Planform Effects for Low-Fineness-Ratio Multibody Configurations at Supersonic Speeds

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An experimental and theoretical investigation of planform effects on low-fineness-ratio multibody configurations has been conducted in NASA Langley Research Center's Unitary Plan Wind Tunnel at Mach numbers 1.6, 1.8, 2.0, and 2.16. Experimental and theoretical values of lift, drag, and pitching moment were obtained on three configurations that varied in outboard panel planform only. The three variations were a 65-deg delta, a 70/66-deg cranked arrow, and a 20-deg trapezoidal planform. The purpose of the study was to determine the effect of wing planform on the supersonic aerodynamics and to evaluate the ability of two existing linearized theory aerodynamic methods to predict these effects. Experimental data showed that the planforms produced the lift, drag-due-to-lift, and pitching moment characteristics typically found on single-body configurations. However, the data also showed that the planform has a relatively small influence on zero-lift drag which is not typical of single-body configurations. Theoretical aerodynamic analysis indicated that codes based on linearized theory adequately predicted the effects of planform on the supersonic aerodynamics.

Nomenclature

$\bar{c}$	= average geometric chord, in.
C_D	= drag coefficient
ΔC_D	= incremental drag, $C_D - C_{D,0}$
$\Delta C_D/C_L^2$	= drag due to lift factor
$C_{D,0}$	= zero-lift drag coefficient
C_L	= lift coefficient
C_{L_α}	= lift curve slope evaluated at $\alpha = 0$ deg
C_m	= pitching moment coefficient
dC_m/dC_L	= longitudinal stability parameter evaluated at $\alpha = 0$ deg
FR	= configuration fineness ratio
L/D	= lift-to-drag ratio
M	= Mach number
Re	= Reynolds number per foot
α	= angle of attack, deg

Introduction

AIRCRAFT design studies[1,2] have indicated that significant performance improvements can be achieved for subsonic passenger and cargo aircraft by utilizing the novel concept of two fuselages. In general, the benefits afforded by two fuselages are an effective increase in wing aspect ratio, reduced wing structural weight due to a reduced wing bending moment, reduced total fuselage weight when both single- and twin-fuselage geometries are designed for the same number of passengers or payload.

These benefits should be independent of aircraft operating speed. To address the supersonic aerodynamics of the multibody concept, a theoretical study[3] was conducted on a twin-fuselage aircraft configured by the joining of two single-fuselage advanced supersonic transport (SST) configurations. This study indicated that a doubling of fuselage volume could be obtained with little or no aerodynamic performance penalty compared to a single-fuselage SST configuration. All these studies alluded to, but did not quantify, aerodynamic interference effects associated with this design concept. However, aerodynamicists rely heavily on positive interference when designing efficient supersonic aircraft, and the concept of twin fuselages offers a challenging opportunity to explore a multitude of aircraft component shapings and arrangements to maximize the performance of supersonic aircraft. To develop an understanding of the geometric parameters that govern the supersonic aerodynamic design of the multibody concept, a research program was initiated at the NASA Langley Research Center. To date, three studies defining the effects of side-body positioning, side-body shaping, and planform shaping have been completed.

In the multibody concept, body interference is the primary drag reduction mechanism because, in a linear theory sense, the multibody concept creates an effectively longer and thinner configuration for a given configuration volume. One of the more obvious geometric parameters governing this drag reduction mechanism is the positioning of the bodies. This parameter was initially investigated in an experimental and theoretical study summarized in Ref. 4. In this study, a set of experimental data was obtained on a generic twin-body wind-tunnel model of high fineness ratio; these data were used to evaluate prediction methods, to assess favorable interference effects, and to identify any unexpected or unpredictable aerodynamic phenomena. The gross geometric characteristics of the high-fineness-ratio model were representative of a supersonic transport. Results showed that significant reductions in zero-lift wave drag are possible through optimum body positioning and that existing aerodynamic prediction methods[5,6] are adequate for making preliminary aerodynamic estimates on the effect of body positioning.

