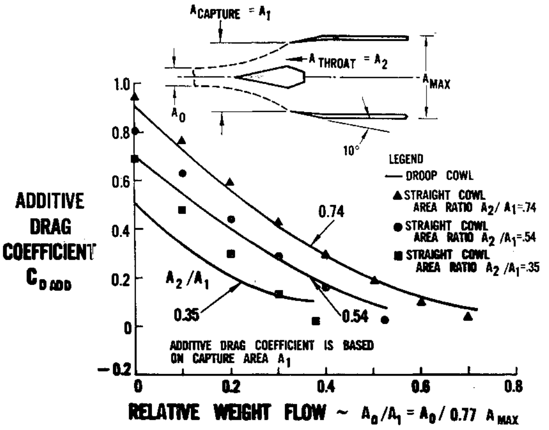

Fig. 16 Comparison between straight cowl and droop-cowl additive drag.

Although the inlets were not designed with good over-all pressure recovery in mind, some data were taken on cowl-lip pressure recovery for the airfoil tests. They indicate that, although additive drag is reduced, the maximum available net thrust F_A is also reduced because of pressure-recovery losses Thus, the maximum propulsive thrust F_p must be considered when optimizing an installation using the airfoil. Similar considerations apply to an installation using the drooped cowl.

The data also indicate that, for A_2/A_1 greater than 0.7, the cowl exterior shape tested did not change the additive drag. This means that cowl drag can be considered independently for cowl angles less than 10° and $A_1/A_{\max}$ less than 0.77, at least.

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A Segmented Wing Test Technique for Obtaining Spanwise Load Distributions

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A wind-tunnel test technique to determine the span loading on the wing of a complete aircraft configuration has been evolved and the data from a preliminary test series have been reduced to develop and to evaluate the method. The method is sufficiently inexpensive to be utilized during the early design phase of an airplane development. An existing model was modified by slitting the wing chordwise at seven spanwise stations leaving the spar intact and attaching strain gages to measure the wing bending moments. The reduction method used avoids the need to differentiate the bending-moment variation by curve-fitting the unknown span loading variation. A curve-fit polynomial with unknown coefficients is integrated, and a relationship is obtained between the bending moment and the unknown coefficients by a least-squares procedure. Data reduced by this technique are presented for typical test conditions. The accuracy of the method and means of improving the technique are discussed.

Nomenclature

a_{ij} = coefficients of $c_l c/\bar{c}$ in bending-moment equations
b = wing span
b_{ij} = coefficients of $c_l c/\bar{c}$ in least-squares equations
B_k = coefficients of kth power of curve-fit polynomial
c = local chord
$\bar{c}$ = mean chord
C_j = constant term of least-squares equations
c_l = local normal force coefficient
$c_l c/\bar{c}$ = span loading parameter
$\bar{C}_m(x_i)$ = estimated bending-moment coefficient at wing station i, bending moment/$\frac{1}{4}qSb$
$C_m(x_i)$ = test data bending moment coefficient at wing station i, bending moment/$\frac{1}{4}qSb$
l_i = ith Lagrangian interpolating polynomial
n = highest power in polynomial curve fit
q = dynamic pressure
S = wing area
W_i = weighting function at ith spanwise station
x = spanwise location from centerline
x_i = ith spanwise station
y = dependent variable in curve-fit polynomial $c_l c/\bar{c}$ or c_l
α = angle of attack, positive nose up
β = angle of sideslip, positive nose left
δ_a = angle of aileron deflection, positive trailing edge down

Subscripts

i, j, k = stations at which lift or moment is given or to be evaluated

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Introduction

In the design and analysis of airplanes, it is necessary that the distribution of the loading on the wing be known in order to perform the stress analysis. In addition, the span

