NASA Technical Memorandum 87710 NASA-TM-87710 19860014084

SOME LESSONS LEARNED WITH WIND TUNNELS

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March 1986

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SUMMARY

A review has been made of some of the milestone events involving the use of wind tunnels in the development and analysis of airplanes and missiles since World War II. It would be presumptuous to think that all important events could be covered. However, enough evidence is presented to indicate that wind-tunnel experimentation has played a very important part in discovering new phenomena, in explaining some phenomena, in developing new systems, and in providing early performance assessments for a wide variety of steadily improved airplanes and missiles.

Among the main developments resulting from wind tunnel experimentation since World War II have been:

- o Understanding and application of swept wings.
- o Use of variable wing sweep.
- o Insight and resolution of problems related to supersonic flight
- o Importance of component arrangement.
- o Improved efficiency through area ruling.
- o Use of canard configurations.
- o Insight into missile aerodynamics.
- o High-speed body shapes.

The evidence is clear that the proper use of wind tunnels has advanced the science of aerodynamic research in a manner that could not otherwise be achieved. The record is such that there is no reason to doubt that the wind tunnel will continue to be vital to advancements yet to come.

INTRODUCTION

NACA wind tunnels were extremely busy and quite productive during the early 1940's due to the press of aircraft developed for wartime use such as the Lockheed P-38, the Bell P-39, the Republic P-47, the North American P-51, the Bell P-59, the Lockheed P-80, the Republic P-84, and so on. It was the work load and the apparent lag of U.S. aeronautical research as compared to Germany and Italy, for example, that lead to the construction of new NACA wind tunnels at Moffett Field, California (now Ames Research Center) starting in 1940, new tunnels at Langley Field in 1940, and new tunnels for propulsion work in Cleveland (now Lewis Research Center) starting in 1944. At the end of the war, the basic research work in the U.S. was bolstered by the influx of technology from Germany and Italy. Much of this work was done at the well-established NACA facilities at Langley Field. The primary emphasis was related to the progression from subsonic aircraft to supersonic aircraft and to the advent of missiles.

The purpose of the present paper is to document some of the major events in the progression of flight as discovered from wind tunnel testing. Such a historical review should provide some appreciation of the role played by the wind tunnel in the advancement of aerodynamic knowledge and should serve as an indicator that the wind tunnel, properly used and properly understood, will continue to be a source of improved knowledge for the future.

SYMBOLS

C_D	drag coefficient
C_{D_o}	drag at zero lift
C_L	lift coefficient
C_m	pitching-moment coefficient
$\partial C_m/\partial C_L$	variation of pitching-moment coefficient with lift coefficient
$\partial C_m/\partial i_t$	variation of pitching-moment coefficient with horizontal tail incidence angle
C_n	yawing-moment coefficient
C_{n_β}	variation of yawing-moment coefficient with angle of sideslip
L/D	lift-to-drag ratio
$\partial \varepsilon/\partial \alpha$	variation of effective downwash angle with angle of attack
α	angle of attack, deg
β	angle of sideslip, deg
l	body length
d	body diameter
δ_c	canard deflection, deg
δ_f	flap deflection, deg
δ_H	horizontal tail deflection, deg
M	Mach number
c.g.	center of gravity

Model components:

B	body
BC	body canard

BW body wing

BWC body-wing-canard

VT vertical tail

Coefficients presented herein are nondimensionalized in various ways. The numerical value of the coefficients, however, does not affect the interpretation of the results.

