Reprinted from JOURNAL OF THE AERONAUTICAL SCIENCES
Copyright, 1956, by the Institute of the Aeronautical Sciences and reprinted by permission of the copyright owner
APRIL, 1956 VOLUME 23, NO. 4

A Method for Predicting Lift Effectiveness of Spoilers at Subsonic Speeds*

ARTHUR L. JONES,† OWEN P. LAMB,‡ AND ALFRED E. CRONK**
FluiDyne Engineering Corporation

SUMMARY

As part of an investigation concerning gust alleviation controls, it was necessary to develop a means for predicting the lift effectiveness of spoilers. Methods for estimating the lift effectiveness of ordinary flap-type control devices can usually be developed by application of thin airfoil theory. However, control devices depending on flow separation for their effectiveness, such as spoilers, have not proved amenable to analyses based solely on potential flow considerations. In the case of plain spoilers, a semiempirical approach utilizing both lifting-surface theory and experimental data has provided a satisfactory basis for analyzing variations in spoiler lift effectiveness. The method for prediction which evolved proved to be applicable at subsonic Mach Numbers up to approximately 0.95 for an angle-of-attack range restricted to an upper limit of about 6°. The method takes into account the effects of the following parameters: aspect ratio, taper ratio, sweepback, airfoil thickness ratio, chordwise location and spanwise location of the control, and spanwise extent of the control. A design chart presentation has been used to show the relative effects of variations in each parameter and to provide for a rapid, straightforward prediction procedure.

SYMBOLS

A = aspect ratio
$C_{L\zeta}$ = rate of change of lift coefficient with spoiler projection for symmetrically deflected spoilers on each semispan
M = free stream Mach Number
c = wing chord measured normal to the quarter-chord line, ft.
c' = streamwise wing chord, ft.
h = spoiler projection, ft.
r = ratio of spoiler lift effectiveness at a given value of a parameter to the effectiveness at the basic value
t = maximum airfoil profile thickness, ft.
x = chordwise location measured from leading edge along profile normal to quarter-chord line, ft.
Λ = sweepback angle of the quarter-chord line
ζ = spoiler projection in terms of streamwise chord, (h/c'), positive downward
η_e = spanwise extent of spoiler, measured in semispans
η_m = spanwise location of mid-span point of spoiler, measured in semispans
λ = ratio of tip chord to root chord

INTRODUCTION

THE TERM SPOILER has been used to designate almost any device which can be installed on a wing and operated to spoil the flow on the upper surface, thereby decreasing the lift. If a spoiler is projected from the lower surface of a wing, it will also spoil the flow and to some extent will increase the lift; the magnitude of the lift increase being somewhat sensitive to spoiler configuration and to other conditions. The degree to which a spoiler, operated as both an upper and lower surface device, will provide symmetrical lift increments has not been satisfactorily determined as yet. Symmetry of lift effectiveness is an important factor in the consideration of spoilers as gust alleviation devices. Further research in regard to the feasibility of lower surface spoiler operation has been scheduled by the Air Force. At present, however, the lift effectiveness results derived and presented herein must be considered as representative of upper surface spoilers in particular, since the derivation was based on upper-surface spoiler data. Moreover, the results are indicative of the lift effectiveness that can be obtained using an unperforated spoiler projected perpendicular to the airfoil surface, or very nearly so. Configurations such as this are often referred to as plain spoilers and that nomenclature has been adopted herein. It is probable that the effectiveness of similar mechanical devices such as flap-type spoilers, slot-lip ailerons, and plug-type ailerons could be predicted by small modifications to the plain spoiler results. No attempt will be made, however, to include such modifications in this analysis.

The values of lift effectiveness presented herein can be considered representative of the variation of lift with spoiler projection between projection limits of 0.01 c' and 0.10 c' where c' refers to the streamwise chord. It is well known that for spoiler projections of 0.01 c' or less, a loss or perhaps a reversal in effectiveness often occurs. Moreover, beyond approximately a 0.1 c' projection the effectiveness usually begins to decrease. Thus the lift increments predicted herein will tend to be somewhat high outside the range of projections from 0.01 c' to 0.1 c'.

