Influence of Drag on the Mission Performance of Hypersonic Aircraft

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The variations of drag during the climb and cruise phases of representative hypersonic-cruise transport missions were examined in detail for several possible hypersonic aircraft to assess the influence of drag on mission performance. During cruise, the drag due to lift has the most influence on estimates of performance, independent of configuration and altitude. During climb, the dominant drag component depends on configuration and/or flight path. In some cases, the friction drag was estimated to be 20 to 40% of the total, a percentage great enough that erroneous estimates would significantly affect performance estimates. Increasing the cruise Mach number increases the drag due to lift during both climb and cruise, and decreasing the allowable sonic-boom overpressure increases the drag due to lift during climb. Significant gains in performance can be realized for reasonably small reductions in drag. In one case, it was found that the payload capacity could be increased from 187 to 231 passengers by reducing the total drag 10% throughout the mission.

Nomenclature

C_D = total drag coefficient
C_{D_f} = skin-friction drag coefficient
C_{D_i} = induced drag coefficient
C_{D_p} = zero-lift pressure drag coefficient
C_L = lift coefficient
M = flight Mach number
Δp = sonic-boom overpressure, psf
α = angle of attack, deg

Introduction

RECENT studies indicate that the performance potential of hydrogen-fueled, air-breathing, hypersonic aircraft is favorable for long-range cruise missions.[1-3] Although the studies employed various structural, propulsive, and aerodynamic inputs, the aircraft in each study were characterized by large volumes, because liquid-hydrogen fuel is the key to favorable performance. The aerodynamic drag of these aircraft is expected to be higher (per cubic foot of payload) than that of supersonic transports of the near future. These relatively high values of drag and/or the variation of drag during a hypersonic mission will influence mission performance; the question arises as to how significant this influence might be.

This paper presents the results of a limited study in which the influence of aerodynamic drag on the mission performance of several representative hypersonic-cruise transport aircraft was examined. The approach to this study is first outlined and then the missions, configurations, and drag analysis are described briefly. Variations of the components of the total drag over specified portions of the missions are presented for each configuration and the relative importance of these drag components is examined. Changes in drag resulting from consideration of an alternate sonic-boom overpressure and an alternate cruise Mach number are also presented. The effect of drag on mission performance is presented for one case.

Approach

The variation of aerodynamic drag during a mission is a complex function of the geometric shape of an aircraft, its attitude during flight, the velocity-altitude profile flown, and the constraints imposed. For example, when structural considerations require a reduced dynamic pressure in a certain velocity range, flight at higher altitudes is usually considered. With the resulting reduction in dynamic pressure, an increased angle of attack is required to generate the increased lift coefficient necessary to support the weight of the aircraft. The increased angle of attack results in an increase in the drag due to lift. Furthermore, the general level of the drag, as well as the change in drag due to change in angle of attack, depends upon the configuration. Thus, to isolate the effect of each of the aforementioned factors on the variation of drag during a mission and to define the flight regimes in which the drag most significantly affects estimates of aircraft performance is an enormous undertaking requiring many hours of computer time to generate large quantities of data. In lieu of such a procedure, a general evaluation of the importance of aerodynamic drag in estimating performance of hypersonic aircraft is obtained by examining in detail existing data. Data previously generated for aircraft performance studies[1-3] are re-examined for this purpose, recognizing that several mission parameters were different for each study. The existing data were generated by mission-synthesis computer programs that integrated the equations of motion and properly related the separate aspects of aerodynamics, propulsion, and structures. For example, for a change in drag coefficient, the program resized the propulsion system, imposed the required changes in aerodynamics and in cruise altitude, re-evaluated the structural and fuel weights, and converted any weight savings into increased payload.