Since the overall geometric characteristics of the generic twin-body model were representative of SST-type geometries (i.e., high fineness ratio), the zero-lift drag was dominated by viscous drag that severely limited the effectiveness of the multibody concept in reducing drag. As illustrated in Fig. 1, the results of a theoretical analysis indicated that the 10% reduction in zero-lift drag achieved for the slender geometries could

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be increased to 30% by working with lower-fineness-ratio configurations for which the zero-lift drag is dominated by wave drag. Based on these findings, the emphasis of the research program was shifted from high-fineness-ratio to low-fineness-ratio configurations.

Theoretical studies of the multibody concept at supersonic speeds have shown that the zero-lift drag can be reduced, compared to a single-body concept, not only through body positioning but also by shaping the body cross section. A theoretical and experimental investigation was conducted to determine the effect of body cross-sectional shape on the supersonic aerodynamics of a low-fineness-ratio configuration. In that investigation, it was found that body shaping does have a significant influence on all the aerodynamic characteristics of the multibody concept and that linear theory methods are adequate in predicting those effects.

Since wingbody integration has always been an important consideration in single-body configurations, wing planform shape was the third parameter investigated in the multibody research program. Reference 8 summarizes how changes in wing planform can significantly alter the zero-lift wave drag and drag due to lift of single-body configurations. These conclusions may not be directly applicable to the multibody concept because the placement of the bodies off the configuration centerline could affect the lifting efficiency of the wing. A preliminary theoretical study[9] of the effect of wingbody integration for a high-fineness-ratio multibody configuration was conducted. In that study, several multibody configurations that varied only in planform were investigated, and the results showed the aerodynamic characteristics to be extremely sensitive to changes in wing planform.

This paper presents the results of a wind-tunnel test conducted to determine the effect of wing planform on low-fineness-ratio multibody concepts. The paper also offers a comparison between the experimental and theoretical data obtained from linear theory methods in order to evaluate the applicability of the linear theory methods.

Model and Test Description

As shown in the model photographs of Fig. 2, the three multibody models tested varied in outboard wing panel planform only. The three outboard wing panels were a 65-deg delta wing, a 70/66-deg cranked arrow wing, and a 20-deg trapezoidal wing with total configuration aspect ratios of 2.0, 2.2, and 2.4, respectively. Each wing was configured with a 4% thick circular arc airfoil. A three-view sketch of the delta wing model is shown in Fig. 3. Each model consisted of a center wing panel containing a balance housing bracketed by two flow-through engine duct systems, twin vertical tails, twin side bodies of circular cross-section shape, and an uncambered outboard wing panel.

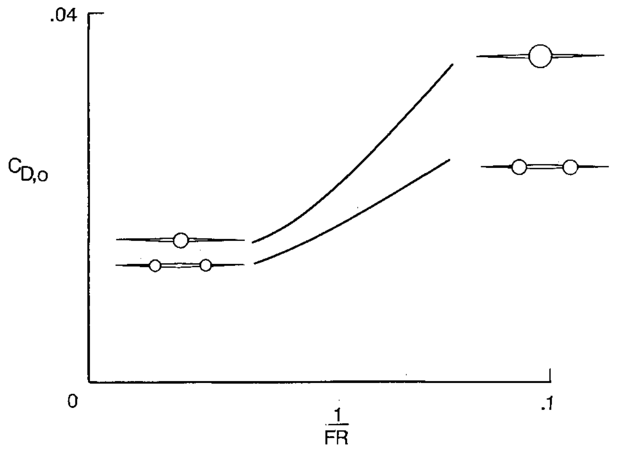

Fig. 1 Variation in $C_{D,0}$ due to configuration fineness ratio for single-body and multibody configurations.

Wind-tunnel tests were conducted in the Langley Unitary Plan Wind Tunnel (UPWT) over a Mach number range of 1.6–2.16 at a Reynolds number of 2×10^6/ft and at angles of attack from -4 to 20 deg. The models were tested with and without the vertical tails attached. The data presented here are for the models with the vertical tails removed. For each configuration, the aerodynamic coefficients were computed using a reference area equal to the model planform area and a reference length corresponding to $\bar{c}$. The pitching moment centers were located at a longitudinal position corresponding to roughly 0.4 $\bar{c}$.