DISCUSSION

Basic Low-Speed Studies

Low-Speed Planform Tests.- By the end of World War II, it was known that German scientists were developing high-speed aircraft and missiles through the use of jet propulsion and appropriate airframe shaping. One of the first items to add to the impetus of NACA basic research was the swept-back wing. The use of wing sweep as a means of achieving higher flight speeds was not unknown but the application of the principle was much further advanced in Germany than in the U.S. Some general studies were quickly undertaken at Langley NACA facilities in the mid 1940's. Among the first experimental efforts were studies of the low-speed characteristics of swept wings (refs. 1 and 2). An illustration of some of these early planform study wings (Fig. 1) shows some swept-back and some swept-forward wings of various sweep angles, aspect ratio, and taper ratio. Also tested were some miscellaneous wings of rectangular planform, trapezoidal planform, diamond planform, and a "W" planform. Some initial results with a 60 degree swept planform (Fig. 2) indicated that high-aspect ratios of the type previously associated with good wing efficiency (AR = 3) were not suitable for highly swept wings. It was discovered that the extensive spanwise flow resulted in flow separation (at the wing tips for $+\Lambda$ and at the centerline apex juncture for $-\Lambda$) so that in either case a severe pitch-up occurred at high lifts. The pitch-up was alleviated by removing half of the wing span thereby reducing the aspect ratio to 1.5. The wing efficiency, as indicated by the drag polars, was impaired by the reduction in aspect ratio and the lift was reduced. The effect of aspect ratio reduction on both lift and drag was more pronounced for the swept-forward wings than for the swept-back wings. In particular, the effect on maximum lift was substantial for the swept-forward wings and neglible for the swept-back wings.

A comparison is shown in Figure 3 for a swept-back and a swept-forward wing having an aspect ratio of 2.1 and a taper ratio of 2.5. The sweep of the quarter chord lines were 55.8 degrees and -46.6 degrees. The most noticeable difference is the much lower maximum lift for the swept-forward wing. The difference in stability level is primarily a result of the moments being referred to the quarter-chord point of the mean aerodynamic chord for each wing which results in more effective lift forward of the moment reference point for the swept-forward wing.

Tuft studies were made of many of the low-speed planform models. In these tests, small lengths of thread (or tufts) are adhered to the wing surface in such a way that they would align with the local flow direction and thus provide a visual observation of the wing flow patterns. Some examples of results obtained in this manner are shown in Figure 4. The reason for the lower maximum lift for the swept-forward wing is shown on the left, for example. At α of about 24 degrees to 25 degrees, the swept-back wing indicates tip stall but a large region of attached flow still exists. For the swept-forward wing, however, the wing is almost completely stalled.

Some tuft results for an inverse taper wing are also shown in Figure 4. The inverse taper was proposed by Republic for the XF-91 Thundercepter airplane with the thought that the adverse effects of sweep on spanwise flow would be partially offset by the inverse taper so that tip stall would be delayed. The inverse taper also resulted in the outboard wing section being thicker than the inboard section which was also expected to delay tip stall. Tuft studies indicated that the anticipated benefits were not inherent in the inverse taper planform and, in fact, the entire wing was essentially stalled at $\alpha = 22.2^0$. A tip slat was found to greatly improve the tip flow and the device was incorporated on the airplane. A considerable amount of work was done in wind-tunnels tests during the 1940's to improve the flow patterns of swept wings through the use of slats, flaps, spoilers, fences, and so on. The first operational airplane to use a swept wing was the North American P-86 which was originally designed with a straight wing. With new wind-tunnel data available, the design was changed to a 35 degree swept wing with automatic leading-edge slats, and the airplane flew in 1947.

Body-Wing-Tail Studies.- Having determined some of the basic characteristics of swept-wing planforms, it was deemed important to study the characteristics in combination with tail surfaces and a body. An example of a tail position study model is shown in Figure 5. The body for this simplified model was made from a 2- by 4-inch pine board. Results for the model shown as well as for many of the other planforms used in the wing planform studies are presented in reference 3. Because of the unusual flow patterns created by the swept planforms, it was found that the location of an aft tail was a critical matter. The results in reference 3 include extensive surveys of the downwash field behind swept wings and were used as a guide in tail location studies.