Missions

The missions studied were for hypersonic-cruise transports capable of carrying about 200 passengers 5000 naut miles while cruising at a Mach number of 6. A limited study was made for a cruise Mach number of 12. The Mach number altitude profile during climb to cruise altitude is affected by, and often determined by, a variety of constraints. The flight profiles and the magnitudes of the constraints imposed during climb for each Mach 6 mission examined in the present study were different, but all were bounded by the Mach number altitude region shown in Fig. 1. The first constraint encountered during climb is the allowable sonic-boom overpressure. The exact altitude at which a specific sonic-boom overpressure is generated is a function of aircraft volume and lift as well

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as Mach number[4] and is usually encountered in the Mach number range from about 1 to 3. As the aircraft accelerates along a flight path to maintain a constant sonic-boom overpressure, the dynamic pressure increases to a limiting value predetermined by structural load factors. The aircraft then climbs and accelerates, maintaining a constant dynamic pressure until, at a Mach number of about 5.5, the internal pressure in the propulsion system ducts increases to a predetermined structural limit. Violation of either the dynamic-pressure or the duct-pressure constraint would result in an undesirable increase in structural weight. Hence, these two constraints, hereinafter, will be referred to collectively as a structural constraint. When cruise Mach number is reached, the aircraft executes a constant Mach number climb to cruise altitude. At this point, a Breguet-type cruise is initiated, resulting in climbing flight which, for the Mach 6 missions considered, was bounded by altitudes from about 95,000 to 110,000 ft.

The descent phase of a mission depends upon the constraints of subsonic loiter time, subsonic cruise range, and reserve fuel requirements. Although variations in one or more of these constraints can greatly affect the gross takeoff weight,[2] the percent of the total fuel required during descent is relatively uneffected. The gross takeoff weight of all configurations studied was from 500,000 to 513,000 lb and, though the descent constraints were different, the fuel used during each descent was from 10 to 12% of the total fuel. Hence, the effects on mission performance due to variations in drag during descent can be expected to be small in comparison to those expected during the climb and cruise phases and, therefore, were not considered in this study.

Configurations

Figure 2 shows the configurations studied: a wing body, a blended body, and an all body. The wing-body configuration,[1] selected for preliminary mission analyses, consisted of a large volume Sears-Haack body and a flat-bottomed delta wing. The propulsion system (same type for all Mach 6 cruise missions) had a two-dimensional mixed-compression variable-geometry inlet beneath the wing (or body) to take advantage of the wing compression field. Four hydrogen-fueled turboramjet engines were used. The blended-body configuration[2] evolved from initial attempts to improve the aerodynamic characteristics of the wing-body configuration by reducing wing-body interference. The blended shape maintained the large volume required for the hydrogen fuel and provided the potential benefit of a lower structural weight relative to the wing-body configuration. The all-body configuration[3] had a delta planform with an elliptical-cone forebody and an elliptical cross-sectional afterbody that formed a smooth surface from its junction with the forebody to a straight-line trailing edge. The all-body configuration was used in the limited study of cruise at Mach 12.

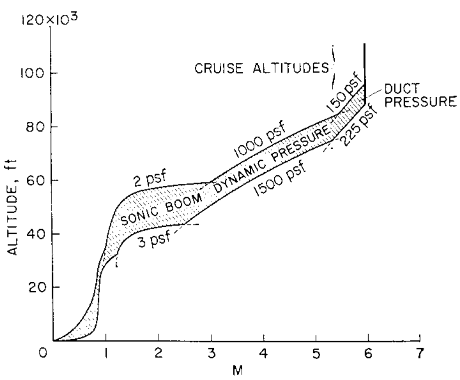

Fig. 1 Mach number altitude profiles and constraints during climb.

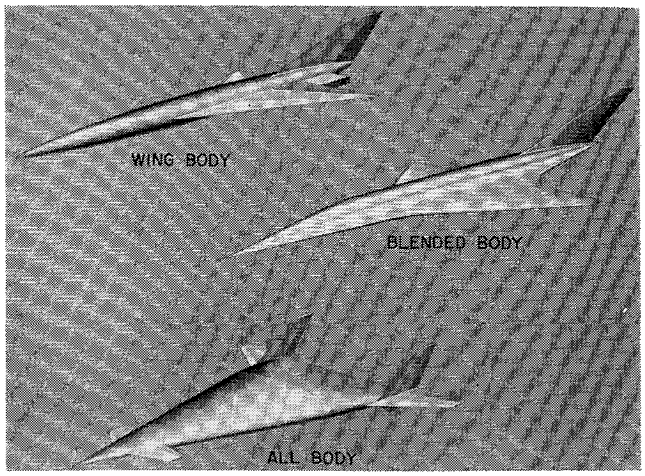

Fig. 2 Types of configurations.

