}{dx} = \frac{1}{2k\sqrt{1 - k^2}} \frac{ds}{dx} \tag{135}$$

Writing equation (82) in the following form

$$\frac{Z}{q} = \pi s^2 \left(1 + \frac{1}{1 - k^2}\right) \alpha + \pi s^2 \left(1 + \frac{1}{1 - k^2}\right)\left(\frac{dr}{dx} - \frac{df}{dx}\right) - \frac{2\pi s^2}{1 - k^2} \frac{dr}{dx} \tag{136}$$

and utilizing equations (133) to (135), we obtain the normal-force coefficient

$$C_Z = \frac{\pi s^2}{S_R} \left\{\frac{2 - k^2}{1 - k^2} \left[\alpha + \frac{1 - 2k^2}{2k\sqrt{1 - k^2}} \frac{ds}{dx}\right] - \frac{1}{k(1 - k^2)^{3/2}} \frac{ds}{dx}\right\} \tag{137}$$

Alternately, it is convenient to form a normal-force parameter

$$\frac{S_R}{s_m^2} \frac{C_Z}{\alpha} = \left(\frac{4}{\mathcal{R}} \frac{C_Z}{\alpha}\right) = \frac{\pi(2 - k^2)}{(1 - k^2)} \left[1 - \frac{k(5 - 2k^2)}{2(2 - k^2)\sqrt{1 - k^2}} \left(\frac{ds/dx}{\alpha}\right)\right] \tag{138}$$

which depends only on k and $\alpha/(ds/dx)$. From equation (137), the term proportional to α is associated with the slope of the normal-force curve. For fixed values of ds/dx and α, the ratio of normal force due to α with and without spanwise camber is given by

$$K \equiv \frac{(Z)_{k\neq o}}{(Z)_{k=o}} = \frac{(2 - k^2)}{2(1 - k^2)} \; ; \quad \beta \leq 90^\circ \tag{139}$$

The quantity K can be thought of as an apparent mass ratio which indicates the extent to which spanwise camber increases the lift-curve slope. If $\beta > 90^\circ$, we can form a similar ratio. The ratio chosen is that of the normal force due to α for the cambered surface to that of the flat surface having the same maximum span, which is now the cone diameter. In this case, we have

$$K \equiv \frac{(Z)_{k\neq o}}{(Z)_{k=o}} = \frac{4\left(\frac{f}{s}\right)^2 \left(1 + \frac{1}{2}\frac{f^2}{s^2}\right)}{\left(1 + \frac{f^2}{s^2}\right)^2} = 2k^2(2 - k^2) \; ; \quad 90^\circ \leq \beta \leq 180^\circ \tag{140}$$

With regard to the angle of zero normal force, the analysis yields

$$\frac{\alpha_o}{df/dx} = \frac{1}{2}\ \frac{5 - 2k^2}{2 - k^2} = \frac{5 + 3\,\frac{f^2}{s^2}}{2\left(2 + \frac{f^2}{s^2}\right)}\ ; \qquad 0 \leq \beta < 180^\circ \tag{141}$$

or in terms of the parameter ds/dx

$$\frac{\alpha_o}{(ds/dx)} = \frac{k(5 - 2k^2)}{2(2 - k^2)\sqrt{1 - k^2}} \tag{142}$$

Results similar to those for normal force can also be obtained for induced drag. From equation (101) and equations (133) and (134) we find

$$\frac{4}{A\!\!\!R}\ \frac{C_{D_i}}{\alpha^2} = \frac{\pi}{2}\left(\frac{2 - k^2}{1 - k^2}\right)\left\{1 - \frac{k(5 - k^2)}{\sqrt{1 - k^2}\ (2 - k^2)}\left(\frac{ds/dx}{\alpha}\right)\right.$$
$$\left. + \frac{\left[4J/\pi - (1 - 2k^2)(2 + 5k^2 - 2k^4)\right]}{4k^2(1 - k^2)(2 - k^2)}\left(\frac{ds/dx}{\alpha}\right)^2\right\} \tag{143}$$

To obtain the part of the normal force due to leading-edge suction, we write equation (123) as

$$\frac{d(\Delta C_Z)_s}{dx} = -\frac{8\pi k^2 r}{S_R}\left\{(1 - k^2)\left[\alpha + \frac{1 - 2k^2}{2k\sqrt{1 - k^2}}\ \frac{ds}{dx}\right] - \frac{1}{2k\sqrt{1 - k^2}}\ \frac{ds}{dx}\right\}^2 \tag{144}$$

Integration of the foregoing equation over the root chord yields the normal-force coefficient

$$(\Delta C_Z)_s = -\frac{8\pi k^2}{S_R}\left\{(1 - k^2)\left[\alpha + \frac{1 - 2k^2}{2k\sqrt{1 - k^2}}\ \frac{ds}{dx}\right]\right.$$
$$\left. - \frac{1}{2k\sqrt{1 - k^2}}\ \frac{ds}{dx}\right\}^2 \int_0^{c_r} r\,dx \tag{145}$$

Since

$$\frac{ds}{dx} = \frac{s}{c_r} \; ; \qquad \frac{r}{s} = \frac{1}{2k\sqrt{1 - k^2}} \tag{146}$$

it can easily be shown that

$$\frac{4}{\mathit{A\!\!R}} \, \frac{(\Delta C_Z)_s}{\alpha} = -2\pi k(1 - k^2)^{3/2}\left(\frac{\alpha}{dx/dx}\right)\left[1 - \frac{k(3 - 2k^2)}{2(1 - k^2)^{3/2}} \; \frac{ds/dx}{\alpha}\right]^2 \tag{147}$$

It is seen that the fractional part of the total normal force due to leading-edge suction thus depends only on the parameters k and $\alpha/(ds/dx)$. If k is zero as for a flat plate, no normal force is associated with leading-edge suction. However, if k is greater than zero, a negative normal force is associated with such suction, and loss of suction results in an increase in normal force.

The induced drag associated with leading-edge suction can be readily obtained from $(\Delta C_Z)_s$ with the help of equation (127). Using the direction cosines derived in Appendix B, we find

$$\frac{4}{\mathit{A\!\!R}} \, \frac{(\Delta C_{D_i})_s}{\alpha^2} = \frac{4}{\mathit{A\!\!R}} \, \frac{(\Delta C_Z)_s}{\alpha}\left[1 + \frac{(1 - 2k^2)(ds/dx)/\alpha}{2k\sqrt{1 - k^2}\left(1 + \frac{\mathit{A\!\!R}^2}{16}\right)}\right] \tag{148}$$

From equations (143) and (148), the induced drag with and without leading-edge suction can be readily calculated.

An additional item is of interest. It is noted in equation (147) that the leading-edge suction is zero at a certain angle of attack. By analogy with airfoil practice, we term this angle of attack the ideal angle of attack, α_{ideal}. From equation (147), this angle is given by

$$\frac{\alpha_{ideal}}{(ds/dx)} = \frac{k(3 - 2k^2)}{2(1 - k^2)^{3/2}} \tag{149}$$

Using the direction cosines we find

$$(\Delta C_{D_i})_s = (\Delta C_Z)_s \left[\alpha + \frac{\cos(n_2,x)}{\cos(n_2,z)} \right] \tag{127}$$

Vortex lift.- It is of interest to determine the probable importance of the vortex-lift concept of Polhamus, reference 6, for all-flexible parawing applications. In this concept, the force of leading-edge suction is no longer assumed to act normal to the leading edge in a plane tangent to the canopy. It is assumed that a separation bubble occurs on the upper surface of the wing extending from the leading edge inward and that the suction force is changed only in direction but not in magnitude. For the present purpose, it is assumed that this bubble is of such a small extent that the force is rotated 90° on the average to a direction along $\vec{n}_1$ normal to the canopy and the leading edge.

To obtain the vortex normal force, $(\Delta C_Z)_v$, we have

$$(\Delta C_Z)_v = C_s \cos(n_1,z) \tag{128}$$

and from equation (125)

$$(\Delta C_Z)_v = (\Delta C_Z)_s \frac{\cos(n_1,z)}{\cos(n_2,z)} \tag{129}$$

The total normal force with vortex lift is then

$$(C_Z)_v = (C_Z) - (\Delta C_Z)_s + (\Delta C_Z)_v \tag{130}$$

In order to obtain the total induced drag with vortex lift, $(C_{D_i})_v$, we have

$$(C_{D_i})_v = (C_{D_i}) - (\Delta C_{D_i})_s + (\Delta C_{D_i})_v \tag{131}$$

Let us turn now to evaluating the increments in normal force and drag associated with vortex lift. From the direction cosines given in Appendix B, we find using equation (129) that

$$\frac{4}{A\!\!R} \frac{(\Delta C_Z)_v}{\alpha} = -\frac{4}{A\!\!R} \frac{(\Delta C_Z)_s}{\alpha} \frac{(1 - 2k^2)}{2k\sqrt{1 - k^2}\sqrt{1 + \left(\frac{A\!\!R}{4}\right)^2}} \tag{150}$$

The induced drag associated with vortex lift becomes, using equation (132),

$$(\Delta C_{D_i})_v = -\frac{\alpha(\Delta C_Z)_s (1 - 2k^2)}{2k\sqrt{1 - k^2}\sqrt{1 + \left(\frac{A\!\!R}{4}\right)^2}} \left[1 - \frac{2k\sqrt{1 - k^2}}{1 - 2k^2}\left(\frac{ds/dx}{\alpha}\right)\right] \tag{151}$$

For purposes of later comparison, it is desired to obtain specific results for k = 0. In this case, the results of equations (138) and (143) yield the following nondimensional results for lift, induced drag, and drag-rise factor with full suction

$$\left.\begin{aligned} \left(\frac{4}{A\!\!R}\right)^2 C_Z &= 2\pi\left(\frac{\alpha}{ds/dx}\right) \\ \left(\frac{4}{A\!\!R}\right)^3 C_{D_i} &= \pi\left(\frac{\alpha}{ds/dx}\right)^2 \\ \frac{C_{D_i}}{C_Z^{\,2}} &= \frac{1}{\pi A\!\!R} \end{aligned}\right\} \tag{152}$$

With no leading-edge suction, we find the same result for C_Z, but for the other quantities we have

$$\left.\begin{aligned} \left(\frac{4}{A\!\!R}\right)^3 C_{D_i} &= 2\pi\left(\frac{\alpha}{ds/dx}\right)^2 \\ \frac{C_{D_i}}{C_Z^{\,2}} &= \frac{2}{\pi A\!\!R} \end{aligned}\right\} \tag{153}$$

With vortex lift the corresponding results are

$$\left.\begin{aligned}\left(\frac{4}{\mathit{AR}}\right)^2 C_Z &= 2\pi\left(\frac{\alpha}{ds/dx}\right) + \pi\left(\frac{\alpha}{ds/dx}\right)^2\\ \left(\frac{4}{\mathit{AR}}\right)^3 C_{D_i} &= 2\pi\left(\frac{\alpha}{ds/dx}\right)^2 + \pi\left(\frac{\alpha}{ds/dx}\right)^3\end{aligned}\right\} \tag{154}$$

$$\frac{C_{D_i}}{{C_Z}^2} = \frac{2}{\pi \mathit{AR}}\left[\frac{1}{1 + \frac{1}{2}\left(\frac{\alpha}{ds/dx}\right)}\right] \tag{155}$$

RESULTS AND DISCUSSION

Theoretical Results for Conical Canopies

The nonplanar slender-body theory described in the preceding section of the report has been used to make a systematic set of calculations for conical canopies formed by segments of circular cones. These calculations illustrate a number of significant qualitative effects which have bearing on the aerodynamics of real parawings. Let us then consider the results for conical parawings and their implications for all-flexible parawings.

It is of interest to have a knowledge of the shape parameters of an all-flexible parawing in order to assess the probable applicability of the theoretical results for conical parawings to those of the all-flexible type. The variation of s and k with chordwise distance are shown in figure 7 as obtained from shape measurements on a twin-keel all-flexible parawing. Examination of the variation of s with x near the trailing edge of the root chord shows that it is not possible to characterize the parawing by a single value of ds/dx as for a conical one. However, figure 7(b) shows that a value of $k = 0.5$ is a good average value for the parawing.

Considering first normal-force results, the apparent mass factor K given by equations (139) and (140) is shown as a function of the spanwise camber parameter k in figure 8(a). It is noted that a surface of semicircular cross section has a normal-force curve slope 50 percent greater than that for a triangular flat wing of the same span. For the limiting case of $k = 1$, the slope is doubled. The limiting configuration for $k = 1$ is not a solid circle because there is still a slit in the bottom meridian, and pressures exist on both sides of the wing surface. Corresponding results for the angle of zero normal force are shown in figure 8(b). The angle is greater than df/dx because the wing has geometric washout.

There exists an ideal angle of attack, calculable from equation (149), for which the leading-edge suction becomes zero at all points along the leading edges. The ratio of ideal angle of attack to ds/dx is shown as a function of k in figure 9 together with corresponding results for α_o. The ideal angle of attack varies from $1.2\ \alpha_o$ at $k = 0$ to $1.5\ \alpha_o$ at $k = 0.707$. For a wing of aspect ratio 2, $ds/dx = 0.5$. For $k = 0.5$, this wing would have an ideal angle of attack close to 0.5 radian. If the wing were operated at an angle less than the ideal angle of attack, the stagnation point would move to the upper canopy surface, and luffing would occur.

It is of interest to examine the effects of leading-edge suction and vortex lift on normal-force and drag characteristics of conical canopies. The effects are functions of the amount of spanwise camber. As a basis of comparison for the effect of spanwise camber, let us examine the effects of leading-edge suction and vortex lift first for $k = 0$. Figure 10 has been prepared for this purpose, based on the simple results given by equations (152) to (155) in a form independent of aspect ratio. Figure 10(a) shows no effect of leading-edge suction on normal force, but a large effect of vortex lift is exhibited at the larger values of $\alpha/(ds/dx)$ attainable with low-aspect-ratio wings. The drag curves in a non-dimensional form are shown in figure 10(b). At small normal-force coefficients the induced drag associated with vortex lift can exceed that with no suction, but at high normal-force coefficients the induced drag with vortex lift approaches that with full suction. The ratio Z/D_i is plotted in figure 10(c) to show the approximate magnitude of the ratio of normal force to induced drag. It is clear the vortex-lift effects on this ratio are important only for smaller values of the ratio. At large values of C_Z, the ratio Z/D_i with vortex lift can be greater than that for full suction.

For comparison with the foregoing results in figure 10 for $k = 0$, a corresponding set is shown in figure 11 for $k = 0.5$. This value of k was chosen because it is the average value measured for a twin-keel all-flexible parawing. In figure 11(a), it is noted that the loss of leading-edge suction now causes an increase in normal force where none was manifest previously. The difference in normal force between the full-suction and no-suction cases is almost as great as that between the vortex-lift and full-suction cases. One important effect of spanwise camber is thus that leading-edge suction can have significant effects on normal force where none occurred for $k = 0$.

For $k = 0.5$, the strength of the leading-edge suction is zero along the entire lengths of the leading edges at a value of $\alpha/(ds/dx)$ equal to 0.96 regardless of aspect ratio. Hence, all three normal-force curves for all three cases have the same normal force at the ideal angle of attack. At the ideal angle of attack, the leading-edge streamline is tangent to the camberline, and small changes in the angle of attack can put a stagnation point on either the lower surface or upper surface of the canopy.

In figure 11(b), the low ranges of the drag curves are presented for the cases of full suction, no suction, and vortex lift. At the normal-force coefficient corresponding to the ideal angle of attack, all drag curves are tangent. The point of maximum Z/D_i for any drag curve corresponds to the point of tangency to the curve of a straight line from the origin. It can thus be seen that the points of maximum Z/D_i ratio occur for values of normal force less than that corresponding to the ideal angle of attack. However, a conical parawing must operate above the ideal angle of attack so that it cannot attain the maximum value of Z/D_i. In figure 11(c), the ratio of Z/D_i is shown versus the C_Z parameter for the three cases. The results of this figure for $k = 0.5$ are qualitatively the same as those in figure 10(c) for $k = 0$.

Direct comparisons of Z/D_i ratios for two values of k are given in figure 12 for the full-suction case and the vortex-lift cases. In this figure it is seen that spanwise camber has a favorable effect on the Z/D_i ratio for both cases.

It appears that appreciable gains in the ratio of lift to induced drag could be realized if an all-flexible parawing could be rigged into a conical shape. For example, the twin-keel all-flexible parawing on which the shape data were taken has a Z/D_i ratio of 2.90 and an L/D_i ratio of 2.76 based on the present theory using measured geometric quantities. Assume that the all-flexible parawing could be rigged into a conical shape with $k = 0.5$. At the point of maximum Z/D_i corresponding to the luffing boundary, figure 11(b) gives the following values

$$\left(\frac{4}{A\!\!\!R}\right)^2 \frac{C_Z}{\pi} = 0.5 \qquad \left(\frac{4}{A\!\!\!R}\right)^3 \frac{C_{D_i}}{\pi} = 0.065$$

The ratio Z/D_i is thus

$$\frac{Z}{D_i} = \frac{0.5}{0.065}\left(\frac{4}{A\!\!\!R}\right) \approx \frac{30}{A\!\!\!R}$$

It thus appears that for any small or moderate aspect ratio all-flexible parawing, substantial gains would result if the parawing could be rigged closer to the conical shape. The gain would result principally from operating closer to the luffing condition which corresponds to the highest useful Z/D_i ratio. This point cannot be attained with present all-flexible parawings because of nose collapse. As long as the ideal angle of attack cannot be attained, vortex lift will be a factor in improved performance.

Measured Shapes and Aerodynamic Coefficients

During the course of this investigation, the Langley Research Center conducted a wind-tunnel program to obtain data on the inflated shapes of both a single-keel and a twin-keel all-flexible parawing. Prior attempts to find the inflated shapes had involved measuring, photographing, or rigidizing the models. These methods were not generally satisfactory, and the method finally adopted by Langley was the use of stereo photography. The experimental arrangement is shown in figure 13. The wing is marked with 1-inch squares. From the stereo pair of photographs, data are obtained on the line intersection points on the wing and read directly into punch cards for use in a computer program which calculates the coordinates of the points in a tunnel axis system. The crosses on the tunnel ceiling are used as control points in setting up the stereo model. In addition to obtaining the stereo photographs, aerodynamic performance was measured.

The measurements described above were made on a single-keel and a twin-keel all-flexible parawing, for both of which considerable prior aerodynamic data had been obtained at the Langley Research Center. The major part of the analysis and data comparisons of the present investigation was conducted using these two configurations. In the following sections of this report, the single-keel and twin-keel parawings referred to are those described below.

Single-keel parawing.- The single-keel parawing configuration used during this investigation is the basic wing configuration of reference 7. The flat canopy arrangement, line attachment locations, and line lengths are shown in figure 14. The inflated configuration is shown mounted in the tunnel in figure 13.

This configuration was tested in the wind tunnel over a range of angles of attack, α_7, from 26° to 35°. The angle at which the highest L/D ratio occurred is 27°, which is the angle at which the inflated shape data were obtained. At this angle the following aerodynamic data were obtained:

$$C_L = 0.95$$

$$C_D = 0.39$$

$$L/D = 2.43$$

The canopy coordinates of the inflated shape, as obtained from the stereo photography, are listed in Appendix C. In order to use these data, it is necessary to know something of the coordinate system set up in the stereo model and the order in which the points were read. This information is contained on the first page of Appendix C.

For purposes of applying aerodynamic theories to the known canopy shape, the data of Appendix C were used to construct chordwise sections at various spanwise stations. These sections are shown in figure 15. The sections were obtained for a given spanwise station by locating those points in the tabular data having y' values within ±0.10 inch of the nominal y' value of the desired semispan station and plotting the points on an x'-z' graph. This procedure gives acceptable results over most of the canopy. Near the maximum span and near the line attachment points along the leading edge, however, the canopy surface is nearly vertical, and small differences in y' give large differences in the z' coordinate. This difficulty can be most easily visualized by examining figures 16(a) and 16(b), which are photographs showing the side and rear views of a single-keel parawing having the same configuration and rigging characteristics as that used in the shape determination tests. Consequently, it is difficult to obtain an accurate section near the tip, as indicated by the sections having η values near 1 in figure 15(b). The most forward points for a given span station are close to, but do not necessarily indicate, the section leading edges, because the high curvature at the leading edge sometimes prevented the first one or two points from being seen properly in the photographs.

Twin-keel parawing.- The twin-keel parawing configuration used in the present investigation is that described in reference 8. The canopy shape data, however, were obtained on a wing having an h_k of 75 inches rather than the 15-foot size used in the investigation reported in reference 8. The flat canopy arrangement, line attachment locations, and line lengths are shown in figure 17.

The configuration described in figure 17 was tested in the wind tunnel over a range of angles of attack, α_s, from 24.2° to 31.8°. The shape data were obtained at an angle of 24.8° which is near the maximum L/D ratio condition. At this angle, the following aerodynamic data were obtained:

$$C_L = 0.840$$

$$C_D = 0.329$$

$$L/D = 2.56$$

The canopy coordinates of the inflated configuration, as obtained from the stereo photography, are listed in Appendix D. As for the single-keel data of Appendix C, an explanation of the data is included in the appendix.

Chordwise sections of the canopy were plotted for purposes of predicting the aerodynamic performance of the parawing. The sections are shown in figure 18. The comments given in the preceding section concerning the methods of obtaining these sections and the accuracy of the section shapes apply equally to the twin-keel data. Generally, however, the twin-keel parawing tends to have a more regular and smoother shape than the single-keel parawing because of the absence of leading-edge lines in the center lobe and the fact that the inflation of the forward portion of the outer lobes is assisted by the presence of the center lobe. These characteristics can be seen by comparing figures 19(a) and 19(b) with figures 16(a) and 16(b).

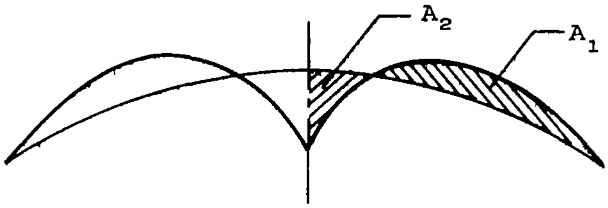
Aerodynamic Performance Comparisons

The slender-wing analysis was applied to the two parawings just described in order to evaluate the method. To apply the method, it is necessary to obtain spanwise canopy sections in planes normal to the root chord and fit circular arcs to these sections. Using the chordwise variation of the circular-arc section properties, the detailed aerodynamic load distribution on the parawing can be computed, from which the gross aerodynamic performance and the rigging line load distributions can be obtained and compared with measured results. A computer program was written to perform the calculations. The canopy fitting procedure and the aerodynamic load calculations are described below. The aerodynamic calculations and comparisons with data were made assuming full leading-edge suction.

As an additional standard of comparison, a planar lifting-surface method was also applied to the two parawing configurations. The method used is that of Multhopp, as modified and programmed by Lamar (ref. 9). An arrangement of 21 spanwise and 10 chordwise control points was used. The predicted angles of attack at which the measured lift coefficients are obtained were compared with measured angles. The predicted angles were low by 10 and 27 percent for the single- and twin-keel parawings, respectively. The differences are due both to an overprediction of the effect of chordwise camber and the inability of the method to account for spanwise camber. The slender-wing results, which follow, illustrate better agreement, which is felt to be the result of accounting for the large amount of spanwise camber.

Single-keel parawing.- The first task in applying the theory to the known parawing shape is to determine spanwise sections in planes normal to the root chord. The procedure adopted was to use the chordwise shape data of figure 15 to obtain a y-z crossplot at regular intervals of x. Some typical y-z plots are shown in figure 20 for several stations along the chord.

It is evident from figure 20 that these spanwise sections do not resemble circular arcs, and fitting circular arcs to the shapes is a somewhat arbitrary process. In order to fit the arcs in a consistent manner, the following approach was used. The circular arc was first made to pass through and terminate at the tip of the section. Then, an attempt was made to adjust the circular arc radius and the center of curvature so that the area (A_1 in the sketch below) between the circular arc and canopy sections outboard of the point where these two lines cross is equal to the area (A_2) between the arc and canopy inboard of the point.



Circular-arc sections were fitted in this manner at 2-inch intervals (intervals in x/c_r of 0.051 where c_r = 38.9 inches) along the root chord, and the quantities r, f, and e were measured. These quantities were then plotted versus x and the resulting curves smoothed. Finally, the semispan values, s, were computed using equation (114) and compared with the planform deduced directly from the photogrammetric data. Any sizable discrepancies in span were eliminated by modifying the values of r and f, and the r and f curves were again smoothed. The resulting circular-arc fits to several spanwise sections are shown in figure 20. The planform fit that was obtained using this procedure is compared with the actual planform obtained from the photogrammetric data (as viewed normal to the root chord) in figure 21. The two planforms are in reasonable agreement, considering the complexity of the leading-edge shape. A table of the circular-arc properties used in the single-keel parawing calculations is given in table I. Since only three quantities may be independently specified, the s values in table I are calculated from the e, f, and r values.

After a satisfactory planform fit was obtained, the slopes of the curves of r, e, and f versus x were obtained graphically to determine dr/dx, de/dx, and df/dx. These values were then plotted versus x to obtain the second derivatives d^2r/dx^2 and d^2e/dx^2. The resulting values were then used as tabular input to the computer program to compute the loading distribution. The pressure distribution was computed using equation (70). From a knowledge of the circular-arc canopy shape, the direction cosines of the local normal to the canopy were obtained and used with the pressure distribution to obtain force distributions in the normal, axial, and side directions. The normal force per unit chordwise length was checked with the analytically integrated values for no suction represented by equations (106)-(112). Finally, the chordwise integrated loadings using 19 stations along the root chord were checked with the analytically integrated normal-force coefficient with and without leading-edge suction using equations (113) and (123). The differences between the numerically and analytically integrated values were generally less than 2 percent.

The normal-force results for the single-keel parawing are shown in figure 22. The ordinate represents the total normal force with leading-edge suction up to the chord station of interest, as predicted from equation (113). The irregular shape of the curve near the nose is caused by the difficulty in fitting circular arcs to the actual canopy spanwise sections. The canopy span begins to decrease rapidly near the 87-percent chord station, which causes the loading to become negative in the slender-wing analysis. Consequently, the total wing normal force is taken as the maximum value, which occurs at $x/c_r = 0.85$.

For purposes of applying the theory as a predictive method, the normal force and induced drag coefficients predicted by the theory should be modified according to the following comments. In the development of the expressions for normal force (eq. (81)) and induced drag (eq. (101)), the factor $\cos \alpha$ was assumed nearly unity and dropped from the force expressions. The angle α is in fact not small, and the $\cos \alpha$ factor should probably be retained. Accordingly, the normal-force coefficient presented in figure 22 should be interpreted as $C_Z/\cos \alpha$ and the values indicated should be multiplied by $\cos \alpha$ to obtain C_Z. For induced drag, equations (87) and (85) indicate that a correction of $\cos^2 \alpha$ is applicable to the induced-drag coefficient. Consequently, the induced-drag coefficient computed from equation (101) should be interpreted as $C_{D_i}/\cos^2 \alpha$. Secondly, it is well known that slender-wing theory tends to overpredict aerodynamic force coefficients, with the difference increasing with increasing aspect ratio. Thus, a slenderness correction should be applied to the predicted force coefficients. Finally, since normal and drag forces represent a mixed set, the lift force should be determined according to the following equations.

$$C_L = C_Z \cos \alpha - C_X \sin \alpha$$

$$C_{D_i} = C_Z \sin \alpha + C_X \cos \alpha$$

Therefore,

$$C_L = \frac{1}{\cos \alpha} \left[C_Z - C_{D_i} \sin \alpha \right] \qquad (156)$$

With the above noted corrections, the predicted results can be compared with the measured results given in the previous section. The predicted normal-force coefficient from figure 22 is 1.53 and the induced-drag coefficient is 0.727. The photogrammetric data (fig. 15) indicate that the root chord makes an angle with the wind vector of 41°. Thus, the normal-force and induced-drag coefficients corrected for the $\cos \alpha$ effect are 1.154 and 0.413, respectively. Using equation (156), the predicted lift coefficient is 1.17. The slenderness correction is based on the aspect ratio of the planform shown in figure 21, which is 1.56. Figure 6-10 of reference 10 illustrates some results for lift-curve slope for triangular wings having aspect ratios up to 4 and indicates for an aspect ratio of 1.56 that slender-wing theory overpredicts measured values by about 32 percent. This correction was applied to the lift and induced-drag coefficients noted above in order to obtain the final predicted values.

The measured drag includes the effect of frictional effects as well as induced drag. In order to make a comparison with measured drag, rough estimates of the canopy skin friction and line drag were made using a flat plate, turbulent-boundary-layer skin-friction coefficient, and a two-dimensional drag coefficient for a cylinder. This calculation indicates a frictional drag coefficient C_{D_o} of 0.06 based on flat canopy area.

The predicted results are compared with the measured values in the following table.

	Predicted	Measured
C_L	0.89	0.95
C_{D_i}	.31	----
C_D	.37	.39
L/D_i	2.83	----
L/D	2.40	2.43

The predicted lift coefficient is somewhat lower than the measured value. This quantity is dependent only on the cross section properties at the last station developing positive lift, according to equation (113). In order to determine the sensitivity of the predicted lift to the circular-arc fits to the sections near the trailing edge, the actual sections at four chordwise stations were refit, keeping the same semispan but varying the radius and spanwise camber of the circular arc. These changes cause a change in C_Z principally through dr/dx. It was found that the predicted C_Z could be increased about 20 percent through changes in r, e, and f that did not appear unreasonably large. Thus, for the single-keel parawing, additional work is required to develop a rational approach for obtaining a unique circular-arc fit to a given spanwise section.

The measured and predicted drag coefficients agree reasonably well. From the relative sizes of the induced drag and estimated frictional drag, it is apparent that the induced drag is a major part of the total drag of a single-keel parawing. The lift-drag ratios agree very well as a result of the underprediction of both lift and drag coefficients.

Twin-keel parawing.- The approach to calculating the aerodynamic performance of the twin-keel parawing is similar to that described above for the single-keel parawing. The first step is to obtain spanwise sections by crossplotting the chordwise section data of figure 18. The results for several chordwise stations are shown in figure 23. The fitting of circular arcs to these sections can be made on a more rational basis than was the case with the single-keel parawing. The procedure followed is to pass the circular arc through the actual canopy points at the vertical plane of symmetry and at the maximum span station (the leading edge). Towards the center, chordwise, of the parawing, the tips of the canopy are reentrant, as shown in figure 23. In this case, the maximum span station does not correspond to the leading edge, and the maximum span station is used. The circular-arc fits are also shown in figure 23. The tabulation of the circular-arc parameters is shown in table II. The nondimensional chordwise values are based on a root chord length c_r of 51.4 inches. The resulting fit of the circular-arc planform to the actual planform obtained from the photogrammetric data is shown in figure 24.

The normal force results obtained using the circular-arc fit properties described above are shown in figure 25. The local span begins to decrease rapidly beyond $x/c_r = 0.86$ and a negative normal force is predicted aft of this point. Thus the total normal force is taken as that at $x/c_r = 0.86$. The dip in the curve at $x/c_r = 0.6$ occurs in the region where the canopy tip is reentrant (see fig. 23), and could possibly be smoothed by a somewhat different approach to the circular-arc fit for this type of spanwise section.

For purposes of comparing predicted and measured performance of the twin-keel parawing, the same corrections were made to the theoretical results as were discussed in the previous section. The predicted normal-force (from fig. 25) and induced-drag coefficients are 1.385 and 0.551, respectively. When these values are corrected for the $\cos \alpha$ and slender-wing effects and the wing lift coefficient is computed, the following results are obtained.

	Predicted	Measured
C_L	0.86	0.84
C_{D_i}	.31	----
C_D	.36	.33
L/D_i	2.76	----
L/D	2.38	2.55

In these calculations, the aspect ratio is that of the planform illustrated in figure 24, which is 1.76. The slenderness correction is then 0.745, based on the values shown in reference 10. The total frictional drag coefficient is estimated to be 0.05, based on the same approach as noted for the single-keel parawing. The predicted total drag coefficient is somewhat larger than the measured value, which gives a lower lift-drag ratio than is measured.

Structural Characteristics

One of the principal advantages of a capability for predicting the detailed load distribution on the canopy is the potential for determining line loads. Using the slender-wing theory, an investigation was made for both the single- and twin-keel parawings to attempt to obtain an understanding of the manner in which the distributed loading on the canopy is led into the discrete support loads represented by the rigging line tensions. In order to make a detailed stress analysis of this problem, it would be necessary to know the shape of the "scalloped" leading edge and the resulting canopy aerodynamic load distribution near the leading edge. It would then be possible to predict the canopy stresses and to solve the static force equilibrium problem at the line attachment points. Since the canopy shape along the leading edge is imperfectly known, and the theory does not model the "scalloped" shape, a simplified approach was taken.

Methods of approach.- It was assumed first that the canopy was made up of circular-arc sections of chordwise width dx, on each of which the spanwise load distribution was known. Further, it was assumed that each section was supported at the leading edge by a "distributed" line tension dT_ℓ/dx and at the keel(s) by a line tension dT_k/dx. The static equilibrium equations were then solved for the distributed line tensions on each section to obtain the chordwise variation of the distributed line tensions. These tension distributions were then apportioned to the discrete lines by assigning a chordwise length of influence to each line and integrating the distributed tension to obtain the line load. In this process, a single confluence point for all lines was assumed known. Thus, in the static equilibrium equations where the distributed line tension is used, direction cosines were assigned to the line tension force as if a discrete line existed between the leading edge (or keel) at that chordwise station and the confluence point.

Four approaches to the static equilibrium equations were examined. These are described briefly below (as applied to the twin-keel parawing) together with comments on the difficulties with the approach.

Method (a): The x and z equilibrium equations on a section were considered, as indicated below.

$$\frac{d(\Delta C_X)_s}{dx} + \frac{dC_X'}{dx} + 2\,\frac{dC_{T_\ell}}{dx}\cos\alpha_\ell + 2\,\frac{dC_{T_k}}{dx}\cos\alpha_k = 0$$

$$\frac{d(\Delta C_Z)_s}{dx} - \frac{dC_Z'}{dx} + 2\,\frac{dC_{T_\ell}}{dx}\cos\gamma_\ell + 2\,\frac{dC_{T_k}}{dx}\cos\gamma_k = 0$$

where the leading-edge suction coefficient is taken as positive down and C_X' and C_Z' are the aerodynamic force coefficients due to the pressure difference loading. The assumption is made in these equations that there is no chordwise variation in the canopy stress. However, near the nose and trailing edge of the parawing, the canopy loads are taken only by the keel lines. At these sections, a differential chordwise canopy tension force $d\sigma_X/dx$ (assumed uniform over the section span) was used in the x equation, with the value thus computed being high at the leading and trailing edges and dropping to zero (uniform chordwise canopy tension) over the central (chordwise) portion of the canopy where the leading-edge lines exist. A major problem with this approach is that the axial canopy tension force is not constant over most of the chord but varies considerably. As a result, the C_X' and $(\Delta C_X)_s$ forces, which are weakly coupled into the line tension because $\cos\alpha_\ell$ and

$\cos \alpha_k$ are small, tend to cause unreasonably large variations in line tension to create equilibrium in the x direction.

Method (b): The y and z equilibrium equations were applied to a strip of width dx extending over only the semispan, using the fact that on the vertical plane of symmetry, a knowledge of the principal radii of curvature of the canopy and the Δp value will yield the canopy stress components. Thus, in the plane of symmetry

$$\frac{\sigma_x}{r_x} + \frac{\sigma_y}{r} = \Delta p$$

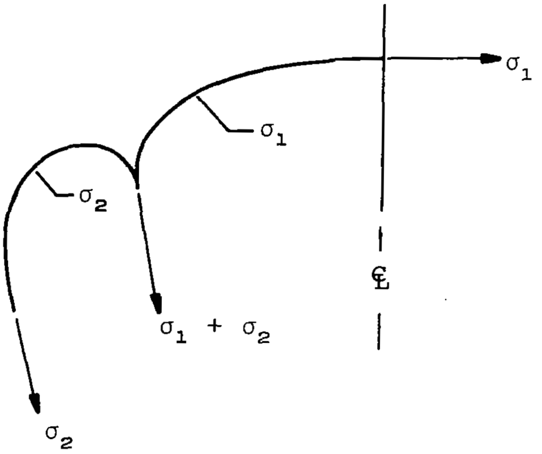
where r_x is the radius of curvature of the canopy in the $y = 0$ plane, and r is the radius of curvature in a constant x plane. The shape data indicate that r_x is generally larger than r, and the assumption was made that σ_x/r_x could be ignored over the entire canopy. The resulting force equilibrium equations neglecting higher-order terms are then

$$\frac{dC'_Y}{dx} + \frac{d(\Delta C_Y)_s}{dx} + \frac{dC_{T_\ell}}{dx} \cos \beta_\ell + \frac{dC_{T_k}}{dx} \cos \beta_k + \frac{\sigma_Y}{qS_R} = 0$$

$$-\frac{dC'_Z}{dx} + \frac{d(\Delta C_{T_Z})_s}{dx} + 2\,\frac{dC_{T_\ell}}{dx} \cos \gamma_\ell + 2\,\frac{dC_{T_k}}{dx} \cos \gamma_k = 0$$

Because of the weak coupling of the line tension into the y force balance equation (small $\cos \beta$), this set of equations is not well conditioned. Consequently, one difficulty with this approach is that if the assumption of $r_x >> r$ is not sufficiently good over the chord, the computed values of line tension tend to vary widely along the chord.

Method (c): It is evident from considerations of two-dimensional static equilibrium that the canopy tension (say, σ_1) in a y-z plane must be constant from the plane of symmetry out to the keel line attachment point and must also be constant over the outer lobe (say, at σ_2), as shown below.



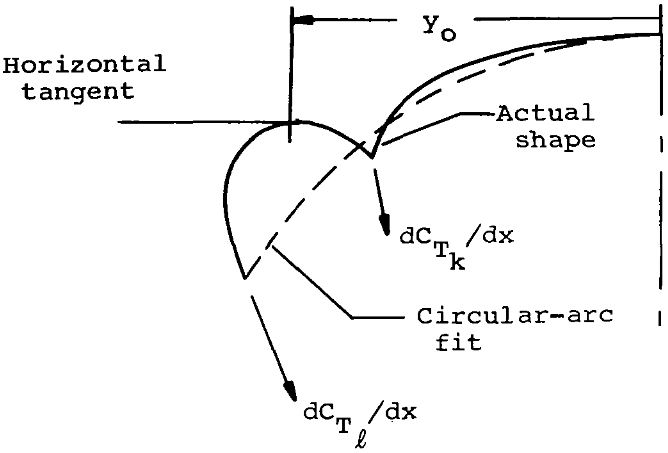
The line tensions must then be $\sigma_1 + \sigma_2$ and σ_2 for the keel and leading-edge lines, respectively, from considerations of force equilibrium at the line attachment points, assuming the cusp angle at the keel line is zero. Thus, y and z equilibrium equations can be written as follows.

$$\frac{dC_Y'}{dx} + \frac{d(\Delta C_Y)_s}{dx} + \frac{\sigma_2}{qS_R}\cos\beta_\ell + \frac{(\sigma_1 + \sigma_2)}{qS_R}\cos\beta_k + \frac{\sigma_1}{qS_R} = 0$$

$$-\frac{dC_Z'}{dx} + \frac{d(\Delta C_Z)_s}{dx} + \frac{\sigma_2}{qS_R}\cos\gamma_\ell + \frac{(\sigma_1 + \sigma_2)}{qS_R}\cos\gamma_k = 0$$

This set of equations tends to have the poor conditioning of those of the previous two approaches, but the assumptions used in the derivation are not so restrictive.

Method (d): The chordwise section of width dx was divided spanwise into portions, as shown in the following sketch.



The inner portion is that part between the span stations (noted y_o) on the actual canopy section where the tangent to the canopy shape in a y-z plane is horizontal. The two outer portions are those parts outboard of $\pm y_o$. For each portion of the canopy, the lateral component (σ_y) of the canopy stress at $\pm y_o$ is horizontal and does not enter into a z equilibrium equation. Thus, the following two equations can be written for the inner and outer portions of the canopy, respectively, assuming that the chordwise canopy stress σ_x is uniform over the section ($d\sigma_x/dx = 0$).

$$-\left.\frac{dC_Z'}{dx}\right|_i + 2\,\frac{dC_{T_k}}{dx}\cos\gamma_k = 0$$

$$-\left.\frac{dC_Z'}{dx}\right|_o + \frac{d(\Delta C_Z)_s}{dx} + 2\,\frac{dC_{T_\ell}}{dx}\cos\gamma_\ell = 0$$

The division of normal force between the inner and outer portions of the canopy section can be approximated by integrating the loading equations from 0 to y_o and from y_o to s, respectively. The assumption is made in so doing that the load out to the span station y_o on the circular-arc section is the same as that on the actual section. This approach has the advantage over the other three of employing only the z direction equations, into which the line tension forces are strongly coupled.

Theoretical results.- A preliminary investigation of the first two methods described above indicated that unreasonable results would be obtained, in accordance with the comments already noted. Consequently, calculations were made only for the latter two methods. The methods were applied first to the twin-keel parawing, since there is less uncertainty in the circular-arc fits for the twin-keel parawing than for the single-keel parawing.

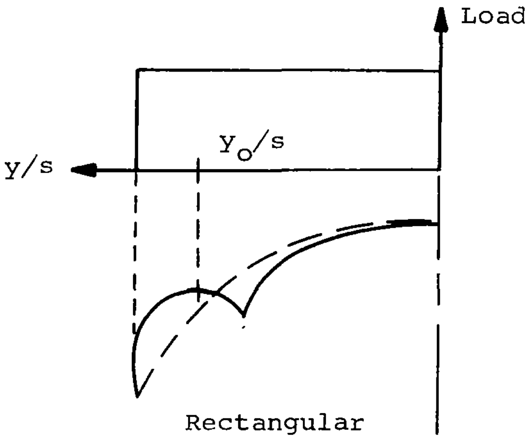
The distributed line tension results for the canopy tension approach (method (c)) are shown in figure 26. The chordwise variation for both the keel and leading edge is large. Near the 65-percent chord station, the loadings for both the keel and leading edge become negative, as a result of the properties of the circular-arc fits in this region. (This result is also illustrated in figure 25.)

Similar results for the z equilibrium approach (method (d)) are shown in figure 27. Again, the chordwise variation is large, and a region of very small loading is indicated near the 0.60 chord station.