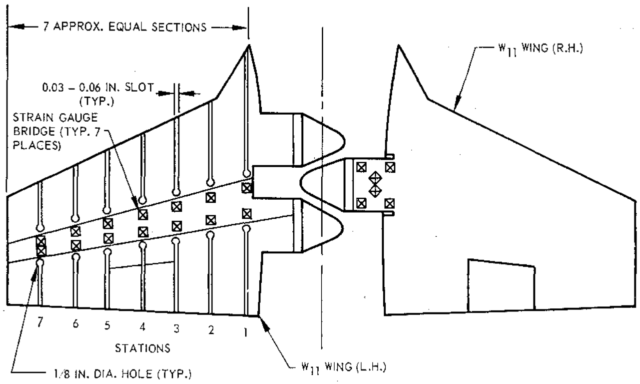


Fig. 1 Wind-tunnel test model wing instrumentation.

loading is an important parameter in estimating many of the static and rotary aerodynamic derivatives. Therefore, it is desirable that an inexpensive and accurate method of determining the span loading be available.

The conventional wind-tunnel method of obtaining the span loading relies on measuring pressures at a large number of points distributed over the wing planform. The instrumentation of a test model of this type is quite elaborate, and the associated costs involved in design, construction, and installation of such a model usually preclude the use of this type of test during the early stages of airplane design and analysis.

The available analytical methods of predicting the loading distribution are equally unsatisfactory as they are generally limited to the linear portion of the angle-of-attack range, with only marginal capability of incorporating effects of planform, sideslip, and control surface deflections. This paper describes a wind-tunnel test technique which will permit a reliable load distribution to be obtained without the restrictions imposed by analytic methods, and yet is sufficiently inexpensive to make it economical to obtain span loading data during the early stages of a design program.

Model Construction and Instrumentation

The model tested was a $\frac{1}{7}$-scale version of the F-5 airplane. This model was constructed for another test series and was modified to suit the requirements of the present test method.

The left wing of the model was slit at seven spanwise locations, leaving only the wing spar intact. At each of these spanwise stations four strain gages were attached to the spar symmetrically, two on the upper side and two on the lower. These gages were connected through a Wheatstone bridge and were used to measure the total bending-moment coefficient outboard of each of the seven spanwise stations. This arrangement is shown in Fig. 1. Two of the slits were made to coincide with the inboard and outboard edges of the aileron, with an intermediate cut near the aileron center. The aileron itself was attached as two separate segments with individual attachment brackets. Necessary wiring for the strain gages was run back to the body along the upper surface of the wing spar and was taped down to minimize interference with the flowfield, as shown in Fig. 2.

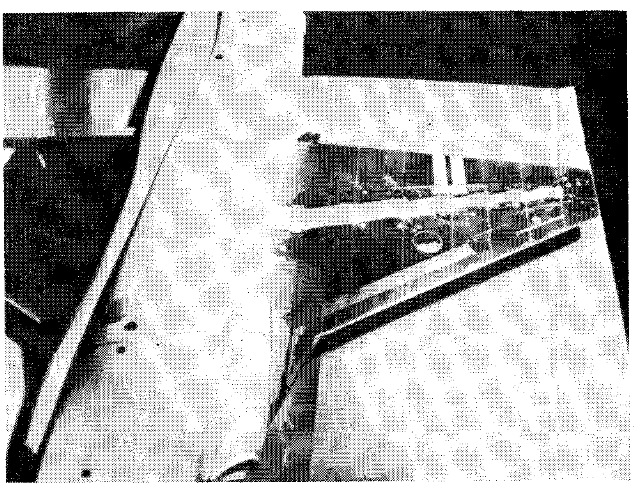


Fig. 2 Test model showing segmented wing arrangement.

The right-hand wing was not segmented, but had 12 strain gages located on its spar at the root (Fig. 1), six on the upper side, and six on the lower. Two sets, consisting of four gages each, were connected in a manner similar to those on the left-hand wing. These two sets of gages were separated a sufficient distance to permit both the normal force and bending moment to be obtained from their differential readings. The four remaining gages were connected to measure the torsion in the wing spar. This arrangement made it possible to obtain the total loading on the right-hand panel. The moments so obtained would then permit a check on the values obtained from the left-hand wing.

The system of gages was calibrated by loading the wing panels before the test series and relating the readings of the gages to the known loadings, using a rms procedure to minimize test inaccuracies. The signal strength from each strain gage was amplified separately to permit accurate readings and recordings for each spanwise location. Except for the aileron edges, which were left uncovered, all of the slits in both wing panels were sealed with a resiliant plastic before gage calibration.