For that study, a scramjet propulsion system was added for use at Mach 6 to 12 and was integrated with the body design to utilize the undersurface of the afterbody as an exhaust-nozzle expansion surface.

Although performance studies have been made to evaluate certain aspects of each of the present configurations,[1–3] these configurations are considered to be preliminary, rather than optimum, shapes.

Drag Analysis

Three main components of the total drag were studied: skin-friction drag, zero-lift pressure drag, and drag due to lift, or induced drag. For each configuration, zero-lift pressure drag included wave drag, drag due to nose and leading-edge bluntness, and base drag. In addition, the zero-lift pressure drag for the wing-body configuration included engine inlet (spillage) drag, and the induced drag for the blended body included trim drag. The three drag components were examined over only the climb and cruise phases of a mission because flight to the end of cruise requires nearly 90% of the fuel (total fuel minus reserves). The climb phase of each mission was examined in detail and is considered equally important as the cruise phase because climb-to-cruise altitude requires nearly half the fuel, at least for a Mach 6 cruise mission.

Estimates of the drag and other aerodynamic characteristics for all configurations were made with state-of-the-art methods.[1–3] The methods were verified whenever possible by comparisons with experimental data, and in some cases semiempirical expressions based on a least-squares curve fit of the experimental data were used. The skin-friction drag coefficients included Reynolds number and Mach number effects of the flight profile and effects of configuration surface temperature. Zero-lift pressure and induced-drag coefficients were evaluated from integrations of pressure distributions estimated from combinations of appropriate theories. The base drag was determined from integrations of the pressures in estimated regions of separated flow over the rearmost portions of the body. In the worst case, at transonic speeds, this contribution was only 5% of the total drag and the spillage drag was nearly an order of magnitude less.

Results and Discussion

Drag Components

The three components of the total drag are shown in Fig. 3 for the three configurations studied. The curves show variations with Mach number of percentages of total drag during climb: friction drag C_{D_f}, zero-lift pressure drag C_{D_p}, and

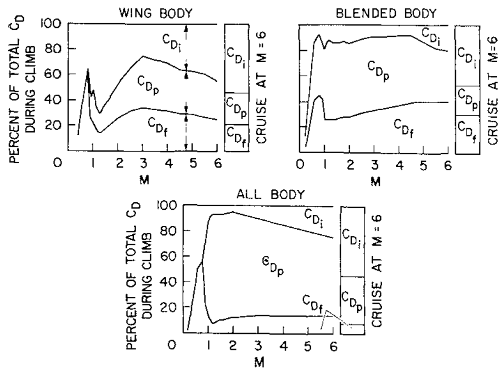

Fig. 3 Drag components during climb and cruise.

induced drag C_{D_i}. Note that the three components sum to 100%. The bar graphs show the percentage of each drag component during cruise. Variations of the drag components during climb at Mach number 6 (see Fig. 1) and transition to the cruise attitude were omitted from this and subsequent figures in the interest of clarity. It is emphasized that, because the configurations and constraints (flight profiles) differ for the missions examined, the data in Fig. 3 are not intended to provide comparisons between configurations and/or constraints, but rather to provide a general evaluation of the relative importance of the drag components in estimating mission performance. First, the large differences in the percentages of the various drag components at subsonic speeds are insignificant in terms of their effect on performance because of the short dwell time of the aircraft in this Mach number range (approximately 2 min or less). The friction drag during climb and cruise for the wing-body and blended-body configurations is a significant part of the total (20 to 40%), and variations in estimates of this component would have a noticeable effect on performance, certainly more so than in the case of the all-body configuration. The zero-lift pressure drag during climb is a very significant part of the total in each case, but in varying degrees. In fact, the all-body configuration is essentially a pressure-drag aircraft (Fig. 3). During cruise, however, precise knowledge of the zero-lift pressure drag is less important in estimating performance in each case. The contribution of induced drag during climb is significant only in the case of the wing-body configuration; however, during cruise, it is the predominant component for all configurations (47 to 55%). The large percentage of induced drag during cruise at Mach 6 is to be expected since all the configurations cruise near maximum lift-drag ratio, and, at the maximum value of this ratio, C_{D_i} for airplanelike configurations can amount to from 50 to 67% of C_D as the flight speed increases from the subsonic to the hypervelocity domain.[5] This increase in C_{D_i}/C_D with increasing velocity, at maximum lift-drag ratio, is a result of a corresponding increase in the degree of nonlinearity of the variation of lift coefficient with angle of attack. For example, for a flat plate, $C_L \sim \alpha$ at $M = 0$ and C_L becomes proportional to α^2 as $M \rightarrow \infty$.[6]