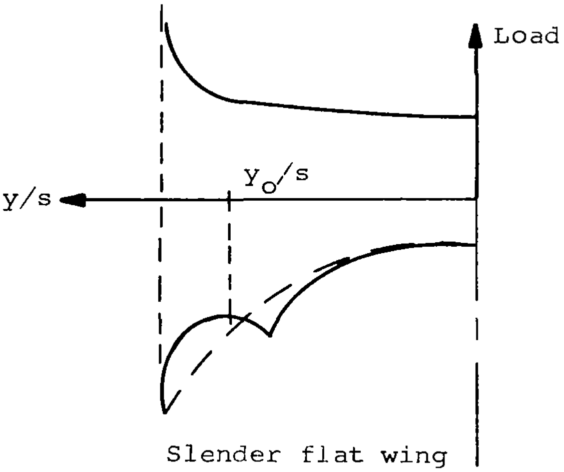
These two sets of results were used to construct discrete line load predictions in the following way. The line attachment points for the twin-keel parawing are shown in figure 24. The x/c_r value of the midpoint of the line joining two adjacent line attachment points was located for all points along the keel and leading edge. Each line was then considered to take the distributed load over an x/c_r range from the midpoint forward of the line attachment point to the midpoint aft of the point. The appropriate distributed loads from figures 26 and 27 were integrated for each line and are shown in figure 28. The large chordwise variation in distributed loading from figures 25 and 26 is carried over into the discrete line loads and is particularly evident near $x/c_r = 0.6$ for both the keel and leading-edge lines. The measured values obtained from unpublished Langley Research Center data are shown in figure 28 to indicate that there is not the degree of chordwise variation in the actual case that is indicated by the predicted values, particularly for the keel lines.

It is possible that some refitting of the circular arc sections would provide a more even chordwise variation of the predicted line loads, particularly since the detailed load distribution is affected by the second derivatives of r and e as well as the first derivatives. A more detailed examination of the structural aspects of all-flexible parawings should include such a study. However, an alternate approach was examined, based on attempting to derive a simple engineering method for estimating line loads.

It was noted previously that the predicted total forces on the parawing are determined by the circular-arc section properties near the maximum span station toward the trailing edge. First, it is assumed that the total normal force is distributed uniformly chordwise over the planform, so that dC_Z/dx is constant. This assumption appears reasonable based on the results of figures 22 and 25. Method (d) was then adopted for computing the distributed line loads. The further assumption is made that the division of load spanwise between the inner and outer portions of any section is determined in part by the y_o/s value at the maximum span station. A further assumption must now be made as to the form of the span load distribution curve. The two alternatives examined were a rectangular span load distribution and a distribution given by the slender-body solution for a flat wing $(1/\sqrt{1 - (y^2/s^2)})$, both illustrated in the sketch below.



Rectangular



Slender flat wing

The goal with this approach is to derive a method based on knowledge only of the parawing section properties at the chord station near the trailing edge where the loading just goes negative according to the slender-wing method. This approach was applied to both the single- and twin-keel parawings, and the predictions were compared with measured values. The results are described in the following sections.

Single-keel parawing results.- The approach described above was applied to the single-keel parawing defined in configuration by figures 14 and 21 and table I. The discrete line loads were predicted using the aerodynamic loads predicted by the slender-wing theory, as corrected for the $\cos \alpha$ and slender-wing factors discussed previously.

The measured line loads were obtained from reference 7. The values for $q = 2$ psf were used. An initial check was made on the force balance on the parawing by comparing the measured normal force obtained from the lift and drag with the sum of the z components of the line tensions obtained from the measured line tensions and the direction cosines of the lines. The C_Z value obtained from the measured C_L and C_D is 0.973, and the sum of the line tension components in the normal-force direction is 1.1, which is 13 percent greater. Although the line tension and aerodynamic data were obtained in different tests, the only known difference between the tests is the q value, which should not account for the 13-percent difference.

The comparison of discrete line loads is shown in figure 29. For the keel lines (fig. 29(a)), the predicted values generally tend to follow the chordwise variations shown by the data. The two predicted curves bracket the data, with the rectangular span load results being higher, as would be expected. For the leading-edge lines (fig. 29(b)), both predicted curves are generally lower than the measured values, with the slender-wing solution giving the higher values.

It is apparent from these results first that both span load distributions place relatively too much lift on the inner part of the canopy and too little on the outer part. One possible reason is an overestimation of leading-edge suction. All of the line load calculations were carried out assuming full suction. Since suction acts in the same general direction as the line tension, loss of suction would require additional line loading to balance the lift due to pressure difference.

Secondly, the sum of the keel and leading-edge line tensions appears low compared to the measured values. The reasons for this are first that the total predicted lift is lower than the measured value by about 7 percent and secondly that the measured line loads exceed the measured lift by 13 percent, as indicated above.

Twin-keel parawing.- The twin-keel parawing to which the line load method was applied is defined by figures 17 and 24 and table II. As in the single-keel parawing case, the aerodynamic loading was corrected for the $\cos \alpha$ and slender-wing factors discussed previously.

The measured line loads were obtained from unpublished NASA data obtained at the Langley Research Center. The data were obtained at $q = 2$ psf. The force balance check between the line loads and the canopy aerodynamic loads indicate that the sum of the z components of the line tension is 14 percent greater than the normal force obtained from the measured lift and drag coefficients.

The comparison of discrete line loads is shown in figure 30. For the keel lines (fig. 30(a)), the predicted values generally tend to follow the chordwise variation indicated by the data, except at the leading and trailing edges. At these two stations (keel lines 1 and 12), the keel lines were considered to carry the entire span load rather than having the load divided between the keel and leading-edge lines; this assumption then accounts for the high predicted loads. The rectangular span load curve tends to agree well with the data, whereas the slender-wing span load results are generally low. For the leading-edge lines (fig. 30(b)), the chordwise variation of the predicted line loads follows the variation shown by the data. The slender-wing span load results tend to agree well with the data, whereas the rectangular span load results are generally low.

These results indicate first that the sum of the keel and leading-edge loads is somewhat lower than that indicated by the data. The comparison on overall aerodynamic loads indicates that the theory predicts reasonably well the measured lift and drag on this parawing. However, the measured line loads exceed the measured normal force, which would tend to account for the line load data being generally higher than predicted loads. Secondly, the actual division of load between the keel and leading-edge lines seems to fall about halfway between the rectangular and slender-wing span load results.

CONCLUDING REMARKS

All-flexible parawings are characterized by large amounts of spanwise camber. Consequently, planar lifting-surface theory is inadequate for predicting the canopy aerodynamic load distribution and a new aerodynamic theory was developed specifically adapted to the all-flexible parawing. The method is based on the use of slender-body theory and considers spanwise sections in the crossflow plane to consist of circular arcs which, from section to adjacent section, may translate and dilate. The theory yields the spanwise and chordwise distribution of loading, the distribution of suction along the leading edge, and the induced drag.

Since the circular-arc fits to all-flexible parawings tend to yield nearly conical wings, systematic calculations were made for conical parawings to assess the importance of spanwise camber. The lift-curve slope increases with increasing camber, such that a parawing having a semicircular cross section has a 50-percent higher slope than a flat wing of the same aspect ratio. Spanwise camber also affects the role that leading-edge suction plays in the overall forces, in that loss of suction causes an increase in normal force with camber but no change in normal force without camber. In addition, spanwise camber has a favorable effect on the ratio of normal force to induced drag for both the full-suction and the vortex-lift cases.

The slender-wing, circular-arc method was applied to two specific parawings for which both aerodynamic, line tension, and shape data exist. For both the single- and twin-keel parawings, the measured shape data were used to obtain spanwise sections normal to the root chord, which were then fit with circular arcs. Application of the aerodynamic theory to the two circular-arc parawing models resulted in predicted lift coefficients that are within 3 and 6 percent of the measured values. In making the comparisons, a correction was made to account for the tendency of slender-wing theory to overpredict lift at moderate aspect ratios. The predicted induced drag was within 20 percent of the measured total drag, which tends to indicate that most of the drag for a parawing is induced drag. With the addition of rough estimates of the line and canopy frictional drag, the predicted total drag coefficients were within 6 and 9 percent of the measured values. It is felt on the basis of these comparisons that the slender-wing, circular-arc method does account properly for the chordwise and spanwise camber present in all-flexible parawings.

The manner in which the predicted canopy aerodynamic loading is transmitted by stresses in the canopy to the rigging lines was investigated. An approach was evolved in which "distributed" line tensions were computed using section span-load distributions, and discrete line loads were then calculated by allotting portions of the continuous line loads to each line. Use of the predicted chord load distributions for both the single- and twin-keel parawings resulted in considerably greater variations chordwise between the line loads than are indicated by the measured values. The probable cause is the circular-arc fits, since there is no way of assessing how accurately the distribution of loading over the canopy is predicted. An engineering method was evolved in which the total normal force was distributed uniformly over the chord, and the division of load spanwise between the keel and leading-edge lines was governed by either a rectangular or a slender flat-wing span-load distribution. This approach was found to give reasonable agreement with measured line loads, with the comparisons indicating that for the twin-keel parawing the actual span load distribution is probably between the rectangular and slender-wing loadings on the average. It is felt that this approach would be useful in assessing the general distribution of aerodynamic loads between lines, but a much more complex canopy stress analysis considering the local canopy shape in the line attachment regions would be necessary to obtain accurate predictions of each line load. Such an investigation should probably await the verification of the capability of the slender-wing method to predict accurately the detailed aerodynamic load distribution on the canopy.

Finally, several comments are in order with regard to basic limitations and growth potential of the slender-body method developed. One basic deficiency of slender-body theory is that the Kutta condition is not imposed at the trailing edge. In the present application, this limitation does not permit calculation of canopy loads aft of approximately the maximum span station, which occurs near the 85-percent chord point. Thus, the tension distribution in the canopy cannot be completely determined, and the line tensions for the most rearward lines cannot be predicted. Secondly, a shape determination method starting with the flat canopy and rigging line characteristics has not been developed. Such a method is necessary to provide a complete capability for predicting aerodynamic load distributions and canopy and line structural loadings. It is felt that some additional work should be done to verify, and perhaps improve, the methods described herein before a shape determination method is evolved.

With regard to growth potential, one important feature of the slender-body method is its potential for handling both deliberate canopy shape changes and bumps. The sorts of deliberate canopy shape changes that might be considered are aspect ratio changes, changes in the size and shape of the center panel of a twin-keel parawing, or changes due to shortening lines for control purposes. The present method could be employed to predict the relative changes in the aerodynamic performance due to these types of shape changes. For bumps, it is felt that the present method could be extended to consider deviations of the canopy spanwise sections from circular arcs by including higher harmonics in the spanwise shape specification. Such an extension would provide a capability, in particular, for examining the aerodynamic and tension loadings due to the local bumps near line attachment points. However, it is probable that many Fourier harmonics would be required, and the calculations would be lengthy.

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APPENDIX A

EVALUATION OF AN INTEGRAL OCCURRING IN THE INDUCED-DRAG CALCULATION

It is required in the derivation of the expression for induced drag that the following integral be evaluated.

$$J(k) = \frac{1}{k^2}\int_0^{\pi} \tanh^{-1}\left(\frac{k \sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\right) \frac{k \sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\, d\beta$$

$$= \frac{1}{2k^2}\int_0^{\pi} \ln\left[\frac{k \sin\beta + \sqrt{1 - k^2\cos^2\beta}}{-k \sin\beta + \sqrt{1 - k^2\cos^2\beta}}\right] \frac{k \sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\, d\beta$$

$$= \frac{1}{k^2}\int_0^{\pi/2} \ln\left[\frac{k \sin\beta + \sqrt{1 - k^2\cos^2\beta}}{-k \sin\beta + \sqrt{1 - k^2\cos^2\beta}}\right] \frac{k \sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\, d\beta \tag{A-1}$$

If

$$I(k) = \int_0^{\pi} \ln\left[k \sin\beta + \sqrt{1 - k^2\cos^2\beta}\right] \frac{k \sin\beta}{\sqrt{1 - k^2\cos^2\beta}}\, d\beta \tag{A-2}$$

then

$$J(k) = \frac{1}{k^2}\left[I(k) + I(-k)\right] \tag{A-3}$$

Integration by parts yields

$$I(k) = - \ln\left[k \sin\beta + \sqrt{1 - k^2\cos^2\beta}\right] \sin^{-1}(k \cos\beta)\Big|_0^{\pi/2}$$

$$+ \int_0^{\pi/2} \frac{\sin^{-1}(k \cos\beta)}{\sqrt{1 - k^2\cos^2\beta}}\, k \cos\beta\, d\beta \tag{A-4}$$

$$= \sin^{-1} k \ln\sqrt{1 - k^2} + \int_0^1 \frac{kx \sin^{-1}(kx)\, dx}{\sqrt{(1 - x^2)(1 - k^2x^2)}} \qquad \text{(A-5)}$$

The integral is to be found in reference 11, p. 607.

$$I(k) = \sin^{-1}(k) \ln\sqrt{1 - k^2} - \frac{\pi}{2}\sqrt{1 - k^2} \qquad \text{(A-6)}$$

The final result is from equation (A-3)

$$J(k) = - \frac{\pi}{2k^2} \ln (1 - k^2) \qquad \text{(A-7)}$$

APPENDIX B

DETERMINATION OF CERTAIN DIRECTION COSINES

In determining the effect of leading-edge suction and vortex lift on normal force and induced drag, it is necessary to know the direction cosines of certain directions associated with the lifting surface. For surfaces formed from the segments of circular cones, such as that shown in figure 6, the cross sections parallel to the y-z plane are all circular arcs, and the x-y plane is the chord plane. Plane OAC is tangent to the lifting surface at its left edge. The unit vector $\vec{n}_2$ is in the plane OAC and lies normal to the leading edge. It is the direction in which the leading-edge suction is usually directed. Under the assumption used herein to evaluate vortex-lift effects, it is assumed that the leading-edge suction force is rotated 90° from $\vec{n}_2$ to $\vec{n}_1$, where it is perpendicular to the leading edge and the lifting surface.

Let us first determine the direction cosines of $\vec{n}_1$. If the plane OAC has the equation

$$Ax + By + Cz = 0 \tag{B-1}$$

then

$$\left.\begin{aligned}\cos(n_1,x) &= \frac{A}{\sqrt{A^2 + B^2 + C^2}}\\ \cos(n_1,y) &= \frac{B}{\sqrt{A^2 + B^2 + C^2}}\\ \cos(n_1,z) &= \frac{C}{\sqrt{A^2 + B^2 + C^2}}\end{aligned}\right\} \tag{B-2}$$

From the equation of OA

$$sx + c_r y = 0 \tag{B-3}$$

and that for OC

$$\frac{s_m}{c_r} x - z \tan \phi = 0 \tag{B-4}$$

we can write the equation of plane OAC as

$$\frac{s_m}{c_r} x + y - z \tan \phi = 0 \tag{B-5}$$

With the definitions

$$k = \frac{f}{\sqrt{f^2 + s^2}} \tag{B-6}$$

$$\tan \phi = \frac{1 - 2k^2}{2k\sqrt{1 - k^2}} \tag{B-7}$$

the direction cosines for $\vec{n}_1$ are

$$\left.\begin{aligned} \cos(n_1, x) &= \frac{-2k\sqrt{1 - k^2}\left(s_m/c_r\right)}{R} \\ \cos(n_1, y) &= \frac{-2k\sqrt{1 - k^2}}{R} \\ \cos(n_1, z) &= \frac{(1 - 2k^2)}{R} \\ R^2 &= 1 + 4k^2(1 - k^2)\frac{s_m^{\,2}}{c_r^{\,2}} \end{aligned}\right\} \tag{B-8}$$

The direction cosines of $\vec{n}_2$ are obtainable from the coordinates of the line CD lying in the plane OAC and normal to OA. The coordinates of C are

$$C \sim (c_r,\ 0,\ s_m/\tan \phi) \tag{B-9}$$

and the coordinates of D are

$$D \sim \left(\frac{c_r}{1 + \frac{s_m^{\;2}}{c_r^{\;2}}} \, , \; \frac{-s}{1 + \frac{s_m^{\;2}}{c_r^{\;2}}} \, , \; 0 \right) \tag{B-10}$$

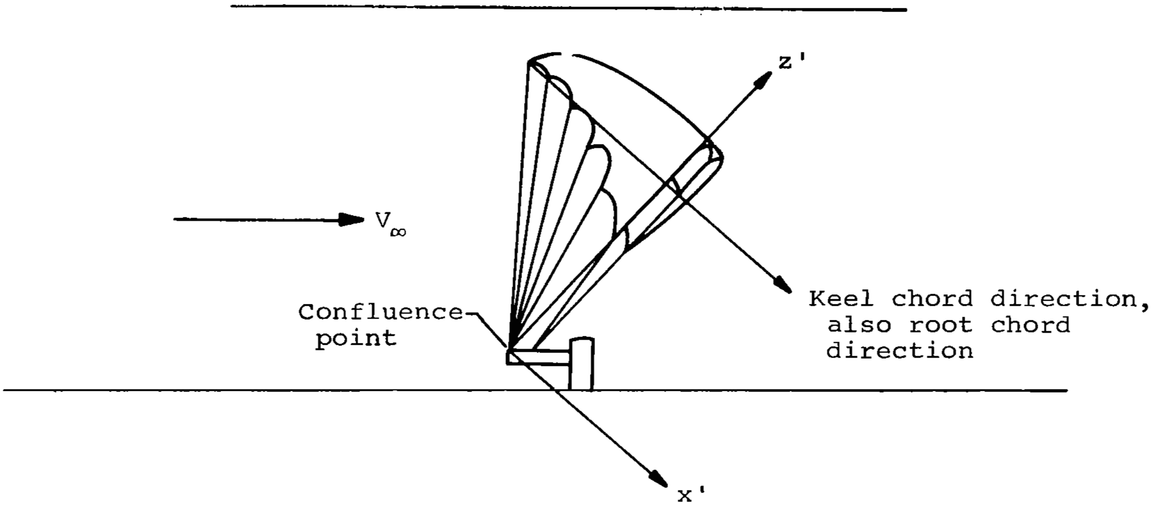
From the coordinates of these points, the direction cosines of $\vec{n}_2$ are found to be

$$\left.\begin{aligned}
\cos(n_2,x) &= \frac{-(1 - 2k^2)(s_m/c_r)}{\sqrt{1 + \frac{s_m^{\;2}}{c_r^{\;2}}} \; R} \\[2ex]
\cos(n_2,y) &= \frac{-(1 - 2k^2)}{\sqrt{1 + \frac{s_m^{\;2}}{c_r^{\;2}}} \; R} \\[2ex]
\cos(n_2,z) &= \frac{-2k\sqrt{1 - k^2}\,\sqrt{1 + \frac{s_m^{\;2}}{c_r^{\;2}}}}{R}
\end{aligned}\right\} \tag{B-11}$$

APPENDIX C

TABULATION OF CANOPY COORDINATES FOR SINGLE-KEEL PARAWING

The following pages are a reproduction of the printed computer output for the canopy coordinates obtained photogrammetrically at the Langley Research Center from the stereo photographs of the single-keel parawing in the wind tunnel. The coordinate system used in the data presentation is illustrated in the sketch below.



The origin of the axis system is on the sting at the confluence point of all the rigging lines except the two tip lines and the last keel line. The x'-axis is parallel to the keel chord, positive downstream. The positive z' direction is upwards towards the canopy, and the positive y' direction is in accordance with a right-hand system.

The data consist of a point identification number, followed by the x', y', and z' coordinates of the point, nondimensionalized by the characteristic length h_k. For the parawing tested, h_k = 60 inches. Points 1-11 are the canopy line attachment point coordinates for the keel lines 1-11, respectively. Points 12-17 are the canopy line attachment point coordinates of the leading-edge lines 1-6, respectively. For the remainder of the coordinates, generally a single streamwise set of points having about the same y' coordinate was read starting at the leading edge and working aft. The sets start at the keel and move out towards the tip.

Point No.	x'/h_k	y'/h_k	z'/h_k	
1	-.70271	.00000	1.12923	K1
2	-.67370	.00901	1.16419	K2
3	-.60197	.00603	1.17326	K3
4	-.54556	.00280	1.18731	K4
5	-.48164	.00670	1.20354	K5
6	-.40816	.00220	1.20334	K6
7	-.32587	.00946	1.22515	K7
8	-.23689	.01045	1.21868	K8
9	-.16808	.00401	1.20567	K9
10	-.10847	.00775	1.17831	K10
11	-.05536	.00000	1.12923	K11
12	-.68955	.09298	1.14844	LE1
13	-.60195	.16424	1.11181	LE2
14	-.52192	.22916	1.11502	LE3
15	-.40689	.31746	1.07370	LE4
16	-.28448	.36787	1.02747	LE5
17	-.17171	.38207	.96742	LE6
18	-.71220	.02126	1.15514	
19	-.67408	.01873	1.17712	
20	-.66029	.00662	1.18125	
21	-.64875	.01174	1.19542	
22	-.62977	.00211	1.19047	
23	-.59538	.00576	1.19733	
24	-.59403	.00384	1.22543	
25	-.57215	.00901	1.21395	
26	-.54445	.01183	1.21886	
27	-.53027	.00916	1.22680	
28	-.51403	.00783	1.22549	
29	-.49935	.00754	1.22061	
30	-.47032	.00746	1.22048	
31	-.45765	.00326	1.22953	
32	-.44271	.00480	1.22696	
33	-.42794	.00553	1.22353	
34	-.40104	.00035	1.22787	
35	-.38851	.00937	1.23600	
36	-.38905	.00630	1.24192	
37	-.37351	.00730	1.24646	
38	-.37217	.01165	1.23782	
39	-.35601	.00596	1.23261	
40	-.34019	.00271	1.22567	
41	-.31591	.00019	1.23744	
42	-.30486	.01781	1.25132	
43	-.28716	.00974	1.23620	
44	-.27495	.01537	1.24022	
45	-.25763	.01459	1.23861	
46	-.23502	.01054	1.23499	
47	-.21496	.02062	1.23163	
48	-.20258	.01787	1.22740	
49	-.18375	.01316	1.22446	
50	-.16707	.02235	1.23372	

Suspension line attachment points

Point No.	x'/h_k	y'/h_k	z'/h_k
51	-.71767	.00388	1.14019
52	-.71481	.00456	1.14723
53	-.71514	.00127	1.16528
54	-.69457	.00155	1.17567
55	-.68571	.00464	1.17270
56	-.68115	.00120	1.17640
57	-.67815	.00345	1.18254
58	-.67061	.00337	1.18569
59	-.66707	.00934	1.19345
60	-.65845	.00714	1.19560
61	-.62511	.00378	1.20756
62	-.61820	.00322	1.21054
63	-.60865	.00335	1.20851
64	-.60224	.00375	1.21117
65	-.55339	.00376	1.21870
66	-.54513	.00173	1.22006
67	-.53701	.00198	1.22253
68	-.52936	.00106	1.22429
69	-.51503	.00164	1.22847
70	-.50759	.00280	1.22957
71	-.49445	.00393	1.22779
72	-.48716	.00042	1.22484
73	-.48082	.00277	1.22851
74	-.47439	.00370	1.23200
75	-.46657	.00381	1.23452
76	-.45860	.00090	1.23543
77	-.45241	.00428	1.23828
78	-.44432	.00293	1.23637
79	-.43577	.00169	1.23449
80	-.42771	.00064	1.23372
81	-.41551	.00081	1.23305
82	-.41141	.00293	1.23697
83	-.40487	.00178	1.24064
84	-.39694	.00168	1.24293
85	-.39036	.00374	1.24841
86	-.38329	.00797	1.25436
87	-.37586	.00652	1.25534
88	-.36790	.00739	1.25700
89	-.35969	.00582	1.25487
90	-.35106	.00365	1.25182
91	-.33738	.00169	1.24294
92	-.32927	.00370	1.23958
93	-.32488	.00306	1.24709
94	-.31467	.00272	1.24959
95	-.31067	.00170	1.24974
96	-.30339	.00314	1.25432
97	-.29714	.00601	1.25918
98	-.28933	.00231	1.25776
99	-.28215	.00403	1.25861
100	-.27428	.00299	1.25496

101	-.25770	.00317	1.25320	151	-.35046	.00432	1.25523	201	-.51036	.00948	1.23807
102	-.26040	.00567	1.25264	152	-.33962	.00867	1.24608	202	-.50359	.01076	1.23661
103	-.25151	.00769	1.24362	153	-.32108	.00194	1.25930	203	-.49063	.01057	1.23692
104	-.24584	.00084	1.24371	154	-.30594	.00017	1.26120	204	-.48556	.00436	1.24569
105	-.23918	.00254	1.24390	155	-.28953	.00160	1.26101	205	-.47712	.00931	1.24290
106	-.23325	.00282	1.24370	156	-.27372	.00497	1.25717	206	-.46388	.00854	1.24476
107	-.22607	.00454	1.24402	157	-.25848	.00348	1.25398	207	-.46121	.00826	1.24703
108	-.21895	.00527	1.24561	158	-.24661	.00410	1.24942	208	-.45404	.00759	1.24865
109	-.21170	.01225	1.25135	159	-.23166	.00516	1.24641	209	-.44504	.00743	1.24618
110	-.20327	.00846	1.24617	16	-.21752	.00248	1.24844	210	-.43700	.01151	1.24474
111	-.19524	.00807	1.24325	161	-.20132	.00128	1.24931	211	-.42973	.01246	1.24262
112	-.18753	.00530	1.23852	162	-.18684	.00010	1.24350	212	-.41917	.01254	1.24200
113	-.18066	.00368	1.23458	163	-.17491	.00139	1.24126	213	-.41335	.01293	1.24446
114	-.17380	.00060	1.22869	164	-.16030	.00052	1.23611	214	-.40687	.01144	1.24961
115	-.16778	.00234	1.22861	165	-.14442	.00518	1.23586	215	-.39943	.01195	1.25278
116	-.16153	.00785	1.23233	166	-.13024	.00308	1.22681	216	-.39214	.00922	1.25766
117	-.15433	.01160	1.23438	167	-.10855	.00351	1.21247	217	-.38369	.01080	1.25862
118	-.14650	.00623	1.23024	168	-.09283	.00312	1.20354	218	-.37648	.00834	1.26197
119	-.12602	.00702	1.21757	169	-.07969	.00929	1.20051	219	-.36850	.00767	1.26101
120	-.11978	.00556	1.21248	170	-.72478	.02014	1.14208	220	-.36014	.01317	1.25760
121	-.11092	.00195	1.20147	171	-.72422	.01690	1.15175	221	-.34580	.01155	1.25571
122	-.10296	.00530	1.20013	172	-.72211	.01597	1.15830	222	-.33226	.01236	1.25423
123	-.09596	.00657	1.19691	173	-.72058	.01107	1.17292	223	-.32597	.01216	1.25611
124	-.08833	.00809	1.19323	174	-.71489	.00952	1.17878	224	-.31977	.01236	1.25847
125	-.08138	.01131	1.19168	175	-.70366	.00714	1.18533	225	-.31261	.00970	1.26241
126	-.07549	.00438	1.18092	176	-.70039	.01058	1.18499	226	-.30537	.00816	1.26593
127	-.05613	.00362	1.15582	177	-.69553	.01034	1.18641	227	-.29756	.00708	1.26725
128	-.72100	.00005	1.17402	178	-.69078	.00716	1.19102	228	-.28859	.00915	1.26519
129	-.69184	.00607	1.18107	179	-.68247	.00947	1.19078	229	-.28228	.00631	1.26770
130	-.68153	.00122	1.18799	180	-.68045	.00057	1.20238	230	-.27312	.00680	1.26514
131	-.66747	.00133	1.19291	181	-.67376	.00029	1.20500	231	-.25842	.00955	1.25991
132	-.65451	.00438	1.20565	182	-.66633	.00129	1.20981	232	-.24529	.01210	1.25394
133	-.63993	.00303	1.21227	183	-.65924	.00265	1.21454	233	-.23843	.01071	1.25456
134	-.62750	.00012	1.21487	184	-.65114	.00047	1.21508	234	-.23134	.00896	1.25481
135	-.60538	.00885	1.21677	185	-.64262	.00705	1.21792	235	-.22490	.00812	1.25602
136	-.59448	.00925	1.22959	186	-.63593	.00238	1.22024	236	-.21745	.00792	1.25555
137	-.57881	.00201	1.23117	187	-.62870	.00773	1.21867	237	-.20947	.00456	1.25793
138	-.54734	.00325	1.22578	188	-.62112	.01067	1.21941	238	-.20125	.00215	1.25781
139	-.53293	.00083	1.23454	189	-.60957	.01109	1.22535	239	-.19386	.00287	1.25607
140	-.51658	.00326	1.23435	190	-.60327	.00318	1.23032	240	-.18531	.00738	1.24918
141	-.50208	.00484	1.23046	191	-.59545	.00836	1.23320	241	-.17215	.00871	1.24325
142	-.48854	.00548	1.22956	192	-.58834	.00789	1.23506	242	-.16582	.00664	1.24290
143	-.47458	.00554	1.23439	193	-.58037	.00843	1.23543	243	-.15792	.00425	1.24267
144	-.45966	.00284	1.24103	194	-.57233	.01001	1.23275	244	-.14969	.00189	1.24263
145	-.44431	.00362	1.24091	195	-.55631	.00994	1.22536	245	-.14230	.00022	1.24262
146	-.42367	.00557	1.23848	196	-.54950	.00768	1.23281	246	-.13467	.00138	1.23706
147	-.41530	.00985	1.23304	197	-.54111	.00718	1.23501	247	-.12813	.00285	1.23293
148	-.40587	.00433	1.24471	198	-.53510	.00422	1.24082	248	-.12129	.00499	1.22695
149	-.39791	.00394	1.25127	199	-.52811	.00335	1.24365	249	-.10375	.00799	1.21191
150	-.37569	.00058	1.25813	200	-.51910	.00475	1.24302	250	-.09600	.00446	1.21027

251	-.08941	.00174	1.20921
252	-.08288	.00134	1.20519
253	-.06482	.01191	1.17740
254	-.05927	.01027	1.17295
255	-.05475	.01707	1.16137
256	-.72767	.02015	1.16361
257	-.72317	.01703	1.17726
258	-.71082	.01438	1.18897
259	-.69732	.01980	1.18822
260	-.68679	.01130	1.19934
261	-.67676	.00409	1.21127
262	-.66272	.00107	1.22079
263	-.64559	.00711	1.22303
264	-.63159	.01316	1.22475
265	-.61056	.01396	1.22810
266	-.59638	.01504	1.23698
267	-.58111	.01733	1.23709
268	-.54983	.01690	1.23509
269	-.53526	.01167	1.24455
270	-.51913	.01545	1.24379
271	-.50407	.01385	1.24[illegible]44
272	-.49146	.01984	1.2[illegible]
273	-.47702	.01843	1.24529
274	-.46702	.01519	1.25125
275	-.44565	.01793	1.24904
276	-.43072	.01811	1.24812
277	-.42034	.02022	1.24563
278	-.40741	.01964	1.25216
279	-.39353	.01581	1.26183
280	-.37750	.01491	1.26620
281	-.36148	.01743	1.26316
282	-.34636	.01308	1.26060
283	-.33298	.02017	1.25773
284	-.31952	.01968	1.26173
285	-.30501	.01531	1.26945
286	-.28941	.01320	1.27219
287	-.27439	.01040	1.27393
288	-.25777	.01839	1.26191
289	-.24511	.01731	1.25930
290	-.23025	.01623	1.25934
291	-.21733	.01910	1.26476
292	-.19957	.01194	1.25903
293	-.17247	.00925	1.25296
294	-.15646	.00738	1.25061
295	-.14089	.01437	1.24862
296	-.12591	.00264	1.24394
297	-.11564	.00981	1.22992
298	-.10124	.01[illegible]	1.22046
299	-.08804	.00959	1.21404
300	-.07516	.00814	1.20420
301	-.06769	.01248	1.19136
302	-.73319	.03387	1.14924
303	-.73012	.03313	1.15600
304	-.72879	.03140	1.16387
305	-.72802	.02741	1.17370
306	-.72285	.02904	1.17743
307	-.71694	.02876	1.18196
308	-.71123	.02537	1.18941
309	-.70485	.02809	1.18910
310	-.69859	.02829	1.19105
311	-.69487	.02029	1.20061
312	-.68885	.01740	1.20598
313	-.68290	.01439	1.21123
314	-.67646	.01472	1.21382
315	-.67242	.00491	1.22249
316	-.66543	.00733	1.22650
317	-.65644	.01366	1.22473
318	-.64884	.01430	1.22809
319	-.64002	.02013	1.22584
320	-.63364	.02075	1.22876
321	-.62512	.02490	1.22885
322	-.61196	.02751	1.23259
323	-.60494	.02475	1.23798
324	-.59788	.02246	1.24201
325	-.59132	.02232	1.24404
326	-.58190	.02685	1.24003
327	-.56466	.02558	1.23346
328	-.55782	.02646	1.23614
329	-.55136	.02307	1.24096
330	-.54433	.02095	1.24666
331	-.53676	.02025	1.24840
332	-.52827	.02279	1.24756
333	-.52061	.02193	1.24314
334	-.51209	.02496	1.24651
335	-.50515	.02501	1.24604
336	-.49325	.02615	1.24520
337	-.48484	.02585	1.24771
338	-.47845	.02391	1.25136
339	-.47011	.02335	1.25353
340	-.46296	.02273	1.25571
341	-.45419	.02465	1.25280
342	-.44609	.02588	1.25227
343	-.43858	.02597	1.25121
344	-.43091	.02753	1.25087
345	-.42178	.02792	1.24967
346	-.41565	.02329	1.25220
347	-.40782	.02384	1.25553
348	-.40164	.02517	1.26175
349	-.39435	.02271	1.26648
350	-.38578	.02447	1.26674
351	-.37741	.02506	1.26793
352	-.37009	.02392	1.26904
353	-.36259	.02565	1.26656
354	-.35433	.02658	1.26579
355	-.34633	.02736	1.26379
356	-.33401	.02755	1.26303
357	-.32759	.02501	1.26776
358	-.31989	.02504	1.26853
359	-.31272	.02489	1.27078
360	-.30489	.02285	1.27330
361	-.29797	.02044	1.27706
362	-.28992	.01931	1.27794
363	-.28197	.01777	1.27925
364	-.27453	.01620	1.27942
365	-.26602	.02197	1.27280
366	-.25850	.02303	1.26965
367	-.25194	.02511	1.26534
368	-.24551	.02468	1.26582
369	-.23705	.02284	1.26646
370	-.22976	.02318	1.26518
371	-.22385	.02034	1.26745
372	-.21584	.01902	1.26859
373	-.20791	.01678	1.26857
374	-.19921	.01780	1.26675
375	-.19149	.01979	1.26256
376	-.18471	.01785	1.26250
377	-.17796	.01924	1.25912
378	-.17000	.01690	1.25899
379	-.16249	.01725	1.25598
380	-.15408	.01478	1.25578
381	-.14597	.01513	1.25354
382	-.13927	.01249	1.25260
383	-.13133	.01213	1.24937
384	-.12542	.01055	1.24763
385	-.11396	.00836	1.24164
386	-.10573	.01410	1.23208
387	-.09881	.01374	1.22859
388	-.09145	.01417	1.22405
389	-.08578	.01200	1.22248
390	-.07035	.01965	1.20040
391	-.06461	.02199	1.19267
392	-.05716	.02450	1.18201
393	-.05402	.02252	1.18055
394	-.73079	.03597	1.16823
395	-.72338	.03529	1.18044
396	-.71280	.03363	1.19163
397	-.70018	.03315	1.19536
398	-.68839	.02650	1.20683
399	-.67696	.02023	1.21731
400	-.66339	.01986	1.23261

401	-.65122	.02029	1.23103	451	-.65446	.02584	1.23492	501	-.22033	.03427	1.27640
402	-.63692	.02576	1.23300	452	-.63904	.03513	1.23438	502	-.22237	.03218	1.27808
403	-.61575	.02792	1.24254	453	-.63258	.03268	1.24106	503	-.21444	.03051	1.27875
404	-.59805	.03159	1.24721	454	-.62572	.03546	1.23968	504	-.20605	.02967	1.27928
405	-.58294	.03279	1.24295	455	-.61547	.03821	1.24333	505	-.19714	.03024	1.27553
406	-.55153	.03147	1.24336	456	-.60765	.03783	1.24553	506	-.18970	.02921	1.27451
407	-.53326	.02569	1.25349	457	-.60525	.02597	1.25825	507	-.18284	.03066	1.27077
408	-.52234	.02547	1.25450	458	-.57202	.03916	1.24707	508	-.17552	.02923	1.26969
409	-.49444	.03248	1.24457	459	-.58455	.03907	1.24708	509	-.16757	.02716	1.26989
410	-.47972	.03151	1.25423	460	-.55114	.03620	1.24725	510	-.16023	.02540	1.26934
411	-.46344	.03041	1.25310	461	-.55338	.03595	1.24957	511	-.15163	.02950	1.26309
412	-.44629	.03452	1.25404	462	-.54541	.03300	1.25564	512	-.14348	.02722	1.26312
413	-.43152	.03459	1.25398	463	-.53904	.03261	1.25767	513	-.13646	.02448	1.26263
414	-.42214	.03559	1.25219	464	-.53057	.03441	1.25691	514	-.12967	.02442	1.25884
415	-.40965	.03377	1.26098	465	-.52229	.03542	1.25540	515	-.12351	.02812	1.25199
416	-.39412	.03254	1.26751	466	-.51437	.03765	1.25428	516	-.11516	.02518	1.24990
417	-.37903	.03126	1.27145	467	-.50225	.04030	1.25060	517	-.10803	.02583	1.24548
418	-.36362	.02907	1.27366	468	-.49487	.04107	1.25213	518	-.10148	.02309	1.24439
419	-.34610	.03634	1.26479	469	-.48748	.03799	1.25664	519	-.09449	.02684	1.23651
420	-.33383	.03441	1.26564	470	-.47984	.03782	1.25902	520	-.08761	.02748	1.23174
421	-.31985	.03353	1.27033	471	-.47230	.03735	1.26103	521	-.08266	.02813	1.22717
422	-.30451	.03233	1.27413	472	-.46392	.03799	1.26083	522	-.07686	.03086	1.21931
423	-.28999	.02420	1.28393	473	-.45613	.03855	1.26082	523	-.07089	.03277	1.21230
424	-.27404	.02423	1.28174	474	-.44987	.03770	1.26227	524	-.06598	.03094	1.20955
425	-.25753	.03212	1.27120	475	-.43716	.04259	1.25725	525	-.06122	.03343	1.20253
426	-.24419	.03081	1.25994	476	-.43119	.04355	1.25589	526	-.05738	.03546	1.19644
427	-.22952	.02772	1.27120	477	-.42348	.04300	1.25645	527	-.05405	.03838	1.19089
428	-.21497	.02747	1.25981	478	-.41869	.04046	1.26207	528	-.70201	.04571	1.20555
429	-.19795	.02330	1.27053	479	-.41150	.03860	1.26749	529	-.69089	.03661	1.21865
430	-.18371	.02549	1.26516	480	-.40367	.03917	1.26990	530	-.67854	.03494	1.22573
431	-.16899	.02337	1.26255	481	-.39573	.03889	1.27275	531	-.65829	.03172	1.23948
432	-.15364	.01930	1.26190	482	-.38674	.03918	1.27331	532	-.64201	.03992	1.23978
433	-.13752	.01919	1.25586	483	-.37914	.03864	1.27523	533	-.62833	.04493	1.24125
434	-.11036	.01663	1.24385	484	-.37179	.03791	1.27685	534	-.61832	.04177	1.25005
435	-.09691	.02070	1.23237	485	[illegible]	.03884	1.27464	535	-.60077	.04547	1.24933
436	-.07312	.02523	1.20392	486	-.35459	.03985	1.27308	536	-.58468	.04814	1.24831
437	-.06275	.02624	1.19984	487	-.34105	.04319	1.26782	537	-.56609	.04696	1.24456
438	-.73446	.04865	1.15250	488	-.33556	.03968	1.27337	538	-.55360	.04395	1.25285
439	-.73151	.04714	1.15917	489	-.32880	.03934	1.27527	539	-.53923	.04150	1.25962
440	-.72377	.04522	1.16748	490	-.32024	.03984	1.27643	540	-.52440	.04215	1.25969
441	-.72589	.04365	1.17546	491	-.31316	.03924	1.27814	541	-.49704	.04446	1.25927
442	-.72373	.04238	1.18312	492	-.30513	.03861	1.28011	542	-.48117	.04367	1.26373
443	-.72157	.03804	1.19204	493	-.29788	.03424	1.28432	543	-.46395	.04722	1.26242
444	-.71573	.03991	1.19524	494	-.28084	.03336	1.28599	544	-.44943	.04516	1.26481
445	-.70158	.03847	1.20175	495	-.28165	.03531	1.28362	545	-.42466	.05012	1.26040
446	-.69676	.03360	1.20916	496	-.26550	.03632	1.28005	546	-.41122	.04817	1.26826
447	-.69125	.02880	1.21596	497	-.25831	.03753	1.27745	547	-.39558	.04708	1.27416
448	-.68363	.02358	1.21329	498	-.25188	.03536	1.27748	548	-.37967	.04466	1.27945
449	-.67741	.02748	1.22153	499	-.24426	.03547	1.27595	549	-.36307	.04961	1.27461
450	-.66054	.02356	1.22457	500	-.23656	.03389	1.27756	550	-.33657	.04675	1.27784

