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RESEARCH MEMORANDUM

RECENT RESULTS PERTAINING TO THE APPLICATION OF THE "AREA RULE"

By Richard T. Whitcomb

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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This paper is concerned primarily with the application of the "area rule" to the interpretation and improvement of the drag-rise characteristics of wing-body combinations at transonic and moderate supersonic speeds.

Consideration of the general physical nature of the flow at transonic speeds, together with comparisons of the flow fields and drag-rise characteristics for wing-body combinations and bodies of revolution has led to the conclusion that near the speed of sound the drag rise for a thin low-aspect-ratio wing—body combination is primarily dependent on the axial distribution of cross-sectional area normal to the airstream (ref. 1). (The drag rise, sometimes referred to as pressure drag, is the difference between the drag level near the speed of sound and the drag level at subsonic speeds where the drag is due primarily to skin friction.) In order to illustrate the concept, figure 1 shows a wing-body combination and a body of revolution. A typical cross section normal to the airstream for the wing-body combination is shown at AA. The cross-sectional area of the wing is wrapped around the body of revolution so that the body has the same cross-sectional area at BB. All the other cross-sectional areas of the body of revolution are the same as those for the wing-body combination at the same axial stations. On the basis of the conclusion just stated, the drag rise for this body of revolution should be similar to that for the wing-body combination.

This relationship of the drag-rise increments for the wing-body combination and the comparable body of revolution is due primarily to the general similarities of the major portions of the extensive flow fields of the configurations. These similarities are illustrated in figures 2 and 3 which present schlieren photographs of the flow fields for unswept- and sweptback-wing—body combinations, together with those for equivalent bodies of revolution. The combinations have been rolled to three positions so that side, plan, and intermediate views are seen. Near the edges of the pictures, the observed shocks for the combinations in each view are generally similar to those for the equivalent bodies. These comparisons are indicative of the similarities of the extensive fields beyond the view of the schlieren. Near the configurations there are differences of the flow fields for the wing-body combinations and equivalent bodies of revolution. However, the major portion of the energy losses associated with the shocks is produced in the extensive regions at appreciable distance from the configuration. Therefore, from a drag standpoint, it may be assumed that these differences near the configuration are of secondary importance. The general similarities of the extensive flow fields at distances from the configuration may be attributed to several aerodynamic phenomena characteristic of flow near the speed of sound. First, the field of any given displacement is concentrated in a plane nearly normal to the airstream. Because of this fact, the streamwise locations of the effects of the displacements of the wing are essentially the same as those for the corresponding effects produced by the comparable body of revolution. Secondly, at these considerable lateral distances from the configuration, the field is primarily dependent on the general displacement of the configuration rather than on the details of the shape. The generally close similarities of the effective fields for the wing-body combination and the comparable body of revolution in the regions producing the main portion of the shock losses suggests that the energy losses associated with the shocks for the two configurations should be similar. Since the drag rise for thin low-aspect-ratio wings is due primarily to shock losses, the drag rise for the combination should be approximately the same as that for the equivalent body of revolution.

In figure 4, the measured drag-rise increments for various swept-, delta-, and unswept-wing—body combinations and complete airplanes at a Mach number of 1.03 are compared with the increments for equivalent bodies of revolution. The aspect ratios of the wings are 4 or less and the thickness ratios are 7 percent or less. Except for one configuration, there is a general qualitative agreement between these drag-rise increments. Deviations from exact agreement are due to second-order effects, such as differences of the flow fields as shown in figures 2 and 3. The single case of marked disagreement is for a swept-wing airplane configuration. This disagreement cannot be fully explained at present. As would be expected, the correlation between the drag-rise increments of the wing-body combinations and the equivalent body of revolution generally becomes less close as the Mach number is increased beyond 1.0. The severity of this divergence varies markedly depending on the configuration.

It would be expected on the basis of this concept that, near the speed of sound, the minimum drag rise would be obtained by designing a wing-body combination with an area distribution similar to that for a smooth body of revolution with the highest possible fineness ratio. The fineness ratio that should be used is probably considerably less than that required for minimum total drag because of such problems as airplane stability and structural weight. One method of obtaining this favorable area distribution is to reshape the body. A number of experiments have been made to determine the effectiveness of such reshaping. Representative results, obtained in the Langley 8-foot transonic tunnel, are presented in figure 5.