Discussion

At supersonic speeds, the zero-lift drag ($C_{D,0}$) is composed of inviscid wave drag and viscous skin-friction drag. Application of the multibody concept typically results in an increase in

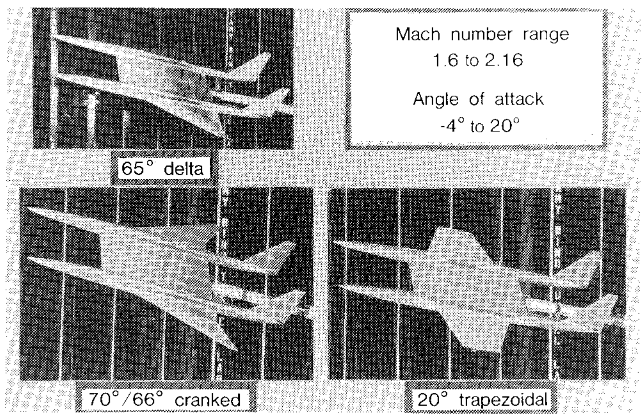

Fig. 2 Photographs of wind-tunnel models.

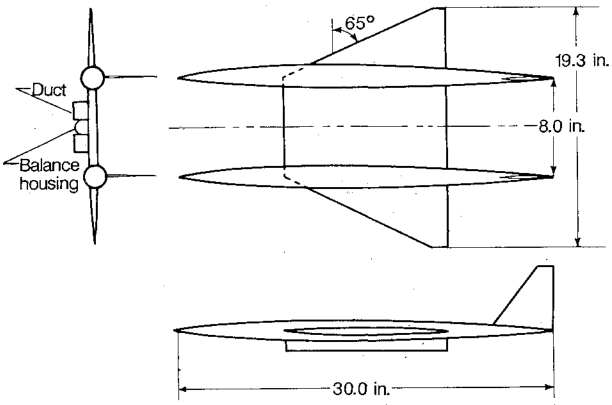

Fig. 3 Three-view graphic of delta wing configuration.

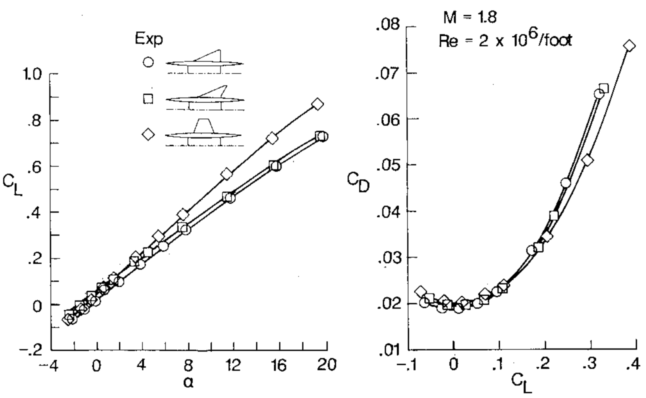

Fig. 4 Effect of planform on longitudinal aerodynamics at $M = 1.80$.

skin-friction drag due to an increased wetted area and a decrease in wave drag due to positive aerodynamic interference. If this increase in skin-friction drag is more than compensated by the decrease in zero-lift wave drag, a total zero-lift drag reduction will result. This present experimental and theoretical study is directed at determining the effects of wing planform on a low-fineness-ratio multibody configuration. Experimental and theoretical results will be examined to evaluate the ability of existing computer codes to predict the effects of wing planform shape.