Test Procedure

Tunnel Facility

The test was conducted in the Northrop Norair 7- × 10-ft, low-speed wind tunnel. This is a single-return, closed-throat wind tunnel operating at atmospheric pressure and a mean temperature of approximately 90°F. The model support was mounted on a turntable, and the model was sting-mounted on the Northrop two-parameter sting support.

Range of test

The test parameters were angle of attack α, angle of sideslip β, and aileron deflection angle δ_a. The model was tested at constant angles of sideslip $\beta = 0°, \pm 5°, \pm 10°, \pm 20°$. For each of these angles, the ailerons were kept at 0°, +15°, and −15°, and α ranged from 0–90° with repetition of α = 0° at the end of each run. The roll angle was kept at zero during all runs.

Test conditions

The test was conducted at a nominal dynamic pressure q = 75 psf at $\alpha = 0°$. At high angles of attack, q went up to 112 psf. This represents Mach numbers ranging from 0.22 to 0.26 and Reynolds numbers from 1.4 to 1.7 million per ft.

Accuracy of Data

The reliability of the data obtained is of utmost importance to the prediction of the correct span loading. This is particularly important with regard to the stations near the wing tip. Although no attempt was made to assess the accuracy of the test data, some indication of the relative accuracy can be obtained from the repeatability of the data. The repeatability of the bending moments based on the rms deviations of repeat points within each run are shown in Fig. 3. Although no attempt was made to instrument the model to obtain a higher accuracy near the tips, Fig. 3 indicates the possibility that either the wing flexibility or the

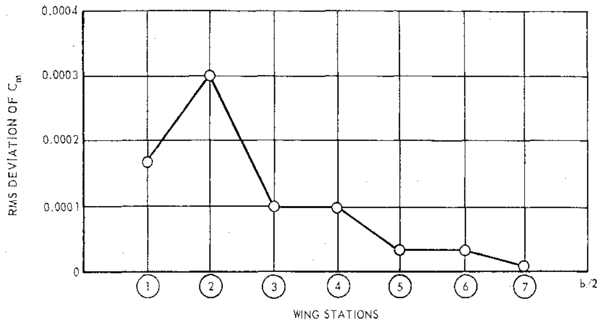


Fig. 3 Test data rms deviation in repeatability.

amplification factors increase the reliability of the tip data to more nearly approach constant percentage error across the span rather than a constant magnitude error.

Reduction of Data from Bending Moments to Span Loading

The data obtained from the test series were the wing bending moments at seven test stations. What was desired was the span loading distribution. To obtain the span loading from the bending moment would normally require that the bending moment be differentiated with respect to the spanwise distance. Since test data invariably have scatter involved, and since values were obtained for discrete points on the span, it was decided that a direct differentiation process would not give sufficiently accurate values for the spanwise loading, since a process of differentiation tends to magnify errors. It is also apparent that moments measured at the station near the wing root chord would be sensitive to the loading distribution near the tip, and this in turn would tend to cause predictions of the span loadings near the root chord to be extremely sensitive to the distribution assumed at outboard points. For these reasons it was decided to formulate a procedure which avoided the need for a direct differentiation. Figure 4 shows a flow chart of the data-reduction method logic.

Description of Data-Reduction Program

The basic curve-fit polynomial is Lagrange's interpolating polynomial of arbitrary degree n:

$$y(x) = \sum_{k=0}^{n} l_k(x) y(x_k) = \sum_{k=0}^{n} B_k x^k \tag{1}$$

where y is the curve-fitted representation of the span loading parameter $c_l c/\bar{c}$, and $y(x_k)$ represents the magnitudes of the span loading parameter at each of $n + 1$ arbitrarily located points on the wing span. The $l_k(x)$ are the Lagrangian coefficient functions:

$$l_k(x) = \frac{(x - x_0) \ldots (x - x_{k-1})(x - x_{k+1}) \ldots (x - x_n)}{(x_k - x_0) \ldots (x_k - x_{k-1})(x_k - x_{k+1}) \ldots (x_k - x_n)} \tag{2}$$

which ensures that $y(x)$ will take on the values of $y(x_k)$ at the point $x = x_k$, thus giving the desired representation of the span loading.

