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RESEARCH MEMORANDUM

AN EMPIRICAL METHOD FOR THE PREDICTION OF
AIRPLANE DRAG DIVERGENCE MACH NUMBER

R. P. Johnson

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SUMMARY

The problem of prediction of airplane drag divergence Mach number was investigated and an empirically determined expression was obtained that is applicable to clean airplane configurations whose wing shapes lie within the general limits of 0° to 47° sweepback, aspect ratios of 2 to 10, and thickness ratios of 4 per cent to 12 per cent. Subsonic-type airfoil sections are implied, and the fuselages are of the conventional convex shape. Comparison of the predicted values with experimental and aircraft manufacturers' performance estimate values indicates that the accuracy of the method is within ± 2 per cent. Such special problems as the prediction of the effect on drag divergence Mach number of thickened wing root air intake configurations and large interference effects of certain nacelle locations are beyond the scope of this paper.

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SYMBOLS

S	= gross wing area
b	= wing span
d	= maximum body diameter
AR	= aspect ratio, b^2/S
Λ	= sweepback angle of wing quarter-chord line
t/c	= thickness ratio of wing airfoil section parallel to center-line (constant value spanwise)
b/d	= wing span to body diameter ratio
λ	= wing taper ratio, tip chord to root chord
c_{ℓ_i}	= design lift coefficient of airfoil section parallel to center-line, index of camber
C_L	= lift coefficient based on gross wing area
C_D	= drag coefficient based on gross wing area
M	= Mach number
M_{DD}	= drag divergence Mach number, M at which $\left. \frac{d C_D}{d M} \right _{C_L = \text{const.}} = 0.1$
$\Delta M_{DD} \{AR, \Lambda\}$	= M_{DD} increment providing primary effect of AR and Λ
$\Delta M_{DD} \{t/c, (\Lambda)\}$	= M_{DD} increment providing primary effect of t/c
$\Delta M_{DD} \{C_L, (t/c, \Lambda)\}$	= M_{DD} increment providing primary effect of C_L
$\Delta M_{DD} \{c_{\ell_i}\}$	= M_{DD} increment providing effect of c_{ℓ_i}
$K \{\Lambda\}$	= sweepback angle correction factor on t/c term in $\Delta M_{DD} \{C_L, (t/c, \Lambda)\}$

INTRODUCTION

Generalized performance studies of aircraft necessitate a knowledge of drag divergence Mach number for any configuration considered. This knowledge is important to both the high speed cruise of subsonic aircraft and to the subsonic cruise of supersonic aircraft. Given a drag divergence Mach number, one needs to know what configurations are permissible; or, given an airplane configuration, what is its drag divergence Mach number?

This paper presents a method of estimating the drag divergence Mach number for a variety of wing-body combinations.

DEFINITION OF DRAG DIVERGENCE MACH NUMBER

The drag divergence Mach number is defined as the Mach number at which $\left. \frac{d C_D}{d M} \right|_{C_L = \text{const.}} = 0.1$. This is illustrated in the accompanying sketch.

SCOPE and LIMITATIONS

The data used in the preparation of this paper were obtained from wind-tunnel model tests, from rocket-propelled model tests, from full-scale airplane flight tests, and from aircraft manufacturers' performance estimates for airplanes.

The ranges of the primary wing geometry parameters, aspect ratio, sweep-back angle, and thickness ratio, for which this method is applicable are given by the dashed-line polygons enclosing the points plotted on Figs. 1A, 1B, and 1C. Each point represents a configuration that was included in the data analyzed. It can be seen that the configuration geometries indicated by these plots quite completely include the spectrum of parameter combinations of current interest to the designer. In addition to the wing geometry parameters given above, design lift coefficient of the airfoil section, c_{l_1} , and airplane lift coefficient, C_{L_1} , were included in the analysis of the data and the resulting empirical M_{DD} prediction method.

Airplane configuration parameters not accounted for explicitly in the preceding section are subject to the following limitations:

1. Wing taper ratio, $.2 \leq \lambda \leq .6$
2. Subsonic airfoil sections are similar to the NACA 64A- or 65A-series
3. Wing thickness ratio is constant spanwise
4. Wing span to body maximum diameter ratio, $b/d \geq 4$
5. Body shape at the wing juncture is convex or cylindrical, and wing is positioned near the maximum body diameter.