Experimental Results

Shown in Fig. 4 is the effect of wing planform on the longitudinal aerodynamic characteristics at $M = 1.8$. The variation in both the lift and drag with wing planform is consistent with wing alone and single-body configuration data. Specifically, the trapezoidal wing is seen to have a higher lift-curve slope and lower drag coefficient at the higher C_L than either of the more highly swept wings. However, the trapezoidal wing is also seen to have the higher zero-lift drag. It should be noted that the value of zero-lift drag produced by the trapezoidal wing is only 5% greater than that produced by the delta or arrow wing configurations. This change in $C_{D,0}$ between planforms for the multibody model is significantly less than the $C_{D,0}$ variation observed for single-body configurations.[8,10] It can be concluded from the aerodynamic characteristics in Fig. 4 that the trapezoidal wing has equivalent or improved aerodynamic performance at cruise and maneuver lift coefficients ($C_L > 0.15$) compared to the highly swept wings. In addition, the reduced wing sweep allows for more efficient flight at subsonic and transonic speeds compared to the swept planforms. It should be noted that the pitching moment curve of each configuration (not shown here) was linear with respect to angle of attack.

In Fig. 5, the aerodynamic characteristics at $M = 1.8$ of the three wing planforms are presented in terms of lift-to-drag ratio at three different values of lift coefficient. At a $C_L = 0.1$, a typical cruise condition, the three configurations have comparable L/D values with the trapezoidal wing having a value 3% lower than the delta wing. However, at the higher C_L of 0.2 and 0.3, the trapezoidal wing has a substantially higher L/D value than either of the highly swept wings. Specifically, the trapezoidal wing has an 8% increase over the delta wing at a $C_L = 0.2$ and a 13% increase at a $C_L = 0.3$.

The previous discussion and results have been limited to a specific Mach number of 1.8; the variations of the major aerodynamic parameters over the Mach range of 1.6–2.16 are given in Figs. 6 and 7. The lift-curve slope (C_{L_α}) characteristics are presented on the left side of Fig. 6. The lift-curve slope is seen to decrease with Mach number for all configurations, with the trapezoidal wing having the higher C_{L_α} over the entire Mach number range. The data also show that, compared to the more highly swept wings, the lift-curve slope of the trapezoidal wing decreases more rapidly with Mach number, resulting in a convergence of all wings to a common value of C_{L_α} at the higher Mach numbers. This effect can be attributed to the development of a supersonic leading-edge condition for all wings. This observation is reinforced by theory, which states that C_{L_α} is a function of Mach number only when a supersonic leading-edge condition exists.

The longitudinal stability (dC_m/dC_L) data, presented on the right side of Fig. 6, indicate that planform has a significant effect on the stability level, such that the arrow wing is stable, whereas the trapezoidal and delta wings are essentially neutrally stable at all Mach numbers. These trends can be explained by observing that, although the moment center locations (roughly 0.4 $\bar{c}$) of the delta and arrow wings are approximately equal, the arrow wing's aerodynamic center is further aft due to the higher sweep; therefore, the arrow wing is more stable. On the other hand, the trapezoidal wing has a forward shift in moment center location compared to the delta wing, and the aerodynamic center is also shifted forward by approximately the same amount due to the lack of sweep; therefore, the trapezoidal and delta wings have comparable longitudinal stability. It is significant that the longitudinal sta-

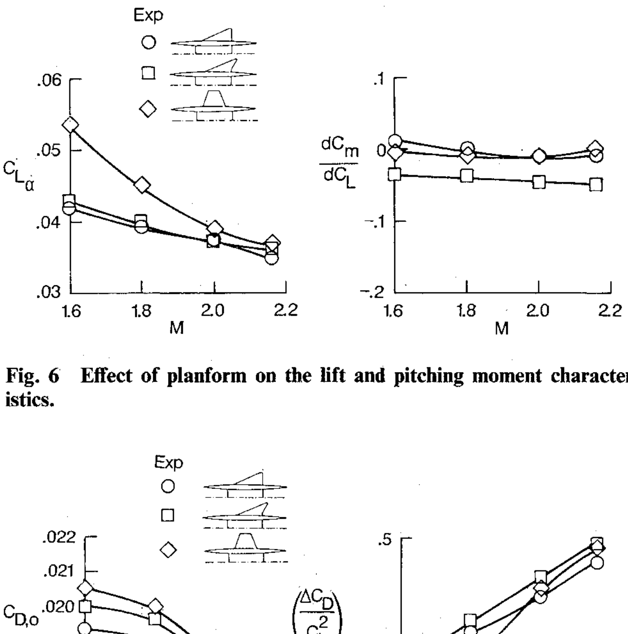

Fig. 6 Effect of planform on the lift and pitching moment characteristics.