It is now necessary to relate these as yet unknown values $y(x_k)$ to the bending-moment distribution. This is done by integrating the loading multipled by its moment arm from the wing tip to an arbitrary spanwise point inboard of the tip. These inboard points will be taken to be the points on the span for which data were obtained. This equation is

$$\bar{C}_m(x_i) = \frac{4\bar{c}}{Sb} \int_{x_i}^{b/2} (x - x_i) \sum_{k=0}^{n} l_k(x) y(x_k) dx \tag{3}$$

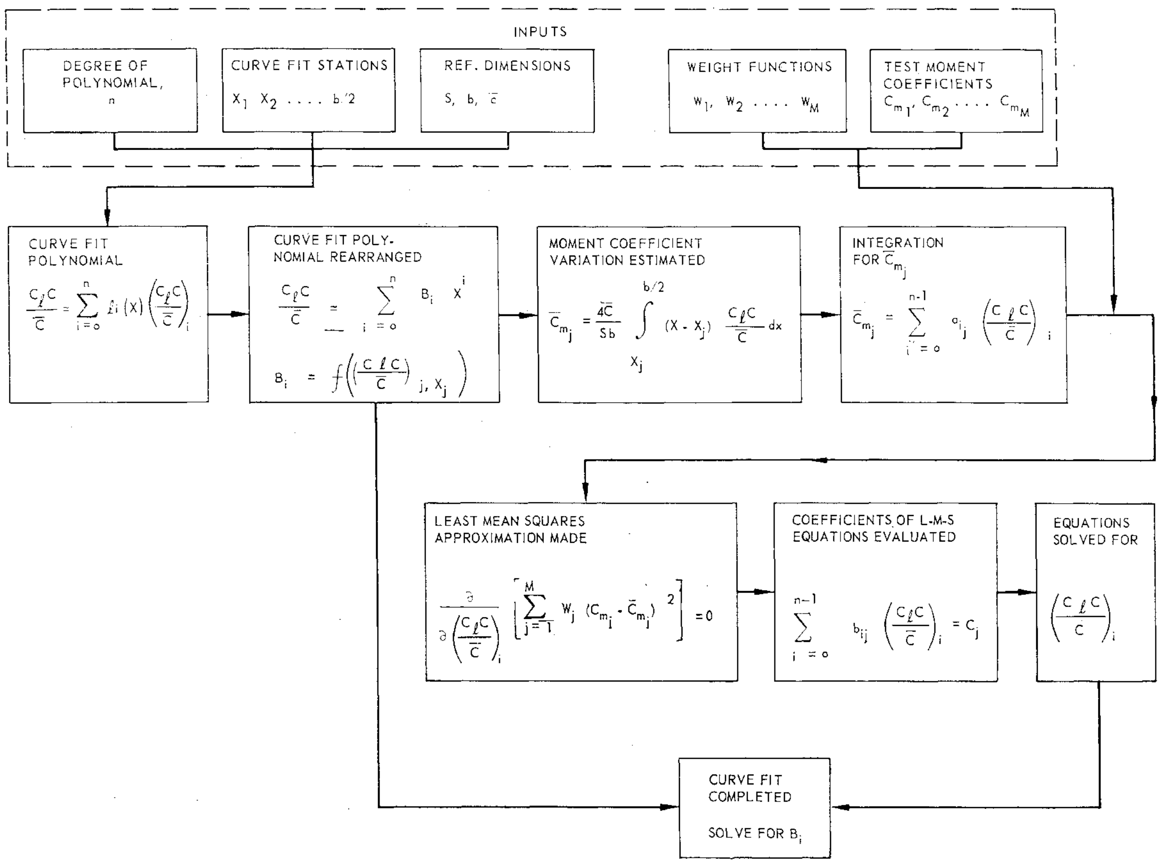


Fig. 4 Logic of data-reduction program.