METHOD OF ANALYSIS

Recognition of the fact that spoiler operation results in a separated flow condition, leads to the conclusion that an analysis based on thin-airfoil potential-flow

---

Presented at the Aerodynamics Session, Twenty-Third Annual Meeting, IAS, New York, January 24–27, 1955.

* The investigation reported in this paper is a portion of the work performed under Contract AF 33(616)-2094 with the United States Air Force, Wright Air Development Center, Aircraft Laboratory, in order to evaluate various aerodynamic control devices for gust alleviation.

† Senior Project Engineer.

‡ Senior Development Engineer.

** Associate Professor, Dept. of Aeronautical Engineering, University of Minnesota; Consultant, FluiDyne Engineering Corp.

theory, exclusively, would not be satisfactory. On the other hand, the experimental data on spoilers which have been compiled to date, do not contain a sufficiently comprehensive survey of the effects of all pertinent wing plan form and profile characteristics to permit the establishment of a strictly empirical procedure for predicting $C_{L\zeta}$, the lift effectiveness. Thus a semiempirical technique was indicated which would combine the available theoretical estimates of the effects of variations in plan form parameters such as aspect ratio, taper ratio, sweep, the spanwise location, and spanwise extent of the device with the experimentally determined effects of section parameters such as airfoil thickness ratio, angle of attack, and the chordwise location of the device. It was felt that the technique to be developed should show directly, insofar as possible, the effects on $C_{L\zeta}$ of variations of the parameters and at the same time provide a reliable, rapid, and straightforward procedure for the calculation of predicted values.

The method that evolved, finally, was developed around certain selected basic values of the parameters. These values are tabulated in Fig. 1 along with the somewhat restrictive range of parameter values this method was intended to cover. There is no particular significance to be attached to the basic values listed in Fig. 1 except that they appeared to be either fairly average values in terms of conventional wing-spoiler configurations or reasonable starting points from which the effects of variations could be ascertained. No basic value of Mach Number was selected because it was felt that the effects of variations in the rest of the parameters could be determined throughout the range of Mach Numbers investigated, namely, 0 to 0.95, and that Mach Number, therefore, could be treated as an autonomous variable.

The plan was to determine the values of $C_{L\zeta}$ for a wing-spoiler configuration corresponding to the combination of basic parameter values and, in addition, to determine the modifications to $C_{L\zeta}$ which would occur when the parameters were changed to other than their basic values. In order to accomplish this, the available spoiler lift-effectiveness data on various finite-span models had to be modified to correspond to the basic configuration. Thus, initially, it was necessary to make some assumption about the manner in which these modifications could be accomplished. The assumption made was that the effect on $C_{L\zeta}$ of a change in any one parameter could be accounted for independently of changes in the other parameters by application of a correction factor. It was felt that the proper choice of the basic parameter values and the restrictions placed on the ranges of the parameters would materially assist in achieving this independence of parameter effects. The correction factor would be the ratio of spoiler lift effectiveness at the arbitrary value of the parameter being varied to the spoiler lift effectiveness at the basic value, with all other parameters remaining fixed.

Parameter		Basic Value	Range of Values Considered
Aspect Ratio,	A	6	$4 \leq A \leq 10$
Taper Ratio,	λ	0.5	$0.25 < \lambda \leq 1.00$
Sweepback,	Λ	0°	$0^\circ \leq \Lambda \leq 60^\circ$
Spanwise Location,	η_m	0.83	$0.17 \leq \eta_m \leq 0.833$
Spanwise Extent,	η_e	0.33	$0 \leq \eta_e \leq 1.00$
Chordwise Location,	x/c	0.7	$0.5 \leq x/c \leq 0.90$
Thickness Ratio,	t/c	0.09	$0.04 \leq t/c \leq 0.20$
Angle of Attack,	α	2°	$-2^\circ < \alpha < 6^\circ$