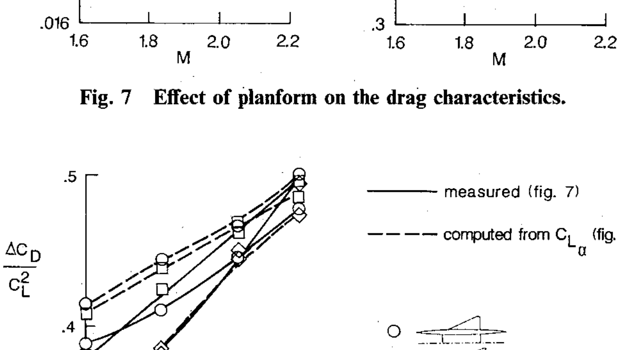

Fig. 7 Effect of planform on the drag characteristics.

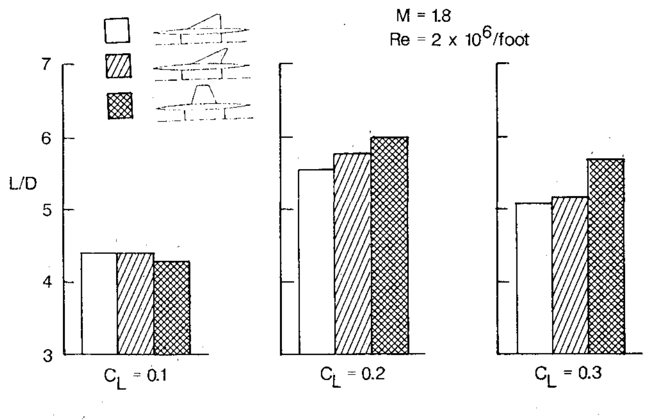

Fig. 5 Effect of planform on aerodynamic performance at $M = 1.80$ for various C_L values.

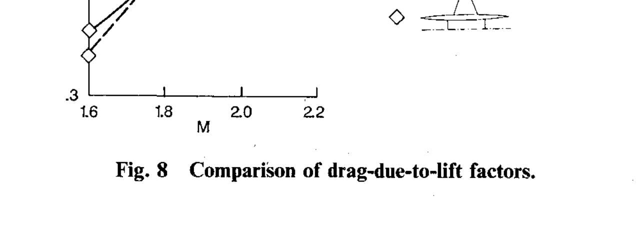

Fig. 8 Comparison of drag-due-to-lift factors.

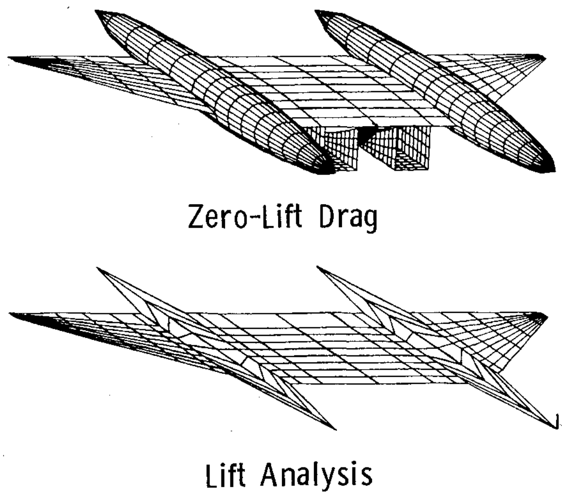

Fig. 9 Graphics of theoretical numerical models.