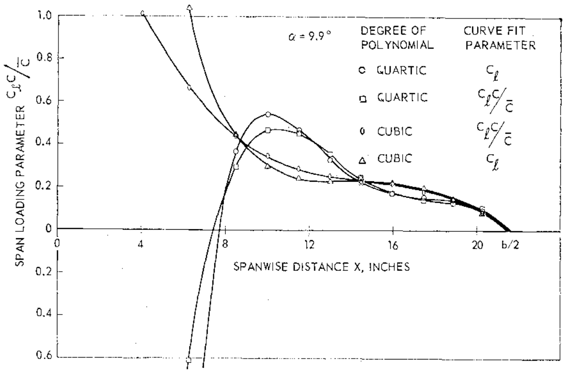


Fig. 5 Effect on $c_l c/\bar{c}$ due to different degree of polynomial and curve-fit parameter.

or

$$\bar{C}_m(x_i) = \frac{4\bar{c}}{Sb} \sum_{k=0}^{n-1} \int_{xi}^{b/2} (x - x_i) l_k(x) y(x_k) dx \qquad (4)$$

The reduction of the summation range to $n - 1$ is made to specify that the lift at the tip ($x = x_n$) is zero.

$\bar{C}_m(x_i)$, the estimated bending moment at station x_i, must now be integrated. This can be done since the $y(x_k)$ are constants, and the remainder of the integrand is a polynomial of degree $n + 1$. It remains to rearrange the terms in the integrand to separate out the coefficients of each power of x, i.e.,

$$\bar{C}_m(x_i) = \sum_{k=0}^{n-1} y(x_k) \int_{xi}^{b/2} (A_{k0}x^{n+1} + A_{k1}x^n + \ldots + A_{kn+1})dx \qquad (5)$$

and to evaluate the coefficients A_{kj}. This is accomplished by expanding the numerator of Eq. (2) multiplied by $x - x_i$, i.e.,

$$(x - x_i)(x - x_0) \ldots (x - x_{k-1})(x - x_{k+1}) \ldots (x - x_n) = x^{n+1} - (x_i + x_0 + \ldots + x_{k-1} + x_{k+1} + \ldots + x_n)\, x^n + (x_ix_0 + x_{i1} + \ldots + x_ix_{k-1} + x_ix_{k+1} + \ldots + x_ix_n + x_0x_1 + \ldots + x_{n-1}x_n)x^{n-1} + (-1)^n\, x_ix_0x_1 \ldots x_{k-1}x_{k+1} \ldots x_n \qquad (6)$$

From this expansion it is possible to evaluate the A_{kj}'s, and the equation is then integrable and has the form

$$\bar{C}_m(x_i) = \sum_{k=0}^{n-1} \left\{ \frac{A_{k0}}{n+2} \left[\left(\frac{b}{2}\right)^{n+2} - x_i^{n+2} \right] + \frac{A_{k1}}{n+1} \left[\left(\frac{b}{2}\right)^{n+1} - x_i^{n+1} \right] + \ldots + \frac{A_{kn}}{2} \left[\left(\frac{b}{2}\right)^2 - x_i^2 \right] + A_{kn+1} \left(\frac{b}{2} - x_i \right) \right\} y(x_k) = \sum_{k=0}^{n-1} a_{ki} y(x_k) \qquad (7)$$

It is important to realize that the expression for $\bar{C}_m(x_i)$ is linear in the $y(x_k)$. This procedure is repeated for each of the test span stations. It is now necessary to relate the mathematical expressions for the bending moments $[\bar{C}_m(x_i)]$ with the test values $[C_m(x_i)]$. If it were assumed that the degree of curve-fit polynomial were equal to the number of spanwise test locations, it would be possible to set the $\bar{C}_m(x_i)$ equal to the $C_m(x_i)$, and to solve directly the linear simultaneous equations for the values of $y(x_k)$. In this manner it would be possible to recreate exactly the test moment coefficients. It has been found, however, that this procedure gives a span loading distribution which is wildly oscillatory because of the inaccuracies in the test data.