FIG. 1. Variable parameters, basic values, and ranges of valves considered in the development of the method.

$$C_{L\zeta} = (C_{L\zeta})_{\text{basic}}\,(r_A)(r_\lambda)(r_\Lambda)(r_{t/c})(r_{x/c})(r_{\eta_m})(r_{\eta_e})(r_\alpha)\,K$$

where $(C_{L\zeta})_{\text{basic}} = C_{L\zeta}$ for the configuration specified by the basic values of the parameters

$$r_A = \frac{(C_{L\zeta})_A}{(C_{L\zeta})_{A=6}} \qquad r_{x/c} = \frac{(C_{L\zeta})_{x/c}}{(C_{L\zeta})_{x/c=0.7}}$$

$$r_\lambda = \frac{(C_{L\zeta})_\lambda}{(C_{L\zeta})_{\lambda=0.5}} \qquad r_{\eta_m} = \frac{(C_{L\zeta})_{\eta_m}}{(C_{L\zeta})_{\eta_m=0.83}}$$

$$r_\Lambda = \frac{(C_{L\zeta})_\Lambda}{(C_{L\zeta})_{\Lambda=0^\circ}} \qquad r_{\eta_e} = \frac{(C_{L\zeta})_{\eta_e}}{(C_{L\zeta})_{\eta_e=0.33}}$$

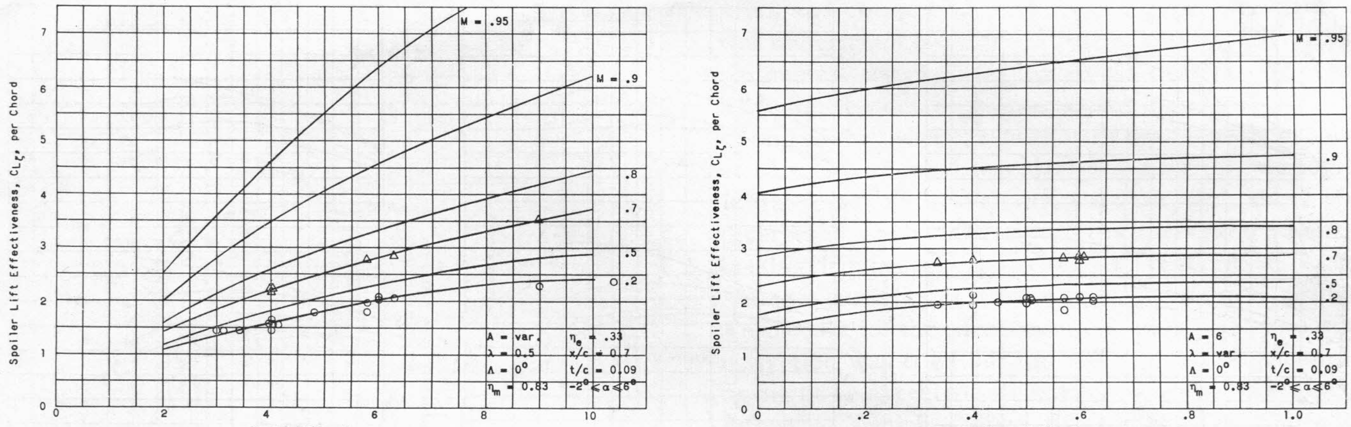
$$r_{t/c} = \frac{(C_{L\zeta})_{t/c}}{(C_{L\zeta})_{t/c=0.09}} \qquad r_\alpha = \frac{(C_{L\zeta})_\alpha}{(C_{L\zeta})_{\alpha=2^\circ}}$$

$$K = f(M, A, \Lambda, \eta_m)$$

FIG. 2. Formula for predicting spoiler lift effectiveness.