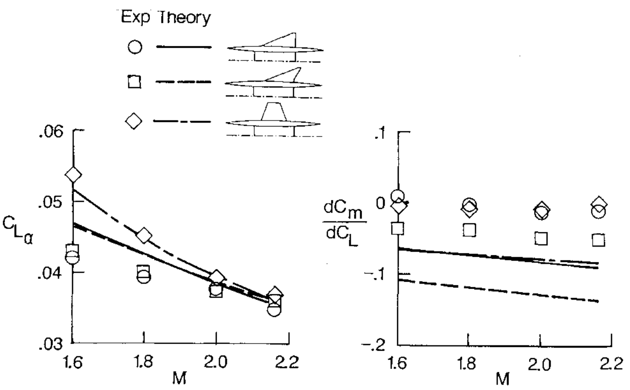

Fig. 10 Comparison between experiment and theory for the lift and pitching moment characteristics.

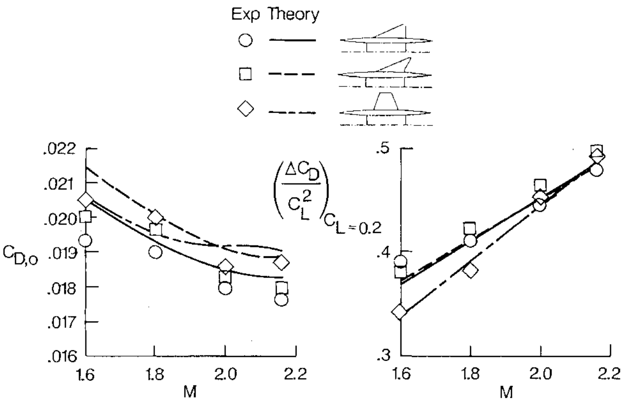

Fig. 11 Comparison between experiment and theory for the drag characteristics.

bility level for each configuration increases slightly with increasing Mach number. This effect is opposite to the trend usually observed for single-body configurations.[11] The apparent ability of the multibody concept to maintain a constant or increasing level of longitudinal stability with increasing Mach number could have a significant impact on future design studies.

The effect of planform on the zero-lift drag characteristics is presented on the left side of Fig. 7. The data show that slight variations in zero-lift drag coefficient result from changes in planform. The maximum variation is approximately 5%. This variation is consistent over the Mach number range. The variations in drag-due-to-lift factor ($\Delta C_D/C_L^2$) with Mach number, presented on the right of Fig. 7, show that the trapezoidal wing has lower and therefore better drag-due-to-lift characteristics than the more highly swept wings. The drag due to lift also increases with increasing M for each configuration. These results are similar to those observed for a single-body configuration with an uncambered sharp leading-edge wing.

Theoretically, for a flat wing, the zero suction drag-due-to-lift factor is inversely proportional to the lift-curve slope. A comparison between the measured drag-due-to-lift factor (taken from Fig. 7) and a computed drag-due-to-lift factor (computed using the C_{L_α} data of Fig. 6) is presented in Fig. 8. The results show a much better correlation between the measured and computed $\Delta C_D/C_L^2$ for the trapezoidal wing than for either of the two highly swept wings. In particular, the computed values for the delta wings are consistently greater than the measured values and, for the arrow wing, the computed values cross over the measured values. For these thin, sharp leading-edge wings, one would expect a close agreement between the $1/C_{L_\alpha}$ and $\Delta C_D/C_L^2$ curves. The discrepancy in the data suggests the existence of near-field interference effects between the outboard wing panel and the other configuration components at all Mach numbers. These interference effects could manifest themselves to create changes in the loadings and drag of the vehicles that could appear similar to leading-edge thrust effects.