551	-.32113	.04567	1.28181	601	-.41295	.05473	1.27420	651	-.07693	.05123	1.23477
552	-.30596	.04251	1.28689	602	-.40559	.05353	1.27855	652	-.08871	.05268	1.24255
553	-.28881	.04477	1.28513	603	-.39633	.05533	1.27725	653	-.10241	.04719	1.25587
554	-.25840	.04514	1.28009	604	-.38785	.05414	1.28058	654	-.11597	.04926	1.26174
555	-.24457	.03997	1.28411	605	-.38043	.05352	1.28235	655	-.13067	.04914	1.27004
556	-.22930	.03816	1.28388	606	-.37201	.05534	1.28085	656	-.14689	.04958	1.27496
557	-.21341	.03952	1.28076	607	-.36397	.05685	1.27979	657	-.16248	.04842	1.28135
558	-.19608	.03552	1.28181	608	-.35556	.05519	1.28064	658	-.17821	.04892	1.28619
559	-.18133	.03826	1.27455	609	-.34169	.06033	1.27339	659	-.19355	.05314	1.28608
560	-.16567	.03625	1.27238	610	-.33567	.05680	1.27951	660	-.21149	.05142	1.29071
561	-.15041	.03291	1.27033	611	-.32893	.05321	1.28541	661	-.22668	.05319	1.29086
562	-.13434	.03283	1.26528	612	-.32151	.05243	1.28703	662	-.24254	.05523	1.29121
563	-.12059	.03066	1.26055	613	-.31343	.05191	1.28901	663	-.25703	.06173	1.28591
564	-.10584	.03332	1.24949	614	-.30569	.05093	1.29059	664	-.28872	.05671	1.29449
565	-.09214	.03417	1.24093	615	-.29734	.04954	1.29173	665	-.30512	.05933	1.29208
566	-.08000	.03799	1.22725	616	-.28935	.04859	1.29329	666	-.32109	.06081	1.28842
567	-.06876	.04037	1.21615	617	-.28190	.04765	1.29377	667	-.33579	.06274	1.28388
568	-.05952	.04333	1.20352	618	-.26470	.05204	1.28721	668	-.34993	.06346	1.27994
569	-.70876	.05188	1.20636	619	-.25805	.05247	1.28586	669	-.36433	.06293	1.28281
570	-.70083	.05290	1.20836	620	-.25092	.04841	1.28843	670	-.38015	.06183	1.28307
571	-.69677	.04706	1.21763	621	-.24285	.05132	1.28549	671	-.39703	.06110	1.28117
572	-.68903	.04729	1.22055	622	-.23510	.04983	1.28633	672	-.41299	.06153	1.27626
573	-.68505	.04123	1.22914	623	-.22782	.04819	1.28680	673	-.42704	.06438	1.26838
574	-.64429	.04997	1.23894	624	-.22043	.04648	1.28724	674	-.44815	.06713	1.26452
575	-.63084	.05492	1.24275	625	-.21249	.04455	1.28802	675	-.46477	.06423	1.26662
576	-.62643	.05168	1.24951	626	-.20454	.04276	1.28813	676	-.48263	.05909	1.26993
577	-.61992	.05024	1.25292	627	-.19485	.04455	1.28534	677	-.49895	.05843	1.26788
578	-.60953	.05442	1.24939	628	-.18791	.04252	1.28524	678	-.51255	.06343	1.25885
579	-.60206	.05406	1.25147	629	-.18017	.04237	1.28306	679	-.52558	.06028	1.26196
580	-.59402	.05534	1.25095	630	-.17271	.04025	1.28306	680	-.54078	.06016	1.26000
581	-.58651	.05563	1.25194	631	-.16431	.04174	1.27952	681	-.55424	.05957	1.25999
582	-.56847	.05212	1.25096	632	-.15725	.03952	1.27922	682	-.56808	.05127	1.25210
583	-.56042	.05417	1.25137	633	-.14932	.04027	1.27600	683	-.57634	.06014	1.24792
584	-.55524	.04974	1.25928	634	-.14054	.04039	1.27233	684	-.58499	.05822	1.24933
585	-.54724	.04926	1.26094	635	-.13270	.04034	1.26949	685	-.59358	.05692	1.25012
586	-.54051	.04885	1.26275	636	-.12547	.03735	1.26833	686	-.60282	.06137	1.25282
587	-.53414	.04815	1.26407	637	-.11869	.03950	1.26244	687	-.61815	.06228	1.24827
588	-.52509	.05209	1.26088	638	-.11151	.04105	1.25691	688	-.63465	.05879	1.24759
589	-.51779	.05112	1.26220	639	-.10414	.03971	1.25421	689	-.64607	.05855	1.23910
590	-.50611	.05231	1.26188	640	-.09739	.04065	1.24967	690	-.68650	.05493	1.22097
591	-.49668	.05540	1.26023	641	-.09079	.04075	1.24542	691	-.69983	.05968	1.21117
592	-.48992	.05141	1.26676	642	-.08429	.04391	1.23693	692	-.70439	.06720	1.20822
593	-.48116	.05293	1.26634	643	-.07905	.04282	1.23389	693	-.69763	.06710	1.21182
594	-.47309	.05446	1.26571	644	-.07336	.04389	1.22840	694	-.69252	.06255	1.21953
595	-.46535	.05373	1.26747	645	-.06763	.04346	1.22374	695	-.68574	.06009	1.22364
596	-.45829	.05291	1.26888	646	-.06256	.04853	1.21522	696	-.67732	.05888	1.22358
597	-.44865	.05772	1.26430	647	-.05796	.04842	1.20980	697	-.64953	.06231	1.24196
598	-.44058	.05670	1.26582	648	-.05366	.05287	1.20174	698	-.64157	.06634	1.24374
599	-.42551	.05996	1.26314	649	-.05575	.05903	1.20851	699	-.63514	.06724	1.24702
600	-.42085	.05425	1.27093	650	-.06500	.05735	1.21997	700	-.63024	.05399	1.25389

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702	-.61275	.06301	1.25364
703	-.60315	.07128	1.25177
704	-.59590	.06873	1.25555
705	-.58740	.07392	1.25221
706	-.56587	.07275	1.25258
707	-.56067	.07017	1.25775
708	-.54345	.06644	1.26289
709	-.53612	.06652	1.26549
710	-.52872	.05602	1.26741
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712	-.50822	.06801	1.26870
713	-.49915	.06885	1.26903
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715	-.48250	.06950	1.27072
716	-.47478	.06383	1.27253
717	-.46653	.06998	1.27200
718	-.45787	.07276	1.26987
719	-.45054	.07094	1.27204
720	-.42468	.07155	1.27367
721	-.42247	.07035	1.27758
722	-.41359	.07174	1.27906
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725	-.38896	.07030	1.28567
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727	-.37298	.06970	1.28803
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731	-.33676	.06836	1.29081
732	-.32957	.06787	1.29267
733	-.32165	.06708	1.29442
734	-.31358	.06618	1.29606
735	-.30554	.06516	1.29757
736	-.29767	.06203	1.30203
737	-.26491	.06456	1.29627
738	-.25737	.06725	1.29288
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740	-.24232	.06352	1.29535
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743	-.21835	.06172	1.29445
744	-.21064	.06012	1.29512
745	-.20239	.05798	1.29534
746	-.19345	.05748	1.29457
747	-.18582	.05572	1.29503
748	-.17767	.05636	1.29130
749	-.16994	.05649	1.28910
750	-.16114	.05863	1.28375
751	-.15409	.05506	1.28496
752	-.14549	.05541	1.28169
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754	-.13011	.05594	1.27431
755	-.12282	.05559	1.27157
756	-.11544	.05523	1.26739
757	-.10850	.05357	1.26598
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759	-.09439	.05607	1.25524
760	-.08876	.05478	1.25252
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762	-.07560	.05907	1.23910
763	-.06983	.05716	1.23699
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767	-.06226	.06888	1.22935
768	-.07423	.06505	1.24297
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774	-.16061	.06178	1.29003
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776	-.19212	.06713	1.29440
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782	-.32115	.07556	1.29558
783	-.33621	.07694	1.29209
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794	-.51691	.07377	1.27034
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796	-.54406	.07415	1.26296
797	-.56806	.07637	1.25749
798	-.58793	.08251	1.25163
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800	-.62294	.07214	1.25374
801	-.63771	.07208	1.24864
802	-.64869	.07408	1.23594
803	-.68204	.06733	1.22170
804	-.69551	.07325	1.21193
805	-.70533	.08037	1.19928
806	-.73128	.07775	1.15196
807	-.72841	.07460	1.15669
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1199	-.17081	.13466	1.30172	1249	-.30847	.16271	1.30998	1299	-.48547	.18217	1.27763
1200	-.15501	.13628	1.29939	1250	-.30046	.16196	1.31039	1300	-.47052	.18095	1.27698

1301	-.45735	.18127	1.28327	1351	-.61205	.17556	1.20693	1401	-.13369	.18357	1.30355
1302	-.44381	.18487	1.29084	1352	-.61767	.17281	1.20119	1402	-.11768	.17597	1.29590
1303	-.42762	.18275	1.29165	1353	-.62451	.17375	1.19773	1403	-.10205	.18082	1.29541
1304	-.41962	.18151	1.29139	1354	-.62942	.17062	1.19221	1404	-.63886	.15471	1.15389
1305	-.41119	.18265	1.29459	1355	-.63319	.16785	1.18664	1405	-.60980	.18223	1.20192
1306	-.39562	.18229	1.29757	1356	-.60712	.18022	1.21460	1406	-.62192	.17931	1.19255
1307	-.38739	.18277	1.29980	1357	-.60035	.17951	1.21776	1407	-.59825	.18749	1.21336
1308	-.37853	.17819	1.29722	1358	-.58736	.18388	1.22858	1408	-.58591	.19232	1.22458
1309	-.36407	.18265	1.30513	1359	-.57192	.18307	1.23483	1409	-.55400	.19493	1.24157
1310	-.34861	.18299	1.30830	1360	-.56677	.18903	1.24336	1410	-.54789	.20108	1.25167
1311	-.33204	.18003	1.30810	1361	-.56174	.19323	1.25011	1411	-.53245	.19924	1.25463
1312	-.31606	.18069	1.31167	1362	-.54749	.19004	1.25318	1412	-.51943	.20606	1.26421
1313	-.29995	.18114	1.31388	1363	-.54114	.19171	1.25673	1413	-.50022	.19994	1.26310
1314	-.28345	.17959	1.31476	1364	-.53347	.19362	1.26042	1414	-.47104	.20270	1.27200
1315	-.26718	.17690	1.31476	1365	-.52528	.19267	1.26155	1415	-.45817	.20575	1.28119
1316	-.25048	.17576	1.31528	1366	-.51705	.19314	1.26376	1416	-.44320	.20940	1.28763
1317	-.23365	.17439	1.31448	1367	-.50957	.19362	1.26574	1417	-.42756	.20999	1.29173
1318	-.21644	.17091	1.31206	1368	-.50146	.19409	1.26800	1418	-.41029	.20653	1.29154
1319	-.20124	.17271	1.31293	1369	-.49489	.19944	1.27449	1419	-.39411	.20753	1.29587
1320	-.18372	.16980	1.30891	1370	-.48575	.19684	1.27283	1420	-.37820	.20816	1.29940
1321	-.16706	.16726	1.30594	1371	-.47804	.19863	1.27332	1421	-.36304	.20890	1.30428
1322	-.15108	.16663	1.30312	1372	-.47115	.19657	1.27479	1422	-.34632	.20638	1.30511
1323	-.13542	.16644	1.30076	1373	-.46527	.19749	1.27962	1423	-.33015	.20667	1.30804
1324	-.11964	.16450	1.29530	1374	-.45969	.19998	1.28590	1424	-.31355	.20396	1.30859
1325	-.10372	.16282	1.28971	1375	-.44414	.20206	1.29099	1425	-.29695	.20193	1.30883
1326	-.08921	.15211	1.28412	1376	-.43654	.20327	1.29214	1426	-.28067	.20200	1.31038
1327	-.65828	.15757	1.16832	1377	-.42742	.20080	1.29257	1427	-.26497	.20152	1.31245
1328	-.61408	.17039	1.21244	1378	-.41187	.20199	1.29646	1428	-.24852	.20189	1.31427
1329	-.62646	.15767	1.20273	1379	-.39426	.19735	1.29562	1429	-.23196	.19865	1.31277
1330	-.63651	.16393	1.19238	1380	-.37819	.19528	1.29803	1430	-.21455	.19880	1.31413
1331	-.60217	.17373	1.22127	1381	-.36246	.19532	1.30109	1431	-.19870	.19565	1.31121
1332	-.58854	.17534	1.23121	1382	-.34703	.19596	1.30559	1432	-.18153	.19339	1.30944
1333	-.57385	.17630	1.23951	1383	-.33077	.19752	1.30926	1433	-.16471	.19127	1.30693
1334	-.56156	.18204	1.25072	1384	-.32243	.19547	1.30842	1434	-.63168	.15689	1.14901
1335	-.54785	.18155	1.25599	1385	-.31385	.19354	1.30752	1435	-.61993	.18703	1.18840
1336	-.53223	.18087	1.25821	1386	-.30551	.19435	1.30937	1436	-.61344	.19627	1.19152
1337	-.51800	.18748	1.26802	1387	-.29740	.19153	1.30891	1437	-.60930	.19254	1.20083
1338	-.50212	.18865	1.27207	1388	-.28957	.19472	1.31278	1438	-.60616	.20088	1.21076
1339	-.48478	.18698	1.27266	1389	-.28088	.19086	1.30981	1439	-.59455	.19064	1.20531
1340	-.47172	.19135	1.27749	1390	-.26561	.19226	1.31338	1440	-.58223	.19695	1.21860
1341	-.45874	.18963	1.28398	1391	-.25776	.19286	1.31478	1441	-.56724	.19558	1.22480
1342	-.44327	.19043	1.28831	1392	-.24914	.19193	1.31499	1442	-.55578	.20106	1.23665
1343	-.42771	.19148	1.29238	1393	-.24052	.19161	1.31440	1443	-.54426	.19951	1.23963
1344	-.41168	.19213	1.29598	1394	-.23209	.18875	1.31249	1444	-.53180	.20655	1.25124
1345	-.39576	.19146	1.29827	1395	-.22319	.19006	1.31393	1445	-.51713	.21090	1.25891
1346	-.37898	.18919	1.29942	1396	-.21474	.18916	1.31355	1446	-.50921	.20642	1.25715
1347	-.31473	.18577	1.30822	1397	-.19937	.18673	1.31190	1447	-.50098	.21117	1.26293
1348	-.29814	.18478	1.30955	1398	-.18197	.18580	1.30971	1448	-.49228	.20807	1.26229
1349	-.64713	.15388	1.15950	1399	-.16557	.18297	1.30799	1449	-.48530	.21218	1.26708
1350	-.64297	.15275	1.16227	1400	-.14986	.18418	1.30699	1450	-.47193	.21261	1.27232

1451	-.45710	.21224	1.27780
1452	-.44276	.21794	1.28723
1453	-.42600	.21514	1.28720
1454	-.41089	.22039	1.29518
1455	-.39419	.21803	1.29630
1456	-.37802	.21431	1.29782
1457	-.37104	.21802	1.30197
1458	-.36198	.21538	1.30140
1459	-.35426	.21589	1.30343
1460	-.34447	.20867	1.29907
1461	-.32862	.21008	1.30279
1462	-.32055	.21238	1.30616
1463	-.31246	.20982	1.30528
1464	-.30422	.21119	1.30696
1465	-.29621	.20890	1.30632
1466	-.28772	.20967	1.30828
1467	-.28026	.21027	1.31013
1468	-.27190	.21106	1.31148
1469	-.26370	.20906	1.31050
1470	-.25628	.20966	1.31232
1471	-.24673	.20482	1.30918
1472	-.23071	.20466	1.31100
1473	-.22150	.20626	1.31218
1474	-.21341	.20444	1.31161
1475	-.19795	.20270	1.31017
1476	-.18033	.19962	1.30839
1477	-.16372	.20003	1.30871
1478	-.14745	.19965	1.30648
1479	-.13187	.19663	1.30356
1480	-.11610	.19824	1.30273
1481	-.10012	.19735	1.29853
1482	-.06909	.19604	1.28836
1483	-.61677	.19123	1.18276
1484	-.60617	.19728	1.19453
1485	-.57978	.20120	1.21270
1486	-.56637	.20575	1.22352
1487	-.54540	.21080	1.23920
1488	-.51657	.21834	1.25471
1489	-.50073	.21869	1.25973
1490	-.48594	.22120	1.26632
1491	-.47180	.22136	1.27096
1492	-.45689	.22114	1.27632
1493	-.44107	.22150	1.28128
1494	-.42506	.22284	1.28515
1495	-.40965	.22332	1.28983
1496	-.39360	.22461	1.29380
1497	-.37765	.22509	1.29864
1498	-.36181	.22486	1.30151
1499	-.34498	.22235	1.30229
1500	-.32866	.22230	1.30508
1501	-.31199	.21956	1.30503
1502	-.29575	.21835	1.30637
1503	-.27943	.21888	1.30904
1504	-.26326	.21606	1.30899
1505	-.24672	.21541	1.31095
1506	-.23044	.21507	1.31249
1507	-.21277	.21253	1.31101
1508	-.19761	.21249	1.31182
1509	-.17971	.20875	1.30916
1510	-.14637	.20466	1.30466
1511	-.13137	.20659	1.30528
1512	-.11490	.20555	1.30297
1513	-.09866	.20403	1.29901
1514	-.61170	.14517	1.12398
1515	-.61520	.20047	1.18048
1516	-.60908	.19964	1.18358
1517	-.60354	.20297	1.18974
1518	-.59574	.20266	1.19277
1519	-.58459	.20940	1.20569
1520	-.57661	.20643	1.20641
1521	-.56911	.20674	1.21139
1522	-.56140	.20666	1.21467
1523	-.54325	.21638	1.23328
1524	-.53690	.21867	1.23776
1525	-.52903	.21905	1.24056
1526	-.52315	.22403	1.24796
1527	-.50800	.22452	1.25256
1528	-.49947	.22502	1.25484
1529	-.49303	.22698	1.25987
1530	-.48540	.22725	1.26214
1531	-.47743	.22513	1.26109
1532	-.47150	.22870	1.26853
1533	-.46448	.22884	1.27076
1534	-.45630	.22897	1.27342
1535	-.44830	.22898	1.27614
1536	-.44083	.22924	1.27840
1537	-.43353	.23197	1.28278
1538	-.42419	.22855	1.28148
1539	-.41674	.22980	1.28420
1540	-.40789	.22798	1.28483
1541	-.39257	.23177	1.2[illegible]128
1542	-.38517	.23202	1.29350
1543	-.37663	.23252	1.29583
1544	-.36743	.22732	1.29260
1545	-.36070	.23117	1.29773
1546	-.35205	.22819	1.29687
1547	-.34424	.22897	1.29916
1548	-.33652	.23023	1.30201
1549	-.32700	.22670	1.29983
1550	-.31962	.23075	1.30543
1551	-.31091	.22604	1.30216
1552	-.29523	.22719	1.30613
1553	-.28641	.22557	1.30544
1554	-.27863	.22702	1.30803
1555	-.26219	.22263	1.30711
1556	-.25376	.22074	1.30607
1557	-.24620	.22330	1.31006
1558	-.23775	.22465	1.31135
1559	-.22903	.22013	1.30855
1560	-.22092	.22015	1.30964
1561	-.21227	.22142	1.31107
1562	-.19640	.21899	1.30996
1563	-.18854	.22104	1.31183
1564	-.17936	.21746	1.30987
1565	-.16980	.21253	1.30527
1566	-.15474	.21657	1.30880
1567	-.14595	.21389	1.3063[illegible]
1568	-.13035	.21184	1.30427
1569	-.12181	.21407	1.30445
1570	-.11377	.21392	1.30413
1571	-.09751	.21071	1.29943
1572	-.08193	.20823	1.29433
1573	-.07024	.21204	1.29430
1574	-.08073	.21783	1.29667
1575	-.09602	.21844	1.29930
1576	-.12965	.22131	1.30514
1577	-.14501	.22487	1.30826
1578	-.16077	.22254	1.30737
1579	-.17810	.22778	1.31007
1580	-.19557	.22870	1.31026
1581	-.21098	.22998	1.31017
1582	-.22815	.22972	1.30855
1583	-.24499	.23034	1.30713
1584	-.26219	.23749	1.31014
1585	-.27777	.23517	1.30592
1586	-.29383	.23478	1.30316
1587	-.30954	.23349	1.29934
1588	-.32605	.23377	1.29679
1589	-.34310	.23677	1.29648
1590	-.35959	.23826	1.29479
1591	-.37536	.23827	1.29167
1592	-.39177	.23920	1.28837
1593	-.40779	.23803	1.28434
1594	-.42375	.23744	1.27957
1595	-.43943	.23695	1.27479
1596	-.45502	.23669	1.26974
1597	-.47013	.23663	1.26466
1598	-.48472	.23385	1.25729
1599	-.49923	.23410	1.25205
1600	-.52806	.22605	1.23595

1601	-.54052	.22002	1.22591	1651	-.24381	.23706	1.30397	1701	-.60395	.21463	1.16235
1602	-.55705	.20826	1.20584	1652	-.23570	.23790	1.30573	1702	-.61025	.20572	1.14960
1603	-.57286	.21125	1.20019	1653	-.22780	.23859	1.30763	1703	-.60637	.19272	1.12410
1604	-.58580	.20767	1.19071	1654	-.21933	.23946	1.30947	1704	-.60704	.21030	1.14361
1605	-.58684	.21000	1.19252	1655	-.21040	.23672	1.30790	1705	-.60434	.21500	1.14974
1606	-.60123	.21100	1.18642	1656	-.20338	.23715	1.30922	1706	-.59991	.21894	1.15637
1607	-.61076	.20283	1.17258	1657	-.19507	.23585	1.30856	1707	-.59447	.22160	1.16219
1608	-.60815	.17799	1.12814	1658	-.18686	.23666	1.31043	1708	-.58753	.22138	1.16647
1609	-.61200	.19811	1.15326	1659	-.17751	.23369	1.30824	1709	-.57583	.22245	1.17414
1610	-.61108	.20590	1.16109	1660	-.16885	.23223	1.30739	1710	-.56882	.22185	1.17671
1611	-.60617	.20754	1.16573	1661	-.15313	.23303	1.30844	1711	-.56237	.22354	1.18187
1612	-.60084	.20923	1.17045	1662	-.14455	.23429	1.30987	1712	-.54745	.22256	1.18979
1613	-.59687	.21580	1.17993	1663	-.12911	.23246	1.30792	1713	-.53308	.23574	1.20906
1614	-.59009	.21460	1.18258	1664	-.12034	.23013	1.30544	1714	-.52105	.24032	1.21670
1615	-.58301	.21414	1.18554	1665	-.11233	.22957	1.30499	1715	-.50408	.25233	1.23433
1616	-.57638	.21561	1.19048	1666	-.09636	.23096	1.30441	1716	-.49578	.25017	1.23520
1617	-.56854	.21399	1.19289	1667	-.08006	.23029	1.30145	1717	-.48802	.25069	1.23778
1618	-.55532	.21827	1.20393	1668	-.07527	.22769	1.29861	1718	-.48184	.25442	1.24402
1619	-.53918	.22757	1.22185	1669	-.09466	.23314	1.30011	1719	-.46733	.25732	1.25244
1620	-.53215	.22752	1.22433	1670	-.11141	.23816	1.30545	1720	-.46016	.25788	1.25479
1621	-.52605	.23217	1.23047	1671	-.12801	.23974	1.30732	1721	-.45215	.25778	1.25765
1622	-.51995	.23643	1.23650	1672	-.14337	.23756	1.30523	1722	-.44457	.25857	1.26100
1623	-.49879	.23952	1.24691	1673	-.15988	.24150	1.30825	1723	-.43721	.26023	1.26499
1624	-.49118	.23975	1.24923	1674	-.17666	.24352	1.30902	1724	-.42998	.26342	1.27001
1625	-.48528	.24487	1.25599	1675	-.19427	.24467	1.30840	1725	-.42213	.26303	1.27201
1626	-.47017	.24476	1.26188	1676	-.20975	.24562	1.30762	1726	-.41441	.26168	1.27340
1627	-.45471	.24507	1.26676	1677	-.22716	.24896	1.30783	1727	-.40569	.26223	1.27569
1628	-.44678	.24517	1.26934	1678	-.24439	.24985	1.30662	1728	-.39770	.26473	1.28005
1629	-.43999	.24788	1.27419	1679	-.25979	.24894	1.30238	1729	-.38916	.26060	1.27866
1630	-.43169	.24631	1.27546	1680	-.27539	.24778	1.29842	1730	-.38104	.26154	1.28029
1631	-.42313	.24560	1.27692	1681	-.29285	.25122	1.29862	1731	-.37356	.26300	1.28400
1632	-.41575	.24532	1.27924	1682	-.30881	.24926	1.29443	1732	-.36591	.26362	1.28587
1633	-.40702	.24607	1.28189	1683	-.32473	.25151	1.29370	1733	-.35670	.25960	1.28400
1634	-.39108	.24696	1.28625	1684	-.34090	.25055	1.28929	1734	-.34918	.26062	1.28651
1635	-.38333	.24769	1.28799	1685	-.35788	.25264	1.28848	1735	-.34078	.26141	1.28841
1636	-.37510	.24686	1.28950	1686	-.37367	.25363	1.28533	1736	-.33225	.25916	1.28828
1637	-.35850	.24441	1.29065	1687	-.38963	.25283	1.28141	1737	-.32445	.25976	1.29023
1638	-.35070	.24514	1.29244	1688	-.40694	.25595	1.28046	1738	-.31566	.26047	1.29238
1639	-.34762	.24556	1.29470	1689	-.42271	.25544	1.27569	1739	-.30750	.25737	1.29144
1640	-.33445	.24651	1.29634	1690	-.43877	.25523	1.27042	1740	-.29955	.26122	1.29641
1641	-.32527	.24218	1.29494	1691	-.45477	.25484	1.26543	1741	-.29167	.25903	1.29601
1642	-.31700	.24304	1.29675	1692	-.46924	.25318	1.25845	1742	-.27614	.26100	1.30185
1643	-.30874	.24023	1.29552	1693	-.48491	.25296	1.25279	1743	-.26005	.25808	1.30226
1644	-.30020	.24085	1.29714	1694	-.49960	.25333	1.24733	1744	-.25223	.25993	1.30497
1645	-.29299	.24330	1.30059	1695	-.52427	.23791	1.22528	1745	-.24324	.25442	1.30154
1646	-.28474	.24079	1.30023	1696	-.53516	.22862	1.21292	1746	-.23410	.25245	1.30073
1647	-.27612	.23820	1.29888	1697	-.55153	.22014	1.19683	1747	-.22645	.25458	1.30421
1648	-.26843	.24149	1.30383	1698	-.56700	.22127	1.19023	1748	-.21708	.25293	1.30369
1649	-.26048	.24041	1.30388	1699	-.57972	.21815	1.17961	1749	-.20927	.25320	1.30548
1650	-.25266	.24239	1.30699	1700	-.59256	.21708	1.17325	1750	-.20169	.25278	1.30632

1751	-.19330	.24931	1.30488	1801	-.60423	.21594	1.13786	1851	-.21543	.26893	1.29935
1752	-.18497	.25054	1.30625	1802	-.60470	.22151	1.12825	1852	-.20741	.27166	1.30336
1753	-.17594	.24754	1.30451	1803	-.60050	.22042	1.13098	1853	-.20008	.26929	1.30303
1754	-.16762	.24880	1.30580	1804	-.59734	.22633	1.13911	1854	-.19235	.26834	1.30341
1755	-.15976	.24944	1.30716	1805	-.59201	.22831	1.14460	1855	-.18386	.26702	1.30333
1756	-.15204	.25034	1.30873	1806	-.58430	.22744	1.14827	1856	-.17492	.26586	1.30324
1757	-.14314	.24754	1.30615	1807	-.57836	.22846	1.15346	1857	-.16618	.26684	1.30502
1758	-.13622	.24905	1.30838	1808	-.56084	.22972	1.16397	1858	-.15891	.26958	1.30820
1759	-.12831	.24856	1.30837	1809	-.55306	.22605	1.16498	1859	-.15097	.26810	1.30754
1760	-.11964	.25018	1.30935	1810	-.54714	.22974	1.17194	1860	-.14248	.26634	1.30749
1761	-.11093	.24486	1.30482	1811	-.53857	.22565	1.17315	1861	-.13487	.26456	1.30601
1762	-.10284	.24630	1.30581	1812	-.53591	.23683	1.18503	1862	-.12666	.26230	1.30476
1763	-.09479	.24710	1.30595	1813	-.53170	.24140	1.19104	1863	-.11743	.26084	1.30404
1764	-.08707	.24468	1.30320	1814	-.52578	.24173	1.19265	1864	-.10973	.26204	1.30523
1765	-.08102	.24412	1.30212	1815	-.52282	.25063	1.20155	1865	-.10173	.26325	1.30651
1766	-.09409	.25502	1.30612	1816	-.51712	.25422	1.20712	1866	-.09343	.26503	1.30721
1767	-.11055	.25522	1.30696	1817	-.51265	.26068	1.21459	1867	-.08596	.26211	1.30432
1768	-.12697	.25533	1.30625	1818	-.49869	.26057	1.21950	1868	-.09267	.26898	1.30446
1769	-.14259	.25501	1.30579	1819	-.49083	.26055	1.22222	1869	-.10925	.27374	1.30770
1770	-.15880	.25592	1.30536	1820	-.48442	.26490	1.22832	1870	-.12607	.27340	1.30688
1771	-.17529	.25760	1.30504	1821	-.47833	.26858	1.23408	1871	-.14078	.27429	1.30587
1772	-.19273	.25918	1.30454	1822	-.47153	.27067	1.23911	1872	-.15758	.27472	1.30477
1773	-.19273	.25918	1.30454	1823	-.46410	.27091	1.24193	1873	-.17403	.27537	1.30293
1774	-.20779	.26014	1.30277	1824	-.44932	.27200	1.24800	1874	-.19099	.27648	1.30152
1775	-.22519	.26069	1.30016	1825	-.44141	.27189	1.25082	1875	-.20629	.27601	1.29856
1776	-.24256	.26395	1.30062	1826	-.43477	.27557	1.25679	1876	-.22445	.28021	1.29883
1777	-.25829	.26444	1.29809	1827	-.42672	.27363	1.25779	1877	-.24046	.28078	1.29500
1778	-.27428	.26794	1.29701	1828	-.42045	.27934	1.26536	1878	-.25673	.27931	1.29175
1779	-.29063	.26523	1.29176	1829	-.41199	.27682	1.26543	1879	-.27322	.28140	1.29059
1780	-.30618	.26275	1.28717	1830	-.40288	.27365	1.26535	1880	-.28903	.28053	1.28618
1781	-.32405	.26889	1.28866	1831	-.39556	.27631	1.27050	1881	-.30548	.28334	1.28410
1782	-.33970	.26786	1.28455	1832	-.38759	.27770	1.27272	1882	-.32188	.28329	1.28151
1783	-.35668	.26840	1.28280	1833	-.37966	.27642	1.27347	1883	-.33792	.28239	1.27712
1784	-.37293	.27083	1.28128	1834	-.37167	.27620	1.27532	1884	-.35386	.28190	1.27283
1785	-.38886	.27097	1.27800	1835	-.35581	.27712	1.27962	1885	-.36928	.28073	1.26893
1786	-.40482	.26924	1.27226	1836	-.34767	.27813	1.28119	1886	-.38597	.28320	1.26729
1787	-.42075	.26877	1.26738	1837	-.33889	.27567	1.28133	1887	-.40226	.28324	1.26342
1788	-.43645	.26891	1.26185	1838	-.33092	.27646	1.28308	1888	-.44743	.27649	1.24154
1789	-.45113	.26630	1.25417	1839	-.32304	.27668	1.28554	1889	-.48997	.27054	1.21973
1790	-.46591	.26621	1.24923	1840	-.31418	.27560	1.28639	1890	-.51275	.25663	1.19836
1791	-.48106	.26391	1.24162	1841	-.31418	.27560	1.28639	1891	-.52225	.24449	1.18494
1792	-.49568	.26458	1.23582	1842	-.30750	.27723	1.28903	1892	-.53200	.23948	1.17760
1793	-.50941	.25936	1.22702	1843	-.29780	.27544	1.28985	1893	-.53615	.23242	1.16971
1794	-.52011	.24905	1.21399	1844	-.29053	.27425	1.29030	1894	-.55060	.23371	1.16267
1795	-.52923	.23842	1.19988	1845	-.27403	.27467	1.29430	1895	-.57172	.22799	1.14422
1796	-.54249	.22319	1.18133	1846	-.26559	.27323	1.29425	1896	-.58547	.23036	1.13668
1797	-.55877	.22783	1.17632	1847	-.25807	.27358	1.29644	1897	-.58730	.23561	1.12762
1798	-.57257	.22740	1.16881	1848	-.23301	.27253	1.29933	1898	-.58384	.23882	1.13479
1799	-.58233	.22429	1.15927	1849	-.24177	.27385	1.29940	1899	-.57710	.23936	1.13974
1800	-.59575	.22293	1.14977	1850	-.22459	.27147	1.30002	1900	-.57014	.23808	1.14364

1901	-.55688	.23147	1.14733
1902	-.54505	.23244	1.15349
1903	-.53715	.23091	1.15584
1904	-.52986	.24483	1.17253
1905	-.51993	.25076	1.18106
1906	-.51475	.25306	1.18455
1907	-.51147	.26247	1.19410
1908	-.50020	.26996	1.20432
1909	-.49421	.27133	1.20815
1910	-.48720	.27377	1.21279
1911	-.48058	.27663	1.21796
1912	-.47307	.27666	1.22049
1913	-.45929	.27815	1.22803
1914	-.44566	.28208	1.23666
1915	-.43162	.28603	1.24545
1916	-.40943	.28874	1.25558
1917	-.40304	.29584	1.26333
1918	-.39269	.28938	1.26052
1919	-.38602	.29294	1.26560
1920	-.37831	.29328	1.26782
1921	-.37036	.29352	1.26966
1922	-.36183	.29476	1.27163
1923	-.35373	.29155	1.27123
1924	-.34641	.29482	1.27629
1925	-.33867	.29522	1.27847
1926	-.32978	.29275	1.27742
1927	-.32093	.28942	1.27686
1928	-.31237	.28982	1.27932
1929	-.30592	.29513	1.28506
1930	-.29681	.29415	1.28585
1931	-.28901	.29138	1.28544
1932	-.27177	.28715	1.28591
1933	-.26357	.29015	1.28973
1934	-.25678	.28931	1.29078
1935	-.24888	.28977	1.29294
1936	-.24017	.28300	1.29283
1937	-.23157	.28866	1.29498
1938	-.22332	.28628	1.29545
1939	-.21465	.28752	1.29807
1940	-.20642	.28463	1.29745
1941	-.19836	.28539	1.29930
1942	-.19055	.28573	1.30035
1943	-.18200	.28338	1.29977
1944	-.17360	.28526	1.30270
1945	-.16464	.28327	1.30242
1946	-.15656	.28170	1.30189
1947	-.14029	.28014	1.30307
1948	-.13361	.28303	1.30644
1949	-.12528	.28077	1.30515
1950	-.11599	.28001	1.30528
1951	-.10858	.28099	1.30664
1952	-.09978	.27788	1.30427
1953	-.09197	.27755	1.30401
1954	-.09099	.28001	1.30593
1955	-.10732	.28925	1.30569
1956	-.12407	.28682	1.30233
1957	-.13972	.29250	1.30442
1958	-.15571	.29097	1.30081
1959	-.17223	.29053	1.29799
1960	-.18928	.29307	1.29602
1961	-.20547	.29510	1.29617
1962	-.22248	.29384	1.29189
1963	-.23874	.29619	1.28983
1964	-.25561	.29760	1.28824
1965	-.27185	.29813	1.28498
1966	-.28755	.29637	1.27999
1967	-.30380	.29676	1.27629
1968	-.31929	.29577	1.27217
1969	-.33617	.29834	1.27031
1970	-.35293	.30024	1.26814
1971	-.36848	.29958	1.26360
1972	-.38406	.29831	1.25923
1973	-.38406	.29831	1.25923
1974	-.40128	.30121	1.25693
1975	-.45830	.29123	1.22714
1976	-.47144	.28461	1.21671
1977	-.48496	.28022	1.20758
1978	-.49834	.27784	1.20013
1979	-.50833	.26693	1.18700
1980	-.51940	.26231	1.17974
1981	-.52700	.25077	1.16748
1982	-.54018	.23413	1.14603
1983	-.55148	.23419	1.14210
1984	-.56520	.23375	1.13583
1985	-.54222	.23889	1.11575
1986	-.53782	.24080	1.12199
1987	-.53146	.23995	1.12517
1988	-.51649	.25427	1.15158
1989	-.50813	.26867	1.15697
1990	-.50468	.27418	1.16273
1991	-.49923	.27726	1.16709
1992	-.49404	.28257	1.17320
1993	-.48946	.28825	1.18049
1994	-.48228	.28844	1.18267
1995	-.47630	.29216	1.18826
1996	-.46944	.29403	1.19296
1997	-.46175	.29401	1.19562
1998	-.45483	.29553	1.19959
1999	-.44850	.29973	1.20542
2000	-.44148	.29844	1.20816
2001	-.43505	.30078	1.21273
2002	-.42874	.30485	1.21871
2003	-.42149	.30501	1.22100
2004	-.41441	.30625	1.22484
2005	-.40783	.31028	1.23098
2006	-.39756	.32050	1.24350
2007	-.38826	.31821	1.24290
2008	-.38061	.31858	1.24503
2009	-.37216	.31541	1.24465
2010	-.36459	.31806	1.24879
2011	-.35697	.31864	1.25129
2012	-.34941	.32022	1.25494
2013	-.34039	.31747	1.25424
2014	-.33264	.31763	1.25672
2015	-.32504	.31792	1.25899
2016	-.31665	.31871	1.26091
2017	-.30794	.31792	1.26244
2018	-.30053	.31922	1.26578
2019	-.29268	.32157	1.26918
2020	-.28476	.31797	1.26859
2021	-.26861	.32069	1.27495
2022	-.25955	.31834	1.27377
2023	-.25318	.32040	1.27822
2024	-.24429	.31671	1.27689
2025	-.23637	.31670	1.27903
2026	-.22745	.31362	1.27817
2027	-.21958	.31536	1.28167
2028	-.20291	.31551	1.28545
2029	-.19539	.31606	1.28737
2030	-.18732	.31639	1.28974
2031	-.17854	.31401	1.28920
2032	-.17004	.31419	1.29189
2033	-.16180	.31392	1.29271
2034	-.15372	.31433	1.29498
2035	-.14650	.31519	1.29642
2036	-.13745	.31253	1.29630
2037	-.13072	.31282	1.29768
2038	-.12225	.31409	1.29963
2039	-.11379	.31489	1.30156
2040	-.10500	.31099	1.29943
2041	-.10080	.31156	1.30018
2042	-.10408	.31508	1.29486
2043	-.12114	.31752	1.29415
2044	-.13643	.31864	1.29223
2045	-.15215	.32082	1.29001
2046	-.16927	.32488	1.29039
2047	-.18631	.32386	1.28577
2048	-.20195	.32365	1.28247
2049	-.21857	.32283	1.27777
2050	-.23488	.32194	1.27325

2051	-.25147	.32493	1.27221	2101	-.22555	.32950	1.27157	2151	-.49127	.28955	1.13606
2052	-.26705	.32416	1.26780	2102	-.21712	.32747	1.27160	2152	-.48559	.29261	1.14105
2053	-.28322	.32353	1.26302	2103	-.20890	.33173	1.27745	2153	-.47412	.30039	1.15137
2054	-.29881	.32291	1.25843	2104	-.20119	.33273	1.27948	2154	-.46845	.30367	1.15672
2055	-.31492	.32208	1.25393	2105	-.19333	.33293	1.28194	2155	-.46115	.30556	1.16149
2056	-.33043	.32216	1.24970	2106	-.18541	.33189	1.28238	2156	-.45405	.30547	1.16401
2057	-.34773	.32440	1.24758	2107	-.17654	.32875	1.28217	2157	-.44697	.30582	1.16771
2058	-.36265	.32381	1.24321	2108	-.16836	.33029	1.28546	2158	-.43977	.30561	1.17043
2059	-.37898	.32384	1.23933	2109	-.15967	.33085	1.28777	2159	-.43290	.30708	1.17499
2060	-.39452	.32109	1.23257	2110	-.15222	.33111	1.28998	2160	-.42026	.31148	1.18373
2061	-.41866	.31056	1.21589	2111	-.14456	.33184	1.29173	2161	-.41344	.31342	1.18774
2062	-.43238	.30751	1.20790	2112	-.13614	.32883	1.29121	2162	-.40761	.31960	1.19617
2063	-.44571	.30422	1.19979	2113	-.12917	.33217	1.29481	2163	-.39955	.32422	1.20151
2064	-.45908	.29919	1.18978	2114	-.12130	.33089	1.29614	2164	-.38758	.33178	1.21054
2065	-.47249	.29530	1.18124	2115	-.11122	.32986	1.29610	2165	-.37973	.33291	1.21305
2066	-.49628	.28291	1.16187	2116	-.10676	.33226	1.29886	2166	-.37427	.34081	1.22069
2067	-.51781	.23908	1.10823	2117	-.11944	.33608	1.28996	2167	-.35898	.34382	1.22704
2068	-.51286	.25607	1.12519	2118	-.13423	.33485	1.28639	2168	-.35215	.34716	1.23127
2069	-.50765	.26503	1.13322	2119	-.15054	.33795	1.28526	2169	-.34298	.34174	1.22906
2070	-.50171	.27821	1.14546	2120	-.16751	.34100	1.28404	2170	-.33497	.34151	1.23212
2071	-.49243	.28599	1.15445	2121	-.18396	.33839	1.27804	2171	-.32697	.34214	1.23469
2072	-.48094	.29245	1.16359	2122	-.19974	.33762	1.27356	2172	-.31909	.34284	1.23656
2073	-.47552	.29664	1.16948	2123	-.21620	.33711	1.26855	2173	-.31114	.34302	1.23906
2074	-.46790	.29643	1.17233	2124	-.23251	.33691	1.26497	2174	-.29529	.34393	1.24339
2075	-.46145	.29908	1.17707	2125	-.24894	.33794	1.26167	2175	-.28678	.34380	1.24524
2076	-.45514	.30211	1.18245	2126	-.26384	.33755	1.25698	2176	-.27882	.34123	1.24577
2077	-.44860	.30575	1.18836	2127	-.28063	.33723	1.25342	2177	-.27064	.34169	1.24803
2078	-.44211	.30731	1.19273	2128	-.29668	.33754	1.24936	2178	-.26320	.34506	1.25238
2079	-.43417	.30571	1.19446	2129	-.31260	.33660	1.24507	2179	-.25496	.34492	1.25537
2080	-.42819	.30857	1.19884	2130	-.32870	.33858	1.24247	2180	-.24804	.34542	1.25715
2081	-.42136	.31009	1.20283	2131	-.34432	.33560	1.23540	2181	-.23969	.34569	1.25968
2082	-.41407	.31133	1.20673	2132	-.35993	.33470	1.23115	2182	-.23179	.34616	1.26182
2083	-.40763	.31434	1.21285	2133	-.39104	.33366	1.22171	2183	-.22362	.34632	1.26443
2084	-.39046	.31859	1.22060	2134	-.40224	.32053	1.20846	2184	-.21550	.34363	1.26457
2085	-.37759	.32960	1.23292	2135	-.41113	.31646	1.20215	2185	-.20669	.34409	1.26704
2086	-.36205	.33024	1.23748	2136	-.42508	.31361	1.19388	2186	-.19882	.34451	1.26922
2087	-.35434	.33059	1.23969	2137	-.43750	.30771	1.18403	2187	-.19081	.34303	1.26963
2088	-.34643	.33082	1.24215	2138	-.45083	.30184	1.17396	2188	-.18295	.34350	1.27174
2089	-.33788	.32915	1.24293	2139	-.46408	.30004	1.16589	2189	-.17495	.34638	1.27627
2090	-.32986	.33008	1.24637	2140	-.47667	.29442	1.15532	2190	-.16592	.34371	1.27667
2091	-.32251	.33165	1.24936	2141	-.48830	.28627	1.14609	2191	-.15760	.34620	1.28005
2092	-.31426	.33238	1.25131	2142	-.49832	.28012	1.13770	2192	-.14969	.34062	1.27772
2093	-.29802	.32936	1.25338	2143	-.50636	.27309	1.12952	2193	-.14202	.34090	1.28002
2094	-.29014	.33243	1.25829	2144	-.51141	.26151	1.12031	2194	-.13412	.34125	1.28234
2095	-.28271	.33289	1.26029	2145	-.51141	.26436	1.11038	2195	-.12680	.34329	1.28469
2096	-.26618	.33368	1.26501	2146	-.50891	.26603	1.11304	2196	-.11924	.34339	1.28717
2097	-.25730	.33193	1.26477	2147	-.50585	.26901	1.11597	2197	-.11212	.34465	1.28869
2098	-.25040	.33398	1.26880	2148	-.50374	.27668	1.12285	2198	-.11771	.34956	1.28208
2099	-.24252	.33103	1.26797	2149	-.49966	.28006	1.12627	2199	-.13242	.34866	1.27870
2100	-.23368	.32843	1.26832	2150	-.49605	.28546	1.13172	2200	-.14847	.34766	1.27385