It was decided, therefore, to reduce the degree of the curve-fit polynomial to a value smaller than the number of test stations, and to reduce the number of the resulting redundant set of equations to the number of $y(x_k)$ by a least-mean-square procedure, i.e., to take the sum of the squares of the difference between the mathematical expression for the moment coefficients and the corresponding test values, and to set the partial differentiations of this with respect to the individual $y(x_k)$ to zero. It also was decided to incorporate a weighting function W_i which would permit the assignment of different levels of importance to each of the spanwise test stations. This was believed to be necessary because of the large difference in magnitude between the values of the bending moments near the wing tip and those near the root. This also appeared to be valid since the repeatability of the data showed a similar trend, as can be seen in Fig. 3. This resulted in the series of expressions

$$\frac{\partial}{\partial y(x_k)} \left\{ \sum_{i=1}^{M} W_i[C_m(x_i) - \bar{C}_m(x_i)]^2 \right\} = 0 \qquad (8)$$

where M is the total number of test stations. This provide the proper number of simultaneous equations in the $y(x_k)$ and the set of equations will be linear in this parameter. This set of linear simultaneous algebraic equations is easily reduced (by a digital computer) and the values of the $y(x_k)$ can be evaluated.

The procedure through Eq. (7) is independent of the values of the test data, and thus can be solved once and retained throughout a series of test reductions, whereas Eq. (8) must be solved for each set of test data. By substituting the values of $y(x_k)$ into Eq. (1), it is possible to obtain the loading at any spanwise station on the wing. This procedure has been programmed and checked out, and the data obtained from the previously described test series were reduced by this method.

Discussion of Reduction Procedure Accuracy

Because of the limited number of spanwise stations at which data were taken, it was felt that the description of the spanwise loading could not be expected to give a detailed picture of the loading, but probably would be limited to showing trends in the loading distribution. The restricting factor was the degree of the curve-fit polynomial which could be tolerated. The higher the degree of this polynomial, the more the span loading would be affected by scatter in the test data, since the reduction procedure would be able to generate better agreement with the test results, and, hence, any error in the data would tend to show up in the loading

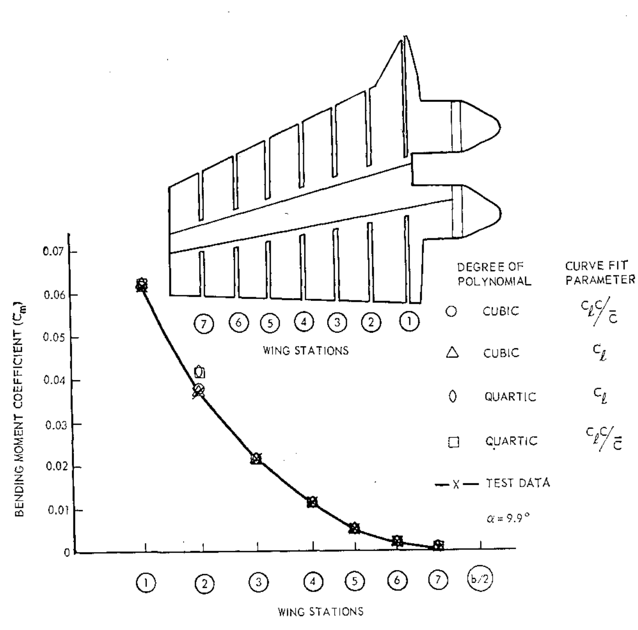
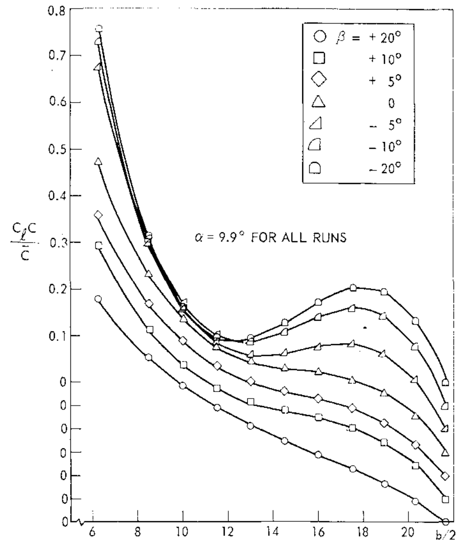
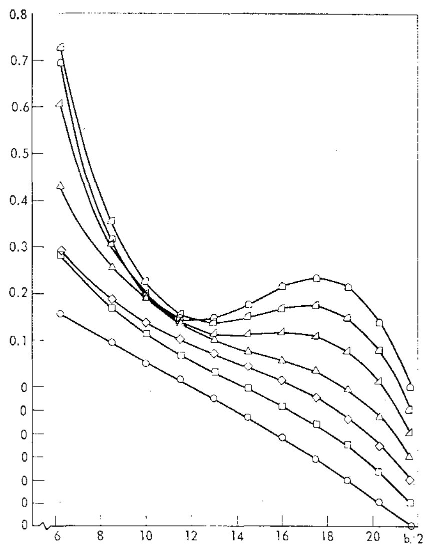