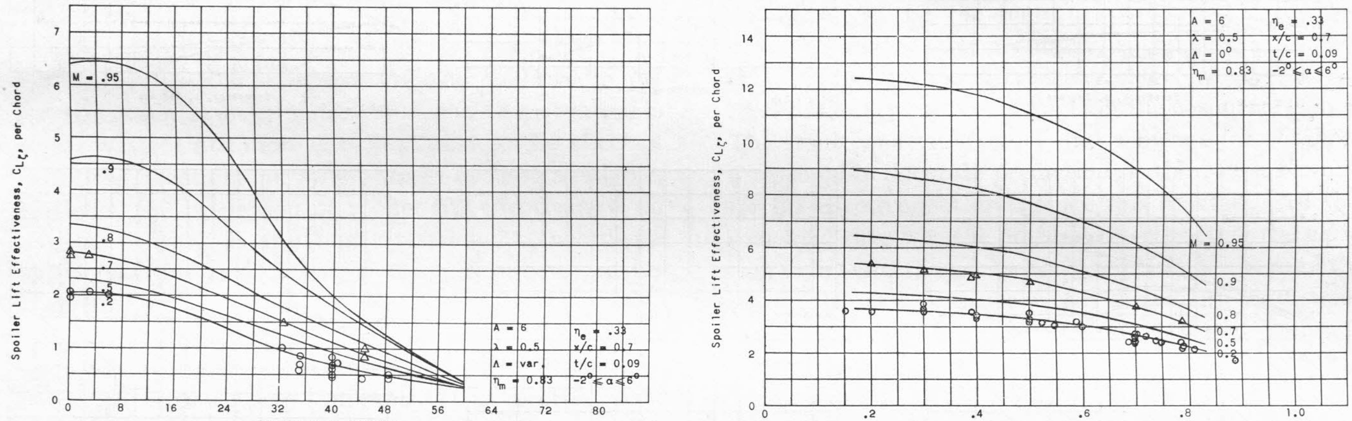
Providing this technique worked and well-defined basic values of $C_{L\zeta}$ were obtained throughout the Mach Number range investigated, the procedure could then be reversed for prediction purposes. That is, the basic value of $C_{L\zeta}$ at a given Mach Number could be taken as a starting point and modified, using the correction factors, to fit any other combination of parameter values, within the limits specified, for which a prediction of $C_{L\zeta}$ might be desired. The expression that would apply for prediction purposes is shown in Fig. 2.

The method was checked and proved feasible by preparation of graphs of the type illustrated in Fig. 3, showing prediction curves for Mach Numbers of 0.2, 0.5, 0.7, 0.8, 0.9, and 0.95 and reduced data points for Mach Numbers of 0.2 and 0.7. On each graph the data points shown were obtained by modifying data from the fairly abundant but uncorrelated supply that exists for three-dimensional wing-spoiler configurations. These data on Fig. 3 were modified to correspond to the basic value of all the parameters except the one used as the abscissa variable. The initial correction factors required for this operation were based on the best preliminary estimates that could be made of the influence on $C_{L\zeta}$ of changes in each parameter. These initial estimates were obtained primarily from two-dimensional experimental data for the section parameters and for the rest of the parameters primarily from the wing theory for symmetrically deflected controls in NACA TR 1071 by DeYoung. It was realized from the outset that the initial estimates of the correction factors based on these sources might not be completely satisfactory. By applying them to the three-dimensional data, however, in the manner just described and comparing the