On the left-hand side of this figure are shown the effects of such a body modification on the zero-lift drag-rise characteristics of a 6-percent-thick, aspect-ratio-4, 45° swept-wing—body combination. The solid line shows the variation of drag for the wing in combination with a body of revolution of fineness ratio of 11. The wing is placed on the body in such a manner that the leading edge of the wing is at the maximum diameter of the body. With this arrangement, the indentation used did not change the maximum cross-sectional area of the body. The dashed lines are the results obtained for the wing in combination with a body of revolution indented circularly to obtain the same area distribution as for the original body alone. For comparison, the results for the body alone are also shown. Indentation eliminated approximately 90 percent of the drag rise associated with the wing at Mach numbers from 1.00 to 1.05. When the Mach number is increased beyond 1.05, the drag rise for the indented wing-body combination approaches that for the original wing-body combination.

On the right-hand side of figure 5 are presented the effects of body indentation on the zero-lift drag-rise characteristics for a 4-percent-thick, 60° delta-wing—body combination. The solid curve shows the drag characteristics for the wing in combination with a body of revolution having a fineness ratio of 7.5. The dashed line indicates the drag variation after the body has been indented circularly to produce an area distribution for the combination the same as that for the original body alone. In this case the indentation reduced the maximum cross-sectional area of the body somewhat. It may be noted that again a significant reduction in the drag rise was obtained by such an indentation at transonic speeds. However, in this case, the drag rise for the indented wing-body combination is significantly greater than that for the body alone. This deviation from the result which might be expected on the basis of the area-distribution concept is probably due to the fact that the body required to obtain the smooth area distribution of the combination had a rather abrupt change in shape near the trailing edge of the wing. This shape probably led to severe local velocity gradients. Since the proper functioning of the body fields in offsetting the drag of the wing depends to a great extent on the velocity gradients being small, it might be expected that these severe gradients would lead to an incomplete reduction in drag. Also, near the speed of sound, a shock was present over this corner and may have caused some separation at this point, which would not be expected on the original body alone. It is probable that a further reduction in drag could have been obtained at transonic speeds by smoothing the contour of the body slightly. Similar reductions in drag near the speed of sound have been obtained by body indentation for other delta and unswept wings.

Results obtained with smooth-surfaced configurations have indicated a marked reduction in drag at subsonic speeds associated with the use of indentation with swept and delta wings. However, with fixed transition this difference is not present. The influence of surface conditions on the effects of indentation apparently decreases with increase in the Mach number to supersonic speeds. The effect of body indentation on the drag characteristics at lifting conditions is discussed in reference 2. Obviously, the volume of the indented wing-body combination is not as great as that for the original wing-body combination. However, increasing the size of the body to recover the volume lost in indentation would increase the drag for the indented combination by a small fraction of this reduction in drag obtained.

The question now might arise as to whether it would be possible to obtain drag reductions at transonic speeds by adding to an existing wing-body combination to obtain a more favorable area distribution. Recently, investigations have been made of such additions on a 60° delta-wing airplane. Results are presented in figure 6. First, the fuselage was extended approximately 8 percent to obtain a more favorable area distribution of the rearward portion of the airplane. This addition resulted in significant reductions in the drag rise. Further reduction was obtained by adding side fairings to the extended configuration to fill the dip in the area distribution as shown. The body lines with these additions were still relatively smooth. Additions which lead to severely irregular body lines would not be recommended.

The effects of the changes in body shape on the total drag coefficients at Mach numbers up to 2.0 are shown in figure 7. The configurations are the same as those shown in figure 5. The results for Mach numbers above 1.15 were obtained in the Langley 4- by 4-foot supersonic pressure tunnel. For the swept-wing—body combination, body indentation had little effect on the drag at Mach numbers from 1.4 to 2.0. For the delta-wing—body combination, body indentation reduced the drag at all Mach numbers up to 2.0 but by a progressively smaller amount. The fact that reductions were obtained at these supersonic speeds indicates that to a certain extent the factors affecting drag at moderate supersonic speeds may be similar to those for transonic speeds for low-aspect-ratio thin wings such as this one. However, since the waves are conical rather than plane in nature when the Mach number is increased to supersonic values, it would be expected that the use of the transonic concept would not give the maximum reductions in drag possible at supersonic speeds.