2201	-.16485	.35154	1.27299	2251	-.33100	.34877	1.21660	2301	-.47751	.30355	1.10896
2202	-.18196	.35303	1.26948	2252	-.32349	.35319	1.22209	2302	-.46526	.31174	1.12113
2203	-.19729	.35136	1.26450	2253	-.31617	.35436	1.22556	2303	-.45750	.31066	1.12398
2204	-.21404	.35074	1.25951	2254	-.30784	.35256	1.22585	2304	-.45175	.31300	1.12872
2205	-.23006	.34924	1.25407	2255	-.29219	.35310	1.23056	2305	-.44384	.31233	1.13223
2206	-.24559	.34640	1.24803	2256	-.28307	.35310	1.23309	2306	-.43033	.31250	1.13940
2207	-.26169	.35093	1.24766	2257	-.27621	.35579	1.23692	2307	-.41834	.31866	1.15024
2208	-.27750	.34836	1.24121	2258	-.26050	.35629	1.24174	2308	-.41079	.31733	1.15216
2209	-.29416	.35012	1.23873	2259	-.25086	.35200	1.24012	2309	-.40371	.31689	1.15511
2210	-.30979	.34963	1.23397	2260	-.24446	.35517	1.24437	2310	-.39844	.32991	1.16574
2211	-.32557	.34866	1.22980	2261	-.23591	.35295	1.24469	2311	-.38898	.34048	1.17529
2212	-.34089	.34842	1.22476	2262	-.22901	.35680	1.25009	2312	-.38342	.34186	1.17729
2213	-.35724	.34800	1.21966	2263	-.21913	.34829	1.24544	2313	-.37862	.34953	1.18427
2214	-.37225	.34446	1.21349	2264	-.21213	.35476	1.25239	2314	-.36645	.35818	1.19327
2215	-.38648	.34132	1.20769	2265	-.20361	.35663	1.25662	2315	-.35846	.35641	1.19463
2216	-.39742	.33017	1.19625	2266	-.19590	.35722	1.25856	2316	-.35072	.35698	1.19659
2217	-.41764	.31807	1.18017	2267	-.18033	.35802	1.26285	2317	-.34298	.35736	1.19879
2218	-.42972	.31238	1.16968	2268	-.17174	.35555	1.26347	2318	-.33598	.36100	1.20386
2219	-.44397	.31068	1.16289	2269	-.16384	.35748	1.26742	2319	-.32796	.36148	1.20661
2220	-.45711	.30742	1.15439	2270	-.15539	.35622	1.26890	2320	-.32001	.36352	1.20983
2221	-.47089	.30594	1.14638	2271	-.14775	.35670	1.27094	2321	-.31210	.36377	1.21224
2222	-.48174	.29572	1.13356	2272	-.14010	.35695	1.27326	2322	-.30424	.36441	1.21474
2223	-.49279	.28895	1.12455	2273	-.13155	.35748	1.27555	2323	-.29748	.37034	1.22113
2224	-.50224	.28383	1.11808	2274	-.12510	.36080	1.27966	2324	-.29034	.37053	1.22341
2225	-.50933	.27555	1.11078	2275	-.11659	.36105	1.28168	2325	-.28148	.37081	1.22614
2226	-.50290	.28507	1.10757	2276	-.14600	.36035	1.26365	2326	-.27356	.36882	1.22646
2227	-.49907	.28544	1.10953	2277	-.16205	.36253	1.26142	2327	-.26454	.36636	1.22657
2228	-.49435	.28910	1.11336	2278	-.21113	.36196	1.24827	2328	-.25734	.36641	1.22900
2229	-.48943	.29173	1.11685	2279	-.22737	.36238	1.24399	2329	-.24866	.36683	1.23147
2230	-.48439	.29633	1.12302	2280	-.24310	.36182	1.23929	2330	-.24189	.37055	1.23580
2231	-.47840	.29981	1.12816	2281	-.25866	.36137	1.23509	2331	-.23380	.37086	1.23820
2232	-.47194	.30102	1.13169	2282	-.27485	.36067	1.23038	2332	-.22620	.36896	1.23894
2233	-.46508	.30204	1.13506	2283	-.29084	.36063	1.22615	2333	-.21783	.36770	1.24037
2234	-.45933	.30419	1.13948	2284	-.30706	.36340	1.22437	2334	-.20999	.37141	1.24511
2235	-.45221	.30660	1.14577	2285	-.32228	.35935	1.21696	2335	-.20156	.37097	1.24794
2236	-.44692	.31054	1.15134	2286	-.33805	.35655	1.21080	2336	-.19327	.37033	1.24917
2237	-.43926	.31013	1.15445	2287	-.35330	.35615	1.20606	2337	-.18530	.36825	1.24907
2238	-.43225	.30980	1.15723	2288	-.36751	.35174	1.19880	2338	-.17803	.37284	1.25431
2239	-.42482	.30966	1.15992	2289	-.38069	.34369	1.18877	2339	-.16997	.37301	1.25680
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2241	-.41238	.31531	1.16987	2291	-.40141	.32673	1.17194	2341	-.14522	.37375	1.26382
2242	-.40630	.31823	1.17531	2292	-.40776	.31548	1.16097	2342	-.13756	.37164	1.26422
2243	-.39825	.32209	1.18033	2293	-.42198	.31555	1.15609	2343	-.12927	.37285	1.26739
2244	-.39347	.32947	1.18634	2294	-.43476	.31260	1.14738	2344	-.12314	.37287	1.26948
2245	-.38287	.33884	1.19611	2295	-.44902	.31353	1.14139	2345	-.12030	.37402	1.26967
2246	-.37531	.33910	1.19838	2296	-.46180	.30908	1.13112	2346	-.12770	.37498	1.25833
2247	-.37013	.34879	1.20729	2297	-.48763	.30146	1.11410	2347	-.15850	.37432	1.24975
2248	-.35518	.35152	1.21326	2298	-.49809	.29052	1.10488	2348	-.17565	.37573	1.24632
2249	-.34732	.35147	1.21544	2299	-.48857	.30757	1.10650	2349	-.19091	.37536	1.24151
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2352	-.23929	.37097	1.22607	2402	-.18972	.38195	1.23765	2452	-.32046	.38037	1.17956
2353	-.25511	.37062	1.22119	2403	-.18254	.38228	1.23973	2453	-.31215	.38035	1.18240
2354	-.27155	.37170	1.21778	2404	-.17479	.38205	1.24145	2454	-.30457	.38081	1.18444
2355	-.28815	.37405	1.21581	2405	-.16617	.37934	1.24171	2455	-.29733	.38301	1.18842
2356	-.30362	.37186	1.21019	2406	-.15734	.38012	1.24439	2456	-.28994	.38705	1.19379
2357	-.31894	.37052	1.20540	2407	-.14240	.38579	1.25339	2457	-.28226	.38502	1.19415
2358	-.33538	.36980	1.20064	2408	-.13457	.38193	1.25180	2458	-.27331	.38667	1.19759
2359	-.35013	.36613	1.19289	2409	-.12675	.38531	1.25697	2459	-.26598	.38693	1.19976
2360	-.36341	.35852	1.18397	2410	-.12323	.38292	1.25504	2460	-.25762	.38742	1.20260
2361	-.37615	.35237	1.17649	2411	-.14052	.38726	1.24399	2461	-.25032	.38785	1.20461
2362	-.38604	.34347	1.16811	2412	-.15618	.38912	1.24115	2462	-.24198	.38752	1.20667
2363	-.39539	.33240	1.15810	2413	-.17324	.38626	1.23461	2463	-.23448	.38736	1.20882
2364	-.41382	.31904	1.14225	2414	-.18762	.38319	1.22805	2464	-.22685	.38765	1.21109
2365	-.42759	.31810	1.13538	2415	-.20468	.38482	1.22497	2465	-.21874	.38662	1.21213
2366	-.43955	.31335	1.12524	2416	-.22038	.38161	1.21814	2466	-.21063	.38687	1.21461
2367	-.45272	.30969	1.11456	2417	-.23589	.37901	1.21177	2467	-.20296	.38681	1.21672
2368	-.46726	.31248	1.10951	2418	-.25211	.38172	1.21009	2468	-.19403	.38704	1.21952
2369	-.47084	.32214	1.10402	2419	-.26818	.38154	1.20605	2469	-.18638	.39073	1.22420
2370	-.45869	.32028	1.11040	2420	-.28359	.37963	1.20008	2470	-.17853	.38730	1.22393
2371	-.44937	.31538	1.11106	2421	-.29947	.38024	1.19630	2471	-.17113	.39022	1.22765
2372	-.44329	.31637	1.11528	2422	-.31503	.37925	1.19156	2472	-.16250	.38960	1.22953
2373	-.43488	.31563	1.11903	2423	-.33078	.37772	1.18564	2473	-.15411	.39015	1.23237
2374	-.42205	.31735	1.12694	2424	-.34639	.37737	1.18191	2474	-.14593	.39005	1.23471
2375	-.41597	.31698	1.12946	2425	-.35991	.37033	1.17278	2475	-.13833	.39239	1.23867
2376	-.40894	.31785	1.13415	2426	-.37238	.36195	1.16339	2476	-.13134	.39209	1.24022
2377	-.39177	.33436	1.15072	2427	-.38143	.35028	1.15345	2477	-.12677	.39226	1.24158
2378	-.38886	.34494	1.15963	2428	-.38925	.34039	1.14551	2478	-.13603	.39286	1.22887
2379	-.38298	.34443	1.16001	2429	-.39848	.33208	1.13754	2479	-.15172	.39512	1.22602
2380	-.37342	.35367	1.16834	2430	-.40473	.31792	1.12659	2480	-.16929	.39487	1.22213
2381	-.36961	.36667	1.17854	2431	-.41809	.31921	1.12050	2481	-.18460	.39445	1.21741
2382	-.36192	.36646	1.17965	2432	-.43034	.31521	1.11114	2482	-.20135	.39320	1.21145
2383	-.34824	.37366	1.18923	2433	-.44236	.31984	1.09537	2483	-.21653	.38975	1.20447
2384	-.34012	.37166	1.18972	2434	-.44012	.31929	1.09788	2484	-.23235	.38864	1.19977
2385	-.33251	.37202	1.19187	2435	-.43281	.31496	1.09842	2485	-.24776	.38895	1.19588
2386	-.32413	.37003	1.19242	2436	-.42584	.31677	1.10414	2486	-.26468	.39188	1.19429
2387	-.31621	.37127	1.19601	2437	-.41392	.32105	1.11414	2487	-.28043	.39188	1.18949
2388	-.30872	.37159	1.19817	2438	-.40216	.32352	1.12248	2488	-.29482	.38376	1.17958
2389	-.30125	.37563	1.20293	2439	-.39855	.32776	1.12532	2489	-.31040	.38458	1.17621
2390	-.29448	.38107	1.20942	2440	-.39447	.33259	1.12989	2490	-.32629	.38405	1.17142
2391	-.28628	.37856	1.20930	2441	-.39049	.33861	1.13533	2491	-.34233	.38659	1.16997
2392	-.27749	.37872	1.21212	2442	-.38409	.35026	1.14467	2492	-.35577	.37899	1.15979
2393	-.27014	.37923	1.21399	2443	-.37888	.35201	1.14607	2493	-.36816	.36993	1.15069
2394	-.26165	.37983	1.21618	2444	-.37354	.35347	1.14786	2494	-.37510	.35392	1.13814
2395	-.25363	.37661	1.21628	2445	-.36952	.36282	1.15527	2495	-.39129	.33475	1.12219
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2764	-.30941	.39882	1.08079
2765	-.30237	.39914	1.08339
2766	-.29402	.39564	1.08305
2767	-.28943	.40446	1.08929
2768	-.28297	.40867	1.09219
2769	-.27626	.41172	1.09419
2770	-.26856	.41115	1.09530
2771	-.26188	.41805	1.10072
2772	-.25441	.42052	1.10431
2773	-.24625	.42112	1.10695
2774	-.23892	.42154	1.10895
2775	-.23061	.42172	1.11157
2776	-.22311	.42171	1.11416
2777	-.21413	.41410	1.11147
2778	-.20736	.41823	1.11682
2779	-.20091	.42009	1.12139
2780	-.19267	.41777	1.12241
2781	-.18502	.41765	1.12517
2782	-.17662	.41799	1.12765
2783	-.16772	.41491	1.12865
2784	-.16089	.41408	1.13202
2785	-.15351	.41250	1.13299
2786	-.14530	.41246	1.13469
2787	-.14024	.41092	1.13487
2788	-.15878	.41256	1.12310
2789	-.17449	.42008	1.12130
2790	-.18927	.41162	1.10933
2791	-.20539	.42049	1.11021
2792	-.22141	.42503	1.10793
2793	-.23682	.42284	1.10126
2794	-.25245	.42221	1.09668
2795	-.26663	.41709	1.08992
2796	-.28046	.40998	1.08467
2797	-.29207	.40027	1.07821
2798	-.30567	.40012	1.07371
2799	-.31934	.40130	1.06935
2800	-.33487	.40253	1.06261

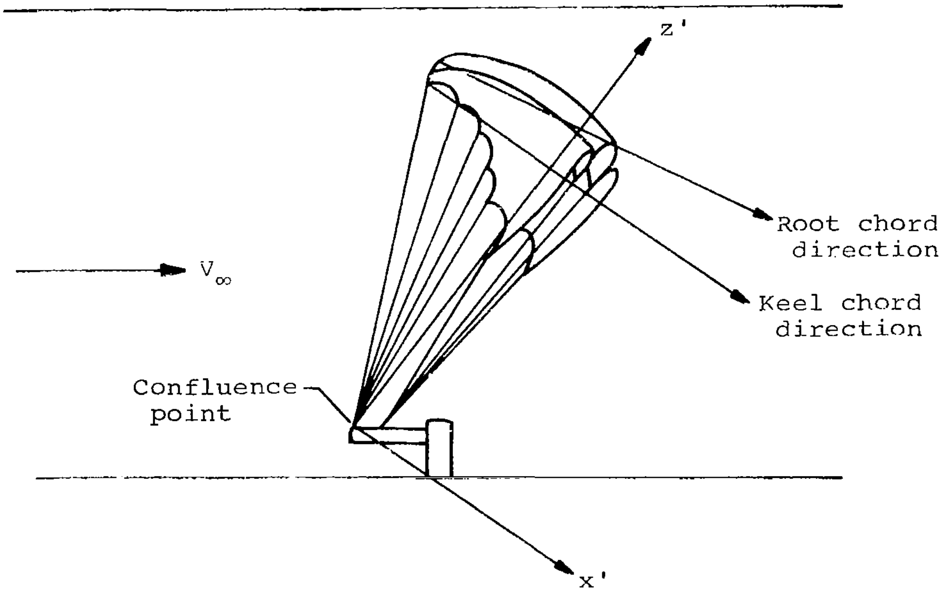
2801	-.33751	.40712	1.05569
2802	-.33154	.40149	1.05492
2803	-.31620	.40009	1.06124
2804	-.30853	.39399	1.06109
2805	-.30229	.39551	1.06476
2806	-.29502	.39589	1.06679
2807	-.28938	.39744	1.06966
2808	-.28489	.40721	1.07522
2809	-.27786	.40847	1.07611
2810	-.27198	.41754	1.08135
2811	-.26514	.41909	1.08356
2812	-.25837	.42792	1.09010
2813	-.24984	.42275	1.08896
2814	-.24138	.42350	1.09152
2815	-.23458	.42619	1.09513
2816	-.22618	.42586	1.09786
2817	-.21825	.42268	1.09754
2818	-.21065	.42239	1.10048
2819	-.20339	.42229	1.10308
2820	-.19586	.41823	1.10371
2821	-.18786	.41706	1.10501
2822	-.18061	.41890	1.10917
2823	-.17154	.41327	1.10883
2824	-.16375	.41257	1.11234
2825	-.15668	.41233	1.11505
2826	-.14948	.41276	1.11700
2827	-.14326	.41293	1.11836
2828	-.15457	.41082	1.10575
2829	-.16984	.41597	1.10283
2830	-.18488	.41626	1.09621
2831	-.20026	.41852	1.09161
2832	-.21560	.42186	1.08858
2833	-.23174	.42457	1.08498
2834	-.24735	.42651	1.08189
2835	-.26300	.42490	1.07849
2836	-.27541	.41398	1.07034
2837	-.29920	.39841	1.05957
2838	-.31203	.39741	1.05194
2839	-.31562	.41074	1.04984
2840	-.30911	.39898	1.04605
2841	-.30176	.39454	1.04613
2842	-.29545	.39564	1.05027
2843	-.29042	.39956	1.05452
2844	-.28489	.40398	1.05668
2845	-.27923	.40833	1.05897
2846	-.27242	.41161	1.06127
2847	-.26639	.41844	1.06523
2848	-.26005	.42122	1.06804
2849	-.25240	.42806	1.07263
2850	-.24509	.42848	1.07463
2851	-.23676	.42840	1.07757
2852	-.22922	.42555	1.07790
2853	-.22112	.42606	1.08062
2854	-.21406	.42543	1.08319
2855	-.20598	.42547	1.08591
2856	-.19846	.42090	1.08548
2857	-.18360	.42071	1.09075
2858	-.17658	.41982	1.09424
2859	-.16742	.41339	1.09325
2860	-.15973	.41246	1.09701
2861	-.15973	.41246	1.09701
2862	-.15234	.40845	1.09651
2863	-.14547	.40861	1.09866
2864	-.15085	.41269	1.09198
2865	-.16577	.41333	1.08609
2866	-.18126	.41766	1.08177
2867	-.19600	.42127	1.07742
2868	-.21114	.42339	1.07305
2869	-.22731	.42867	1.07196
2870	-.24195	.42547	1.06461
2871	-.25701	.42394	1.06013
2872	-.26984	.41614	1.05506
2873	-.28167	.40621	1.04949
2874	-.29290	.39682	1.04480
2875	-.29236	.39062	1.03103
2876	-.28290	.39895	1.03957
2877	-.27880	.40728	1.04370
2878	-.27322	.41197	1.04439
2879	-.26662	.41307	1.04531
2880	-.26088	.42000	1.04952
2881	-.25452	.42439	1.05263
2882	-.23952	.42739	1.05755
2883	-.23084	.42774	1.06007
2884	-.22422	.42312	1.06060
2885	-.21541	.42136	1.06068
2886	-.20899	.42195	1.06439
2887	-.20121	.42328	1.06765
2888	-.19391	.42287	1.07064
2889	-.18655	.41730	1.07092
2890	-.17851	.41735	1.07359
2891	-.17181	.41701	1.07741
2892	-.16400	.41277	1.07849
2893	-.15599	.41245	1.08162
2894	-.14912	.41174	1.08262
2895	-.16189	.41203	1.07122
2896	-.17676	.41705	1.06626
2897	-.19138	.41841	1.05957
2898	-.20741	.42610	1.05940
2899	-.22211	.42612	1.05436
2900	-.23661	.42675	1.04865
2901	-.25171	.42572	1.04473
2902	-.26454	.41491	1.03776
2903	-.28056	.41650	1.03094
2904	-.27447	.40598	1.02415
2905	-.26907	.41354	1.02906
2906	-.26329	.42090	1.03268
2907	-.25611	.42223	1.03353
2908	-.24847	.42339	1.03475
2909	-.24060	.42528	1.03683
2910	-.23337	.42672	1.04036
2911	-.22530	.42771	1.04414
2912	-.21863	.42455	1.04518
2913	-.21141	.42465	1.04697
2914	-.20438	.42433	1.04976
2915	-.19684	.42419	1.05306
2916	-.19004	.42419	1.05537
2917	-.18278	.41824	1.05556
2918	-.17486	.41514	1.05758
2919	-.16833	.41465	1.06039
2920	-.15988	.40660	1.05920
2921	-.15111	.40681	1.06246
2922	-.14909	.40965	1.06467
2923	-.15957	.41806	1.05980
2924	-.17304	.41439	1.04976
2925	-.18716	.41559	1.04294
2926	-.20180	.42223	1.04153
2927	-.21588	.42278	1.03605
2928	-.24590	.42274	1.02585
2929	-.26078	.42027	1.02373
2930	-.26538	.42499	1.01709
2931	-.25810	.41832	1.01444
2932	-.25154	.42332	1.01778
2933	-.24401	.42413	1.01938
2934	-.23624	.42793	1.02351
2935	-.22000	.42416	1.02642
2936	-.21299	.42396	1.02904
2937	-.20048	.42302	1.03444
2938	-.19352	.42234	1.03763
2939	-.17833	.41589	1.04013
2940	-.17089	.41521	1.04345
2941	-.16462	.41153	1.04512
2942	-.15618	.41123	1.04833
2943	-.15216	.41104	1.04994
2944	-.16990	.41377	1.03459
2945	-.19771	.41898	1.02435
2946	-.21032	.42556	1.02254
2947	-.22380	.42015	1.01236
2948	-.24042	.42212	1.00929
2949	-.24264	.42224	.99968
2950	-.23871	.42666	1.00504

2951	-.23032	.42721	1.00725
2952	-.22329	.42940	1.01083
2953	-.21528	.42800	1.01360
2954	-.20831	.42403	1.01471
2955	-.19557	.41837	1.01709
2956	-.18846	.41759	1.02045
2957	-.17548	.41704	1.02554
2958	-.16751	.41061	1.02564
2959	-.16046	.40970	1.02913
2960	-.15487	.40758	1.02872
2961	-.16517	.40709	1.01723
2962	-.19375	.41580	1.00887
2963	-.20572	.42299	1.00700
2964	-.21971	.42397	.99998
2965	-.22141	.42518	.99098
2966	-.21771	.42962	.99610
2967	-.21000	.42540	.99615
2968	-.20289	.42150	.99841
2969	-.19116	.41399	1.00010
2970	-.18401	.41566	1.00483
2971	-.17769	.41531	1.00741
2972	-.16370	.40965	1.01195
2973	-.15715	.40813	1.01341
2974	-.16094	.40365	1.00040
2975	-.20025	.42187	.99132
2976	-.21582	.42784	.98963
2977	-.20114	.42261	.98056
2978	-.19735	.42185	.98262
2979	-.18593	.41332	.98613
2980	-.17351	.40800	.98988
2981	-.16677	.40372	.99043
2982	-.15819	.40001	.99148
2983	-.16268	.40388	.97897
2984	-.17007	.40460	.97559
2985	-.18044	.40674	.96952
2986	-.18514	.42096	.97347
2987	-.17983	.41531	.96839
2988	-.16583	.40209	.95869

APPENDIX D

TABULATION OF CANOPY COORDINATES FOR TWIN-KEEL PARAWING

The following pages are a reproduction of the printed computer output for the canopy coordinates obtained photogrammetrically at the Langley Research Center from the stereo photographs of the twin-keel parawing in the wind tunnel. The coordinate system used in the data presentation is illustrated in the sketch below.



The origin of the axis system is on the sting at the confluence point of all the rigging lines except those on the trailing edge. The positive x' direction is parallel to the keel chord direction, which differs slightly from the root chord direction, with positive x' downstream. The positive z' direction is upward towards the canopy, and the positive y' direction is consistent with a right-hand system.

The data consist of a point identification number, followed by the x', y', and z' coordinates of the point, nondimensionalized by the characteristic length h_k, which is 75 inches for the parawing tested. Points 1-12 are the canopy line attachment points for keel lines 1-12, respectively. The six leading-edge line attachment points are listed as points 13-18. For the remainder of the coordinates, generally, a single streamwise set of points having about the same y' coordinate was read, with the sets starting near the vertical plane of symmetry and moving out toward the tip.

Point No.	x'/h_k	y'/h_k	z'/h_k	
1	-.41920	.10703	.86478	K1
2	-.38668	.13789	.88237	K2
3	-.33674	.14857	.89325	K3
4	-.27954	.16197	.90401	K4
5	-.22207	.17916	.93441	K5
6	-.16443	.17318	.93674	K6
7	-.11003	.16909	.94245	K7
8	-.04790	.17185	.94557	K8
9	.00896	.16517	.93223	K9
10	.06727	.15954	.92205	K10
11	.11607	.15628	.89836	K11
12	.15994	.15061	.86478	K12
13	-.38303	.17650	.82932	LE1
14	-.30536	.26011	.81751	LE2
15	-.23315	.34008	.78933	LE3
16	-.14934	.40491	.72147	LE4
17	-.06162	.42228	.65039	LE5
18	.02084	.36495	.57049	LE6
[illegible]	-.48273	.01552	.94830	
	-.48610	.00622	.94999	
	-.48780	.01687	.96861	
22	-.48478	.02689	.96133	
23	-.48155	.03106	.94659	
24	-.47942	.04186	.93856	
25	-.47577	.05374	.93150	
26	-.47534	.06436	.92592	
27	-.47477	.07617	.92056	
28	-.47222	.08537	.91757	
29	-.47014	.09019	.90510	
30	-.46633	.09701	.89360	
31	-.46470	.10282	.87967	
32	-.45754	.10845	.87026	
33	-.44772	.11461	.86722	
34	-.43404	.11591	.85867	
35	-.49393	.01736	.94905	
36	-.50335	.02229	.94390	
37	-.47140	.00116	.98910	
38	-.45855	.00000	.99241	
39	-.44503	.00050	.99417	
40	-.43236	.00187	.99482	
41	-.41910	.00211	.99619	
42	-.40589	.00102	.99912	
43	-.39253	.00228	.99897	
44	-.37979	.00417	.99737	
45	-.36690	.00381	.99918	
46	-.35326	.00237	1.00206	
47	-.34029	.00241	1.00205	
48	-.32659	.00147	1.00348	
49	-.31418	.00310	1.00200	
50	-.30098	.00485	1.00127	
51	-.28740	.00437	1.00346	
52	-.27411	.00299	1.00242	
53	-.25087	.00136	1.00887	
54	-.23919	.00293	1.00656	
55	-.22581	.00244	1.00863	
56	-.21177	.00110	1.01179	
57	-.19864	.00031	1.01490	
58	-.18583	.00225	1.01271	
59	-.17361	.00460	1.01164	
60	-.16136	.00512	1.01643	
61	-.14768	.00319	1.01989	
62	-.13398	.00240	1.02091	
63	-.12140	.00425	1.01930	
64	-.10768	.00199	1.02255	
65	-.09430	.00199	1.02322	
66	-.08042	.00072	1.02562	
67	-.06704	.00001	1.02658	
68	-.05550	.00395	1.02203	
69	-.04057	.00040	1.02698	
70	-.02732	.00113	1.02598	
71	-.01524	.00274	1.02308	
72	-.00063	.00007	1.02568	
73	.01087	.00377	1.02023	
74	.02540	.00113	1.02320	
75	.03814	.00232	1.02095	
76	.05237	.00065	1.02125	
77	.06560	.00081	1.01918	
78	.07885	.00001	1.01744	
79	.09098	.00001	1.01429	
80	.10396	.00093	1.00930	
81	.11815	.00136	1.00878	
82	.12988	.00021	1.00315	
83	.14116	.00227	.99656	
84	.15412	.00087	.99407	
85	.16727	.00049	.99093	
86	.18203	.00232	.98978	
87	.19267	.00000	.98237	
88	.20505	.00102	.97733	
89	.21737	.00027	.97407	
90	-.49483	.00333	.95219	
91	-.50400	.00697	.94845	
92	-.48346	.01185	.98245	
93	-.47150	.01277	.98814	
94	-.45852	.01186	.98962	
95	-.44519	.01156	.99211	
96	-.43229	.01212	.99479	
97	-.41878	.01125	.99589	
98	-.40579	.01167	.99762	
99	-.39265	.01281	.99981	
100	-.37938	.01291	1.00127	

Suspension line attachment points

101	-.36634	.00978	.99848
102	-.35237	.01279	1.00329
103	-.33968	.01116	1.00146
104	-.32675	.00932	.99976
105	-.31352	.01124	1.00303
106	-.29992	.01155	1.00486
107	-.28705	.01033	1.00544
108	-.27341	.01271	1.00490
109	-.26405	.01267	.99518
110	-.25100	.01324	1.00747
111	-.25082	.01374	1.00783
112	-.23904	.01052	1.00708
113	-.22507	.01189	1.01057
114	-.21141	.01219	1.01226
115	-.19903	.01024	1.01078
116	-.18576	.01076	1.01298
117	-.17282	.01043	1.01430
118	-.16081	.01052	1.01901
119	-.14719	.01088	1.02106
120	-.13396	.01080	1.02124
121	-.12108	.00908	1.01943
122	-.10747	.01075	1.02183
123	-.09408	.01104	1.02288
124	-.08216	.00814	1.01999
125	-.06842	.00947	1.02213
126	-.05485	.01053	1.02368
127	-.04063	.01190	1.02541
128	-.02825	.01035	1.02327
129	-.01471	.01084	1.02327
130	-.00132	.01134	1.02331
131	.01208	.01203	1.02349
132	.02585	.01250	1.02317
133	.03864	.01235	1.02245
134	.05208	.01161	1.01992
135	.06523	.01247	1.01850
136	.07810	.01215	1.01544
137	.09230	.01416	1.01521
138	.10545	.01414	1.01180
139	.11671	.01168	1.00520
140	.13022	.01202	1.00167
141	.14228	.01229	.99800
142	.15554	.01367	.99578
143	.16642	.01126	.98834
144	.18064	.01297	.98619
145	.19302	.01283	.98155
146	.20535	.01254	.97708
147	.21575	.01077	.96983
148	-.49506	.00749	.95082
149	-.49506	.00749	.95082
150	-.49506	.00749	.95082
151	-.49506	.00749	.95082
152	-.48262	.02267	.97847
153	-.47057	.02407	.98349
154	-.45779	.02550	.98784
155	-.44466	.02489	.98989
156	-.43132	.02756	.99557
157	-.41839	.02294	.99196
158	-.40504	.02419	.99538
159	-.39186	.02460	.99658
160	-.37884	.02424	.99744
161	-.36571	.02437	.99923
162	-.35174	.02513	1.00082
163	-.33930	.02419	.99986
164	-.32616	.02224	.99820
165	-.31340	.02266	.99931
166	-.29948	.02348	1.00121
167	-.28689	.02309	1.00256
168	-.27407	.02403	1.00127
169	-.25129	.02384	1.00299
170	-.23803	.02546	1.00850
171	-.22471	.02502	1.00893
172	-.21126	.02501	1.01070
173	-.19809	.02461	1.01115
174	-.18600	.02164	1.00891
175	-.17268	.02266	1.01247
176	-.16025	.02290	1.01611
177	-.14763	.02213	1.01738
178	-.13429	.02287	1.01862
179	-.12055	.02357	1.01981
180	-.10734	.02400	1.02080
181	-.09436	.02285	1.02027
182	-.08050	.02504	1.02379
183	-.06782	.02313	1.02127
184	-.05533	.02267	1.02088
185	-.04099	.02395	1.02271
186	-.02762	.02405	1.02281
187	-.01497	.02312	1.02127
188	-.00155	.02421	1.02142
189	.01228	.02499	1.02176
190	.02640	.02614	1.02263
191	.03974	.02644	1.02263
192	.05169	.02391	1.01710
193	.06463	.02380	1.01507
194	.07832	.02492	1.01393
195	.09128	.02481	1.01065
196	.10463	.02545	1.00784
197	.11747	.02555	1.00441
198	.13028	.02583	1.00083
199	.14350	.02727	.99860
200	.15391	.02442	.99127
201	.16906	.02831	.99133
202	.17996	.02570	.98336
203	.19260	.02619	.97932
204	.20397	.02440	.97240
205	.21528	.02415	.96723
206	-.49383	.02047	.94927
207	-.49370	.01849	.94713
208	-.49370	.01849	.94713
209	-.49370	.01849	.94713
210	-.46967	.03638	.97962
211	-.45763	.03520	.98028
212	-.44381	.03710	.9851
213	-.43096	.03492	.9848
214	-.41769	.03697	.98977
215	-.40473	.03497	.98905
216	-.39128	.03717	.99278
217	-.37823	.03519	.99172
218	-.36522	.03634	.99462
219	-.35130	.03590	.99479
220	-.33875	.03564	.99517
221	-.32539	.03578	.99584
222	-.31281	.03615	.99652
223	-.29909	.03562	.99715
224	-.28752	.03465	.99817
225	-.27475	.03587	.9966
226	-.26504	.03775	.99246
227	-.25134	.03334	.99686
228	-.25134	.03334	.99686
229	-.23844	.03560	1.00220
230	-.22543	.03491	1.00323
231	-.21153	.03627	1.00572
232	-.19839	.03714	1.0083
233	-.18523	.03643	1.0087
234	-.17237	.03624	1.0097
235	-.16073	.03285	1.00827
236	-.14801	.03459	1.01353
237	-.13487	.03464	1.01427
238	-.12087	.03612	1.01654
239	-.10838	.03552	1.01655
240	-.09607	.03350	1.01515
241	-.08123	.03672	1.01966
242	-.06867	.03551	1.01778
243	-.05571	.03504	1.01758
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1795	-.01219	.39463	.86021
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1797	.01333	.39285	.86144
1798	.02470	.39357	.86295
1799	.03997	.39380	.86495
1800	.05391	.39318	.86541
1801	.06710	.39550	.86918
1802	.08029	.39550	.86970
1803	.09307	.39411	.86974
1804	.10634	.39375	.87055
1805	.12011	.39510	.87336
1806	.13201	.39247	.87257
1807	.12983	.40259	.86410
1808	.12242	.40149	.86229
1809	.10918	.40141	.86077
1810	.09616	.40279	.86006
1811	.08230	.40160	.85793
1812	.06934	.40120	.85703
1813	.05585	.39983	.85501
1814	.04261	.40135	.85465
1815	.02920	.40133	.85323
1816	.01548	.40000	.85095
1817	.00224	.39962	.84914
1818	-.01026	.40063	.84937
1819	-.02262	.40223	.84912
1820	-.03611	.40099	.84614
1821	-.04939	.40397	.84671
1822	-.06144	.40360	.84491
1823	-.07327	.40555	.84558
1824	-.08656	.40502	.84402
1825	-.09944	.40662	.84355
1826	-.11283	.40288	.83978
1827	-.12525	.40540	.84079
1828	-.13841	.40199	.83639
1829	-.15126	.40068	.83452
1830	-.16440	.39874	.83230
1831	-.17534	.39927	.83202
1832	-.18837	.39342	.82538
1833	-.20080	.39118	.82174
1834	-.21266	.38340	.81616
1835	-.22072	.37147	.80773
1836	-.22072	.37147	.80773
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1838	-.24110	.33808	.78576
1839	-.23150	.35544	.78364
1840	-.21865	.37900	.79701
1841	-.21865	.37900	.79701
1842	-.20909	.38749	.80255
1843	-.19912	.39089	.80659
1844	-.18624	.39484	.81108
1845	-.17283	.39680	.81632
1846	-.16182	.40144	.81955
1847	-.14997	.40206	.82055
1848	-.13826	.40438	.82276
1849	-.12534	.40749	.82536
1850	-.11141	.40861	.82749
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1855	-.04706	.40980	.83525
1856	-.03358	.40867	.83653
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1858	-.00874	.40670	.83803
1859	.00412	.40624	.83888
1860	.01681	.40632	.84003
1861	.03106	.40839	.84298
1862	.04354	.40578	.84193
1863	.05709	.40584	.84362
1864	.06922	.40332	.84267
1865	.08290	.40367	.84371
1866	.09656	.40588	.84673
1867	.11019	.40515	.84776
1868	.12241	.40225	.84712
1869	.12039	.40748	.83590
1870	.11091	.40658	.83378
1871	.09952	.40887	.83426
1872	.08438	.40795	.83170
1873	.07035	.40532	.82991
1874	.05967	.41111	.83184
1875	.04632	.41052	.82989
1876	.03341	.41338	.83074
1877	.01885	.41044	.82704
1878	.00533	.40908	.82454
1879	-.00690	.41183	.82529
1880	-.02051	.41096	.82308
1881	-.03200	.41361	.82373
1882	-.04511	.41462	.82283
1883	-.05799	.41561	.82223
1884	-.07105	.41477	.82024
1885	-.08383	.41534	.81899
1886	-.09669	.41629	.81980
1887	-.10924	.41603	.81723
1888	-.12351	.41263	.81355
1889	-.13534	.41152	.81329
1890	-.14701	.40883	.81174
1891	-.15919	.40411	.80754
1892	-.16916	.40131	.80575
1893	-.18148	.40182	.80328
1894	-.19472	.39863	.79790
1895	-.20703	.39241	.79189
1896	-.21646	.38685	.78755
1897	-.22404	.37631	.78071
1898	-.22903	.37053	.77785
1899	-.22443	.38683	.77177
1900	-.21558	.38929	.77298

1901	-.20356	.39779	.77982	1951	-.17499	.39893	.77289	2001	-.13737	.41348	.75683
1902	-.19143	.39936	.78257	1952	-.18812	.39814	.76789	2002	-.15600	.39660	.75021
1903	-.17879	.39933	.78602	1953	-.20046	.39708	.76481	2003	-.16644	.40280	.75212
1904	-.16636	.40140	.79158	1954	-.21146	.40029	.76482	2004	-.18251	.39771	.74126
1905	-.15597	.40608	.79412	1955	-.19919	.40249	.75390	2005	-.16710	.39948	.73599
1906	-.14497	.40895	.79589	1956	-.18559	.39775	.75474	2006	-.16411	.39801	.73652
1907	-.13293	.41617	.80051	1957	-.17102	.40077	.76077	2007	-.15339	.39406	.73725
1908	-.12203	.41751	.80079	1958	-.16074	.39919	.76426	2008	-.15339	.39406	.73725
1909	-.10758	.42174	.80393	1959	-.14956	.40504	.76722	2009	-.13685	.41089	.74446
1910	-.09463	.42205	.80566	1960	-.14105	.40705	.76609	2010	-.12551	.42083	.74560
1911	-.08147	.42231	.80705	1961	-.12872	.42160	.77446	2011	-.11468	.42990	.74976
1912	-.06918	.41954	.80630	1962	-.11931	.42604	.77565	2012	-.10085	.43517	.75312
1913	-.05572	.42140	.80961	1963	-.10441	.43031	.77910	2013	-.08791	.43711	.75519
1914	-.04276	.42106	.81097	1964	-.09111	.43203	.78169	2014	-.07535	.43464	.75476
1915	-.02984	.42038	.81230	1965	-.07761	.43355	.78420	2015	-.06221	.43526	.75768
1916	-.01792	.41780	.81147	1966	-.06593	.42901	.78252	2016	-.04830	.43533	.75993
1917	-.00552	.41475	.81093	1967	-.05305	.42508	.78174	2017	-.03575	.43222	.75975
1918	.00818	.41661	.81395	1968	-.03952	.42793	.78529	2018	-.02334	.42869	.75964
1919	.02040	.41602	.81507	1969	-.02704	.42386	.78429	2019	-.01115	.42697	.76031
1920	.03463	.41705	.81733	1970	-.01637	.41894	.78251	2020	-.00009	.42371	.75931
1921	.04848	.41717	.81917	1971	-.00306	.41886	.78391	2021	.01332	.42399	.76086
1922	.06145	.41592	.82039	1972	.01047	.42120	.78696	2022	.02503	.42032	.76106
1923	.07393	.41354	.81922	1973	.02238	.42035	.78842	2023	.03840	.41915	.76262
1924	.08685	.41336	.82091	1974	.03764	.42108	.79085	2024	.05191	.41681	.76353
1925	.10040	.41319	.82245	1975	.05110	.42013	.79184	2025	.06423	.41314	.76352
1926	.11126	.40679	.81964	1976	.06457	.42066	.79443	2026	.07622	.41052	.76435
1927	.11483	.40653	.82001	1977	.07619	.41463	.79228	2027	.08936	.40540	.76385
1928	.11124	.40607	.80699	1978	.08924	.41407	.79417	2028	.09557	.40403	.76410
1929	.10076	.41015	.80609	1979	.09915	.40521	.79020	2029	-.13737	.41241	.73217
1930	.08925	.41499	.80758	1980	.10352	.40407	.79007	2030	-.12342	.42205	.73256
1931	.07529	.41391	.80490	1981	.09739	.39720	.77325	2031	-.12342	.42205	.73256
1932	.06288	.41584	.80471	1982	.08752	.40603	.77483	2032	-.11273	.43045	.73592
1933	.04992	.41920	.80546	1983	.07640	.41126	.77645	2033	-.09953	.43445	.73788
1934	.03656	.41892	.80403	1984	.06423	.41490	.77649	2034	-.08639	.43875	.74225
1935	.02412	.42188	.80470	1985	.05093	.41816	.77702	2035	-.07381	.43678	.74207
1936	.01049	.42173	.80230	1986	.03899	.42160	.77708	2036	-.05937	.43879	.74547
1937	-.00274	.41969	.79963	1987	.02421	.42045	.77489	2037	-.04579	.43775	.74638
1938	-.01692	.41789	.79643	1988	.01106	.41942	.77155	2038	-.03409	.43303	.74573
1939	-.02735	.42403	.79914	1989	-.00112	.42231	.77217	2039	-.02186	.42831	.74511
1940	-.04055	.42596	.79917	1990	-.01330	.42538	.77262	2040	-.01043	.42636	.74549
1941	-.05411	.42516	.79699	1991	-.02576	.42472	.77046	2041	.00029	.42170	.74422
1942	-.06696	.42495	.79514	1992	-.03693	.43182	.77374	2042	.01217	.41915	.74359
1943	-.08059	.42381	.79267	1993	-.04931	.43339	.77222	2043	.02635	.42120	.74867
1944	-.09232	.42900	.79540	1994	-.06324	.43351	.77044	2044	.03925	.41783	.74930
1945	-.10516	.42789	.79312	1995	-.07621	.43556	.77035	2045	.05131	.41292	.74739
1946	-.11999	.42155	.78797	1996	-.08794	.43927	.77175	2046	.06350	.40672	.74591
1947	-.12961	.42246	.78971	1997	-.10161	.43621	.76880	2047	.07353	.40002	.74404
1948	-.14152	.41261	.78452	1998	-.11587	.42965	.76393	2048	.08627	.39606	.74423
1949	-.15346	.40513	.78035	1999	-.12699	.42124	.75905	2049	.09752	.39576	.74418
1950	-.16264	.40370	.77919	2000	-.13737	.41348	.75683	2050	.08369	.39551	.73146