Variable-Sweep Studies.- The model that was used in low-speed tests of the Bell X-1 airplane was modified in the mid 1940's to serve as a wind-tunnel test vehicle in the further study of the effects of variable wing sweep for a complete airplane. The modified wings investigated on the X-1 model are shown in Figure 6 and results of the investigation are reported in references 4 and 5. As a result of these wind-tunnel tests, the variable-sweep Bell X-5 research airplane was developed and, later, other variable-sweep airplane designs evolved. The tests with the swept-forward wings, while not done with the X-29 in mind, did provide early information relative to the low speed behavior of such designs.

Other variable-sweep studies in the mid 1950's were directed toward supersonic designs and were instigated, in part, by the British design of Barnes Wallis known as the Swallow. This configuration, shown in Figure 7, as I, together with some Langley concepts shown as II, III, and IV were the forerunners of such concepts as the U.S. supersonic transport, the tactical-fighter TFX which became the F-111, the B-1, and the F-14. The first supersonic tests of these concepts were done with configuration IV and are reported in reference 6.

High-Speed Studies

Transonic Characteristics.- In view of the development of jet propulsion and of the aerodynamic shaping concepts for high speeds, the doorway to supersonic flight was opening in the mid 1940's. Supersonic tunnels were small and scarce--transonic tunnels were nonexistent. Some early techniques for obtaining transonic data included drop tests from high altitudes, rocket model tests, wing-flow tests on airplanes, and transonic bump tests in wind tunnels. The transonic bump technique consisted of placing an airfoil-shaped bump on the floor of a high subsonic speed tunnel so that the resultant flow induced over the bump would become transonic. Models were mounted in the locally induced transonic flow field over the bump either by using semi-span models contoured to fit the surface of the bump or by using complete models sting-mounted just above the surface of the bump.

Some transonic bump results obtained with a semi-span model of a 45 degree swept-wing-tail model (Fig. 8) indicated some of the new aerodynamic phenomena to be encountered. The tail effectiveness indicates a decrease, the effective downwash at the tail essentially disappears, and the longitudinal stability increases. This was an early indication of some approaching supersonic airplane concerns--increasing longitudinal stability with less control power from an aft-mounted tail which could lead to limitations on trim lift and maneuverability.

Supersonic Trim Drag.- This concern became known as the supersonic trim-drag problem and is illustrated in Figure 9. For higher stability levels, greater control deflections are required for trim and the control surface drag produces a trim-drag polar much more severe than the untrimmed-drag polar. The problem tends to worsen as the stability level increases (and, also, as the control effectiveness decreases). The problem was not fully appreciated by some 1950-era designs when performance predictions obtained from insufficient test data were sometimes based on untrimmed characteristics and resulted in significant over-estimates of the performance.

The trim-drag problem can be alleviated by introducing trimming moments without added drag. There have been several ways to achieve this, one of which is the use of body camber as illustrated in Figure 10. With this method, it has been demonstrated that the lift distribution of a symmetrical body can be altered through cambering the body to produce positive increments of pitching moment with no change in drag. Hence, the control requirements for trimming are reduced and the trim drag is less.

Supersonic Directional Stability.- The first supersonic tests of a large-scale model were conducted at Langley in 1948 in the new 4- by 4-foot supersonic pressure tunnel with a model of the Bell X-2 airplane. Tests of the X-2 revealed several problem areas that were to confront supersonic airplanes, one of which was low directional stability. Shown in Figure 11 is the directional stability characteristics for the X-2 configuration with the vertical tail on and off at $\alpha = 0^0$ as determined by several test techniques. The results show an increase in directional stability at subsonic speeds followed by a rapid decrease in directional stability at supersonic speeds. The increment in directional stability followed the vertical tail lift-curve slope variation that would be expected with Mach number and indicated that further increase in speed would probably result in still lower directional stability. This problem for the X-2 was documented in several reports (see refs. 7 and 8, for example). Unfortunately, an X-2 airplane was lost in an accident due, in part, to the low level of directional stability.