Considering the conical nature of the flow at moderate supersonic speeds, a method has been developed which interrelates the wave drag of wing-body combinations at these speeds with axial distributions of cross-sectional area (ref. 3). With this method a number of area distributions are used to determine the drag at a given supersonic Mach number. These distributions are obtained by cutting the configuration with planes inclined to the airstream at the Mach angle. This method is basically the same as one developed by Jones considering the linear theory of Hayes (ref. 4). Some preliminary results obtained at Langley are presented in figure 8 which show how the drag may be reduced at supersonic speeds by reshaping the fuselage on the basis of this method. The results are for a delta-wing—body combination. The first three configurations shown are the same as those shown in figure 7. The body of the fourth configuration was indented circularly so that the various area distributions determined by this supersonic method for a Mach number of 1.4 were relatively smooth. It may be seen that this indentation reduced the total drag coefficients at supersonic speeds by significantly greater amounts than did the indentation designed for a Mach number of 1.0 (dashed line). At a Mach number of 1.4, the further reduction is roughly half the remaining pressure drag of the wing.

In conclusion, the results presented have shown that, near the speed of sound, the drag rise for a low-aspect-ratio thin wing—body configuration is generally a function of the axial distribution of cross-sectional area normal to the airstream. By using this relationship, it is possible to reduce greatly the drag rise of the conventional wing-body combinations by redesigning the fuselage to produce a smooth axial distribution of area for the combination. The resulting reshaped fuselage of the combination should not have abrupt changes in contour. Of course, to obtain the lowest possible drag coefficients, the fineness ratio of the equivalent body should be sufficiently high.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 3, 1953.