In addition to those restrictions on the above mentioned parameters it should be noted that the method developed in this paper is applicable to clean airplane configurations of the wing-body-tail type. Additional or unusual components whose effects are large enough to govern the initial drag rise of the configuration will invalidate the use of these results. Examples of these components are heavily thickened inboard wing panels to provide engine air intakes in the wing leading edge at the wing-fuselage juncture and an aerodynamically unfavorable positioning of engine nacelles pylon-mounted or at the wing-fuselage juncture.

RESULTS

The empirical equations given below along with the data supplied by Figs. 2 and 3 permit the calculation of drag divergence Mach number for configurations within the limits specified above.

$$M_{DD} = .828 + \Delta M_{DD} \{R, \lambda\} + \Delta M_{DD} \{t/c, (\lambda)\} + \Delta M_{DD} \{C_L, (t/c, \lambda)\} + \Delta M_{DD} \{c_{\ell_1}\}, \quad (1)$$

where

$$\Delta M_{DD} \{R, \lambda\} \text{ is given by Fig. 2,} \quad (2)$$

$$\Delta M_{DD} \{t/c, (\lambda)\} = 1.375 \text{ } (.08 - t/c) \cos \lambda, \quad (3)$$

$$\Delta M_{DD} \{C_L, (t/c, \lambda)\} = -C_L \left[.05 + K \{ \lambda \} (t/c - .04) \right], \quad (4)$$

with $K \{ \lambda \}$, given by Fig. 3,

and

$$\Delta M_{DD} \{c_{\ell_1}\} = -.05 c_{\ell_1}. \quad (5)$$

This may be expanded to :

$$M_{DD} = .828 + \Delta M_{DD} \{R, \Lambda\} + 1.375 (.08 - t/c) \cos \Lambda - C_L \left[.05 + K \{ \Lambda \} (t/c - .04) \right] - .05 c_{\ell_1} \quad (6)$$

The basic value, .828, was arrived at from a study of section data.

The value, $M_{DD} = .828$, corresponds to an infinite aspect ratio, unswept wing with eight per cent thick symmetric airfoil sections at zero lift.

$\Delta M_{DD} \{R, \Lambda\}$ is given in the form of empirically derived curves (Fig. 2) as a function of sweepback angle for constant values of aspect ratio. The complex nature of the variation of the curves prevents the writing of a simple analytic expression for this increment.

$\Delta M_{DD} \{t/c, \Lambda\}$ can be written analytically. This increment primarily represents the effect of thickness ratio, but this effect is somewhat dependent on the sweepback angle.

$\Delta M_{DD} \{C_L, (t/c, \Lambda)\}$, with the use of the sweepback factor $K \{ \Lambda \}$ given by Fig. 3, can also be written in analytic form. This increment gives the effect of variation of lift coefficient which is in turn dependent on thickness ratio and sweepback angle.

$\Delta M_{DD} \{c_{\ell_1}\}$ provides a first approximation to the effect of wing camber and is expressed in terms of the design lift coefficient of the wing airfoil section.

To illustrate the calculation procedure, M_{DD} values will be determined by this method for a wing-body configuration that was the subject of a transonic wind tunnel investigation, Ref. 27. The pertinent physical characteristics of this model are:

$R = 3.5$, $\Lambda = 35^\circ$, NACA 65A204 Airfoil Section (approx.),

$c_{\ell_1} = .2$,

and $t/c = .04$.