2051	.07220	.39228	.72707	2101	-.06872	.43862	.70260	2151	.03628	.38323	.64803
2052	.06294	.40294	.73155	2102	-.08167	.43757	.70033	2152	.02773	.39541	.65120
2053	.05071	.40832	.73224	2103	-.09374	.44058	.70047	2153	.01926	.40548	.65486
2054	.03870	.41266	.73150	2104	-.10832	.43550	.69634	2154	.01115	.41415	.65738
2055	.02635	.41655	.73190	2105	-.12003	.43543	.69760	2155	-.00184	.41560	.65586
2056	.01319	.41856	.73065	2106	-.10684	.43532	.69197	2156	-.01425	.41673	.65178
2057	.00168	.42147	.73106	2107	-.09156	.44224	.68815	2157	-.02653	.42143	.65079
2058	-.00734	.42796	.73314	2108	-.07960	.43826	.68765	2158	-.02749	.41936	.64961
2059	-.01994	.42999	.73268	2109	-.06833	.43484	.68715	2159	-.05089	.42578	.65055
2060	-.03162	.43619	.73443	2110	-.05528	.43445	.68844	2160	-.05598	.42728	.65114
2061	-.04558	.43584	.73158	2111	-.04221	.43226	.68916	2161	-.04759	.42182	.63663
2062	-.05818	.43809	.73029	2112	-.02865	.43164	.69211	2162	-.03562	.42213	.64093
2063	-.07202	.43684	.72760	2113	-.01520	.42994	.69544	2163	-.03562	.42213	.64093
2064	-.08342	.44241	.72948	2114	-.00168	.43005	.69811	2164	-.01383	.41297	.63898
2065	-.09685	.43985	.72693	2115	.00730	.42054	.69637	2165	-.00237	.40828	.64017
2066	-.11034	.43438	.72417	2116	.01670	.41449	.69305	2166	.00931	.40666	.64213
2067	-.12194	.42722	.72065	2117	.02576	.40333	.68761	2167	.02041	.40172	.64364
2068	-.13237	.41643	.71679	2118	.03716	.39709	.68713	2168	.02852	.39263	.64020
2069	-.13930	.40593	.71166	2119	.04863	.39150	.69666	2169	.03883	.38385	.63921
2070	-.13517	.41494	.70075	2120	.05954	.38272	.68461	2170	.04708	.37336	.63509
2071	-.12206	.42841	.70685	2121	.06803	.38838	.69055	2171	.04393	.37576	.62487
2072	-.10945	.43765	.71188	2122	.06274	.38435	.67594	2172	.03901	.37969	.62609
2073	-.09641	.43919	.71247	2123	.04919	.38949	.67551	2173	.02708	.38358	.62543
2074	-.08251	.44207	.71514	2124	.03786	.39505	.67593	2174	.02012	.39525	.63041
2075	-.06890	.44240	.71735	2125	.02760	.40253	.67618	2175	.01109	.40491	.63175
2076	-.05664	.43930	.71691	2126	.01681	.40925	.67759	2176	-.00133	.40445	.62693
2077	-.04405	.43522	.71695	2127	.01010	.42210	.68518	2177	-.01291	.40908	.62580
2078	-.03044	.43551	.72019	2128	-.00229	.42446	.68259	2178	-.01291	.40908	.62580
2079	-.01944	.43062	.71949	2129	-.01635	.42361	.67867	2179	-.02403	.41108	.62661
2080	-.00511	.43092	.72281	2130	-.02899	.42616	.67662	2180	-.03058	.41535	.62599
2081	.00698	.42643	.72322	2131	-.04058	.43093	.67630	2181	-.01391	.42010	.62271
2082	.01489	.41852	.71834	2132	-.05262	.43595	.67897	2182	-.00034	.40254	.61768
2083	.02576	.41084	.71566	2133	-.06700	.43177	.67601	2183	-.00034	.40254	.61768
2084	.03658	.40564	.71429	2134	-.07794	.43691	.67610	2184	.00981	.39751	.61779
2085	.05010	.40385	.71649	2135	-.08981	.43889	.67466	2185	.01933	.39009	.61792
2086	.06023	.39319	.71355	2136	-.07535	.43470	.66428	2186	.02797	.38010	.61402
2087	.07111	.38643	.71135	2137	-.06461	.43130	.66483	2187	.04036	.37643	.61410
2088	.07544	.38517	.71135	2138	-.05206	.42845	.66350	2188	.03699	.37418	.60316
2089	.06750	.37617	.69354	2139	-.03982	.42713	.66150	2189	.02768	.37365	.60075
2090	.06014	.38894	.69922	2140	-.02824	.42298	.66218	2190	.01900	.38291	.60313
2091	.04915	.39694	.70117	2141	-.01397	.42336	.66633	2191	.00748	.38516	.60047
2092	.03749	.40225	.70135	2142	-.00243	.42039	.66872	2192	-.00104	.39410	.60342
2093	.02635	.40776	.70121	2143	.01075	.41906	.67137	2193	-.00740	.40118	.60217
2094	.01691	.41719	.70564	2144	.01842	.40886	.66683	2194	.00547	.39931	.59770
2095	.00502	.41915	.70700	2145	.02622	.39569	.66088	2195	.00908	.38669	.59369
2096	-.00389	.42707	.70766	2146	.03802	.39078	.66219	2196	.01866	.37842	.59189
2097	-.01618	.43100	.70738	2147	.04906	.38424	.66157	2197	.02954	.37467	.59241
2098	-.02822	.43640	.70825	2148	.05494	.37534	.65947	2198	.03206	.37420	.59218
2099	-.04158	.43722	.70593	2149	.05271	.37551	.64771	2199	.02906	.37629	.58393
2100	-.05611	.43646	.70250	2150	.04892	.37922	.64891	2200	.02064	.37865	.58291
								2201	.02071	.37880	.58302

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TABLE I

PROPERTIES OF THE CIRCULAR-ARC FITS TO THE SINGLE-KEEL PARAWING

x (in.)	x/c_r	e (in.)	f (in.)	r (in.)	s (in.)
2	0.052	0.60	5.40	8.60	7.98
4	.103	.50	6.50	9.50	9.01
6	.154	1.65	7.60	13.30	12.02
8	.206	3.05	8.60	15.50	13.88
10	.256	4.50	9.50	16.50	14.94
12	.308	5.95	10.30	17.80	16.14
14	.360	7.40	11.00	19.10	17.30
16	.411	8.80	11.60	20.60	18.53
18	.462	10.30	12.10	22.40	19.89
20	.514	11.85	12.50	24.20	21.18
22	.575	13.45	12.85	25.60	22.20
24	.616	15.15	13.15	26.00	22.60
26	.668	16.90	13.40	26.00	22.74
28	.720	18.70	13.50	26.20	22.92
30	.771	20.50	13.50	27.00	23.38
32	.822	22.00	13.50	27.00	23.38
34	.874	23.75	13.50	27.00	23.38
36	.925	25.00	10.00	18.00	16.12
38	.977	27.00	6.00	17.00	12.96

TABLE II

PROPERTIES OF THE CIRCULAR-ARC FITS TO THE TWIN-KEEL PARAWING

x (in.)	x/c_r	e (in.)	f (in.)	r (in.)	s (in.)
2	0.039	-0.9	4.0	11.4	8.67
4	.078	.1	9.6	13.6	13.00
6	.117	1.1	10.5	18.0	16.36
8	.156	2.1	11.2	23.7	20.14
10	.194	3.2	11.9	25.5	21.57
12	.234	4.2	12.5	28.5	23.58
14	.272	5.2	13.1	31.2	25.41
16	.312	6.2	13.8	33.4	27.04
18	.350	7.3	14.5	34.3	28.01
20	.389	8.3	15.4	35.5	29.26
22	.429	9.3	16.5	35.9	30.21
24	.466	10.3	18.4	36.0	31.40
26	.505	11.3	21.4	36.0	32.91
28	.545	12.3	24.0	36.0	33.94
30	.585	13.4	25.4	36.1	34.48
32	.622	14.6	25.6	36.3	34.69
34	.662	15.8	23.7	36.9	34.46
36	.700	17.1	20.4	37.7	33.50
38	.740	18.4	18.5	38.8	33.07
40	.780	19.9	17.0	40.0	32.73
42	.818	21.4	16.1	41.4	32.77
44	.856	23.2	15.4	43.0	32.97
46	.895	24.9	10.0	24.5	19.75
48	.934	26.7	5.8	12.0	10.27
50	.973	28.5	2.2	4.5	3.87

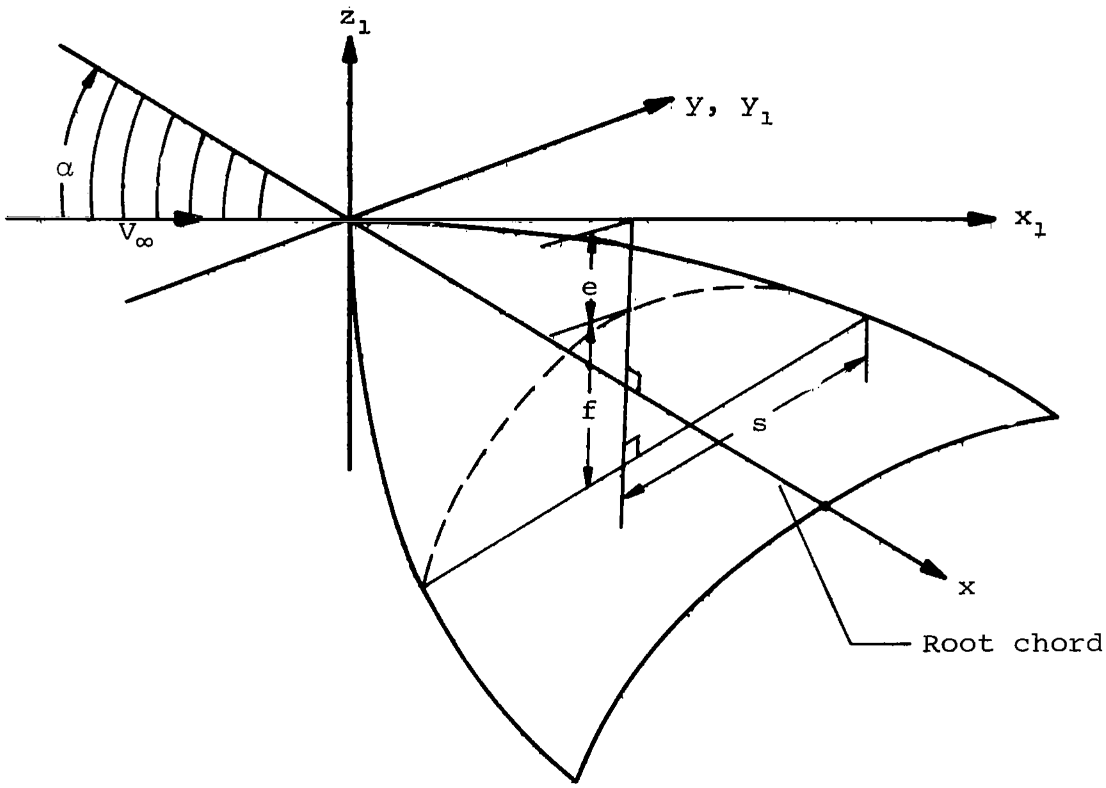
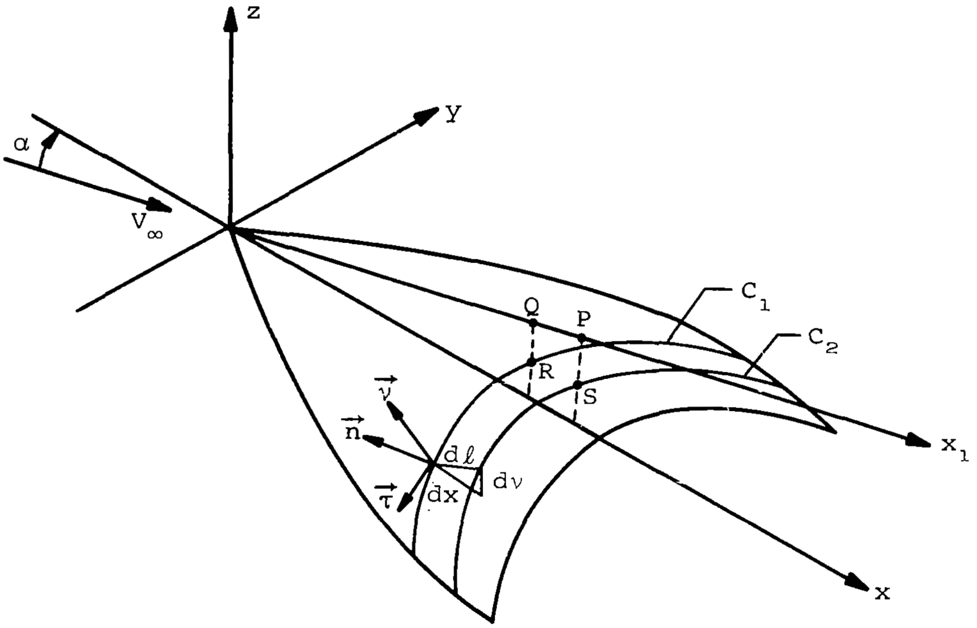
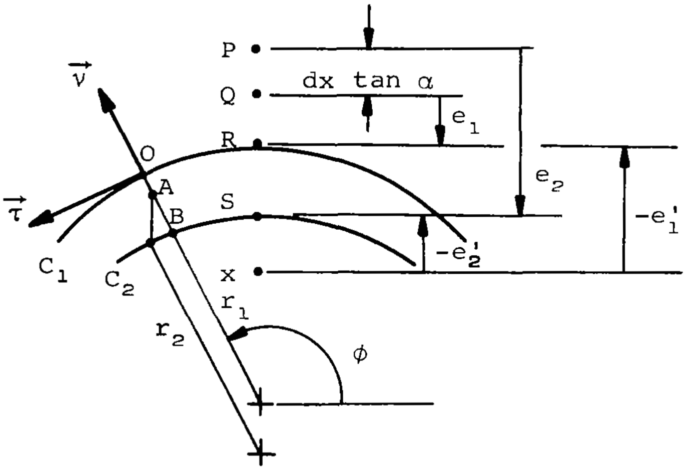


Figure 1.- Axes and crossflow plane used in theory.

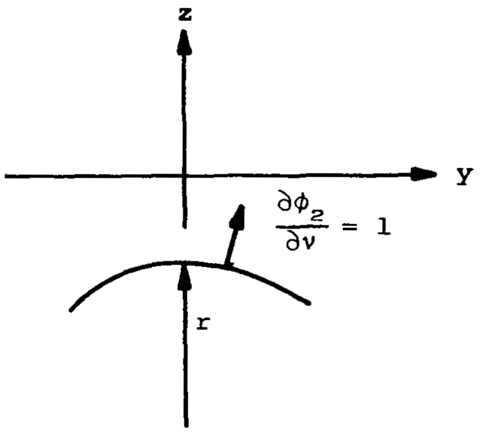


(a) Boundary condition for stationary parawing.

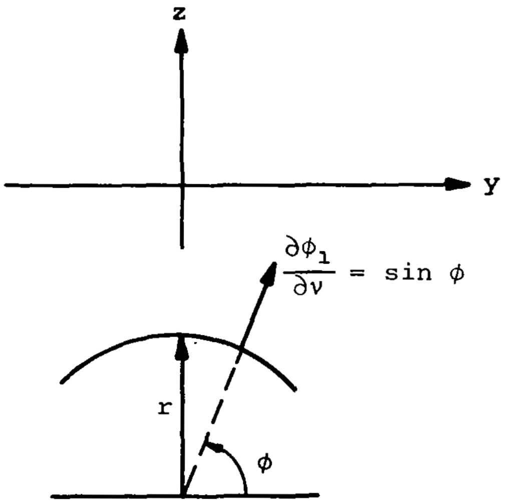


(b) Boundary condition in fixed crossflow plane through which parawing is moving.

Figure 2.- Boundary conditions for all-flexible slender parawing.

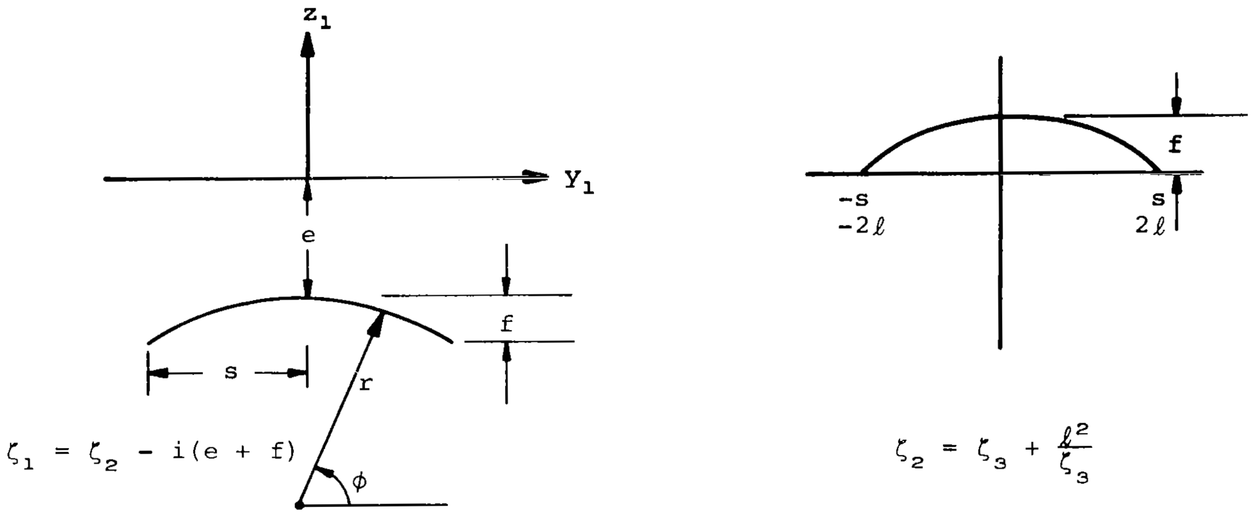


(a) ϕ_2 boundary condition for an expanding circular arc.



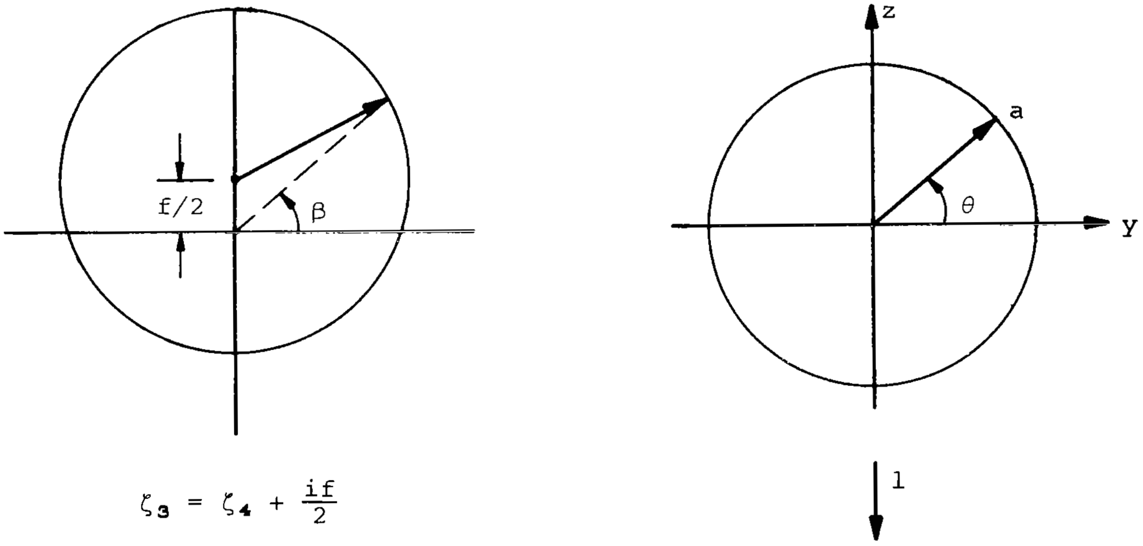
(b) ϕ_1 boundary condition for a translating circular arc.

Figure 3.- Unit potential solutions arising in all-flexible slender parawing theory.



(a) ζ_1 plane.

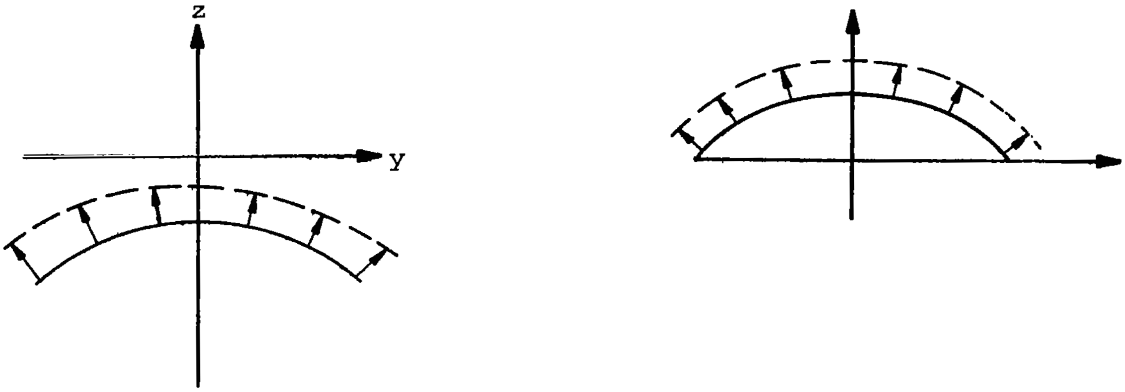
(b) ζ_2 plane.



(c) ζ_3 plane.

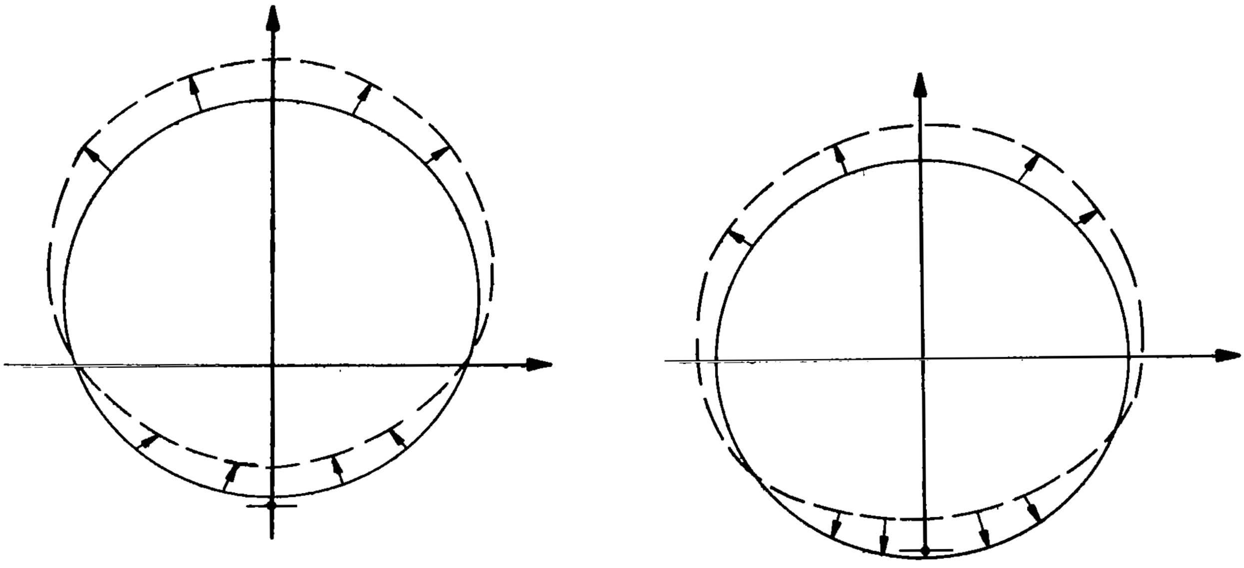
(d) ζ_4 plane.

Figure 4.- Transformations used in obtaining complex potential for translating arc.



(a) ζ_1 plane.

(b) ζ_2 plane.



(c) ζ_3 plane.

(d) ζ_4 plane.

Figure 5.- Transformations and flows used in obtaining complex potential for dilating arc.

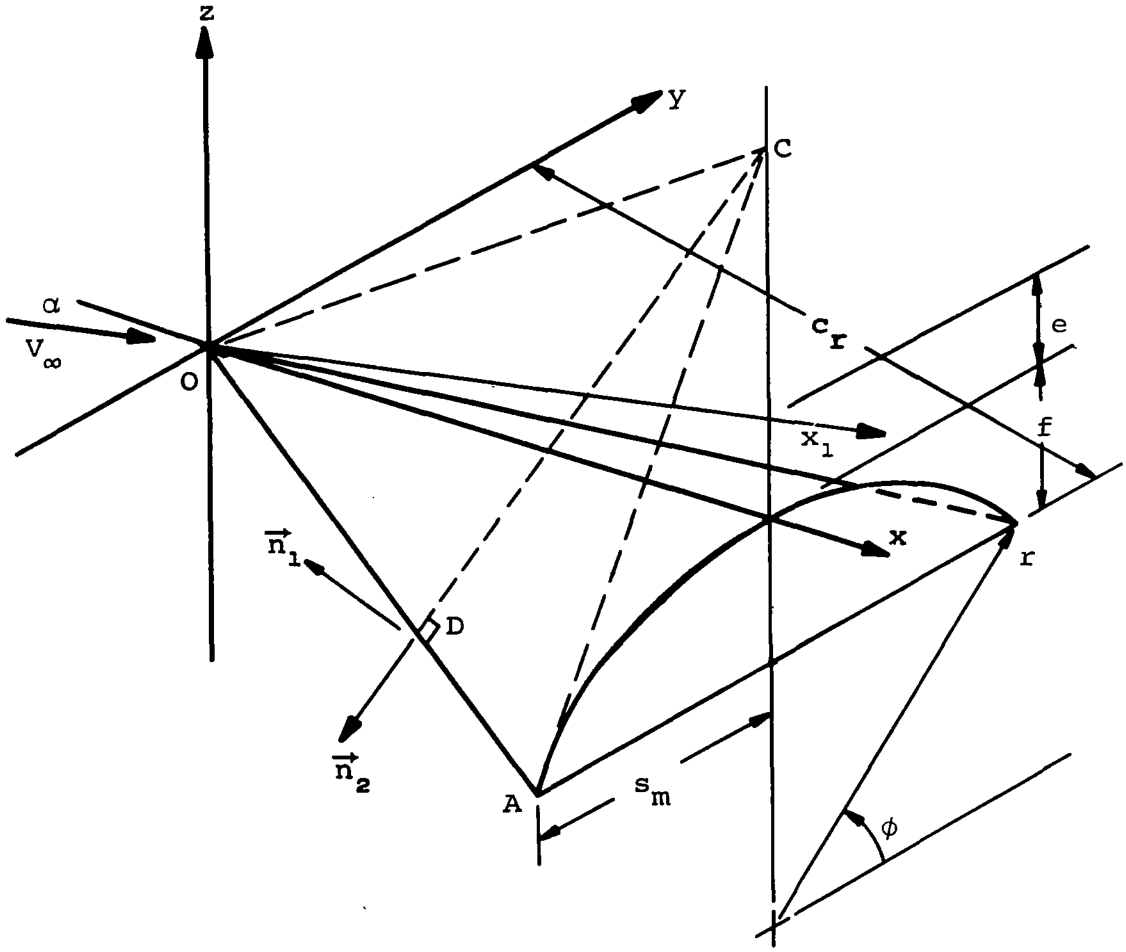
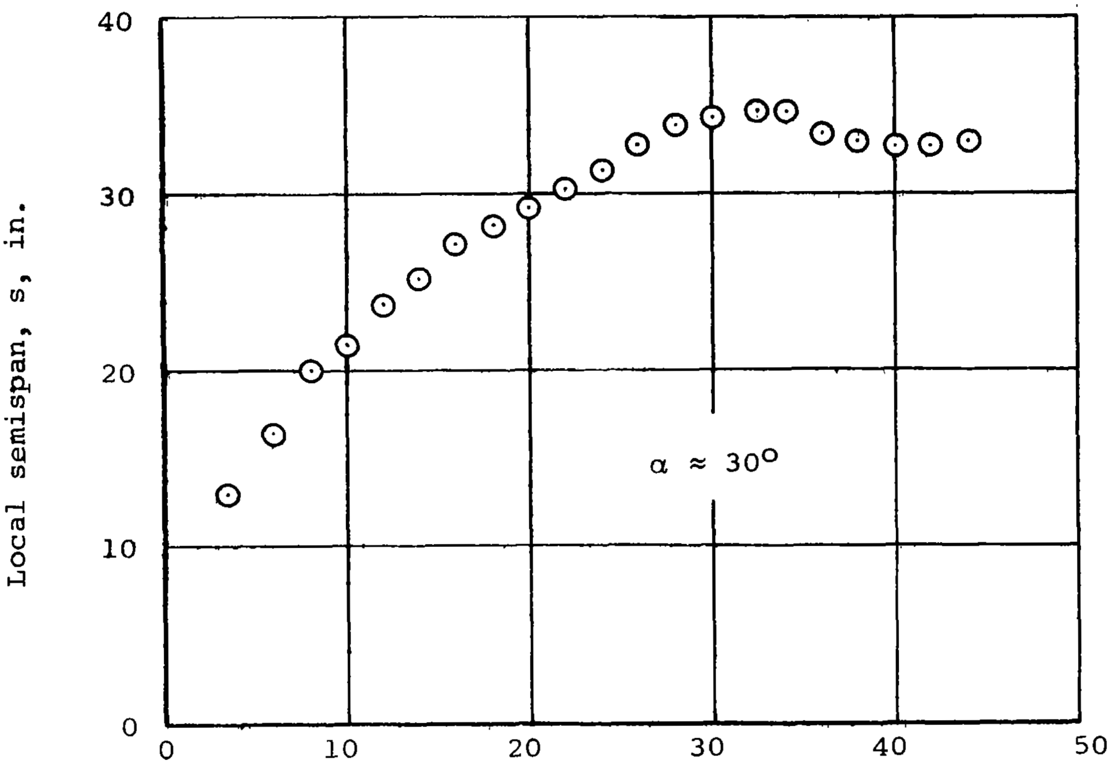
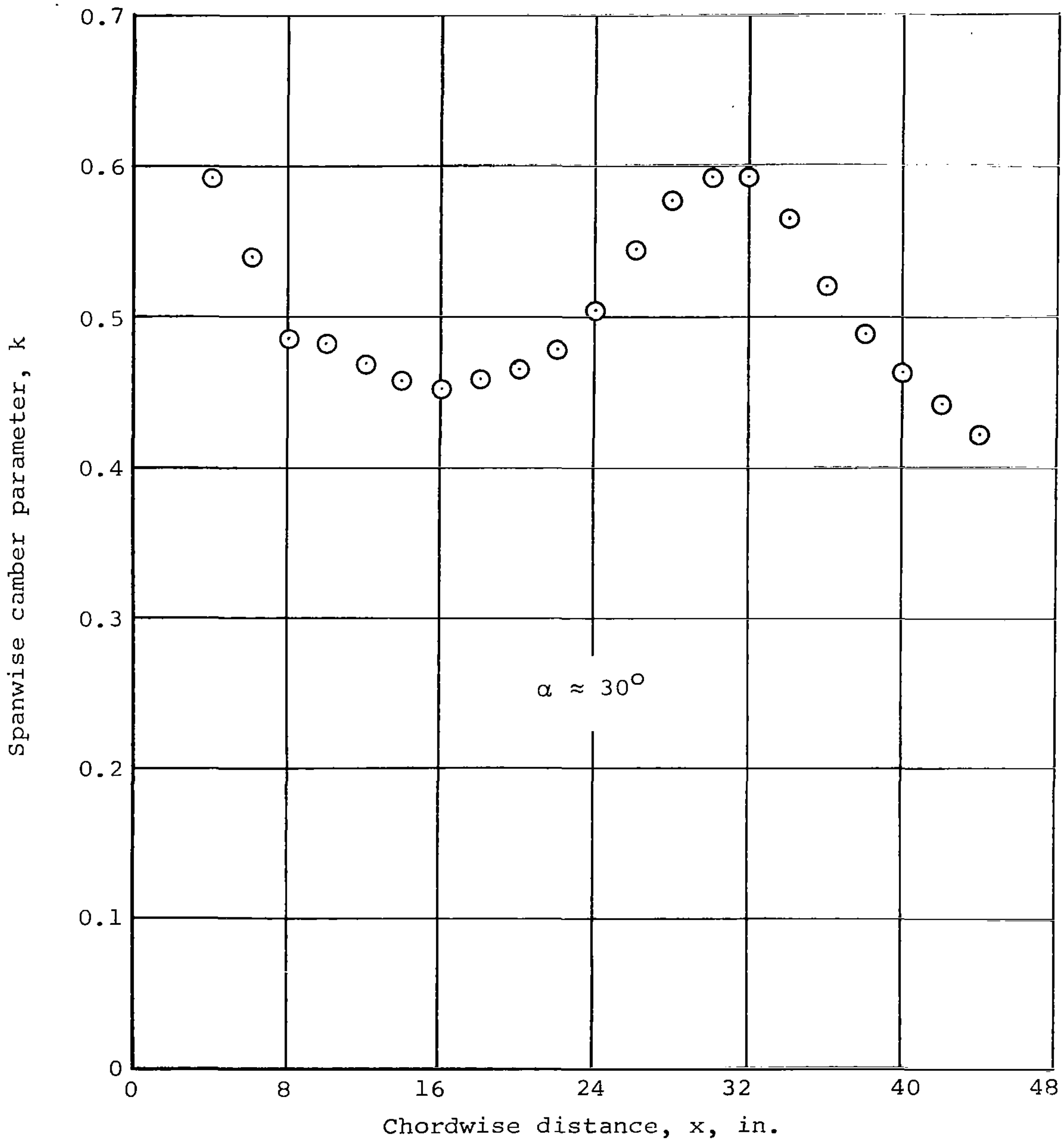


Figure 6.- Normal directions associated with surface formed from segment of a circular cone.



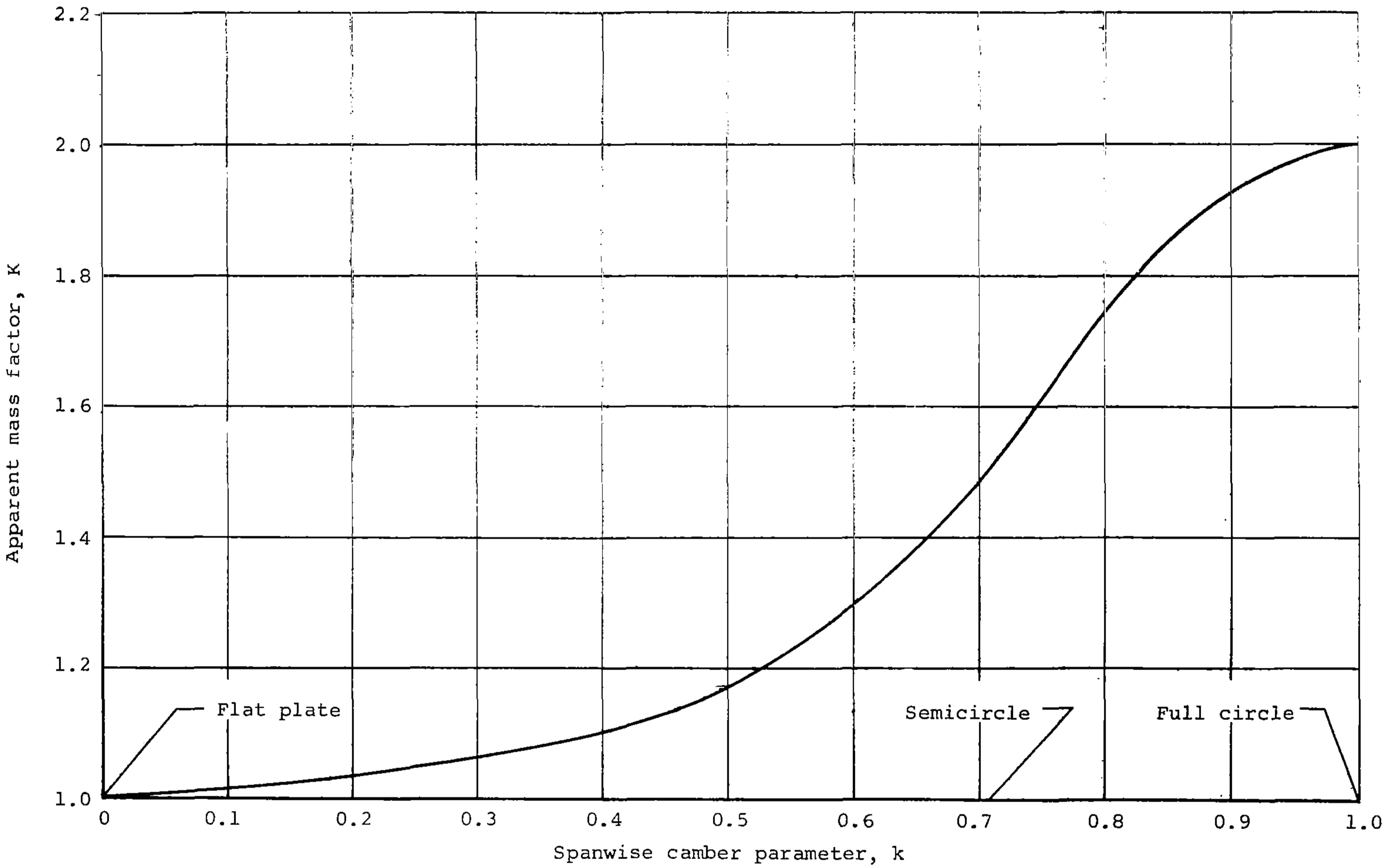
(a) Local semispan.

Figure 7.- Geometric characteristics of twin-keel, all-flexible parawing based on wing tunnel shape measurements.



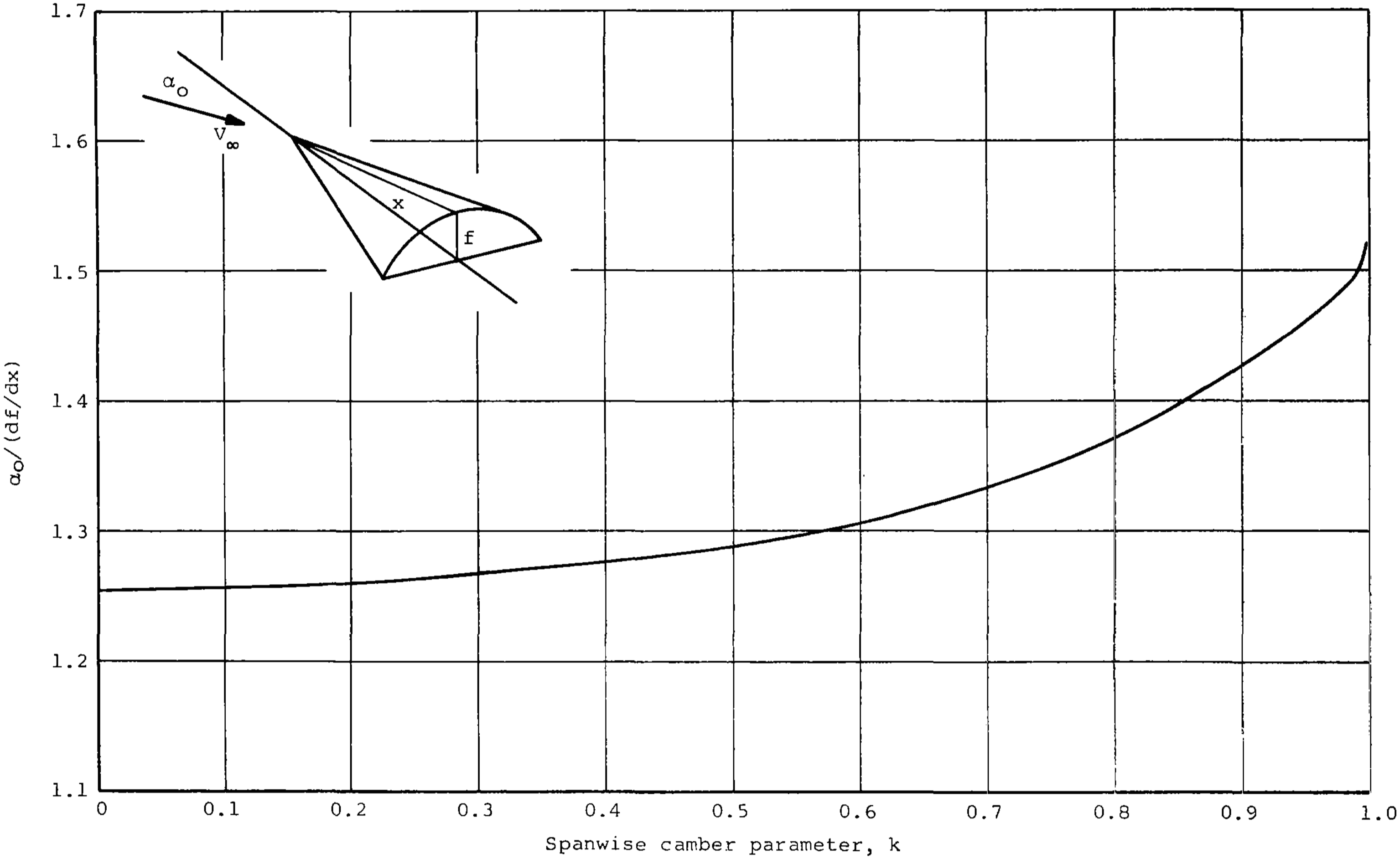
(b) Spanwise camber parameter, k.

Figure 7.- Concluded.



(a) Apparent mass factor.

Figure 8.- Effect of spanwise camber on normal-force curve slope and angle of zero normal force for conical parawing.



(b) Angle of zero normal force.

Figure 8.- Concluded.