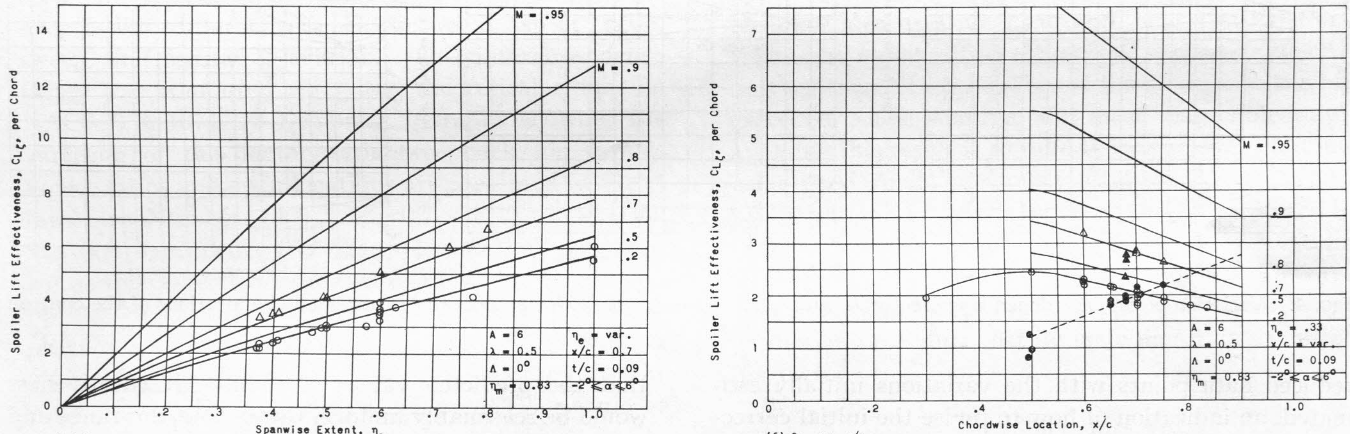
(a) C_{L_ζ} vs. A

(b) C_{L_ζ} vs. λ



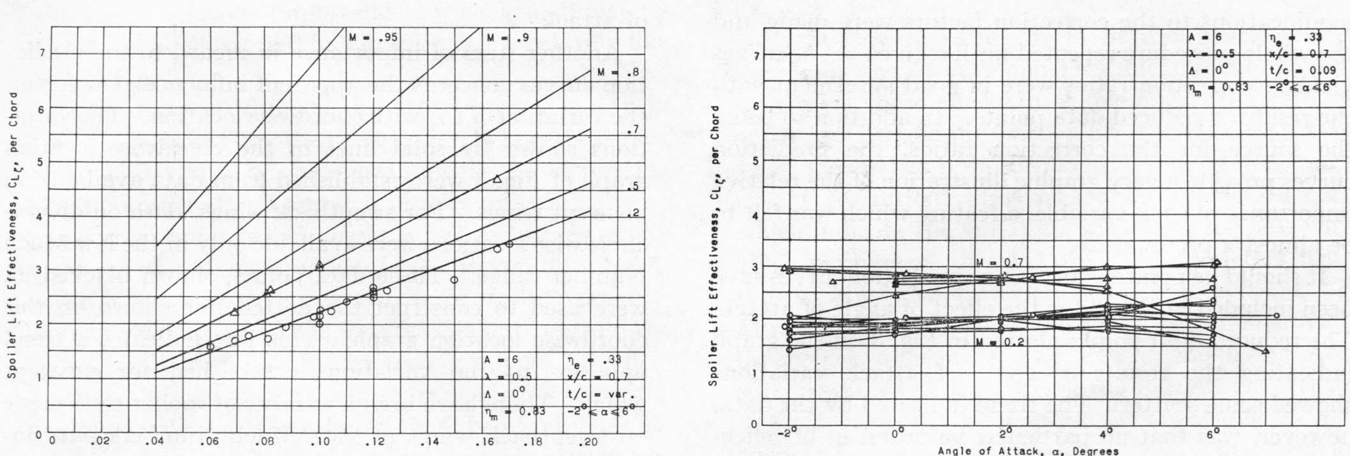
(c) C_{L_ζ} vs. Λ

(d) C_{L_ζ} vs. η_m



(e) C_{L_ζ} vs. η_e

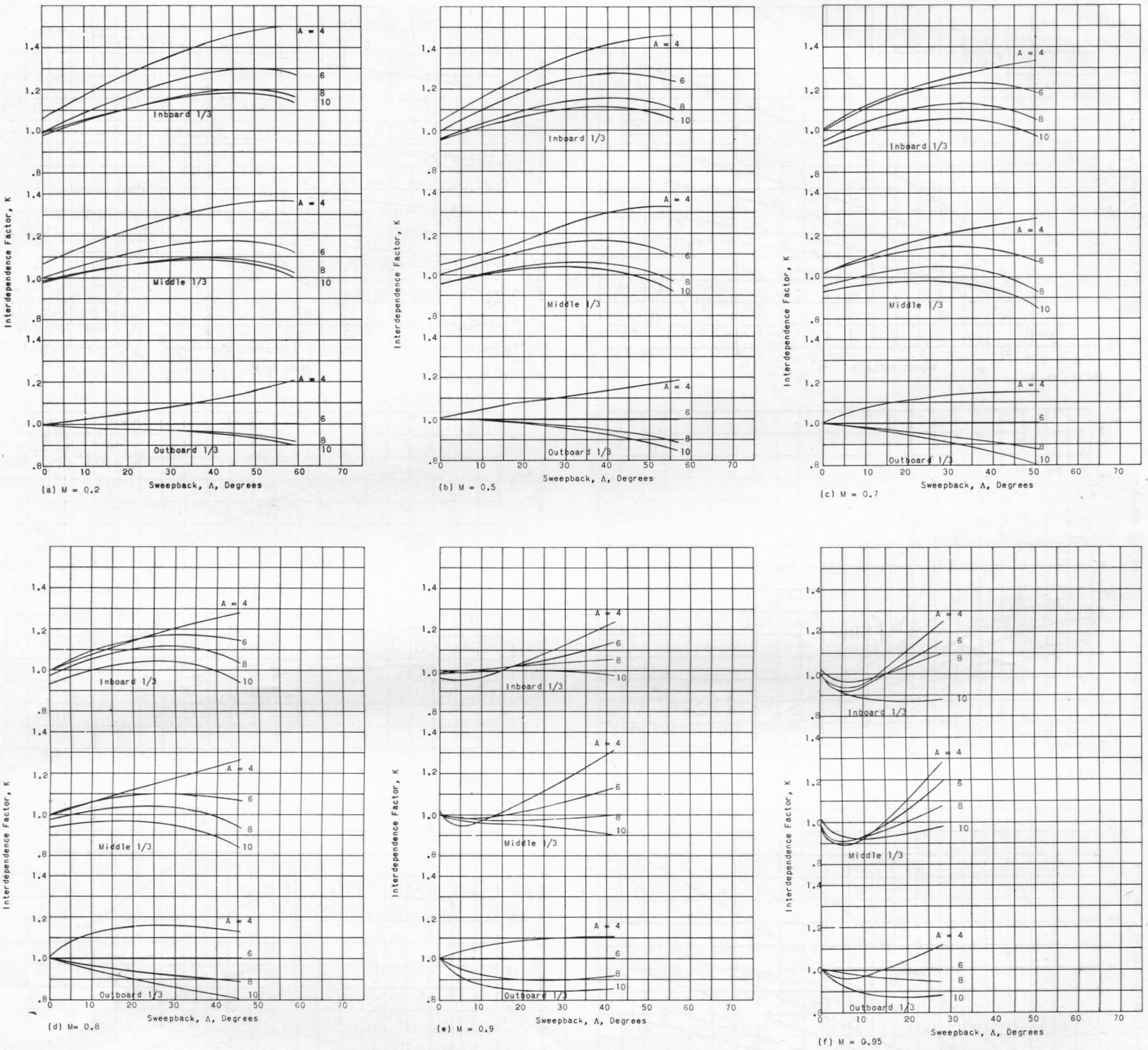
(f) C_{L_ζ} vs. x/c



(g) C_{L_ζ} vs. t/c

(h) C_{L_ζ} vs. α

FIG. 3. Variation of upper-surface spoiler lift effectiveness with the aerodynamic and geometric parameters investigated.