The determination of the several increments of M_{DD} is given below:

$$\Delta M_{DD} \{R, \Lambda\} = +.100 \text{ as given by Fig. 2,}$$

$$\begin{aligned} \Delta M_{DD} \{t/c, \Lambda\} &= 1.375 (.08 - t/c) \cos \Lambda \\ &= 1.375 (.08 - .04) (.819) \\ &= +.045, \end{aligned}$$

$$\begin{aligned} \Delta M_{DD} \{C_L, t/c, \Lambda\} &= -C_L [.05 + K \{\Lambda\} (t/c - .04)] \\ &= -C_L [.05 + 1.11 (.04 - .04)] \\ &= -.05 C_L \\ &= 0, -.015, \text{ and } -.030 \text{ for } C_L = 0, .3, \text{ and } \\ &\quad .6 \text{ respectively,} \end{aligned}$$

and

$$\begin{aligned} \Delta M_{DD} \{c_{\ell_1}\} &= -.05 c_{\ell_1} \\ &= .05 \times .2 \\ &= -.01. \end{aligned}$$

The M_{DD} estimates are obtained by adding these increments to the basic value, as follows:

	$C_L = 0$	$C_L = .3$	$C_L = .6$
Basic M_{DD}	.828	.828	.828
$\Delta M_{DD} \{R, \Lambda\}$	.100	.100	.100
$\Delta M_{DD} \{t/c, \Lambda\}$	.045	.045	.045
$\Delta M_{DD} \{C_L, t/c, \Lambda\}$	- .000	- .015	- .030
$\Delta M_{DD} \{c_{\ell_1}\}$	- .010	- .010	- .010
$M_{DD} \Bigg\} \text{Est.}$	<u>.963</u>	<u>.948</u>	<u>.933</u>
$M_{DD} \Bigg\} \text{Data}$	.955	.945	.930
Per cent difference	.83	.31	.32

For this sample calculation the per cent differences between the estimated M_{DD} 's and the experimental M_{DD} 's are well within the experimental error.

The accuracy of the results of this method is shown by Figs. 4 through 6 in which the predicted values are plotted versus the experimental or performance estimate values. In Fig. 4 where the sweepback angles are near 0° and in Fig. 5 where they are near 35° , comparisons between predicted and experimental values were made at lift coefficients of 0, .3, and .6. For the cases with approximately 45° of sweepback as shown in Fig. 6, the comparisons were made at lift coefficients of 0, .3, and .5. The numbers beside the points on Figs. 4, 5, and 6 correspond to the numbers on Figs. 1A, 1B, and 1C, respectively, where the wing plan form geometries are given approximately and the type of data is noted. Table I describes these geometries more completely and lists the references from which the data were taken for each point number.

DISCUSSION OF METHODS USED

The various increments of drag divergence Mach number which are added to the basic number of Equation (1) were gradually evolved from efforts to investigate the effects of the wing geometric parameters separately. The technique employed in this analysis for developing the drag divergence Mach number increments can be described by the detailed description of the development of M_{DD} increments at sweepback angles of about 45° . This description also serves to partially substantiate the results for these high angles of sweepback. For these sweepback angles the effects of aspect ratio and thickness ratio were different from those that might be anticipated from experience with zero or low sweep configurations.

A number of the references show the results of tests of wing-body combinations with wings having 45° of sweepback, and NACA 65A006 airfoil sections. The M_{DD} data from these tests permitted a study of the effect of aspect ratio. Having established an aspect ratio variation, the several tests of configurations with 45° of sweepback and different thickness ratios were examined to develop a thickness ratio effect. Similarly the variation of M_{DD} with lift coefficient was inspected for each configuration to establish the relationship between these parameters. Finally, the data from the configurations with airfoil section camber were compared with those from cases with symmetric sections and the effect was noted.

A comparison was made between these four tentative expressions for M_{DD} at sweepback angles of about 45° and the corresponding relations for unswept wings. From this comparison, simple factors were established for estimating the expressions for M_{DD} at sweepback angles between 0° and 45° . In the case of the $\Delta M_{DD} \{R, \Lambda\}$ increment, the effects of R on M_{DD} were opposite in sign at 0° to that at 45° , so that

a graphical relation as shown by Fig. 2 appeared to be the desirable choice. The $\Delta M_{DD} \{t/c, (\Lambda)\}$ expressions could be made proportional to $\cos \Lambda$ [see Equation(3)], and the $\Delta M_{DD} \{C_L, (t/c, \Lambda)\}$ expressions could be shown to be a function of sweep-back angle [see Equation (4) and Fig. (3)].