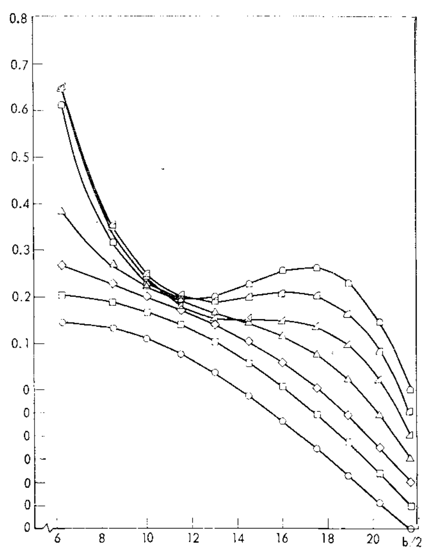
Fig. 6 Computed bending-moment coefficients.



a) $\delta_{al} = -15°$, $\delta_{ar} = +15°$



b) $\delta_a = 0$



c) $\delta_{al} = +15°$, $\delta_{ar} = -15°$

Fig. 7 Effect of side slip angle β on spanwise wing loading for various aileron deflection δ_a.

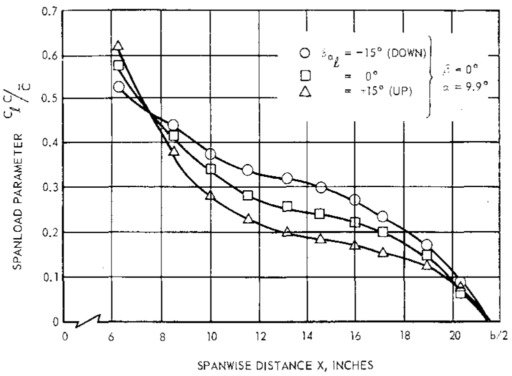


Fig. 8 Effect of aileron deflection on spanwise loading.

as an oscillation about the true span loading. But, to be able to reproduce any localized loads, e.g., those due to aileron deflection, it is necessary for the curve-fit polynomial to be of sufficiently high order to allow inflections in the span loading variation. To determine what degree polynomial should be used, one test run was examined thoroughly before the remainder of the test data was reduced. The no-sideslip, no-aileron deflection case was selected for this check.

Both cubic and quartic polynomials were input and compared as to their loading distribution; the agreement between the two sets of data was not good, as can be seen in Fig. 5. It appears that the loading predicted by the quartic is excessively influenced by test error. This may also be true for the cubic curve fit, but it was felt that to obtain a reasonable amount of flexibility in the distribution the cubic polynomial should be used. The possibility of curve-fitting the local c_l instead of $c_l c/\bar{c}$ was considered, since it was thought possible that the break in the wing leading edge might be causing the loading near the break to be predicted inadequately. This is shown in Fig. 5. To demonstrate that the disagreements in the span loadings are not due to inability to create a loading distribution to match the text moment distribution, Fig. 6 is shown. The various points on the curve are for the moments predicted by the reduction program for the conditions shown in Fig. 5. It can be seen that all four loading variations give acceptable agreement with the test curve, indicating the sensitivity of the loading to small changes in the moment distribution. It has been determined by hand calculations that this is not due to any program error. This demonstrates the need for more accurate test values and/or more redundancy in the data reduction equations. It was decided to reduce the remainder of the data using a cubic curve-fit polynomial and the parameter $c_l c/\bar{c}$.