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WING-BODY COMBINATION AND EQUIVALENT BODY OF REVOLUTION

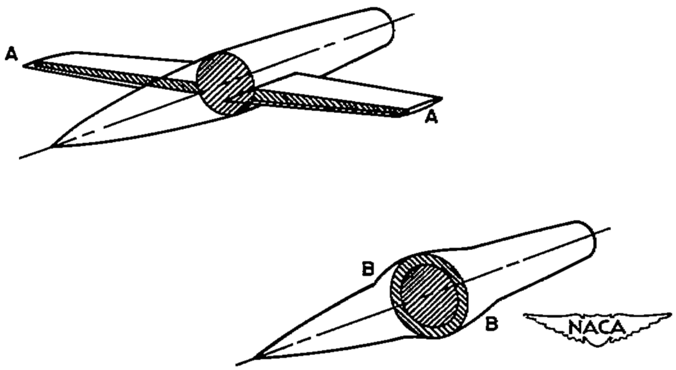

Figure 1

TRANSONIC FLOW PAST BODY WITH STRAIGHT WING

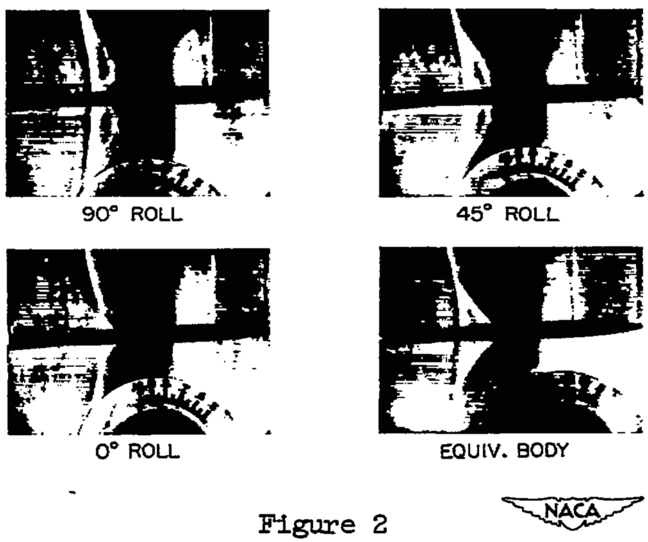

Figure 2

TRANSONIC FLOW PAST BODY WITH 45° SWEPT WING

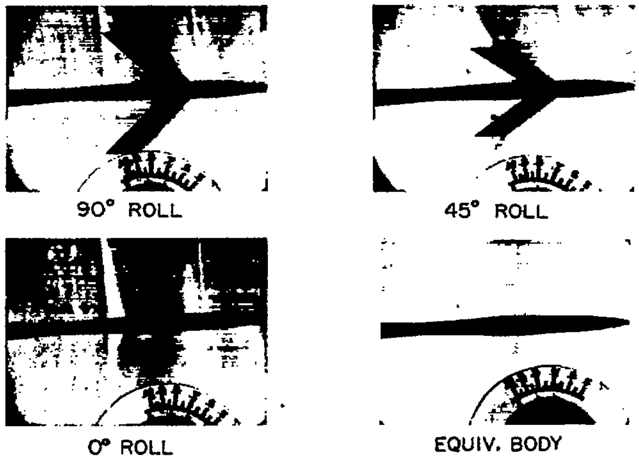

Figure 3

COMPARISON OF DRAG-RISE INCREMENTS AT M=1.03

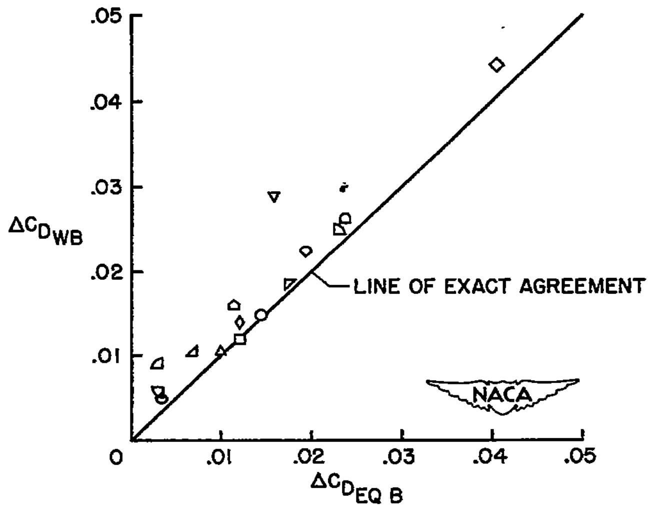

Figure 4(a)

DETAILS OF CONVENTIONAL CONFIGURATIONS

PLAN FORM	Λ	A	t/c	λ	SYMBOL	PLAN FORM	Λ	A	t/c	λ	SYMBOL
	11° L.E.	2.6	.04	.2	○		52° L.E.	2	.06	.33	⌂
	34° L.E.	4	.04	0	□		60° L.E.	2.2	.04	0	◇
	23° L.E.	3	.045	.4	◇		45° c/4	4	.06	.6	◇
	60° L.E.	2.2	.03	0	▽		45° c/4	4	.06	.3	△
	65° L.E.	1.87	.04	0	▷		45° c/4	3.5	.07	.3	▽

Figure 4(b)

DETAILS OF INDENTED CONFIGURATIONS

PLAN FORM	Λ	A	t/c	λ	SYMBOL
	11° L.E.	2.6	.04	.2	◁
	34° L.E.	4	.04	0	▽
	60° L.E.	2.3	.03	0	△
	60° L.E.	2.2	.04	0	◁
	45° c/4	4	.06	.3	○

Figure 4(c)