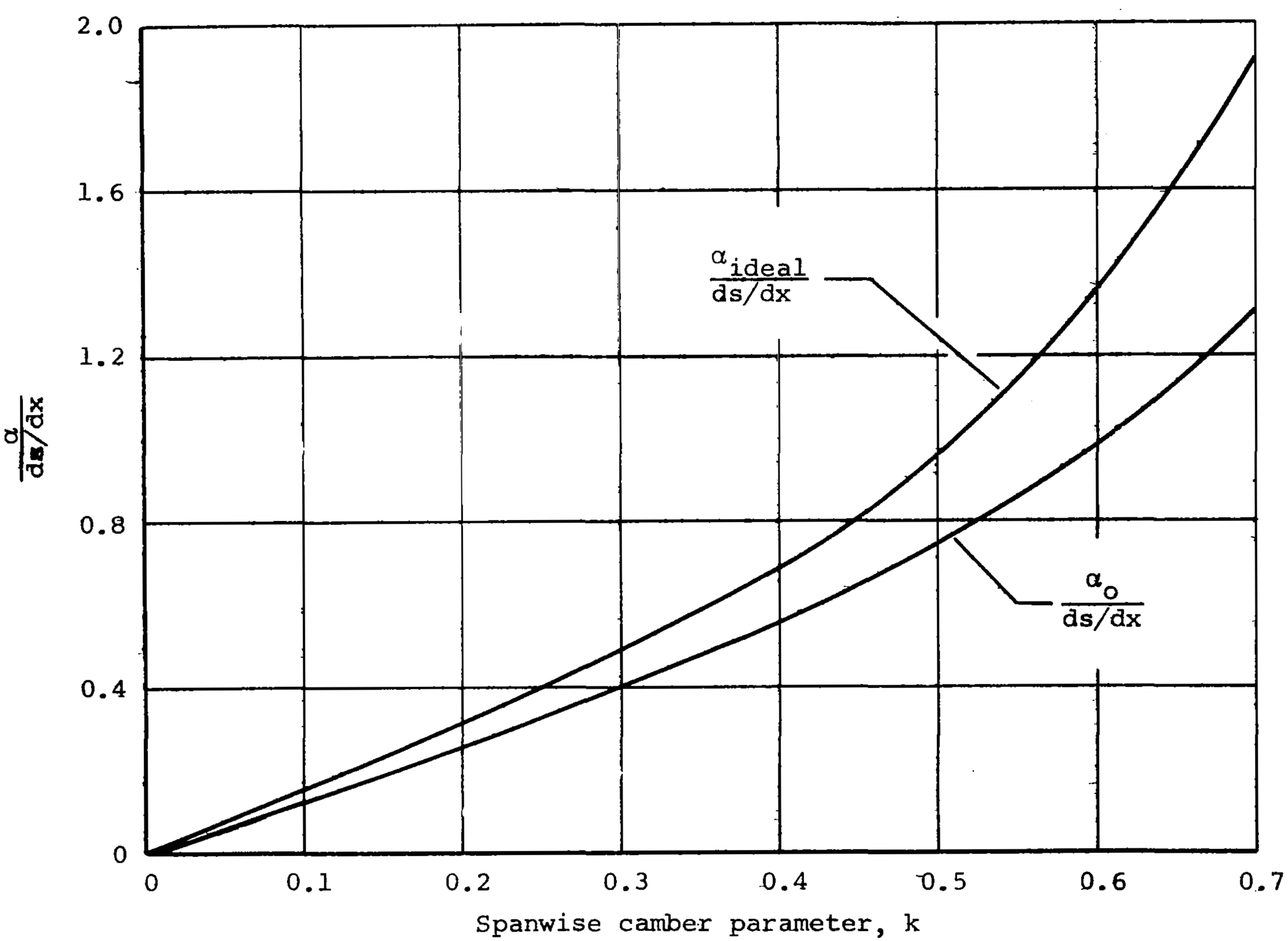
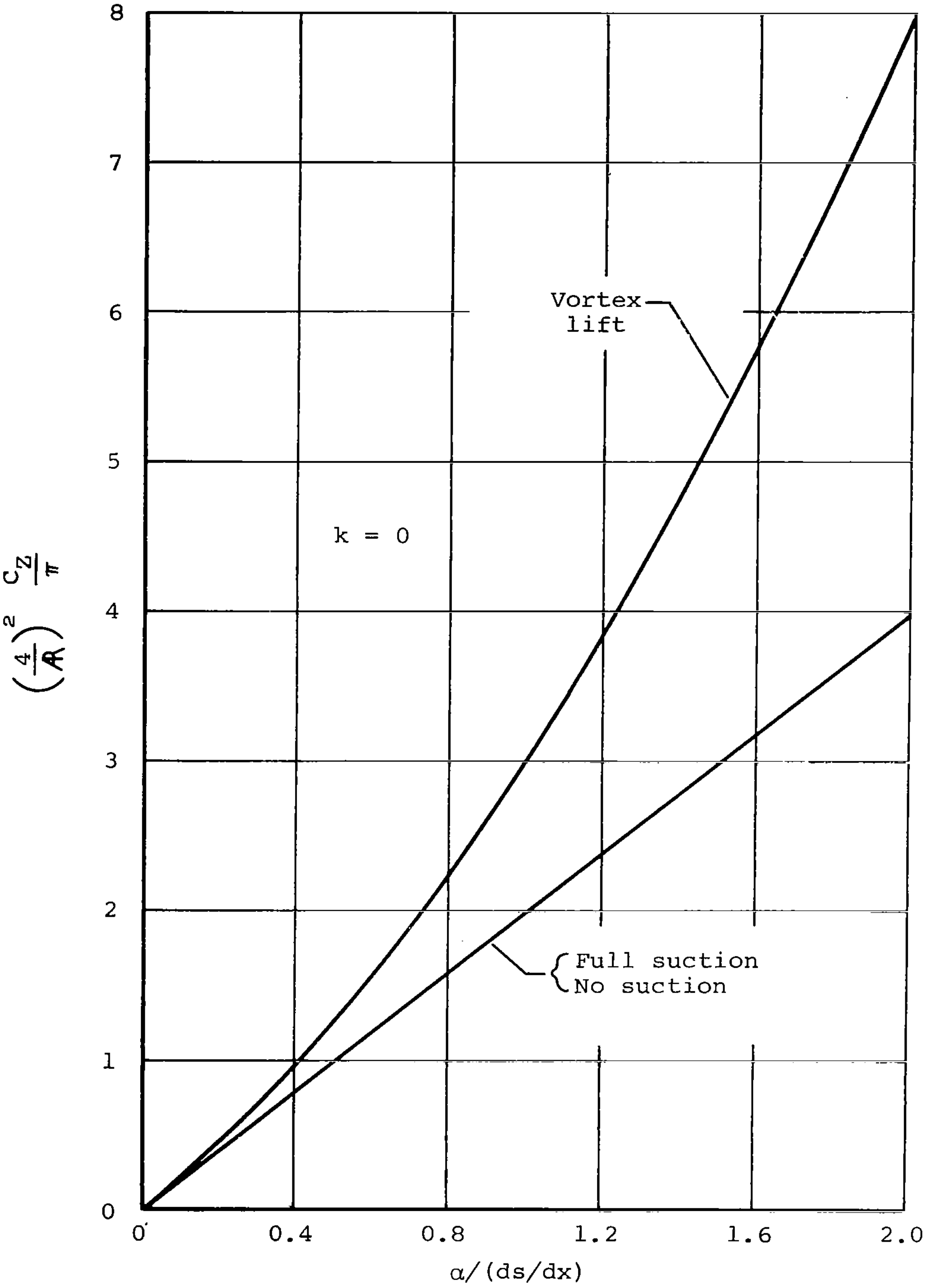
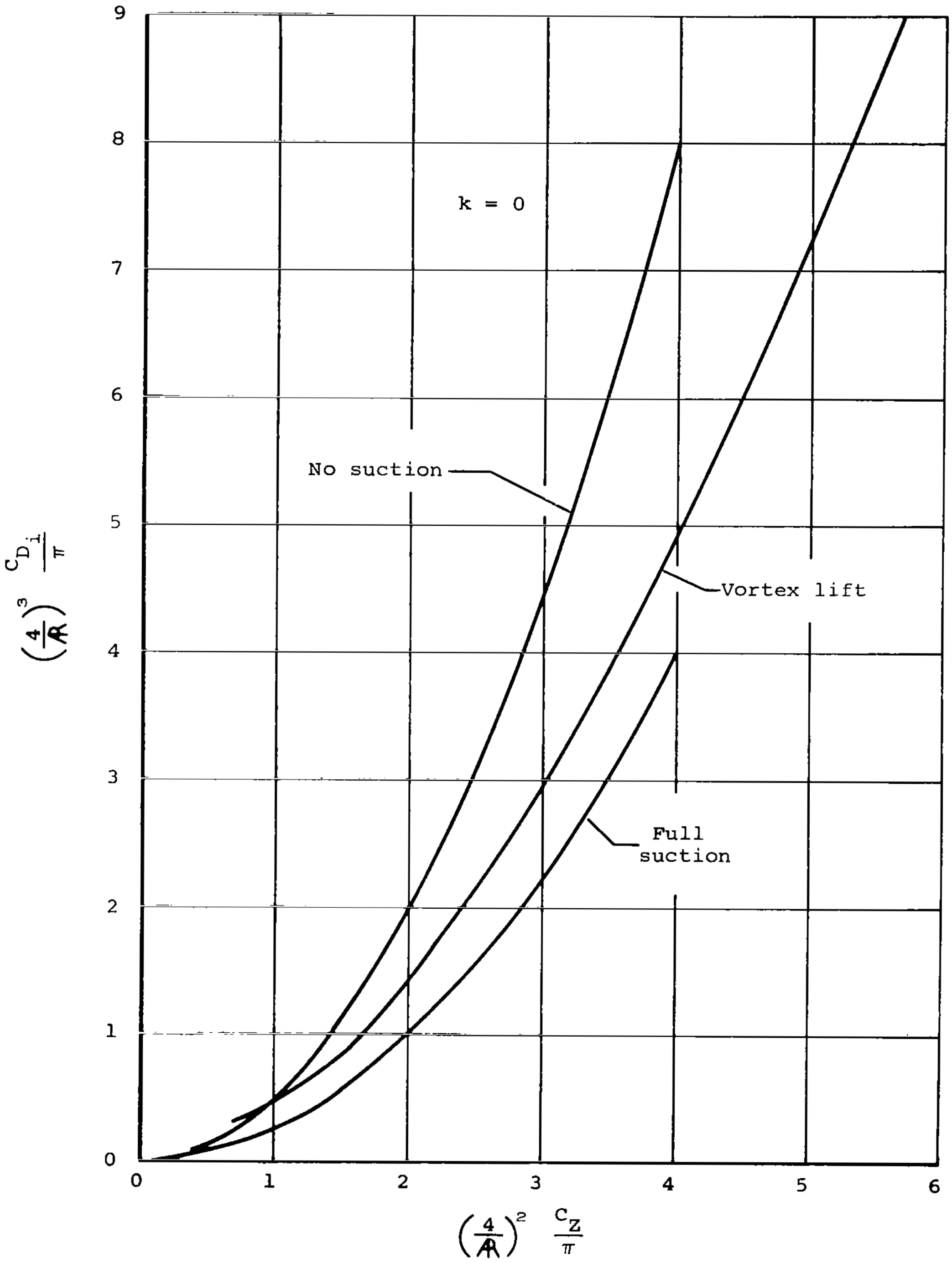


Figure 9.- Effect of spanwise camber on angle of zero normal force and ideal angle of attack.



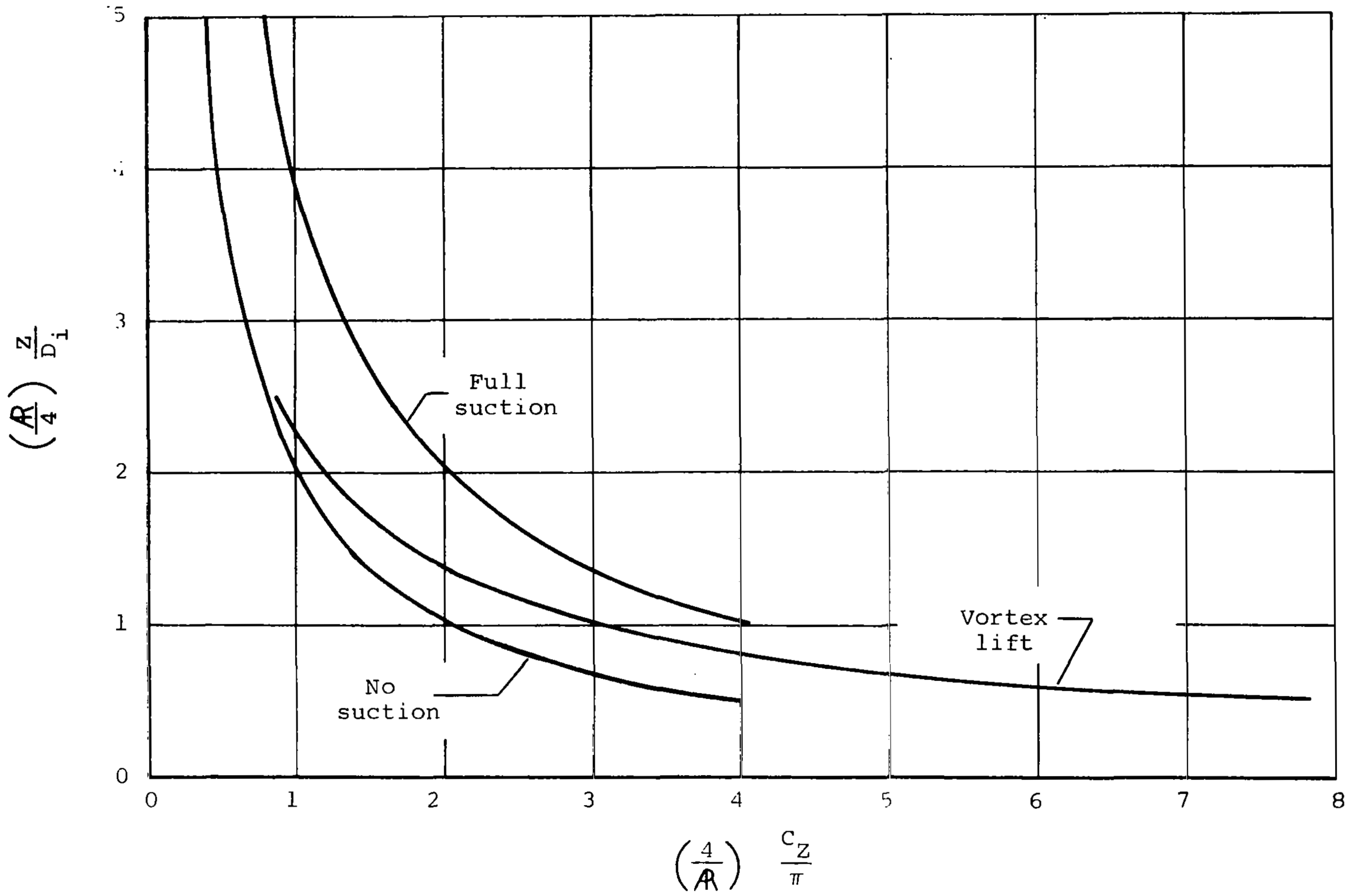
(a) Normal-force curves.

Figure 10.- Effect of leading-edge suction and vortex lift on aerodynamic characteristics of flat delta wings of low aspect ratio.



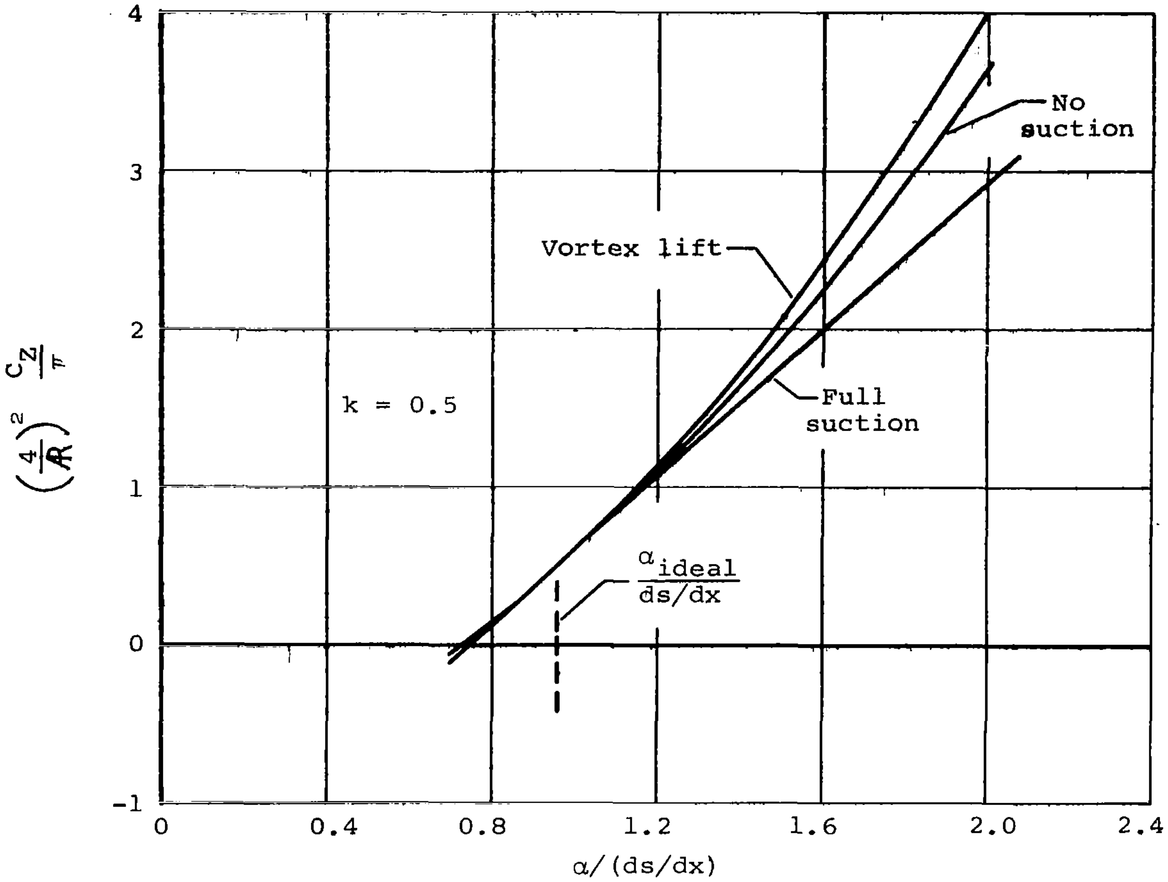
(b) Drag curves.

Figure 10.- Continued.



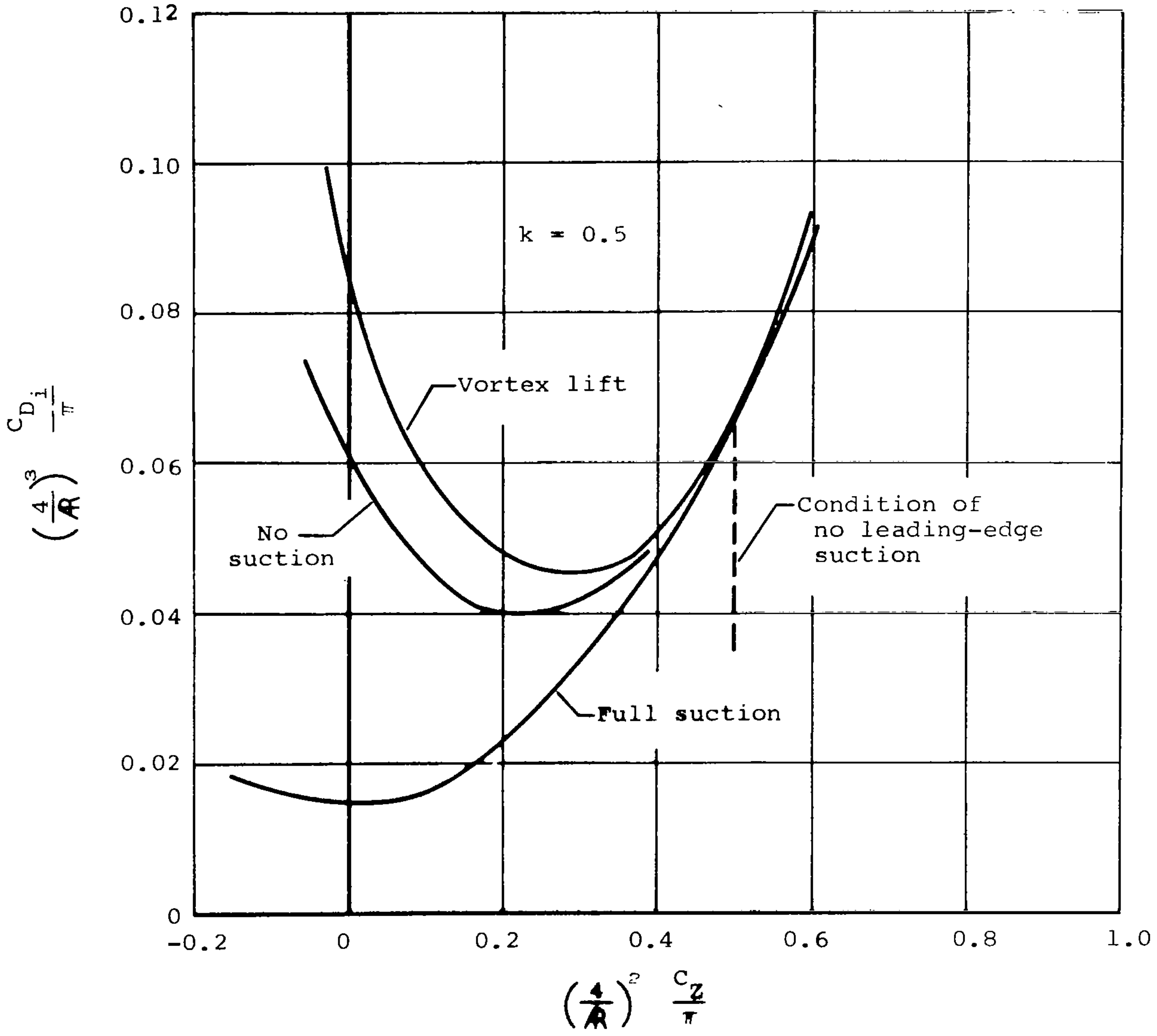
(c) Z/C_{D_i} ratio.

Figure 10.- Concluded.



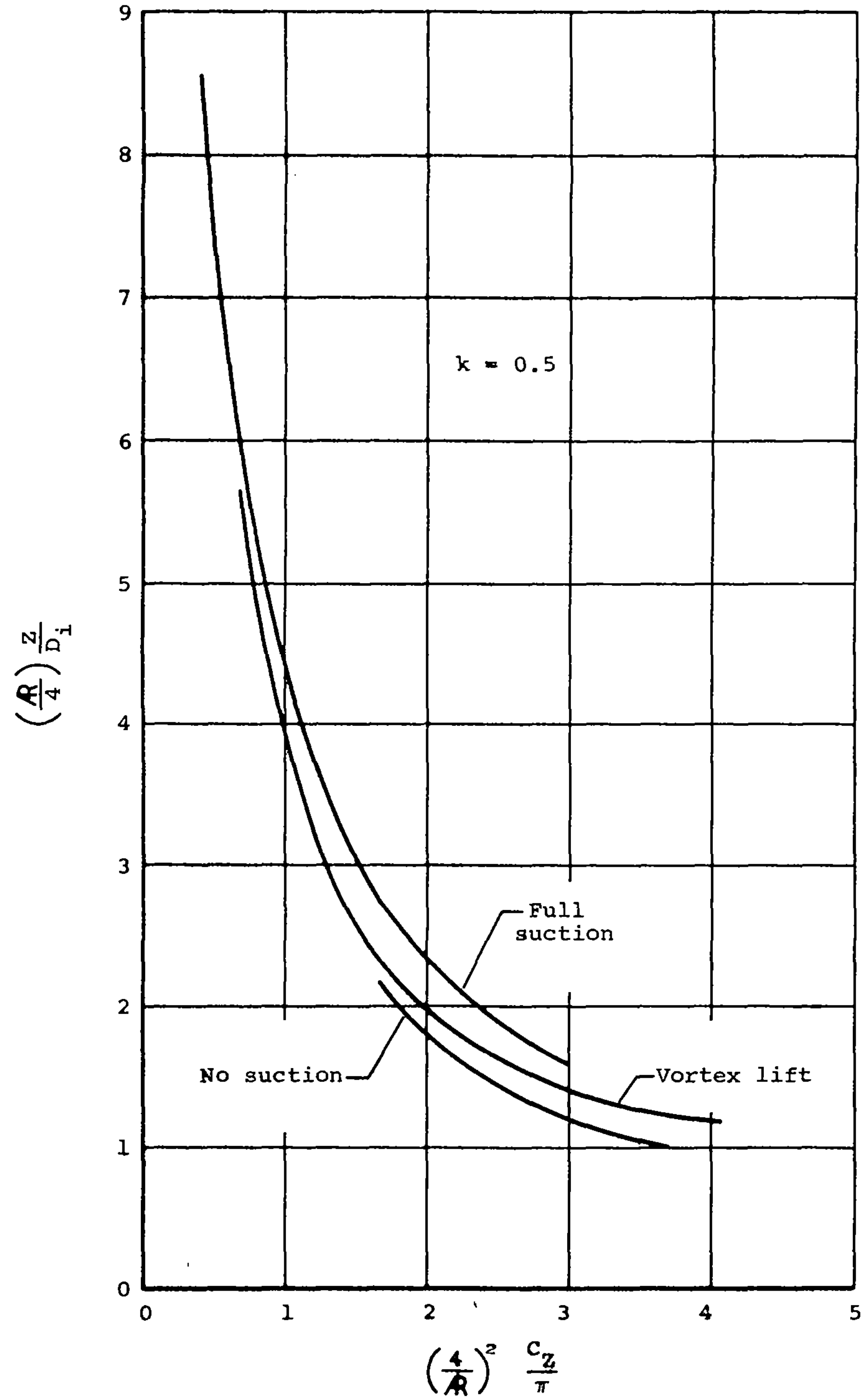
(a) Normal-force curves.

Figure 11.- Effect of leading-edge suction and vortex lift on aerodynamic characteristics of parawing formed by segments of circular cones.



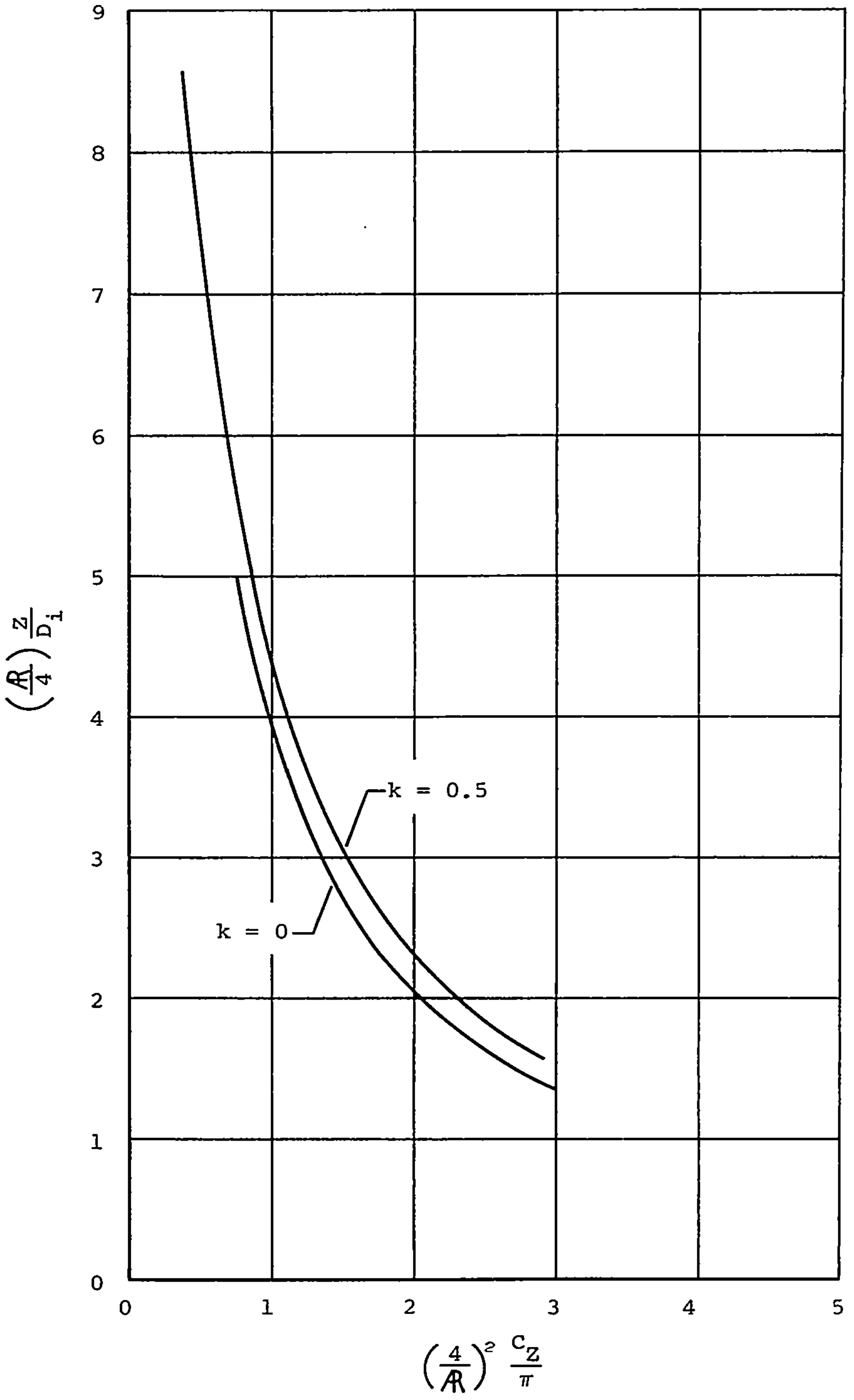
(b) Drag curves.

Figure 11.- Continued.



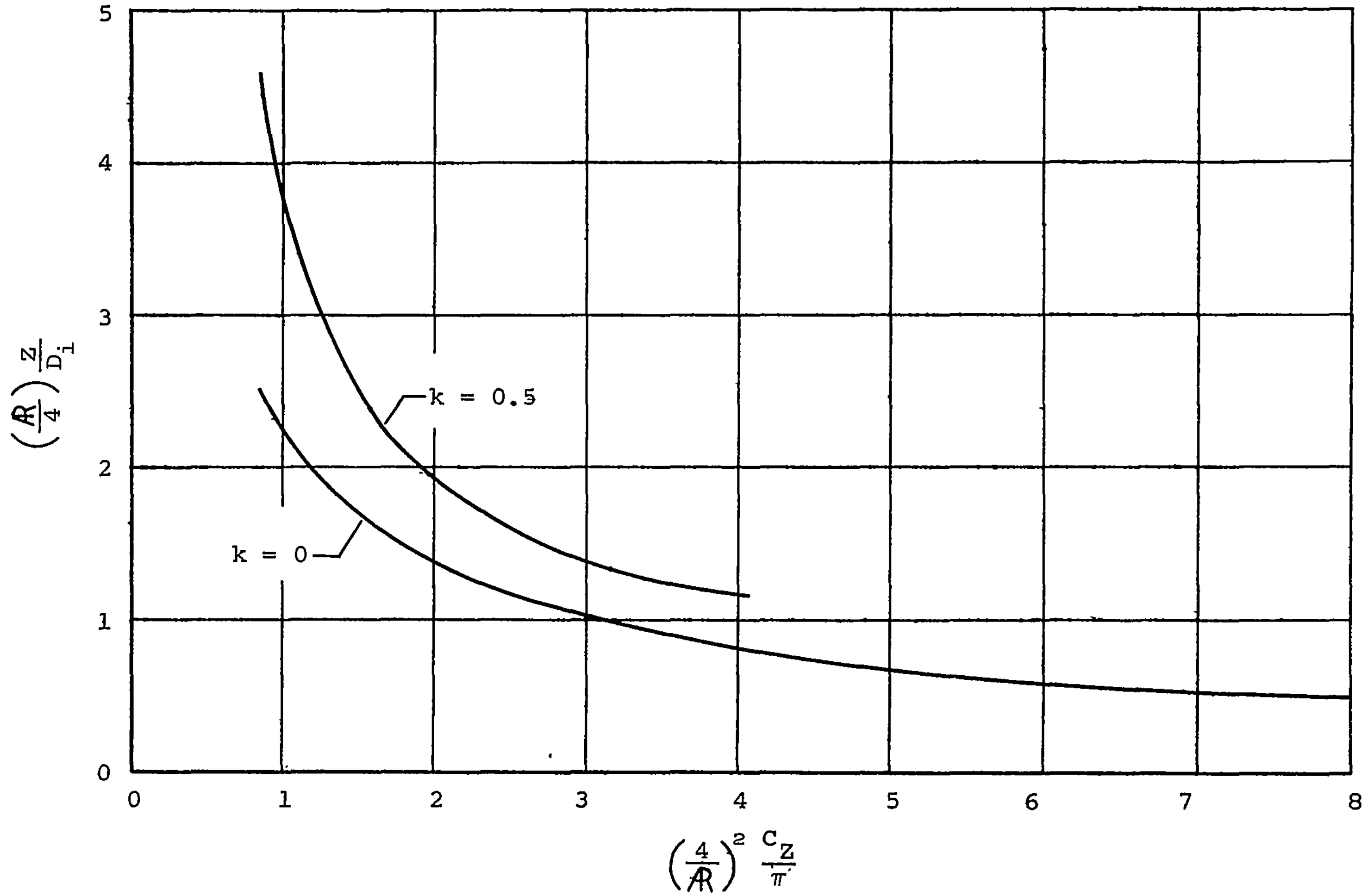
(c) Z/D_i ratio.

Figure 11.- Concluded.



(a) Full suction.

Figure 12.- Effect of k on ratio of normal force to induced drag for conical lifting surfaces.



(b) Vortex lift.

Figure 12.- Concluded.

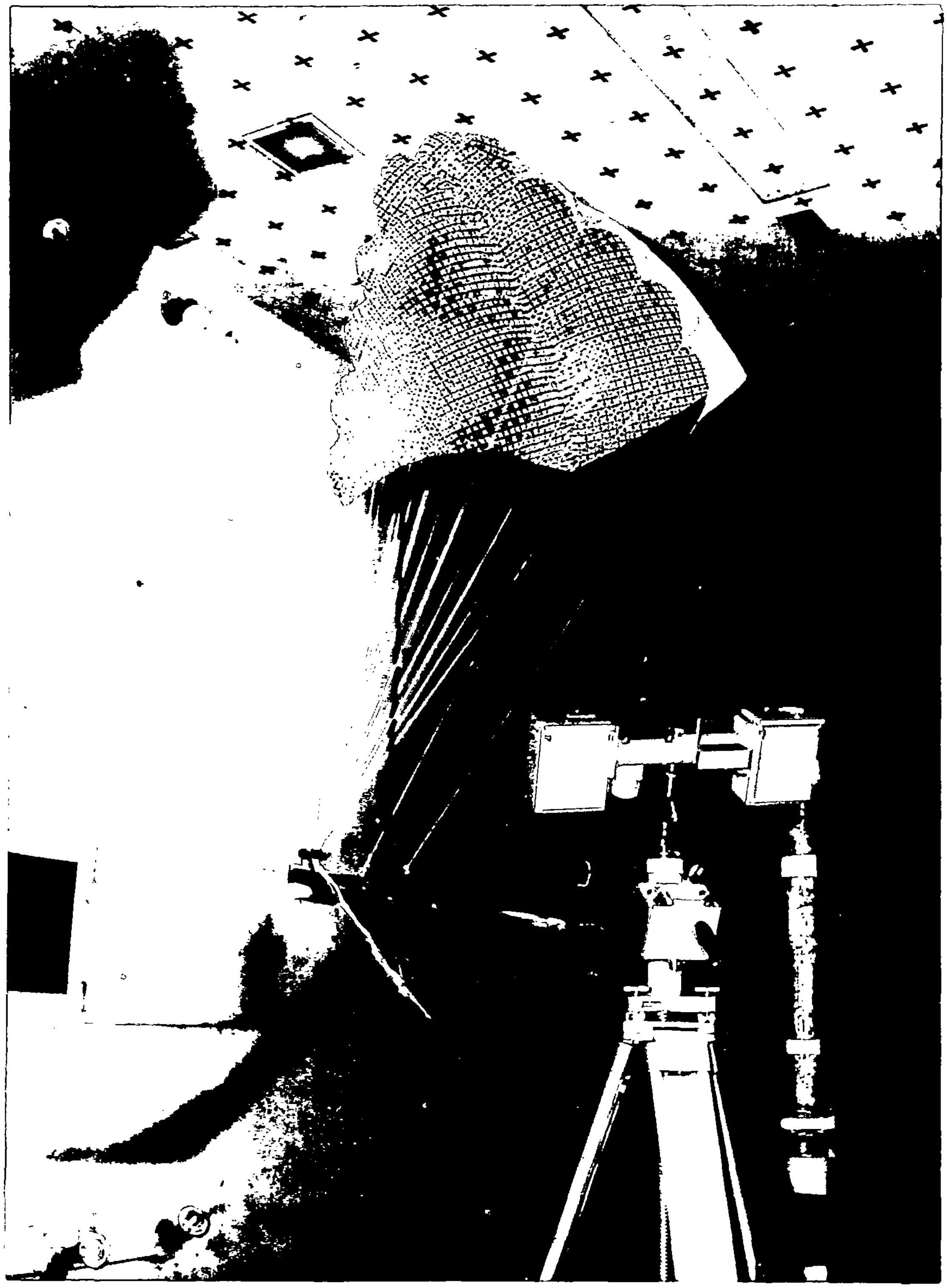
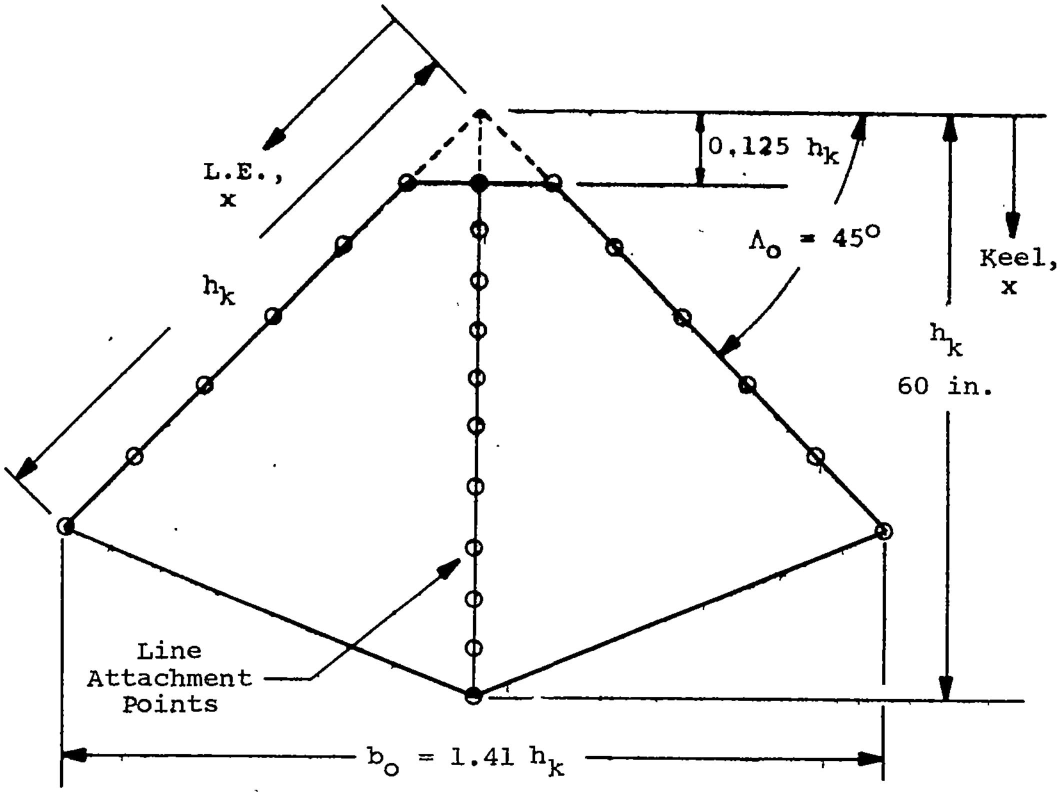


Figure 13.- Equipment setup for photogrammetric test.