Curves of drag coefficient versus Mach number for constant lift coefficient were prepared by cross-plotting each available set of lift-drag polars at constant Mach numbers. This was done for test results of each wing alone, wing-body combination, and complete airplane, and for airplane performance estimates made by the manufacturer in cases when flight test data were not available.

As implied by the definition of airplane drag divergence Mach number, the data recorded were the Mach numbers at which curves of drag coefficient versus Mach number for constant values of lift coefficient have a slope of 0.1.

The M_{DD} values taken from the plots of C_D versus M were plotted against lift coefficient. This made it possible to avoid the use of occasional doubtful data points and to study the general variation with lift coefficient. For each set of values of M_{DD} versus C_L , a notation was made of parameters such as aspect ratio, sweepback angle, thickness ratio, camber, taper ratio, airfoil section and wing span to body diameter ratio.

DISCUSSION OF DATA USED

The data collected for reduction and analysis were obtained from wind-tunnel model tests over a wide range of configuration geometries, from rocket-propelled model tests, from full-scale airplane flight tests, and from aircraft manufacturers' performance estimates for airplanes. High subsonic speed wind-tunnel tests, Refs. 1 through 20, covered the most complete range of wing geometries but the value of many of these tests was limited because of tunnel choking. The more reliable transonic wind-tunnel tests, Refs. 25 through 29, were much more limited in number. Rocket-propelled model tests, Refs. 30 through 37, also were more reliable than the subsonic wind-tunnel tests, but they were restricted to measurements of drag at zero lift and a limited number of wing geometries. Only two drop model tests, Refs. 38 and 39, were employed. The full-scale flight tests, Refs. 40 through 50, were valuable and were weighted heavily in the data correlation, but the configuration range was quite limited. All these test techniques had certain inherent limitations and susceptibility to error. Perhaps the most difficult to evaluate were the airplane performance estimates made by the various aircraft manufacturers, Refs. 51 through 66. There are appreciable differences between the drag divergence Mach number data of some of the airplane performance estimates and the results of this study. These estimates were included in this study because the effort and experience that led to them merits serious attention. However it was difficult to assess how much previous flight test experience, how much reliable wind-tunnel data, and how much of individually developed methods for M_{DD} prediction went into each estimate.

In general, the data employed in this correlation were quite complete and included the latest transonic wind-tunnel tests available at the time the analysis was made. However, many of the data considered have been available for some time but apparent contradictions could not be explained satisfactorily. As an example of this, consider Fig. 7. The final curve of M_{DD} versus C_L for this one configuration was prepared from three high subsonic speed wind-tunnel tests, Ref. 11, 13, and 14, one transonic wind-tunnel test, Ref. 25, one rocket-propelled model test, Ref. 35, and two drop model tests, Ref. 38 and 39. Considered separately, the results of the 8-foot high speed and the 7 by 10-foot high speed tunnel tests would have led to serious underestimation of M_{DD} for low values of C_L . The transonic tunnel-test results were the most optimistic over a range of lift coefficients, but when the drop test and rocket-propelled model test results at zero lift and the 16-foot high speed wind-tunnel test results at moderate values of lift coefficient were considered, a slightly higher level than that of the transonic tunnel results, was obtained. Thus, the resultant curve drawn on Fig. 7 was arrived at by a consideration of all available data and was used as a contribution to the overall correlation, whereas the direct use of the high subsonic speed wind-tunnel data of Ref. 13 and 14 directly would have distorted the results unnecessarily.

Additional data considered, but not employed because of disqualifying conditions of the tests, were from the early series of cruciform-wing-body drop model tests. Each pair of wings provided different data for nominally the same configuration due to interference effects that are not likely to be found in configurations to which the results of this paper would be applied.

Some of the airplane flight test data and wind-tunnel test data for airplane configurations show incompatibility with the overall results of this study. Discrepancies in these special cases can be accounted for qualitatively by the apparent differences in configuration from the clean configuration prescribed here. For example, the value of M_{DD} predicted by the method of this paper is high for one straight-wing configuration, unless an allowance of $\Delta t/c = .03$ is made for the thickened inboard wing panel where the engine air intakes are located. Refer to Fig. 4, points 20 and 20a.