Effect of Cruise Mach Number on Drag Components

Figure 4 shows the effect of Mach number on the drag components for the all-body configuration for cruise Mach numbers of 6 and 12. The climb phase of each mission was identical in Mach number and altitude up to a Mach number of 6; then, of course, one aircraft accelerated to the higher Mach number while climbing to a higher altitude. These data show no pronounced effect of Mach number on the drag components. For both missions, the zero-lift pressure drag makes the largest contribution to the total during climb and the induced drag is predominant during cruise. The gradual increase in the percentage of induced drag at Mach numbers above 6 during climb and the slight increase in induced drag during cruise at Mach 12 results primarily from the aforementioned increase in the nonlinearity of the lift characteristics with increasing Mach number.

Effect of Sonic-Boom Overpressure on Drag Components

Figure 5 shows the effect of sonic-boom overpressure on the drag components for the wing-body configuration. The differences in drag shown for the 3- and 2-psf overpressure constraints result primarily from flying different Mach number altitude profiles in order not to exceed the specified overpressures. For example, in the Mach number range from 1 to 3, the lower overpressure (shown by the dashed lines) requires flight at a higher altitude where the dynamic pressure is reduced; hence, an increase in lift coefficient is required to support the weight of the aircraft. The increased lift coefficient is obtained by increasing the angle of attack and this is accompanied by an increase in induced drag. Thus, as the sonic-boom constraint becomes more stringent, the induced drag in that region becomes more important in estimating performance, and, in the case shown in Fig. 5, the friction drag becomes less important.

Effect of Drag Reduction on Mission Performance

Figure 6 shows one example of how performance can be improved by reducing the drag over specified portions of a mission. The data are for the wing-body configuration (see Fig. 2) which, for the nominal mission, carries 187 passengers 5000 naut miles. The improvements in performance are shown as the number of passengers that can be added as a function of the percent reduction in drag.† Also shown in the upper left part of the figure are the drag components for the nominal mission (reproduced from Figs. 3 and 5 for $\Delta p = 2$ psf). For reductions in any drag component at subsonic speeds (up to $M = 0.8$), the passenger capacity was unaffected for drag reductions up to 15% (the limit of the study). This, again, is a result of the short dwell time in this Mach number range. For Mach numbers from 0.8 to 3, the region of the sonic-boom constraint, the drag-component chart indicates that the induced drag is the greatest part of the total. Hence, as might be expected, the data show ($0.8 < M < 3$, lower left) that the greatest number of passengers can be added for a given percent reduction in drag in this Mach number range by reducing the induced drag. For Mach numbers from 3 to 6, the region of the structural constraint, the total drag appears to be nearly equally divided among the three components (see drag-component chart). Accordingly, the number of added passengers for a given percent reduction in C_{D_f}, C_{D_p}, and C_{D_i}

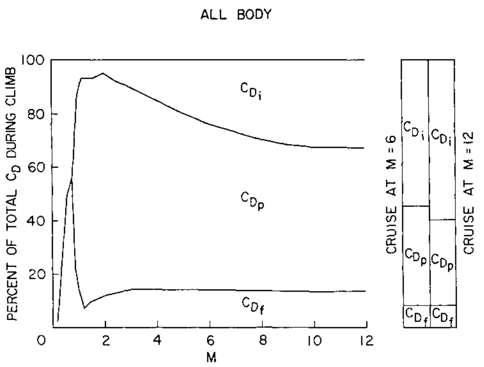

Fig. 4 Effect of cruise Mach number on drag components.

† These data in Fig. 6 were obtained from NASA, Office of Advanced Research and Technology, Mission Analysis Division, Moffett Field, Calif.