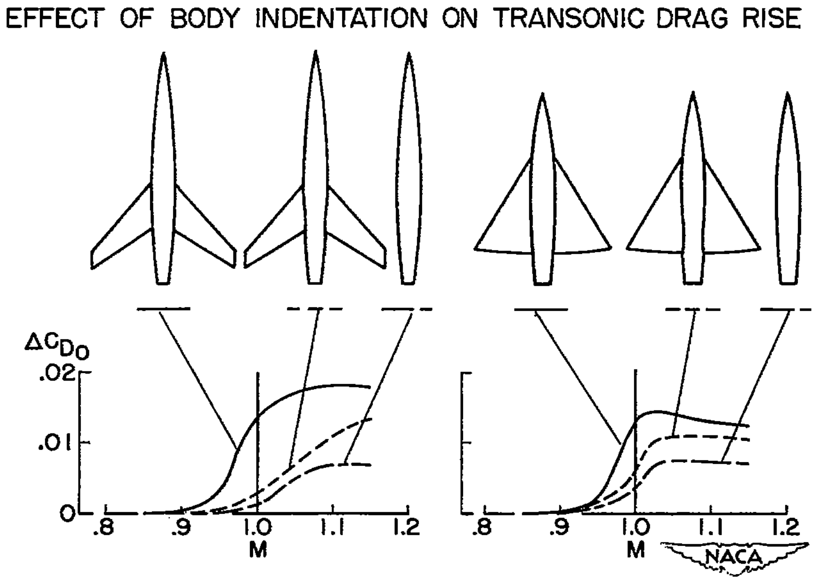

Figure 5

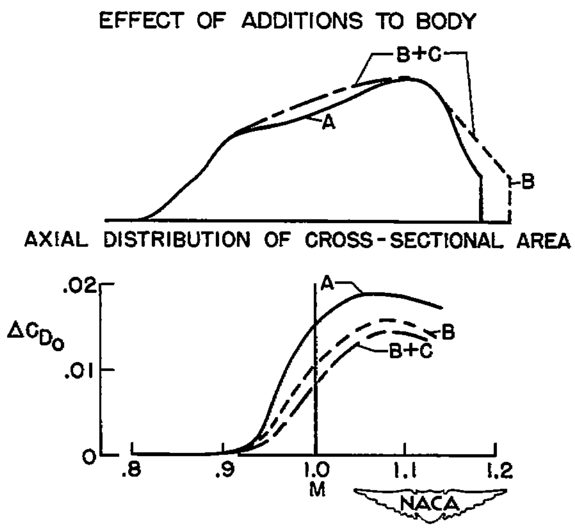

Figure 6

EFFECT OF BODY INDENTATION ON SUPERSONIC ZERO-LIFT DRAG

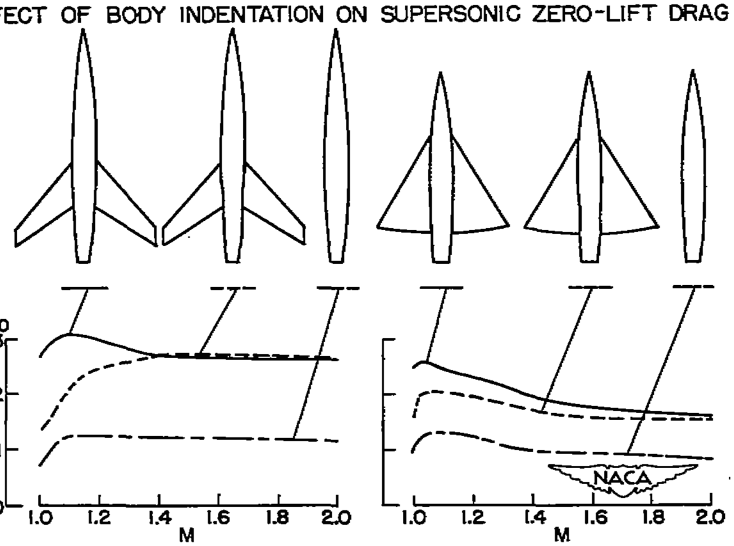

Figure 7

EFFECT OF INDENTATION BASED ON OBLIQUE AREA CUTS FOR M=1.4

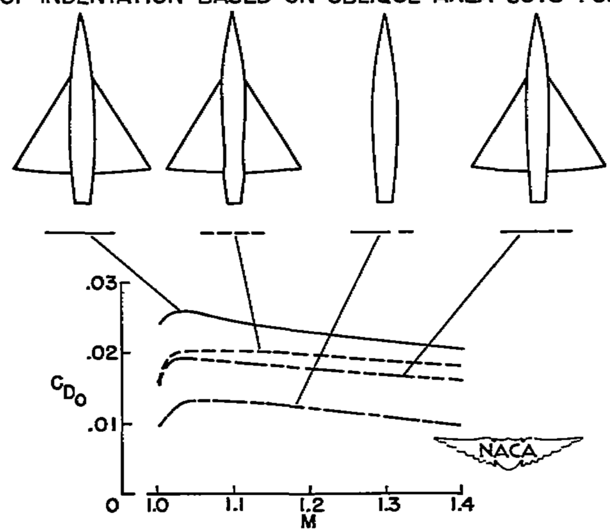

Figure 8

[redacted]