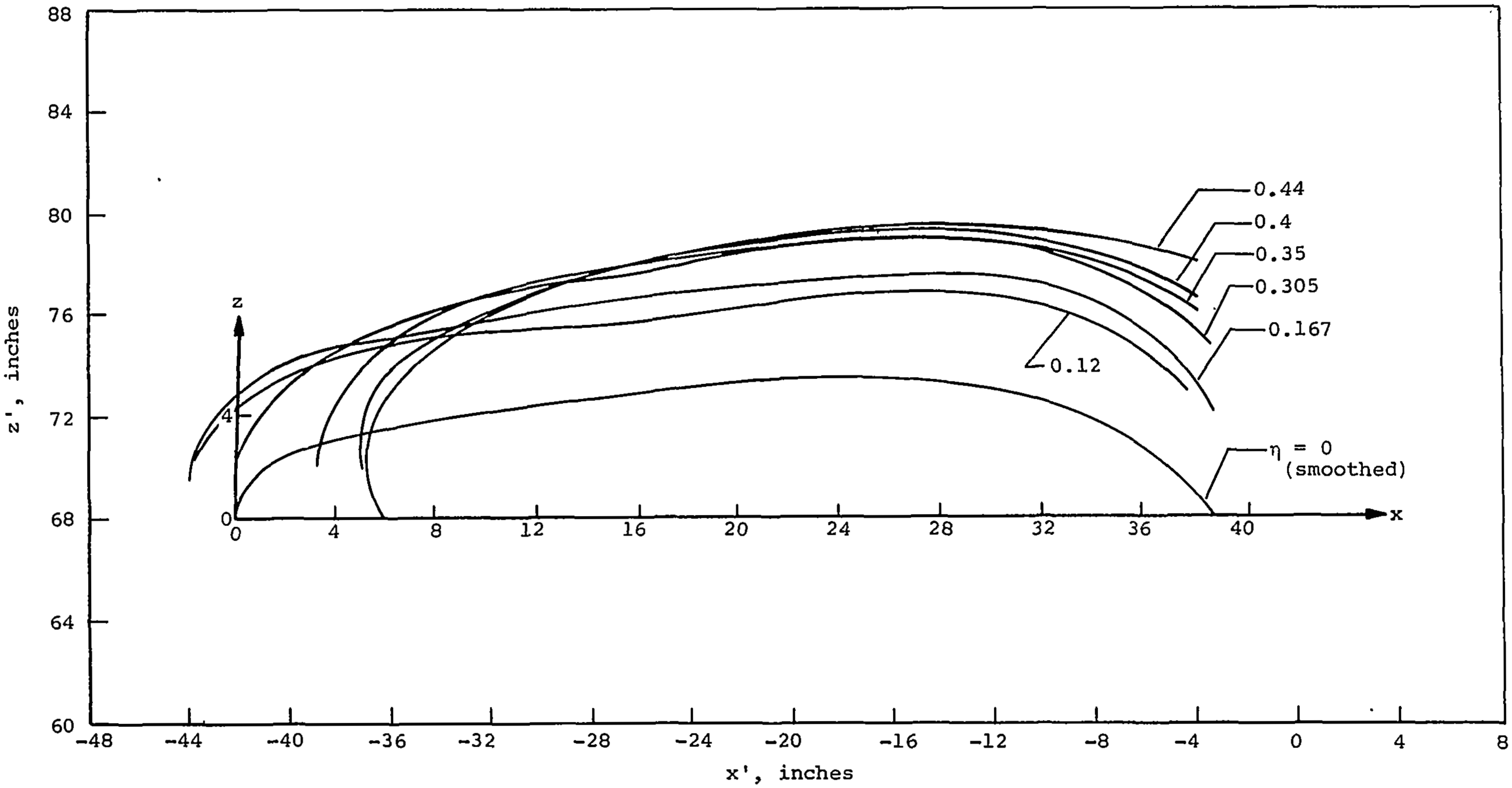
h/h_k		
Keel	Leading Edge	
	Right	Left
1.35	1.368	1.365
1.36	1.304	1.317
1.352	1.309	1.26
1.34	1.202	1.216
1.322	1.168	1.162
1.308	.994	.985
1.292		
1.270		
1.242		
1.205		
1.092		

Line Lengths

x/h_k	
Keel	Leading Edge
0.125	0.177
.208	.333
.292	.500
.375	.667
.459	.833
.542	1.000
.645	
.750	
.833	
.917	
1.000	

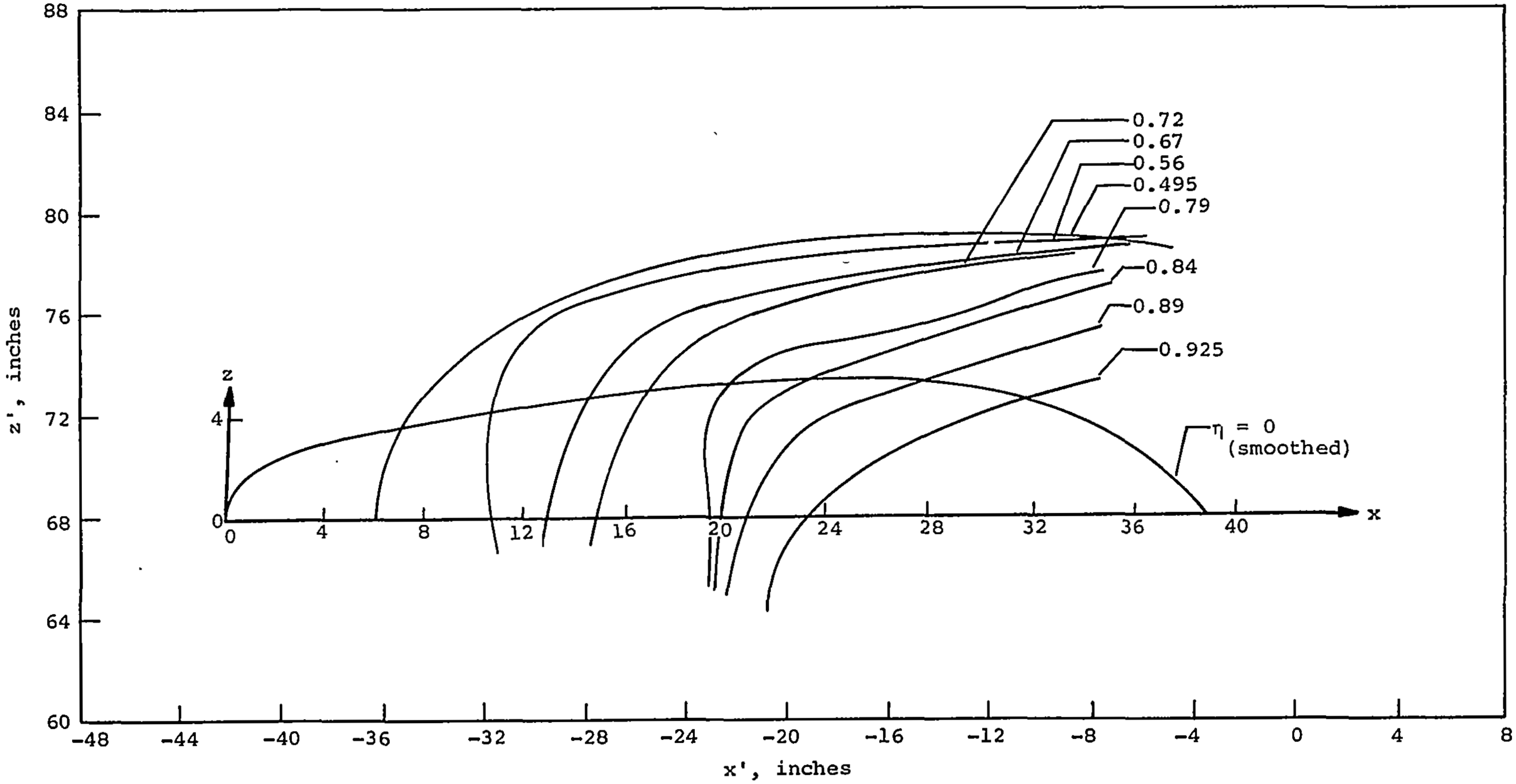
Line Attachment Location

Figure 14.- Single-keel parawing configuration.



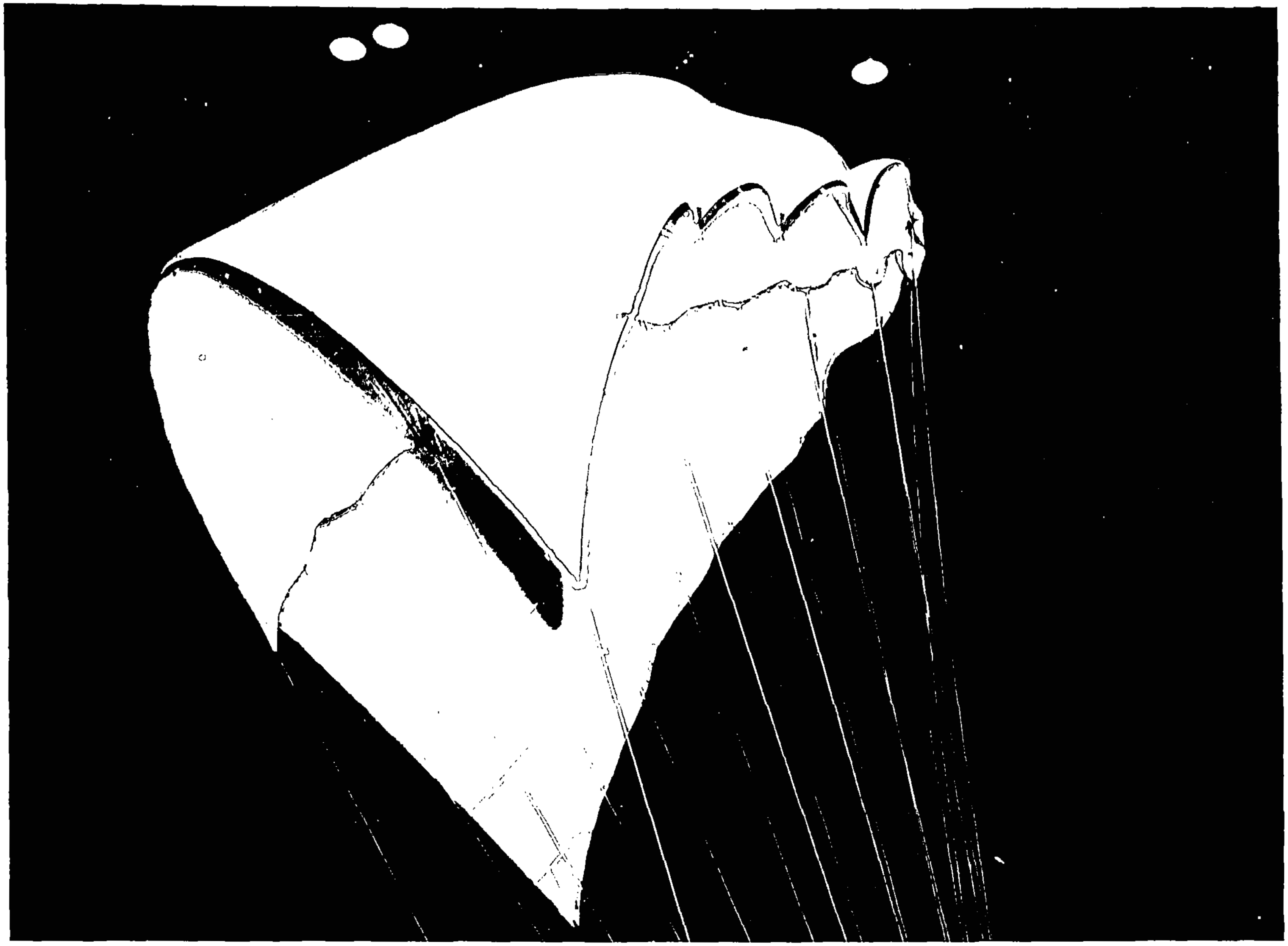
(a) Sections for $0 < \eta < 0.44$.

Figure 15.- Chordwise sections of single-keel parawing obtained from measured canopy shape data.



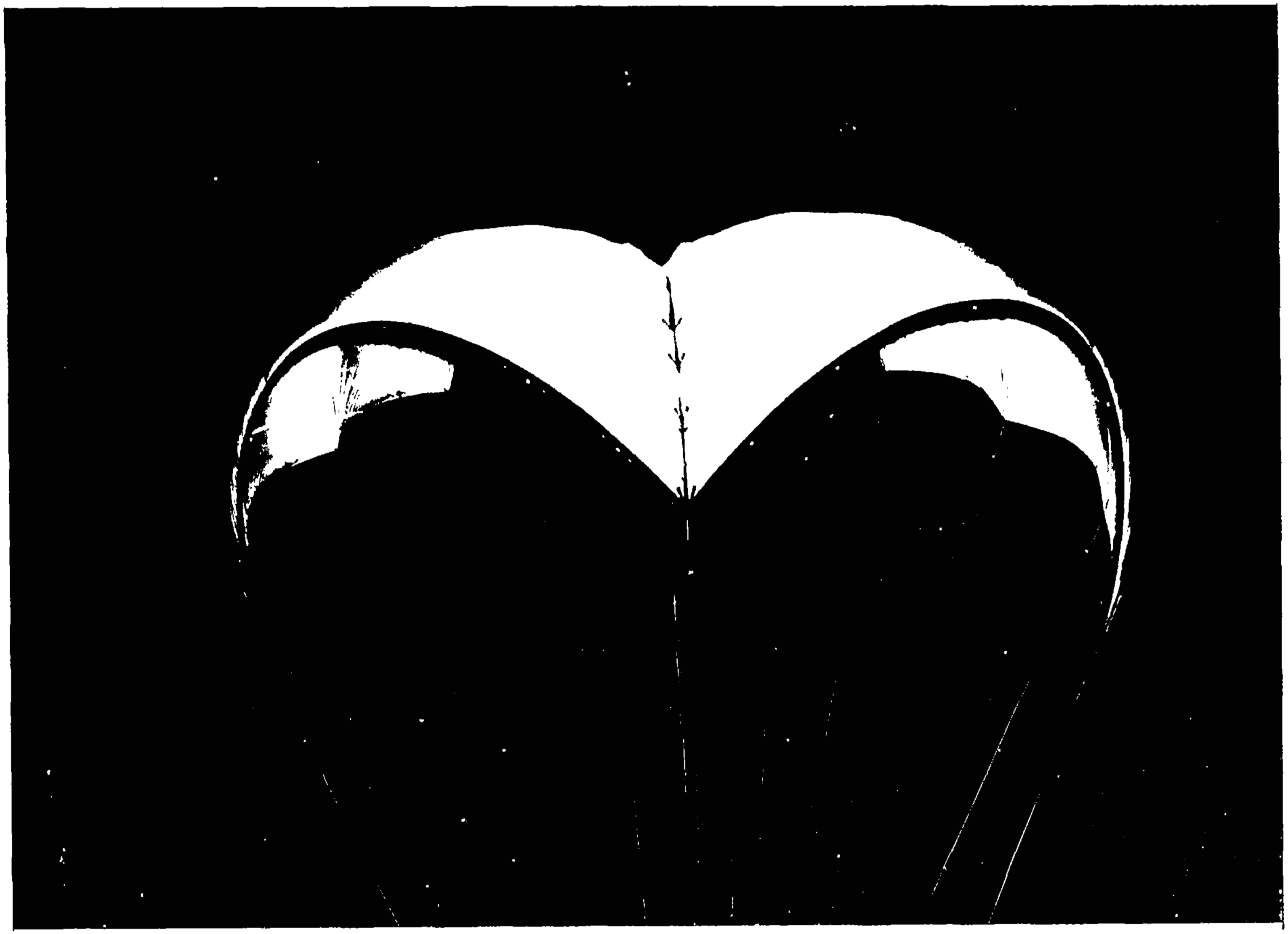
(b) Sections for 0.56 < η < 0.925.

Figure 15.- Concluded.



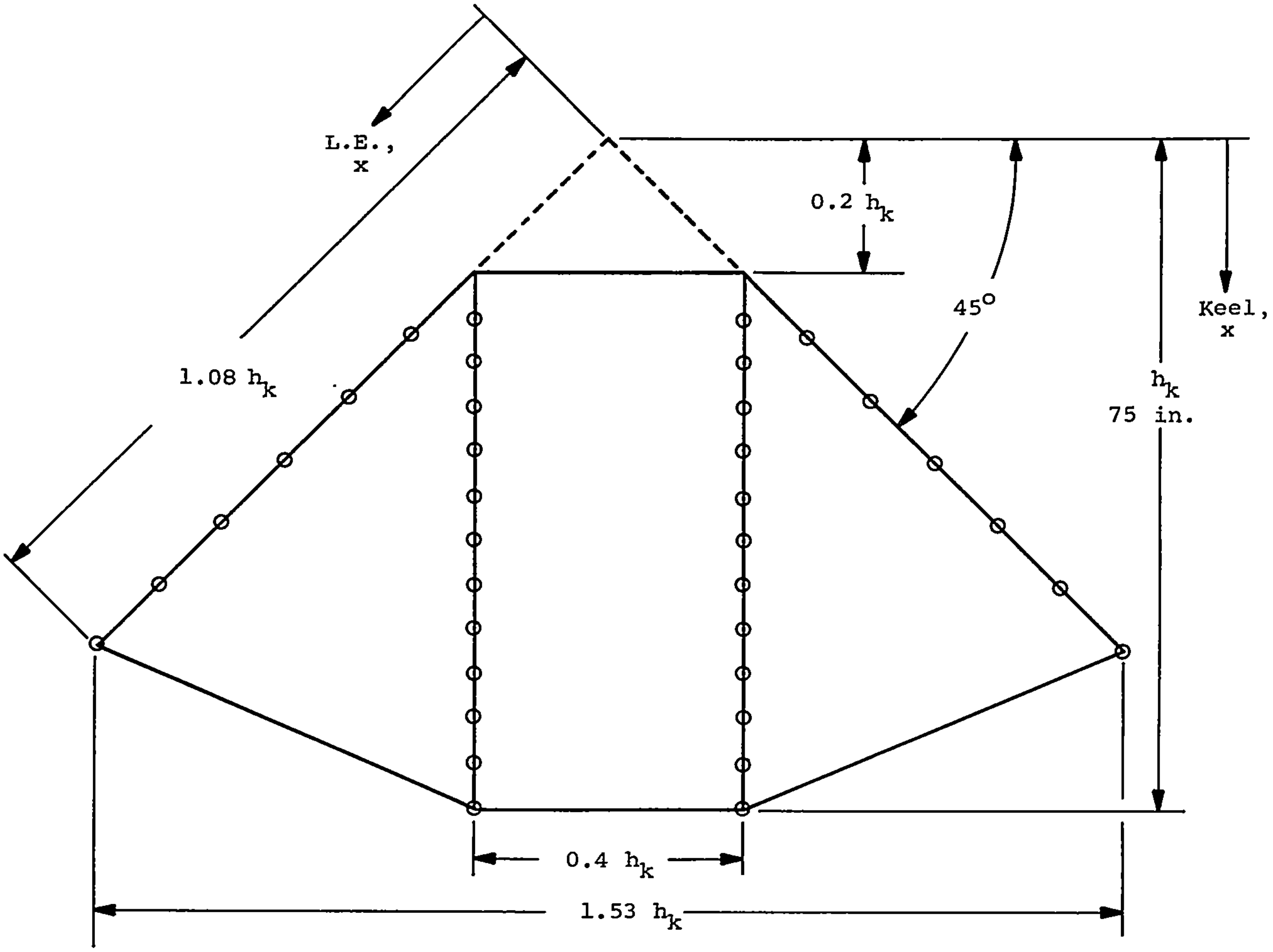
(a) Side view.

Figure 16.- Photographs of single-keel parawing in Langley Research Center wind tunnel.



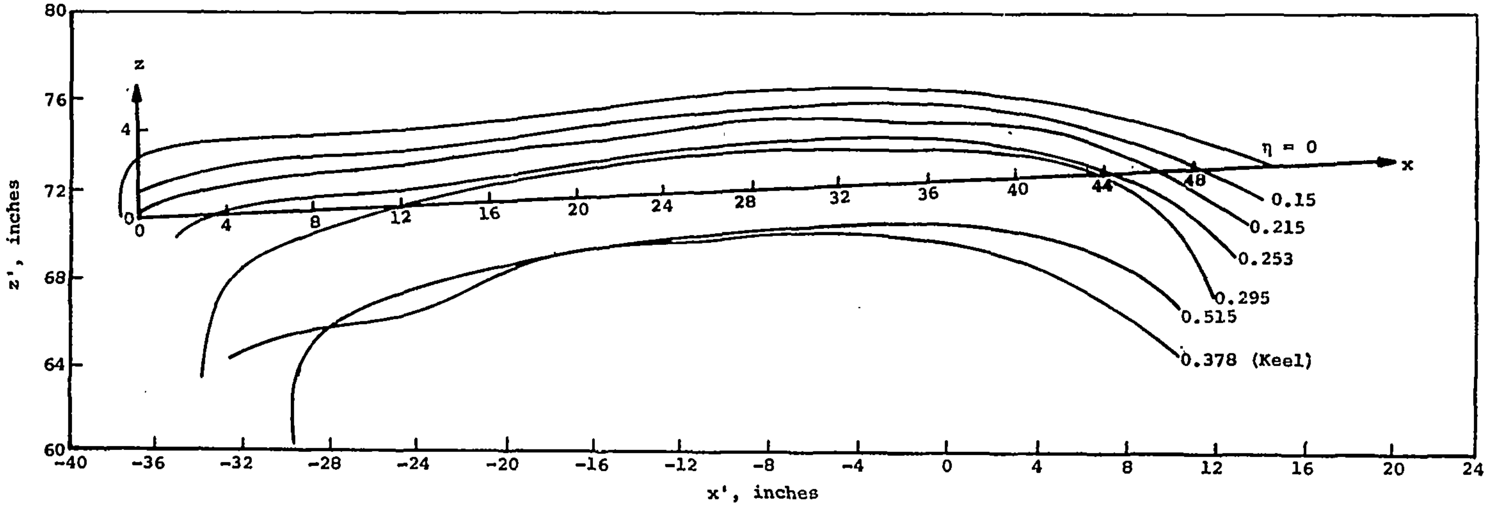
(b) Rear view.

Figure 16.- Concluded.



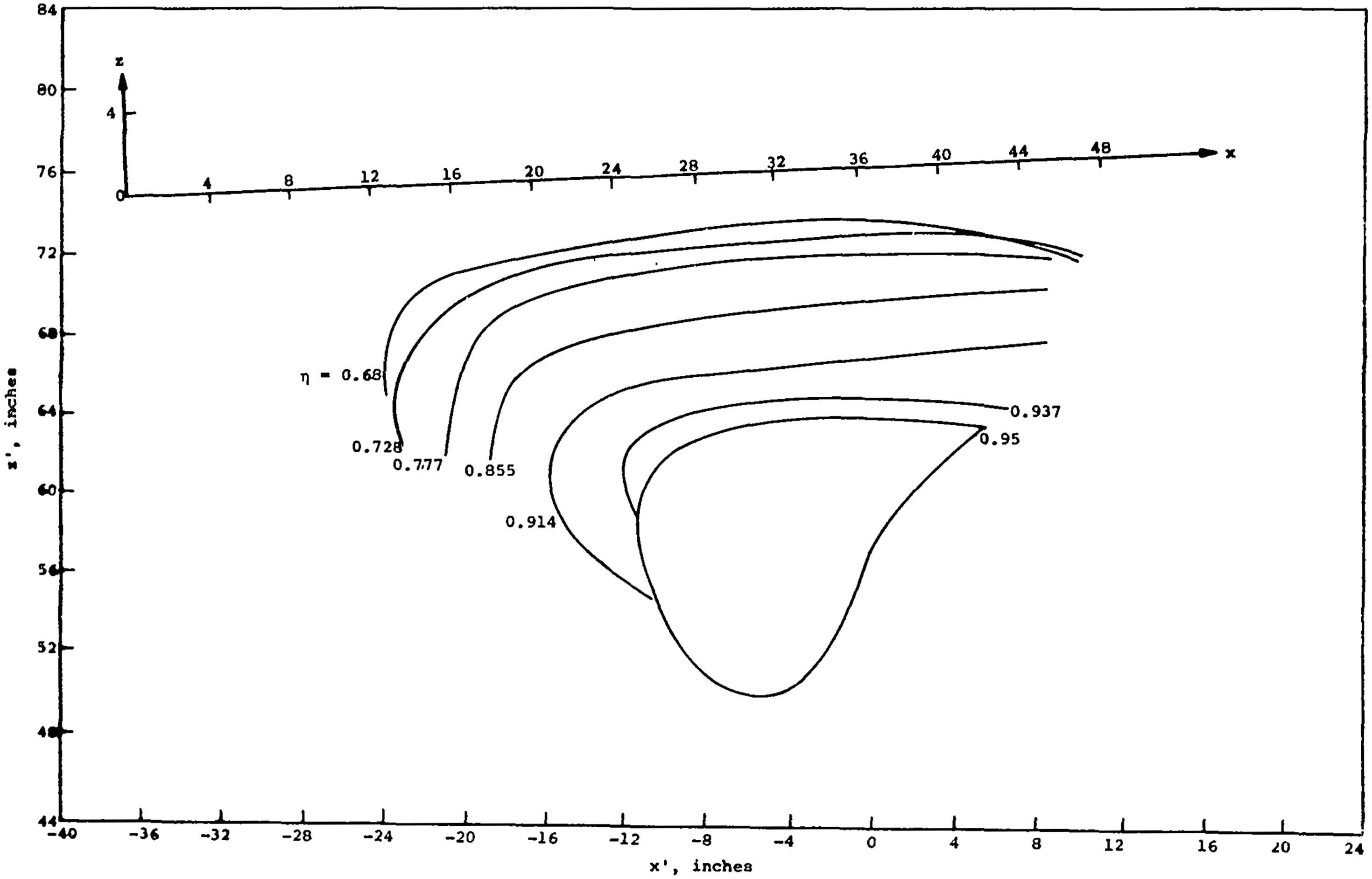
h/h_k				x/h_k	
Keel		Leading Edge		Keel	Leading Edge
Left	Right	Left	Right		
0.975	0.973	0.935	0.935	0.267	0.416
.988	.985	.911	.911	.333	.549
.982	.982	.895	.885	.400	.684
.975	.973	.848	.846	.466	.816
.981	.978	.785	.787	.533	.950
.980	.977	.622	.62	.600	1.083
.988	.982			.667	
.981	.977			.733	
.970	.969			.800	
.964	.963			.867	
.938	.938			.933	
.856	.856			1.000	
Line Lengths				Line Attachment Location	

Figure 17.- Twin-keel parawing configuration.



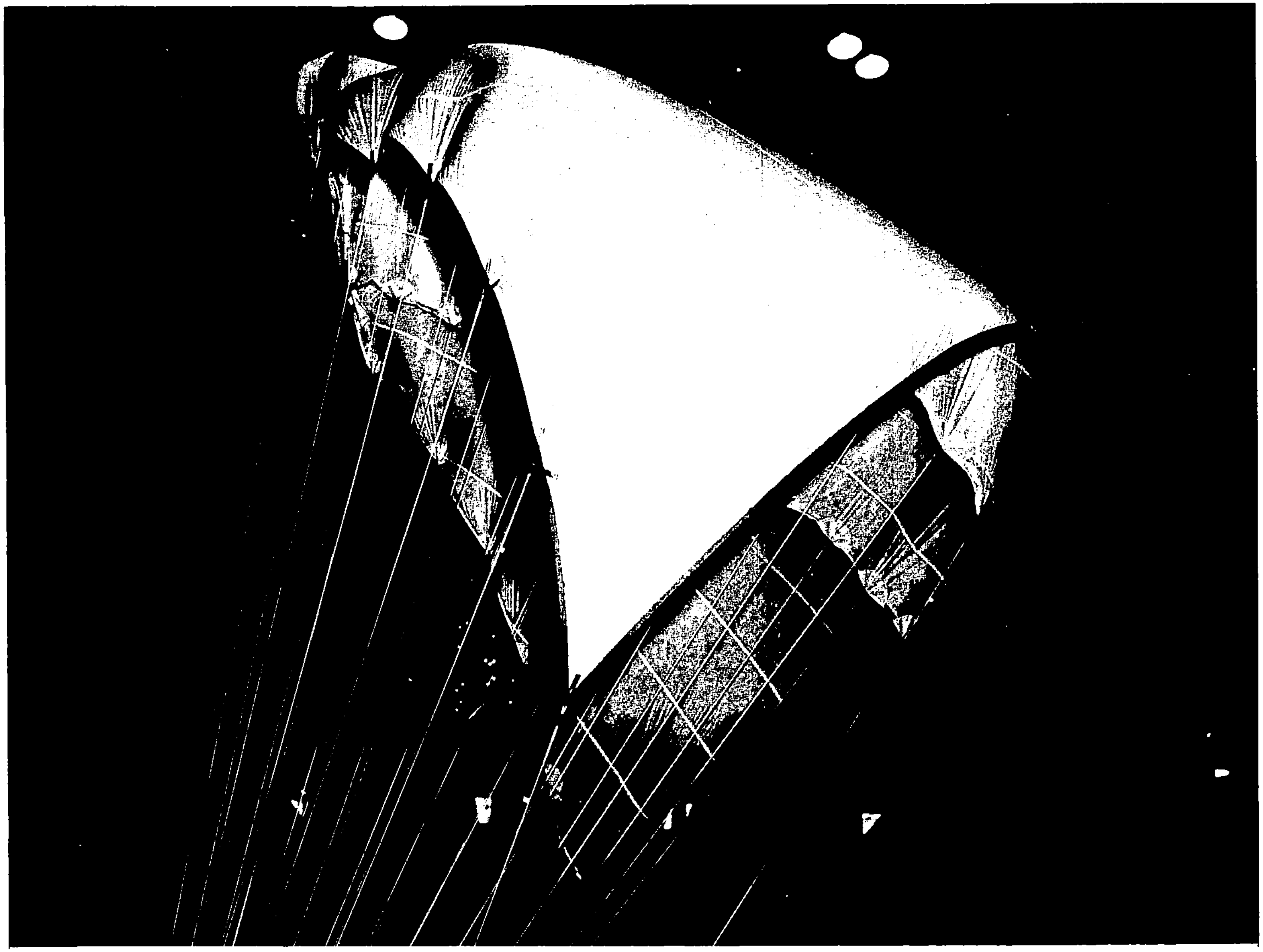
(a) Sections for $0 < \eta < 0.515$.

Figure 18.- Chordwise sections of twin-keel parawing obtained from measured canopy shape data.



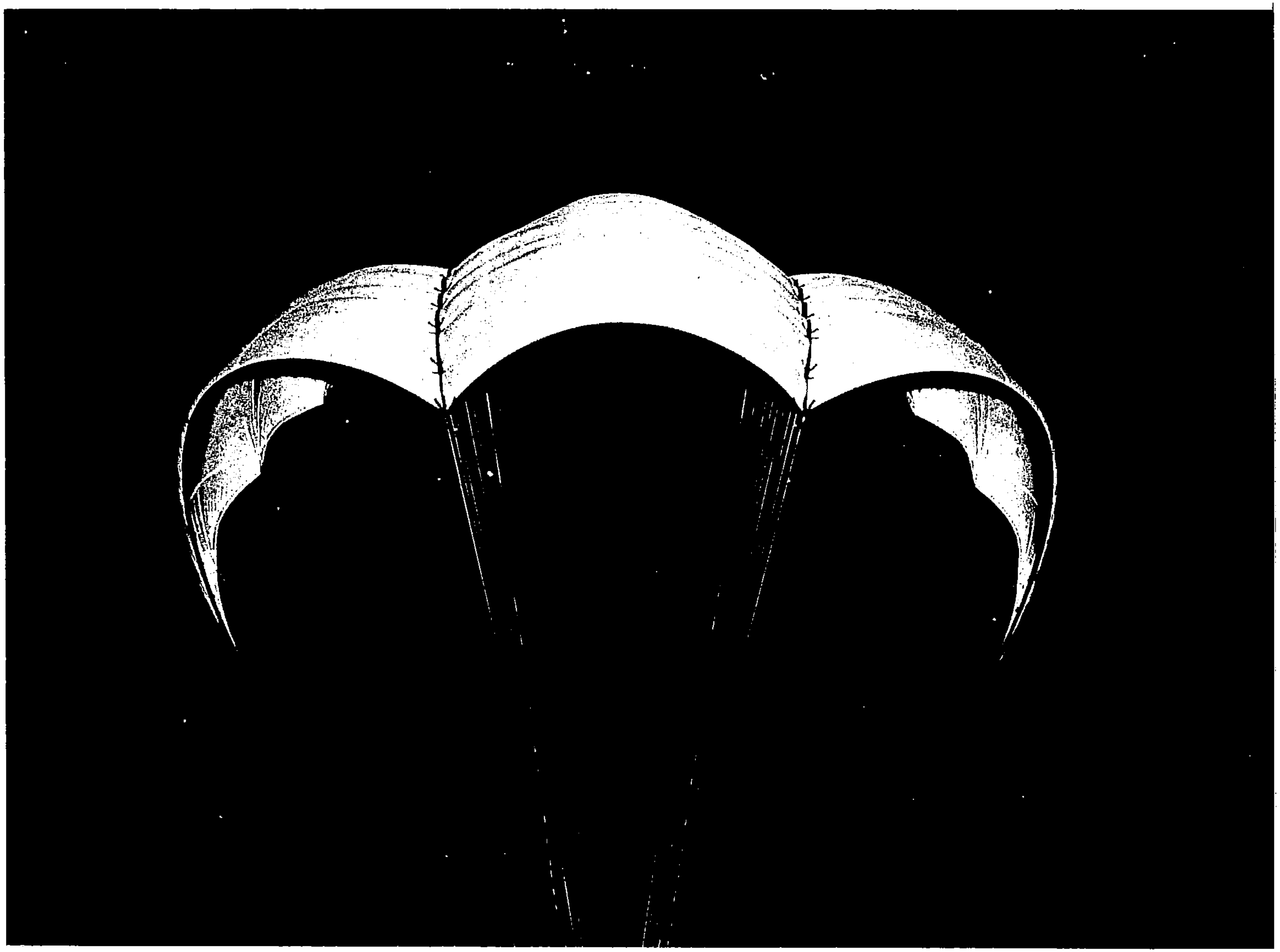
(b) Sections for $0.68 < \eta < 0.95$.

Figure 18.- Concluded.



(a) Side view.

Figure 19.- Photographs of twin-keel parawing in Langley Research Center tunnel.



(b) Rear view.

Figure 19.- Concluded.

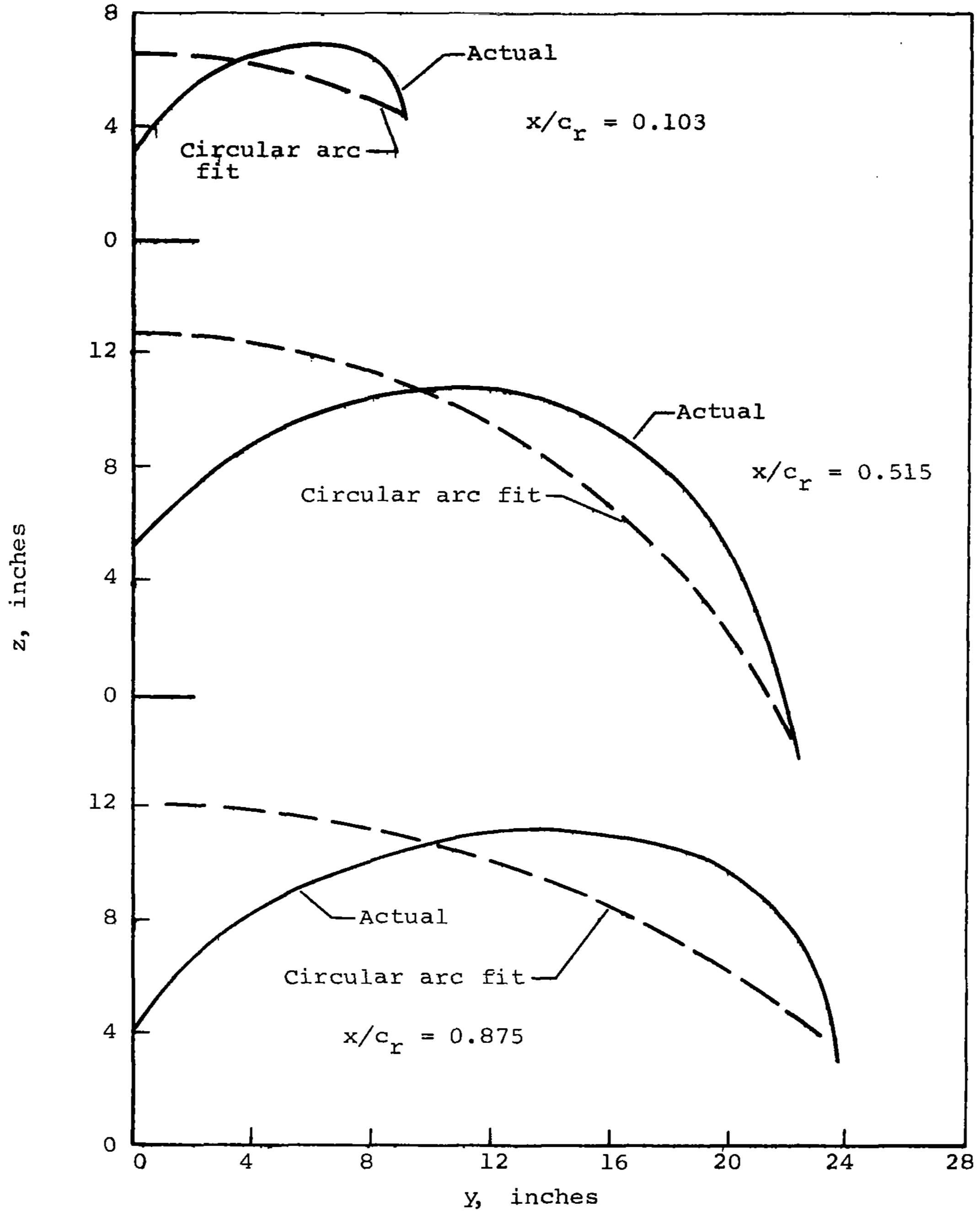


Figure 20.- Spanwise sections for single-keel parawing.

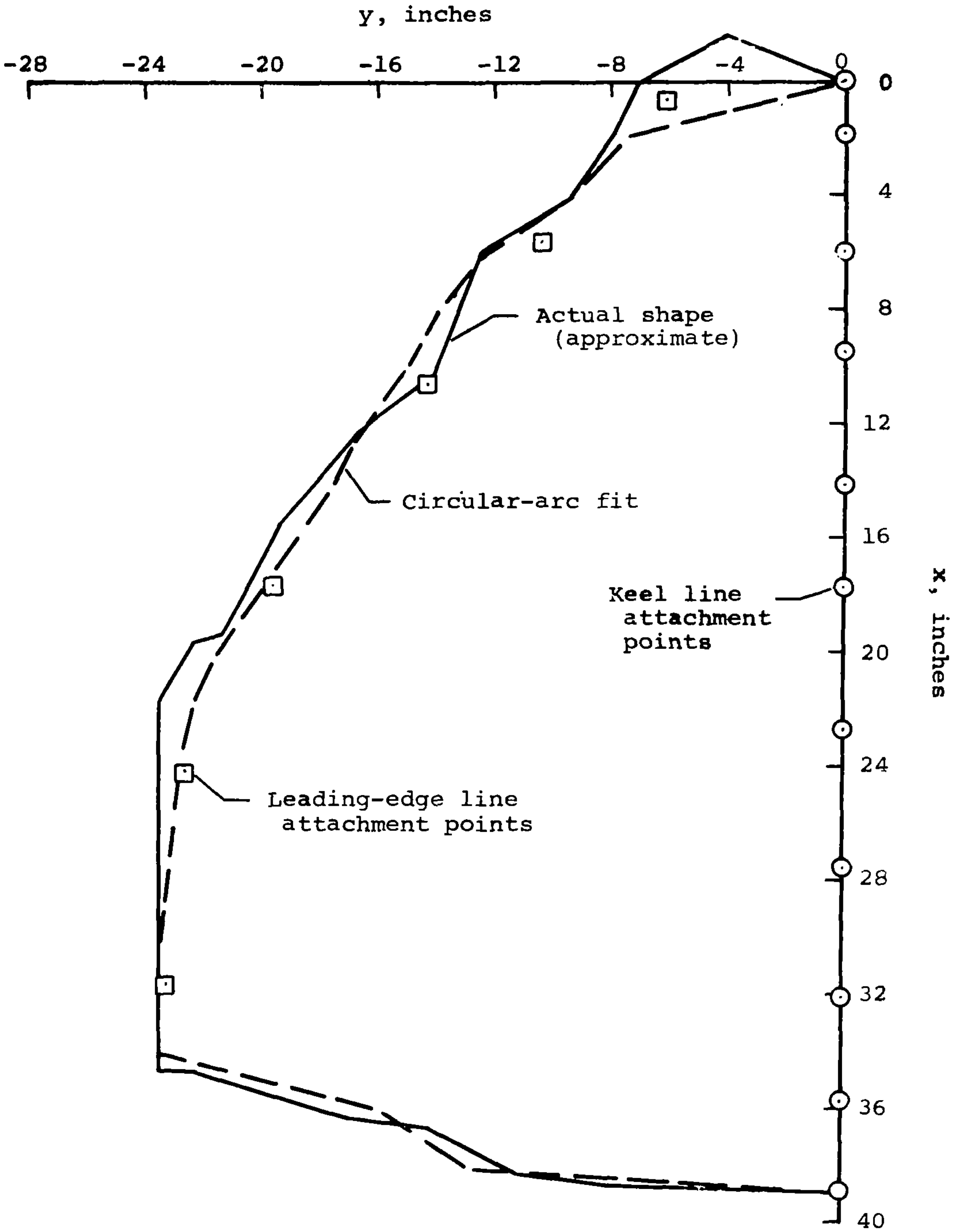


Figure 21.- Comparison of actual planform with circular-arc planform for single-keel parawing.

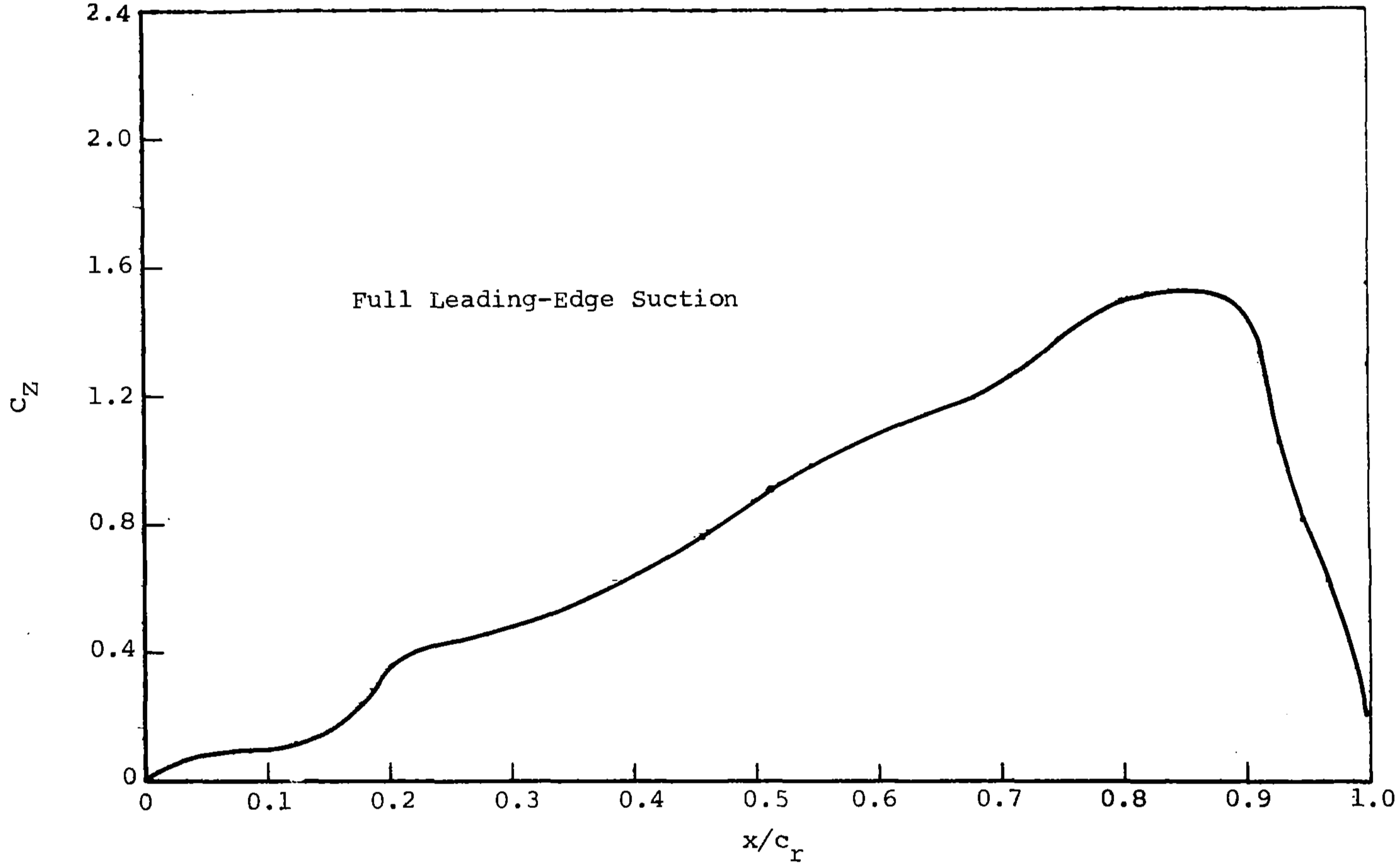


Figure 22.- Predicted chordwise buildup of normal force on single-keel parawing.