(a) M = 0.2

(b) M = 0.5

(c) M = 0.7

(d) M = 0.8

(e) M = 0.9

(f) M = 0.95

FIG. 4. Variation of the interdependence factor K with angle of sweep for various aspect ratios and spanwise locations of the control.

reduced data points with the variations initially estimated, an indication of how to revise the initial correction factors was obtained. Then, wherever necessary, modifications to the correction factors were made and the whole procedure repeated until a given set of curves yielding correction ratios were in good agreement with the resulting reduced data points. In addition to being the source for the correction ratios, the prediction curves provide a very graphic illustration of the relative importance of each variable, a feature which was felt to be almost a prerequisite.

It should be pointed out that no prediction curves have been included in Fig. 3 for the effect of angle of attack. The reduced data points plotted in Fig. 3 on the graph indicating the results of angle of attack variations showed some scatter. The trend indicated by the data, however, was that no particular variation in lift effectiveness with changes in angle of attack existed in the range from $-2°$ to $6°$. Consequently, it was assumed that the predicted values of spoiler lift effectiveness would be reasonably uniform throughout this range and that no correction ratios would be necessary for angle of attack.

Another item of importance in regard to the prediction curves concerns the apparent influence of sweep on the variation of $C_{L\xi}$ with chordwise location. The variations shown by solid lines in the chordwise location graph of Fig. 3 were established from data available on unswept wings. For sweptback wings, data on diverse chordwise locations were available only in the low Mach Number range. These data points, shown blacked in, were used to construct the dotted line shown on this chordwise location graph. This line indicates a trend opposite to the variations established for unswept wings. There have been a number of spoiler tests made on sweptback wings at high Mach Numbers but, unfortunately, all the spoilers in these tests were located very close to the 0.7 c position. Thus no estimation of

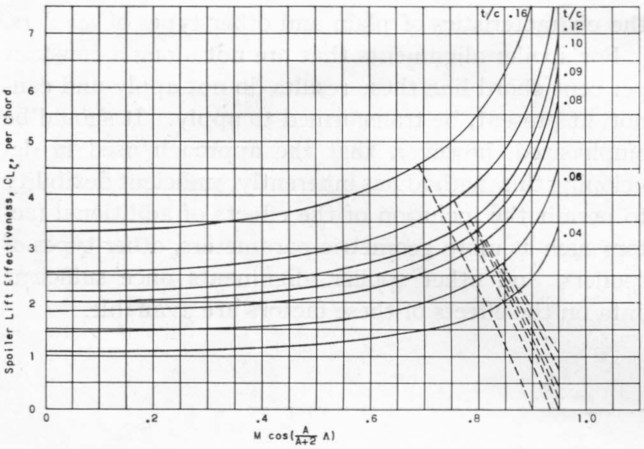


FIG. 5. Variation of spoiler lift effectiveness with a lift-divergence parameter $M \cos [A/(A + 2)]\Lambda$ for various thickness ratios.

the variations with chordwise location could be made. An experimental investigation to clarify this situation is under way. Until more data pertinent to the effect of chordwise locations on swept wings become available, however, the prediction of spoiler lift effectiveness on sweptback wings is apparently restricted to chordwise locations of 0.7 c, at least for Mach Numbers greater than 0.2.

A further imperfection in the complete independence hoped for between parameter effects was noted. In order to satisfactorily minimize the scatter that occurred in the reduced experimental data, a correction factor was needed to account for what proved to be an irrepressible interdependence between aspect ratio, sweep, and spanwise location. This interdependence factor was computed using the theoretical results in NACA TR 1071 by DeYoung. Graphs showing the variation of this factor with sweepback for various aspect ratios and span locations are presented in Fig. 4 for Mach Numbers of 0.2, 0.5, 0.7, 0.8, 0.9, and 0.95. The interdependence factor is applied in the same manner as the correction ratios as shown in the formula on Fig. 2. It should be emphasized that although complete independence between parameter effects was not achieved, this did not impair the accuracy of the method nor the celerity with which predictions could be made. The interdependence affects only the degree to which the relative importance of each parameter's effects can be illustrated in a graphical presentation like that of Fig. 3.