Figure 7 presents typical data obtained by this method. The data shown are for a constant angle of attack (9.9°) and show the effects of sideslip and aileron deflection. There is a consistent trend in both the sideslip effects and the aileron effects. Figure 8 shows the effect of aileron deflection and indicates that, though the trend to be expected is present, the true shape of the loading distribution is not indicated accurately over the planform. Figure 9 gives the local normal force coefficient throughout the angle-of-attack range at several spanwise stations. The data appear to show a consistent pattern of stall.

Possible Refinements in Test Procedure and Reduction

From the data shown it can be seen that, although the method as presently constituted is capable of giving only relatively crude span loadings, general trends can be seen in the data. To provide an acceptable tool for early design work, it will be necessary to refine either the test technique or the reduction method. The most critical factor in the test data accuracy is the accuracy of the individual strain-

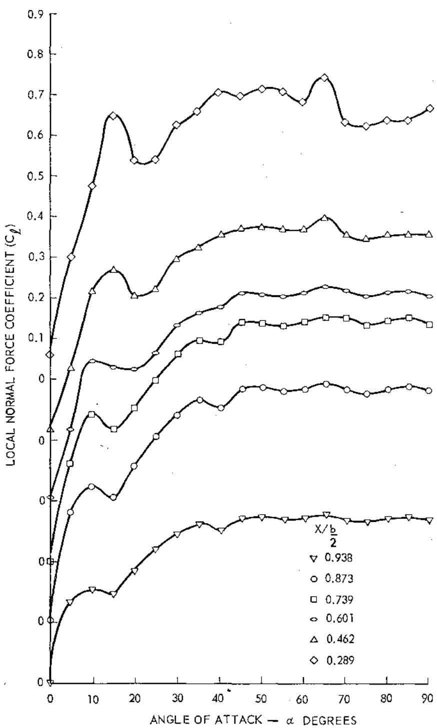


Fig. 9 C_l vs α at various spanwise stations.

gage readings. Of special concern here is the possibility of a strain gage which has either a consistently high or a consistently low reading. This appears to have a very critical effect in attempting to determine span loadings, since this will give a permanent distortion in the loading distribution. Further, if such a gage is located near the tip, its effect will be carried in toward the root and cause low (or high) loadings to be predicted, with the effect growing stronger as the root chord is approached.

Since errors in measurements near the tip are of critical importance in obtaining reliable span loadings, a model should be designed with sufficient flexibility near the wing tips to give a large strain-gage reading under the expected loading conditions. This would permit greater reliability to be placed on the data in this region and minimize errors in the span loading.

Another restriction is the limited number of cuts in the wing. The seven cuts of the present tests appear to be near the minimum that could be considered useful. The addition of several more slits should permit a much more reliable loading to be obtained, since a higher degree polynomial should be usable if there is a significant increase in the number of cuts.

It might also be possible to modify or to replace the polynomial curve fit to permit a more reliable span loading. In particular, it might be possible to provide a basic loading and to modify this loading by the chosen curve fit.

It might also be possible to take several readings at each test point, giving a scatter of data which could then be programmed into the reduction program to give additional redundancy in the data. This method appears promising, but it would be of only limited usefulness in case of an out-of-calibration gage. It appears, however, that various avenues of improvement are available and, with a carefully executed test program, it should be possible to get sufficiently accurate data for advanced design purposes.

Conclusion

This test technique appears to have promise of becoming a useful method for determining the span loading of wings. The test model, while more sophisticated than the usual force measurement model, is considerably simpler than the model required for measuring pressure distribution. The instrumentation required is also less cumbersome and less expensive.

It appears that this technique will permit obtaining detailed and relatively accurate information on the span loadings of wings. Possessing this information will provide a greater understanding of the loading distribution as affected by stall, control surface deflection, and changes of planform. This is information from which a more efficient and reliable vehicle can be designed.