Throughout this discussion of the experimental data, it has been shown that the trapezoidal planform has the better lifting characteristics of the three multibody configurations but has higher zero-lift drag. However, as shown in Figs. 4 and 5, at lifting conditions the improved lifting characteristics more than compensate for the zero-lift drag penalty. As mentioned previously, these lifting characteristic result are consistent with those found for single-body concepts. In particular, a direct comparison between the present data set with data obtained for a similar set of planforms on a single-body model[10] shows that with the application of the multibody concept the trapezoidal planform suffers a lower zero-lift drag penalty. The ability to incorporate a low sweep trapezoidal wing into a multibody low-fineness-ratio configuration without a significant impact on zero-lift drag is due to the improved volumetric efficiency inherent to the multibody concept. For a single-body model, the effective aerodynamic fineness ratio, and thus the drag, is strongly influenced by the wing planform, resulting in a nonsmooth area distribution. However, the effective aerodynamic fineness ratio of a multibody model is influenced by both the wing planform and body, resulting in a much smoother area distribution and thus lower drag. These data suggest that the multibody design concept provides more freedom in selecting wing planform for an aerodynamic vehicle compared to a single-body configuration.

Theoretical Analysis

Two supersonic aerodynamic prediction computational codes were selected for performing the theoretical analysis. The codes chosen were an arbitrary geometry far-field wave drag code[12] and the supersonic design and analysis system (SDAS).[5]

SDAS is an integrated system of computer programs that has been developed for the design and analysis of supersonic configurations. Included in the system is the lift-analysis method of Ref. 13 and the skin-friction calculation method of Ref. 14. Also included in the SDAS code is a version of the far-field wave drag code that employs the solution technique described in Ref. 15. However, since the fuselages were located off the configuration centerline, a modified version of the far-field wave drag code was utilized.[12] The modified far-field wave drag code and the skin-friction code were used to obtain the zero-lift drag characteristics. The lift analysis code was used to obtain the lift, drag-due-to-lift, and pitching moment characteristics.

Shown in the top portion of Fig. 9 is the zero-lift drag theoretical model for the delta wing configuration. This representation of the total configuration was employed to compute the wave drag and skin friction. At the bottom of Fig. 9, the lift-analysis theoretical model of the delta wing configuration is shown. This modeling was chosen based on a lifting surface modeling study conducted on a low-fineness-ratio single-body configuration.[16] The study of Ref. 16 illustrated that a mean-chord-plane representation of the fuselage/planform yields improved results over those obtained for planform alone or the planform with thick fuselage representations.

A comparison between experiment and theory for the lift-curve slope and pitching moment characteristics is illustrated in Fig. 10. The lift-curve slope data show that the lift analysis method predicts the correct trend with respect to changes in planform and Mach number. On the right side of Fig. 10, the longitudinal stability data show that theory overpredicts the stability of the configuration but predicts the proper variation due to planform. This result is consistent with previous applications of the theory.

Presented in Fig. 11 is a comparison between experiment and theory for the zero-lift drag and drag-due-to-lift characteristics. The $C_{D,0}$ data indicate that the theoretical codes did not consistently predict the correct trend with changes in planform but did predict the correct trend with Mach number. However, the theoretical codes predicted that the changes in $C_{D,0}$ with respect to changes in planform are small as was found experimentally. The drag-due-to-lift data indicate that the lift analysis method is sufficient for predicting the effect of planform and Mach number.

Conclusions

For the purpose of examining the effect of planform, a series of three uncambered wings have been tested on a low-fineness-ratio multibody configuration. The planform geometries varied in outboard panel planform only. The three variations were a 65-deg delta, a 70/66-deg cranked arrow, and a 20-deg trapezoidal planform. The experimental test results showed that the lift, drag-due-to-lift, and pitching moment characteristics of the various planforms on a multibody configuration are similar to those typically found on a single-body configuration. However, for the multibody configuration the results also showed that planform has a relatively small influence on the zero-lift drag, which is contrary to results typically found on single-body configurations. Thus, the multibody concept appears to offer a mechanism for employing wing planforms of lower leading-edge sweep for improved subsonic and transonic performance.

The experimental results were compared to results obtained using linear theory computational codes. This comparison showed that linear theory methods are adequate for estimating the effect of planform on supersonic aerodynamics of low-fineness-ratio multibody configurations.

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