The variations of $C_{L\zeta}$ with Mach Number shown in Fig. 3 are based on the well-known Prandtl-Glauert rule. This is a very convenient means for estimating Mach Number effects and it is usually quite reliable up to a certain point, which might be set as low, generally speaking, as a Mach Number of 0.7. Beyond this point, however, discrepancies begin to show up between predicted values based on the Prandtl-Glauert rule and the experimental results. In the case of spoiler lift effectiveness, the experimental values tended to fall below the predicted values. It was found that the Mach Number at which theory and experiment began to diverge in this case was primarily a function of thickness ratio, aspect ratio, and sweepback. Consequently, an investigation was undertaken to ascertain the manner in which these parameters affected this divergence Mach Number. Two-dimensional experimental data on spoilers were examined for the effects of thickness ratio and the point at which lift effectiveness started to drop off was noted. It was observed incidentally, that the variation of lift-divergence Mach Number with thickness ratio obtained in this manner closely paralleled the critical Mach Number variation with thickness for flapped airfoils. To account for the effect of sweepback, a straight cosine correction was tried but did not work so satisfactorily as might be expected. It was felt that the tip and root influences, which reduce the beneficial influence of sweep in delaying the onset of adverse compressibility effects, might be the factors invalidating the cosine rule. Consequently, a simple aspect ratio correction often used in predicting lift-curve slope, $(A/A + 2)$, was used to modify the sweep angle in the cosine correction. The result was satisfactory and a means for obtaining a reasonably accurate prediction of the Mach Number for lift-effectiveness divergence was assured. All that remained then was the problem of estimating the variation in lift-effectiveness with Mach Number beyond this point. In view of the fact that mixed sub- and supersonic flow conditions prevail in this high subsonic Mach Number range, these variations were estimated by a procedure involving primarily an inspection of experimental data. The results are shown in Fig. 5. Their use is not mandatory in the prediction procedure but is recommended as a means of obtaining a rational or at least more conservative estimate of spoiler lift effectiveness once the Mach Number of lift divergence has been exceeded. The simplest and most reasonable way of applying this result is to take the value of $C_{L\zeta}$ obtained using the formula previously established and reduce it by the ratio of $C_{L\zeta}$ given by the appropriate dotted line in Fig. 5 to $C_{L\zeta}$ given by the appropriate solid line. This operation amounts to another simple ratio correction which can be readily incorporated into the overall prediction procedure just by including it as a multiplying factor.

CONCLUSION

By considering the effects of each parameter individually and by developing a semiempirical method of combining these effects, a simple straightforward procedure for predicting spoiler lift effectiveness at subsonic speeds has been developed. The method makes use of correction ratios picked off prediction curves which indicate the variation of lift effectiveness with a given parameter. A total of eight parameters in addition to Mach Number were taken into account. For Mach Numbers beyond the point of lift-effectiveness divergence, a means is suggested for modifying the results predicted on the basis of the Prandtl-Glauert rule.

As developed, the method is applicable to plain spoilers located along a constant per cent chord line. With no alterations the method probably is applicable also to step spoilers of 0.10 semispan or less having their mid-spans distributed along a constant per cent chord line. The lift effectiveness of other types of spoilers such as slot-lip ailerons, flap-type spoilers, etc., could possibly be predicted by modifications to the results presented. For instance, a simple ratio of their section lift effectiveness to the plain-spoiler section lift effectiveness might be adequate. It is possible, however, that a better means of modification could be developed by further investigation of the overall differences between the characteristics of plain and other types of spoilers.

For spoiler alignments that are not along a constant per cent chord line these results do not apply and cannot, at present, be transformed to apply. It should be emphasized, however, that the approach used in developing this method has inherently, sufficient flexibility to permit the inclusion of the effects of additional factors such as more geometric parameters, other types of spoilers, and other spoiler alignments once sufficient data on the effects of these factors are available.