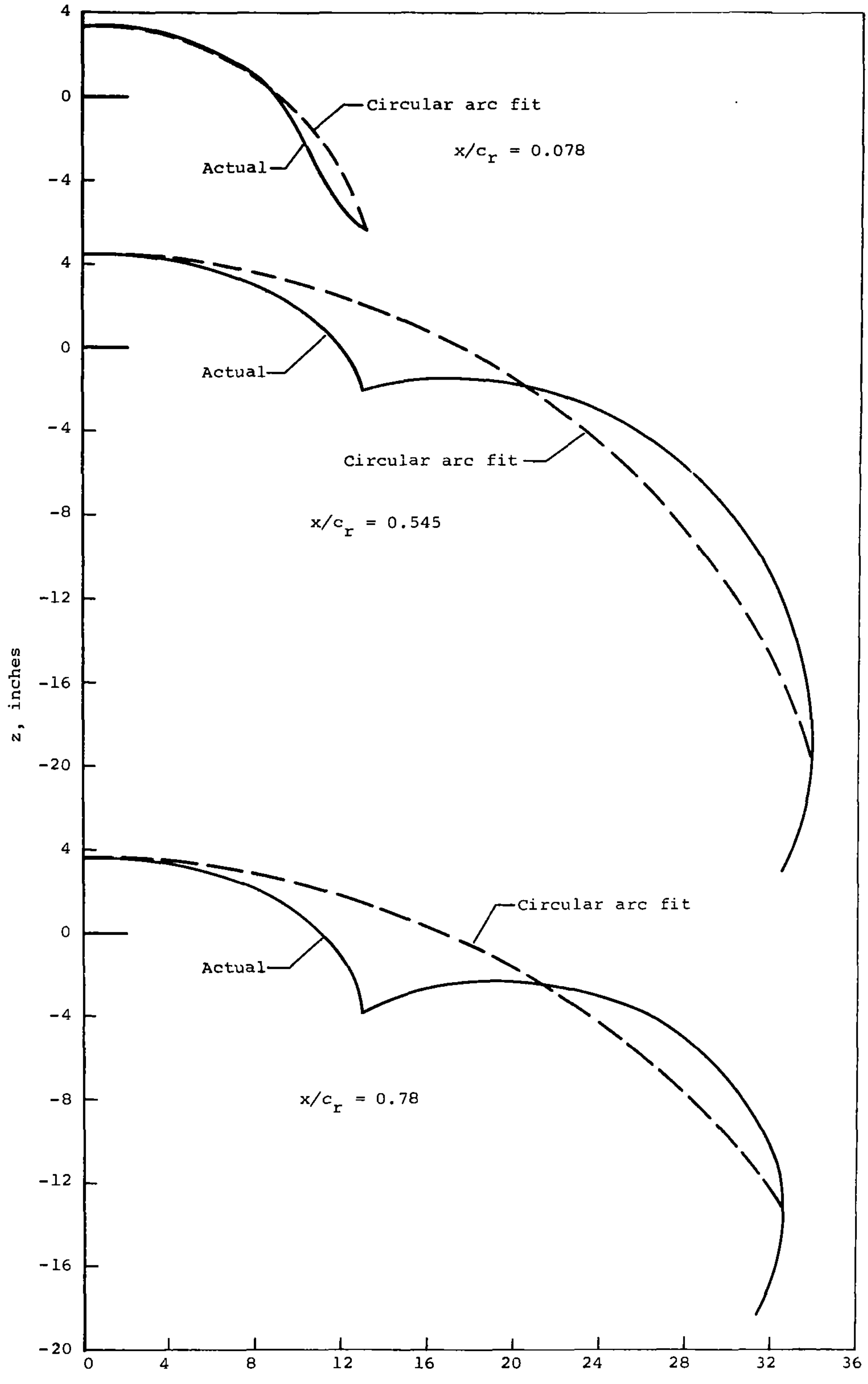


Figure 23.- Spanwise sections for twin-keel parawing.

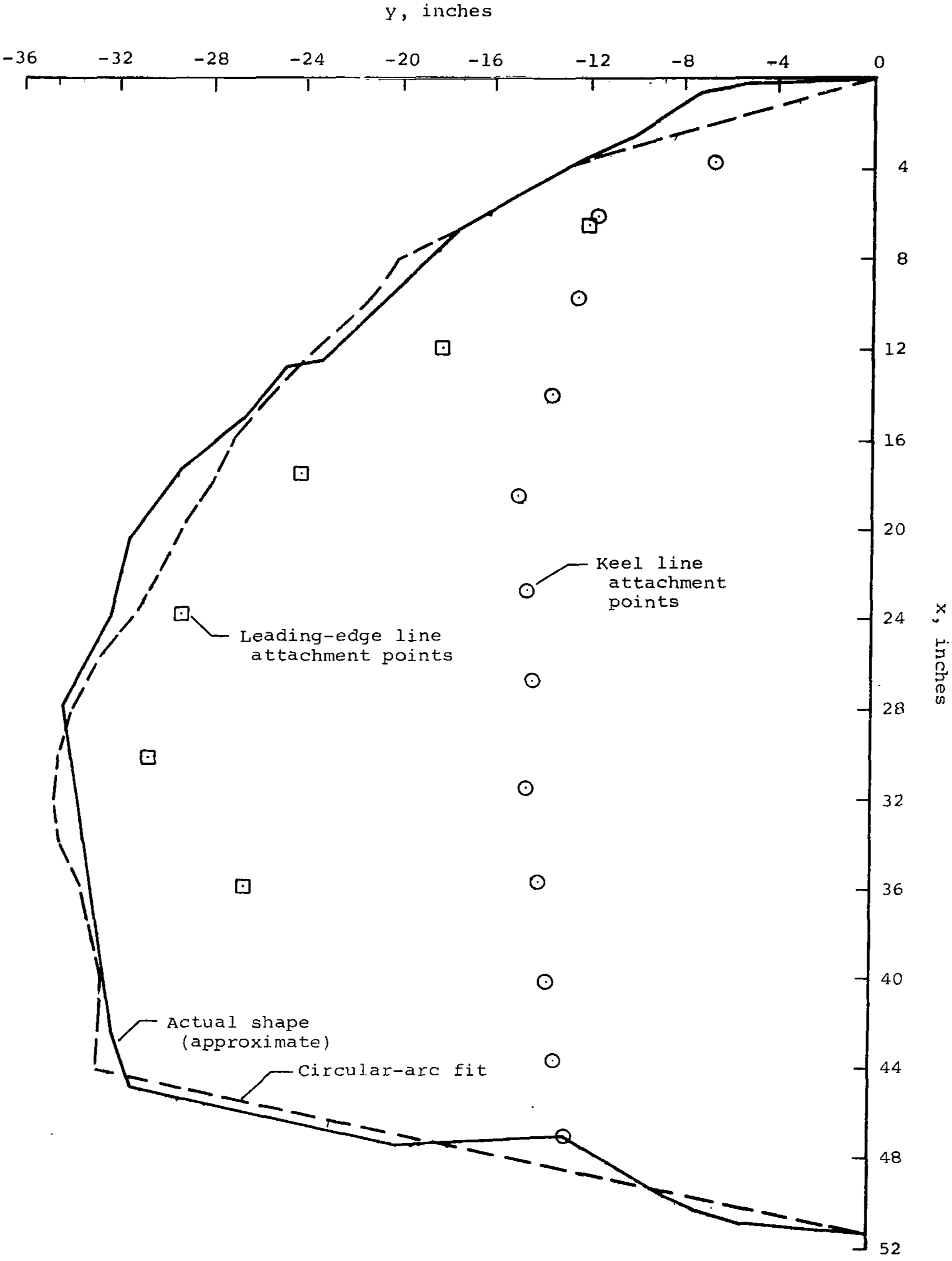


Figure 24.- Comparison of actual planform with circular-arc fit planform for twin-keel parawing.

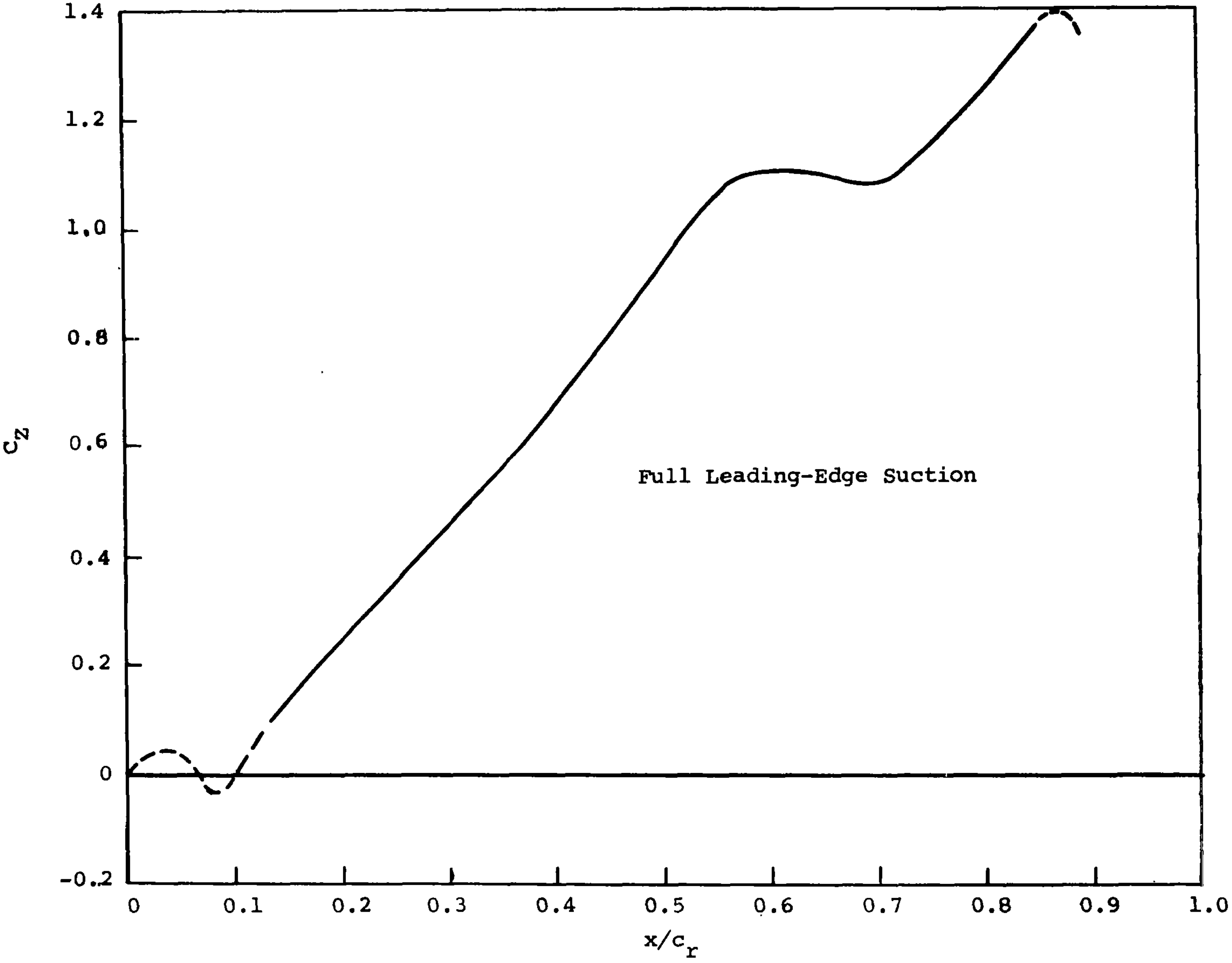


Figure 25.- Predicted chordwise buildup of normal force on twin-keel parawing.

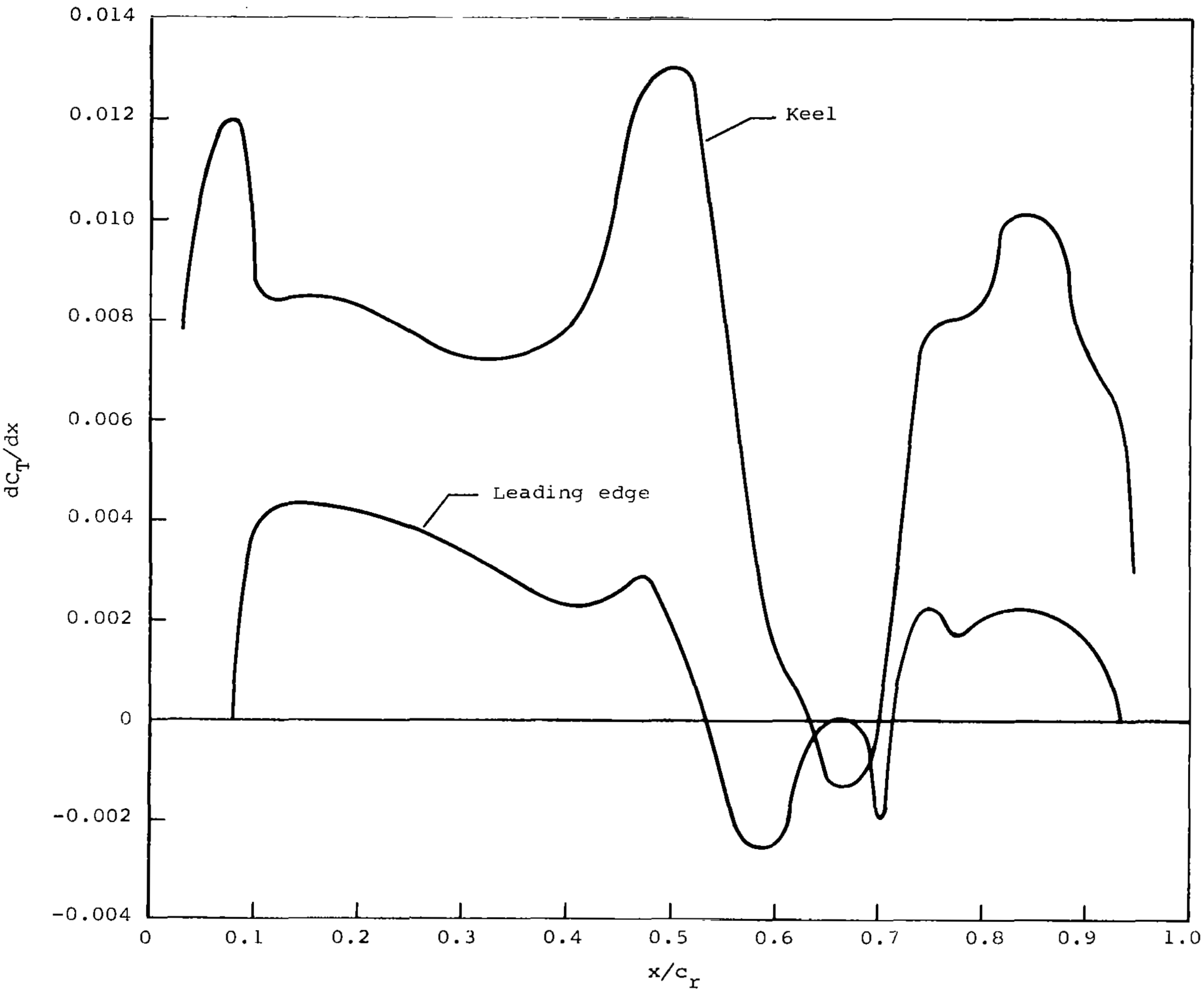


Figure 26.- Predicted distributed line tension load on twin-keel parawing obtained from Canopy Tension Approach (method c).

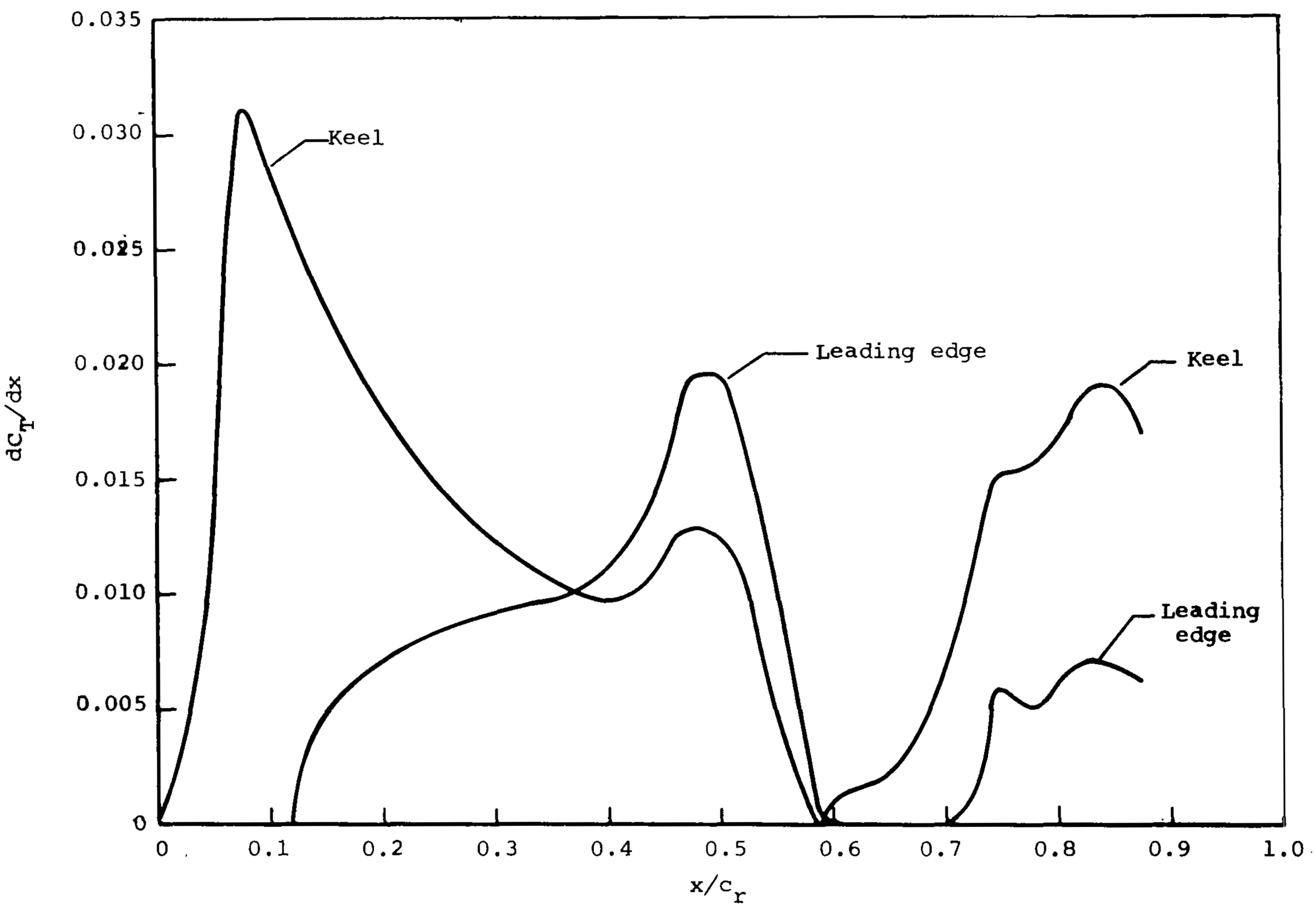
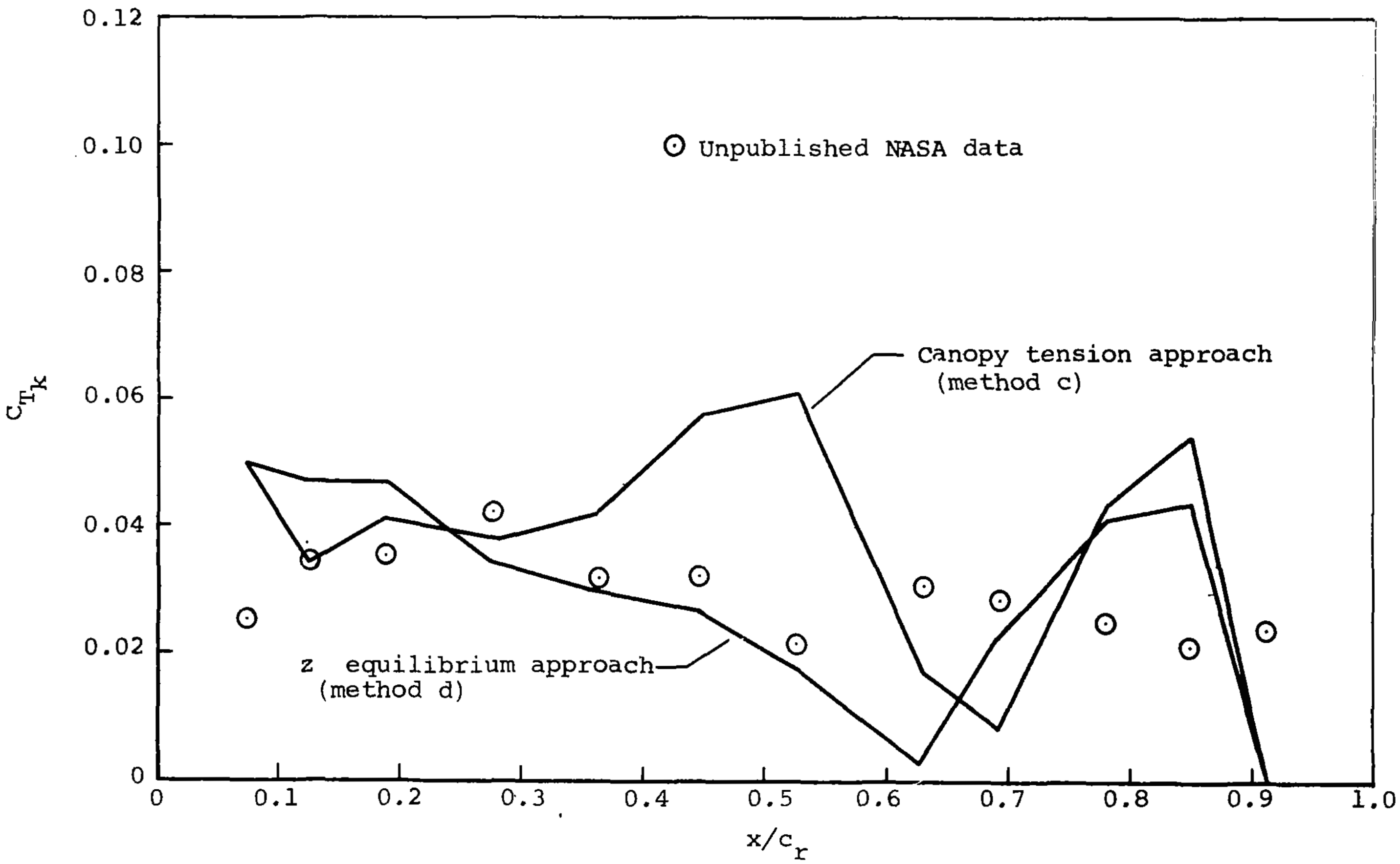
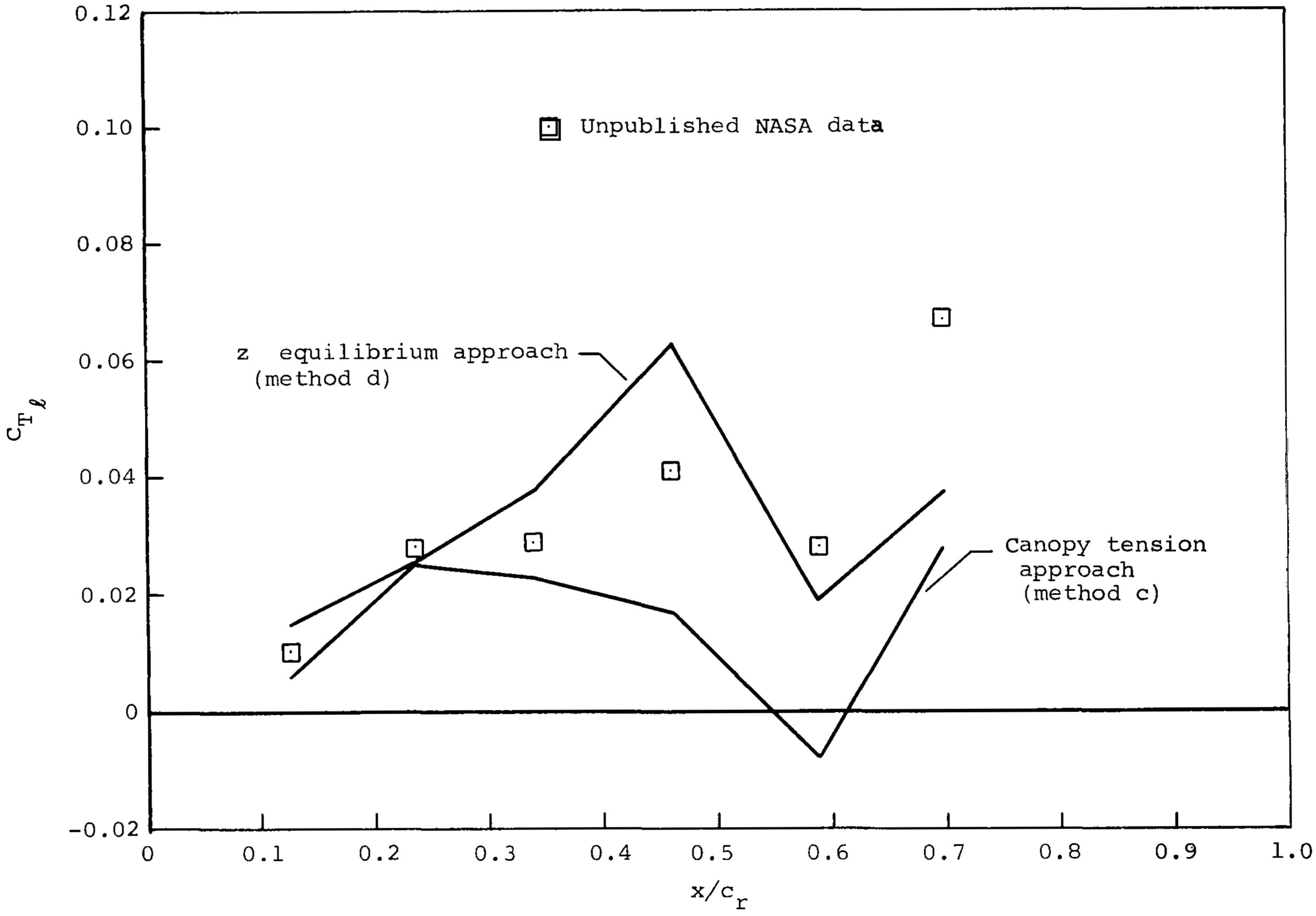


Figure 27.- Predicted distributed line tension load on twin-keel parawing obtained from z Equilibrium Approach (method d).



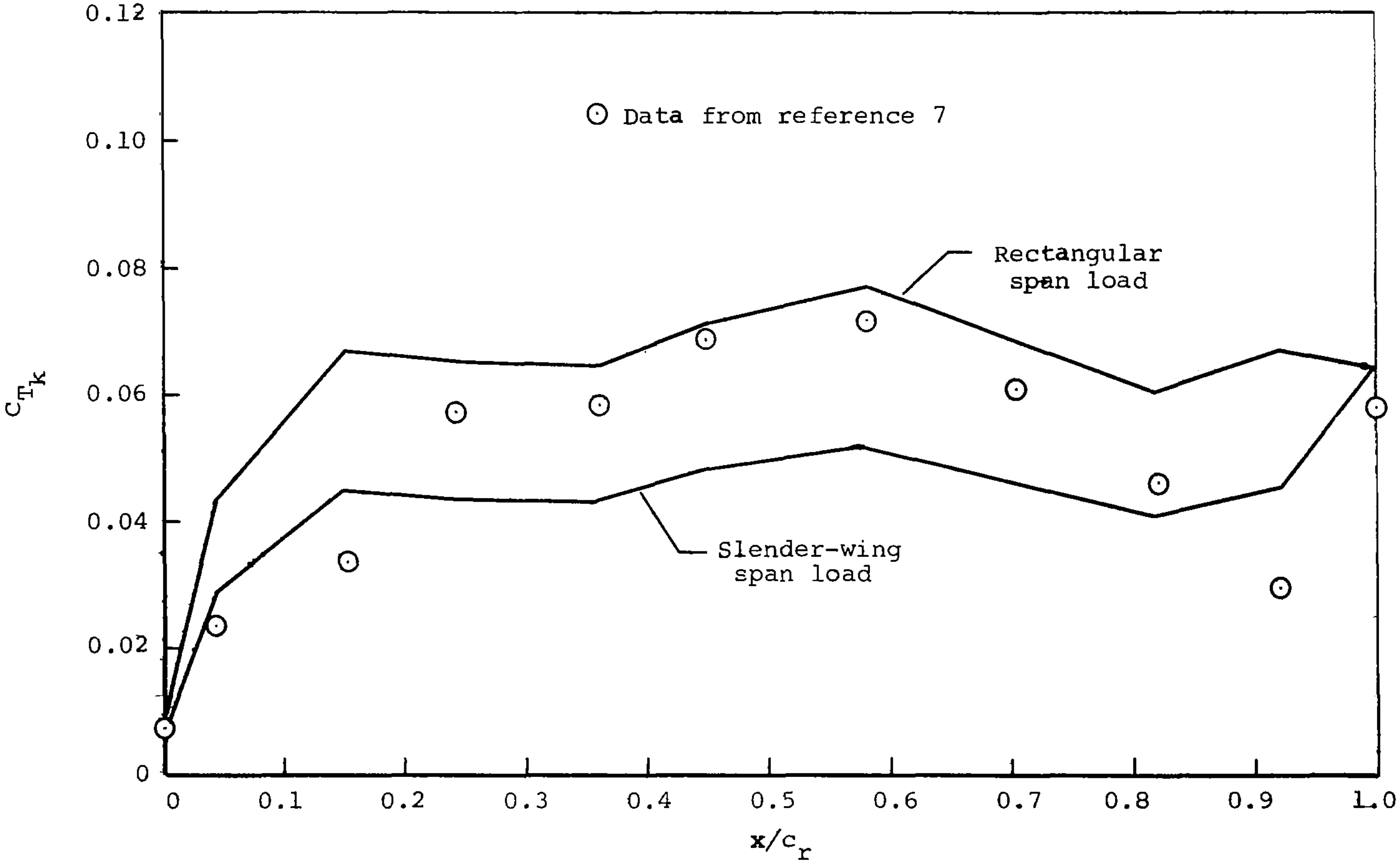
(a) Keel line loads.

Figure 28.- Comparison of line loads for two theoretical load distribution models for twin-keel parawing.



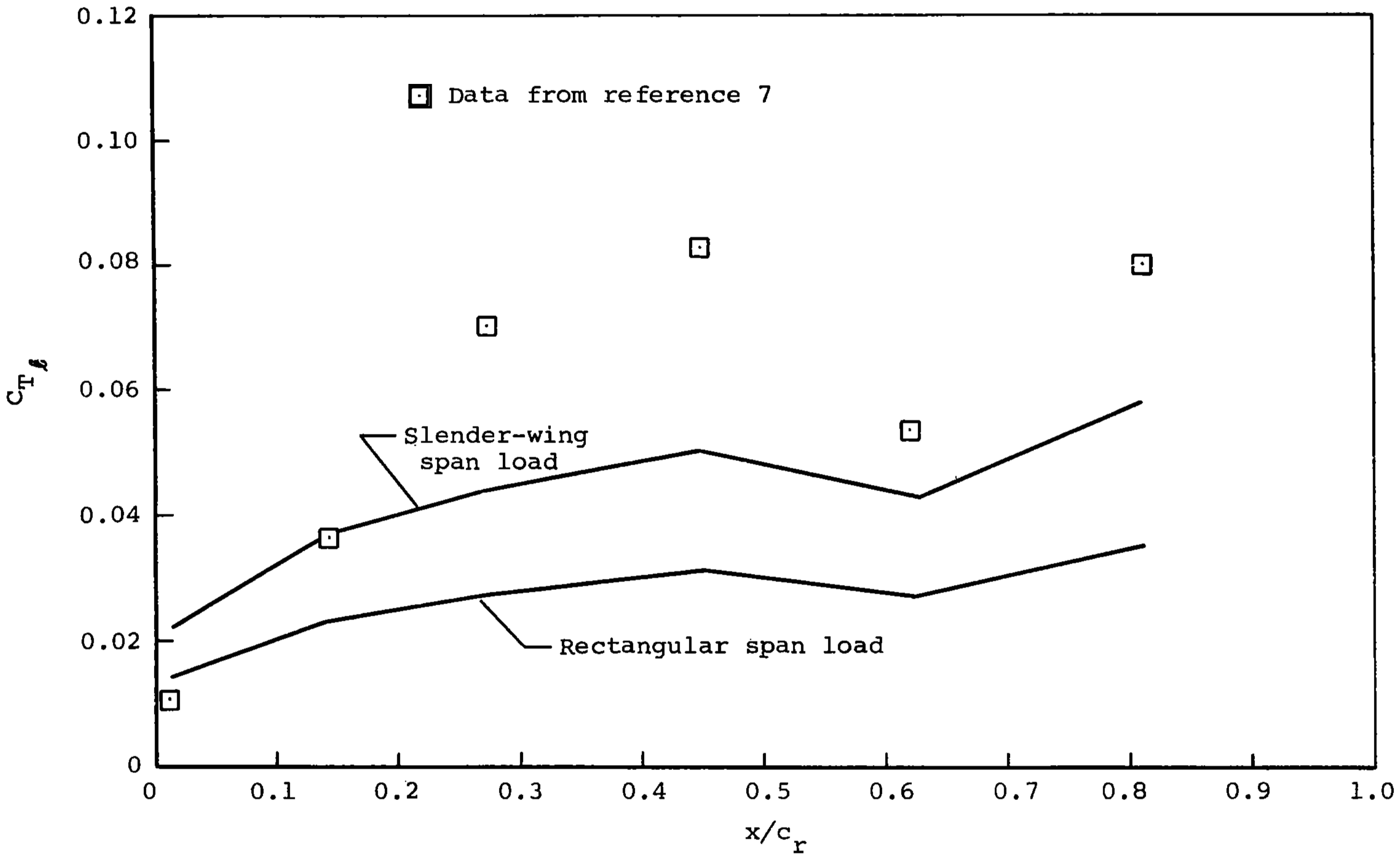
(b) Leading-edge line loads.

Figure 28.- Concluded.



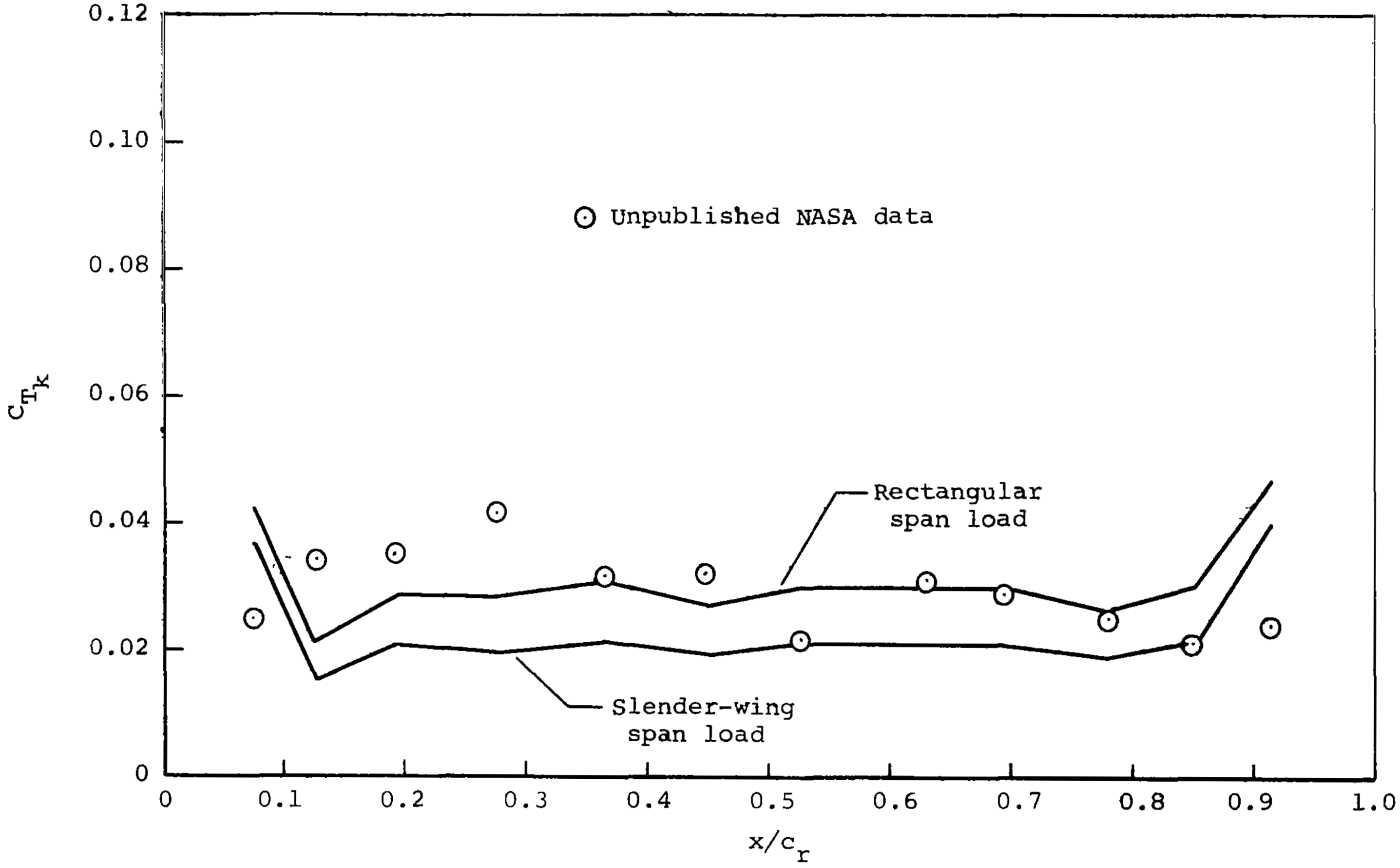
(a) Keel line loads.

Figure 29.- Comparison of predicted and measured line loads for the single-keel parawing.



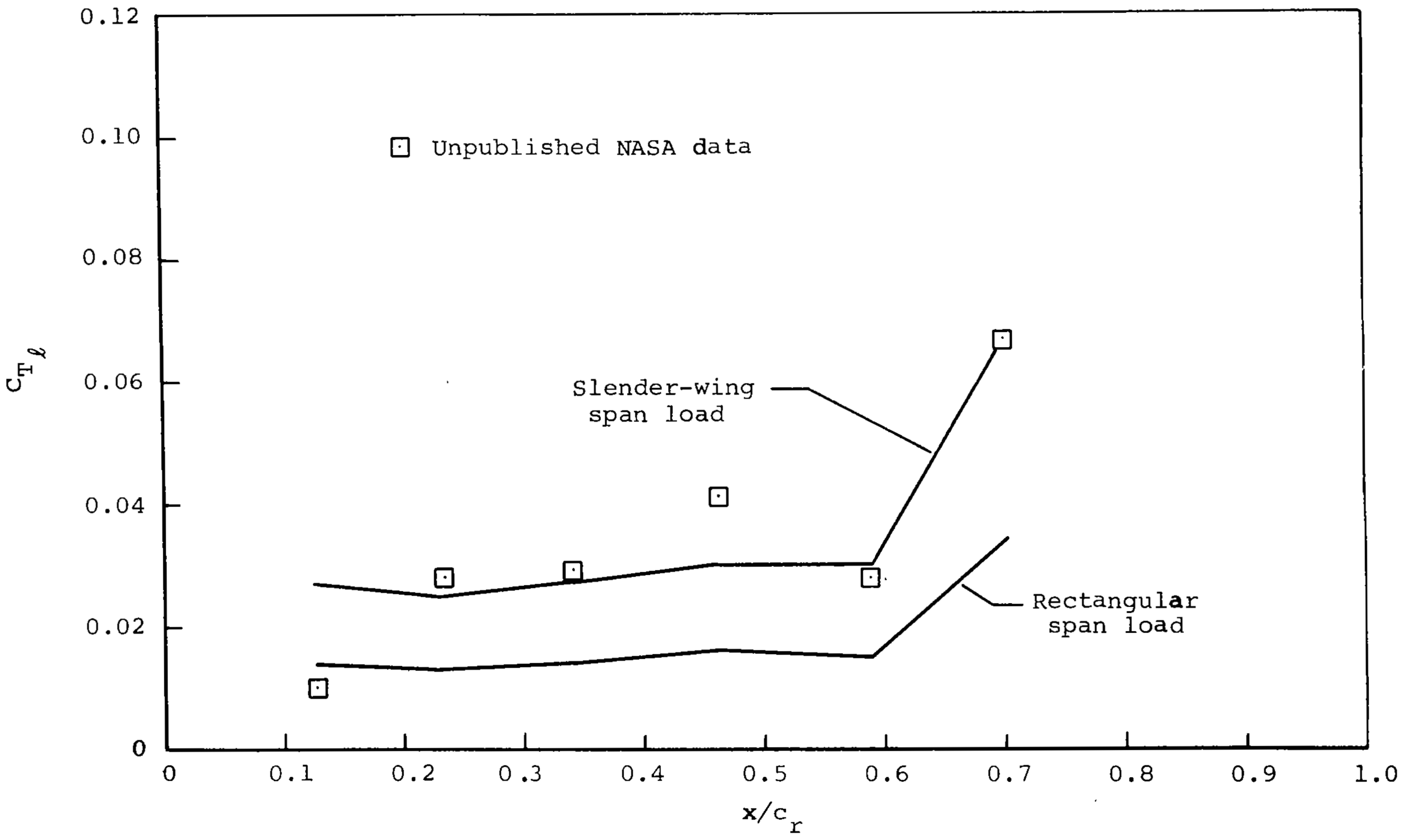
(b) Leading-edge line loads.

Figure 29.- Concluded.



(a) Keel line loads.

Figure 30.- Comparison of predicted and measured line loads for the twin-keel parawing.



(b) Leading-edge line loads.

Figure 30.- Concluded.

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