The data for points 21 of Fig. 4 have been calculated with a $\Delta t/c = .03$ allowance also. The experimental data are from a wind-tunnel test of an airplane configuration that hints of considerable interference drag. This same correction was applied to the calculation for point 22. In this case the experimental data are from a flight test of another airplane with engine air intake similar to those on the configuration corresponding to points 20.

In the case of a swept-wing airplane with engine air intakes in the inboard wing panel, the predicted M_{DD} results are higher than those given in the manufacturers' performance estimate, even making an allowance of $\Delta t/c = .03$ for increased wing root thickness ratio. Refer to Fig. 5, points 45 and 45a. Thus the primary cause of the initial drag rise, the fuselage and the forward wing juncture including air intakes, was unchanged although the wing geometry was nominally changed by increased sweepback angle. As discussed in the section on "Scope and Limitations" (pp. 2 and 3) the parameters aspect ratio, sweepback angle, thickness ratio, and airfoil camber were considered to be of primary importance, whereas the parameters wing taper ratio, wing span to body diameter ratio, and the family of airfoil

section were taken to be of secondary importance. There were some indications of the effects of wing taper ratio, Refs. 28, 29, and 35. However, they were relatively small and well within the scatter of the data. Consideration of airfoil section data suggested that there was considerable variation in the drag rise characteristics for different families of airfoil sections, e.g., the NACA 64A0XX and the NACA 00XX-64 series (see Refs. 21 and 22). The increase in M_{DD} indicated by airfoil section tests for the latter series over the former series was not borne out in the three-dimensional case for which the flight test results of an airplane employing the 00XX-64 airfoil was checked against the overall correlation which is based primarily on configurations employing the NACA 64A- and 65A-series sections. Of course, the use of an exceptionally blunt airfoil section, of Ref. 23, or a double wedge airfoil section, of Ref. 24, would reduce the drag divergence Mach number; however, these cases are beyond the scope of the present effort. The data for configurations having wings which are tapered-in-thickness ratio was limited in amount and was not used in determining the correlations. The effect of tapered-in-thickness ratio will be treated in a subsequent supplement on drag divergence Mach number prediction methods. The parameter, wing span to maximum body diameter ratio has been investigated only incidentally, and a brief survey of the collected data did not reveal any significant, separable effects attributable to this parameter. The transonic and supersonic area rule concepts of contouring the fuselage will be treated in a subsequent supplementary paper. It should be noted that the preliminary data on this subject indicated significant increase in M_{DD} for some configurations as a result of this contouring.

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39. Matthews, C. W., and Thompson, J. R., "Comparison of the Transonic Drag Characteristics of Two Wing-Body Combinations Differing Only in the Location of the 45° Sweptback Wing," NACA RML7101 (Confidential)
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41. McFadden, N. M., Rathert, G. A., Jr., and Bray, R. S., "The Effectiveness of Wing Vortex Generators in Improving the Maneuvering Characteristics of a Swept-Wing Airplane at Transonic Speeds," NACA RMA51J18, February 28, 1952 (Confidential)
42. One Air Force report which provided flight test data for one airplane configuration.
- 43-50. Eight performance reports which provided flight test data from five aircraft manufacturers.
- 51-66. Sixteen performance reports which provided estimated data for sixteen airplanes by ten aircraft manufacturers.