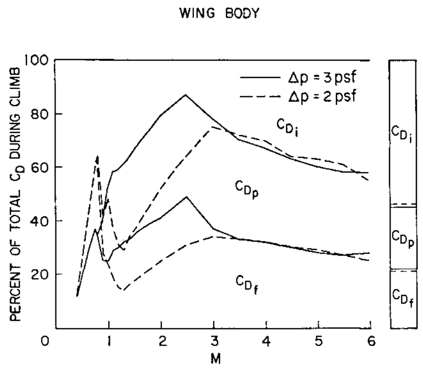

Fig. 5 Effect of sonic-boom overpressure on drag components.

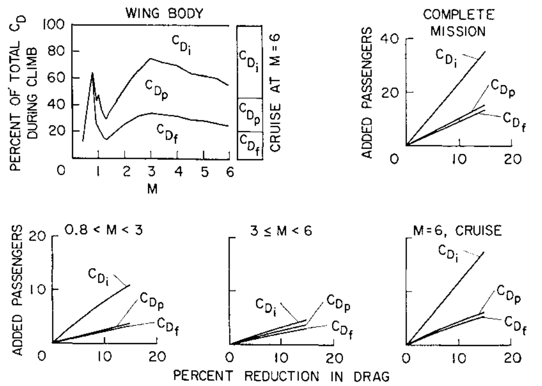

Fig. 6 Effect of drag reduction on mission performance.

for $3 \leq M < 6$ is nearly the same (lower center in Fig. 6). The bar graph (upper left) indicates that during cruise, at Mach 6, the induced drag is the greatest component. The corresponding performance data (lower right) indicate the greatest number of passengers can be added for a given percent reduction in induced drag during cruise. For the wing-body configuration and mission constraints considered in Fig. 6, the cruise condition and sonic-boom constraint rank in that order of importance as to where in the mission one can expect to make the greatest gains in performance by reducing the drag, and in this case, by reducing the induced drag.

It is emphasized that other combinations of configuration and/or mission constraints would show different results. For example, as shown in Fig. 5 for the wing-body configuration and a 3-psf overpressure, the total drag appears nearly equally divided among the three drag components in the region of the sonic-boom constraint; hence, in that case, one could expect a nearly equal improvement in performance for the same percent reduction in each of the three drag components in the Mach number range from 0.8 to 3. For the data shown in Fig. 5, relaxing the sonic-boom constraint from 2 to 3 psf resulted in a 17.5% increase in passenger capacity.

The upper right portion of Fig. 6 shows the number of passengers that can be added by reducing each component of drag throughout the complete mission. Since the effect on performance of reducing each drag component separately is essentially independent of drag reductions in the other components, these data can be added linearly to estimate performance gains that result from drag reductions in more than one component. As an example, for a 10% reduction in total drag (10% for each component), 10 passengers each can be added for reductions in friction and zero-lift pressure drag and 24 for a reduction in induced drag, for a total of 44 passengers. This represents a 23% increase in passenger capacity for a 10% reduction in total drag throughout the complete mission. It should be noted that the data in Fig. 6 also can be interpreted as being indicative of errors in performance due to errors in estimating the drag.

Concluding Remarks

The variations of skin-friction, zero-lift pressure, and induced drag throughout representative hypersonic-cruise transport missions have been examined for several hypersonic aircraft to assess the influence of drag on mission performance. Although the results suggest that each combination of configuration and mission profile should be examined separately to determine the detailed influence of drag on mission performance, some general trends are indicated. During cruise, the drag due to lift generally has the most influence on estimates of performance. This result is independent of configuration and altitude. During climb, the dominant drag component depends upon configuration and/or flight path (mission constraints). In some cases, the friction drag was estimated to be as much as 20 to 40% of the total, a percentage great enough that erroneous estimates would significantly affect performance estimates. Increasing the cruise Mach number from 6 to 12 slightly increases the drag due to lift during both climb and cruise, and decreasing the allowable sonic-boom overpressure increases the drag due to lift during climb. Additional results indicate significant gains in performance for reasonably small reductions in drag. In one case, it was shown that the passenger capacity could be increased 23% by a 10% reduction in total drag throughout the mission.

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