TABLE I

PT. NO.	R	A	t/c	C _L	REF.	PT. NO.	R	A	t/c	C _L	REF.	PT. NO.	R	A	t/c	C _L	REF.
1	4.00	0	.06	0,.3,.6	1	31	4.78	35.2	.096	0,.3,.6	56	56	4.00	45	.06	0,.3,.5	*
2	4.00	3.6	.06	0,.3,.6	2	32	4.78	35.2	.096	0	47	57	3.55	45	.09	0	36
3	2.50	0	.09	0	30	33	4.78	35.2	.096	.15	41	58	6.00	45	.09	0	33
4	3.00	0	.09	0	30	34	4.00	32.6	.06	0,.3,.6	2	59	3.71	45	.06	0	35
5	4.50	0	.09	0	30	35	4.00	35.0	.06	0,.3,.6	8	60	4.10	45	.064	0	38
6	3.70	0	.12	0	30	36	3.50	35.0	.04	0,.3,.6	27	61	3.50	47	.04	0,.3,.5	27
7	3.70	0	.06	0	30	37	9.46	35.0	.12	.3,.6	48	62	3.50	47	.06	0,.3,.5	26
8	2.00	8.5	.10	0,.3,.6	3	38	6.04	35.0	.103	0,.3,.6	9	63	3.50	47	.09	0,.3,.5	26
9	6.00	1.9	.08	0,.3,.6	40	39	9.00	35.0	.09	0,.3,.6	4	64	5.00	45	.074	.3,.5	15
10	3.50	10.8	.04	0,.3,.6	27	40	2.67	34.0	.075	0	32	65	3.00	45	.077	.3,.5	16
11	9.98	11.3	.14	0,.3,.6	4	41	4.50	31.4	.089	0,.3,.6	57	66	3.50	47	.055	0,.3,.5	64
12	9.23	21.3	.135	0,.3,.6	4	42	2.94	35.0	.096	0,.3	58	67	6.00	45	.09	.5	17
13	6.67	5.5	.13	0,.3,.6	51	43	8.55	35.0	.096	0,.3,.6	59	68	3.00	45	.085	0	50
14	6.08	4.5	.10	0,.3,.6	52	44	6.95	36.0	.10	0,.3,.6	60	69	4.00	45	.06	0,.3,.5	18
15	5.10	3.2	.12	0,.3,.6	43	45	4.00	35.0	.10	0,.3	61	70	3.00	45	.077	0,.3,.5	19
16	6.75	0	.145	0,.3,.6	53	46	5.14	35.0	.12	0,.3,.6	10	71	3.00	45	.077	0,.3,.5	20
17	4.50	7.6	.10	0,.3,.6	5	47	10.07	35.0	.12	0,.3,.6	10	72	3.00	45	.085	0,.3,.5	65
18	2.50	15.0	.09	0,.3,.6	4	48	5.14	35.0	.12	0,.3,.6	10	73	3.43	40	.081	0,.3,.5	66
19	3.10	11.2	.03	.3	6	49	10.07	35.0	.12	0,.3,.6	10	74	8.00	45	.12	0	34
20	4.93	0	.10	0,.3,.6	54	50	4.49	35.0	.081	0	62	75	1.50	45	.064	0	31
21	4.46	0.9	.088	0,.3,.6	55	51	4.49	35.0	.081	0	49	76	2.67	45	.064	0	31
22	5.92	4.3	.12	0	44	52	8.02	35.0	.17	0,.3,.6	63	* 25, 11, 13, 14, 32, 35, 36					
23	4.17	4.1	.10	0,.3	45,46	53	6.00	35.0	.06	.3,.6	11						
24	3.04	16.0	.045	0	34	54	3.00	27.7	.12	0,.3	12						
25	1.00	0	.10	.3,.6	7	55	8.55	35.0	.096	.25,.45	42						
26	2.00	0	.10	0,.3,.6	7												
27	4.00	0	.10	.3,.6	7												
28	6.00	0	.10	.3,.6	7												
29	1.50	0	.09	0	31												
30	2.67	0	.09	0	31												

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Fig. 1A—Ranges and values of primary wing geometry parameters of test configurations (low sweepback)

Fig. 1B—Ranges and values of primary wing geometry parameters of test configurations (medium sweepback)

Fig. 1C— Ranges and values of primary wing geometry parameters of test configurations (high sweepback)

Fig. 2— Drag divergence Mach number increment due to sweepback angle and aspect ratio

Fig. 4A — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (low sweepback)

Fig. 4B — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (low sweepback)

Fig. 4C — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (low sweepback)

Fig. 5A — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (medium sweepback)

Fig. 5B — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (medium sweepback)

Fig. 5C — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (medium sweepback)

Fig. 6A — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (high sweepback)

Fig. 6B — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (high sweepback)

Fig. 6C — Comparison of calculated values with experimental, flight test and performance estimate values of drag divergence Mach number (high sweepback)

Fig. 7—Comparison between experimental data from various sources and resulting curve of M_{DD} versus C_L