This problem did plague many early supersonic airplane designs. Another example was the North American F-100, several of which were lost in accidents that appeared to be related to low-directional stability. A wind tunnel investigation was undertaken to study the problem and the loss of directional stability was confirmed (ref. 9). The F-100 directional stability variation with angle of attack at M = 1.6 is shown in Figure 12. These tests revealed some additional sources of directional stability problems other than that associated with the decrease in tail lift-curve slope at supersonic speeds. For example, the tail contribution to directional stability (increment between tail-on and tail-off) is reasonably large, however, much of the tail contribution is used in simply overcoming the large instability of the body-wing (VT off) and, with only a modest decrease in vertical tail effectiveness, static directional instability was reached at $\alpha = 16^0$. The instability of the body for supersonic designs had not previously been fully appreciated and was often an unexpected factor contributing to static and dynamic stability problems of many supersonic configurations. The source of this instability was, in general, the long slender bodies desired for low drag and the far-aft center-of-gravity locations caused by aft-mounted jet engines. The loss in tail contribution that did occur with increasing angle of attack was the result of an adverse sidewash angle at the tail that was induced by the wake and vortex flows from the forebody and from the wing body juncture.

Insofar as the F-100 was concerned, the most likely fix to the directional stability deficiency was to enlarge the tail area by 27 percent so that the tail contribution was increased and the angle of attack at which static directional instability occurred was increased to 21 degrees (Fig. 12). The F-100 tests did reveal some other factors that were not seriously considered previously and several general studies were undertaken to provide a better understanding of the supersonic stability phenomena. One of the additional factors, as revealed by the F-100 tests, is illustrated in Figure 13. This factor is the variation of C_n with β. This factor had often been neglected in wind-tunnel tests or, at best, looked at for only small angles of β. The F-100 results, however, indicated a highly nonlinear variation of C_n with β which, even at $\alpha = 0^0$, showed an unstable variation at $\beta > 8^0$. This characteristic was again dictated by the highly unstable tail-off configuration, and, even though the tail contribution was increasing, lead to a directionally unstable condition. At $\alpha = 16^0$, the condition is even more serious (Fig. 13).

Another possible problem in wind-tunnel data interpretation is illustrated in Figure 14 where the directional stability variation with α for the F-100 at M = 1.6 is shown for the body axis and the stability axis systems. The body axis data correspond to that previously discussed and indicate static instability above $\alpha = 16^0$. The results computed for the stability axis, however, indicates no directional instability at all. This results from the fact that, with the stability axis system, a component of roll is transferred into yaw and for conditions of large rolling moments and small yawing moments can result in a substantial difference in the value of C_{n_β}. A complete analysis on either axis system, properly done, will reveal the same flight characteristics. However, a cursory examination of the wind-tunnel data could lead to erroneous conclusions. Directional stability investigations of many types were undertaken to add insight to the problem. These studies include:

- o Tail planform effects.
- o Ventral fins.
- o Tail longitudinal location.
- o Twin or multiple tails.
- o Wing location effects.
- o Body cross-section effects.
- o Folding fins and folding wing tips.
- o Forebody fences or strakes.
- o Horizontal tail location and deflection.

An example of the effects of a forebody strake is shown in Figure 15. The purpose of the strake was to modify the crossflow over the forebody at combined angles of attack and sideslip in such a way as to provide a stabilizing directional moment. Strakes were found to be quite effective in reducing the forebody instability and, as shown in Figure 15, the tail-off instability was reduced to about zero above $\alpha = 16^0$. As a result, the tail-on configuration realized an increase in the angle of attack for the onset of instability from about 14 degrees to 23 degrees.

A generic model for general stability research is shown in Figure 16. Used extensively for both longitudinal and lateral stability investigations, the model had previsions for testing the effects of:

- o Wing planform.
- o Wing vertical location.
- o Wing geometric dihedral.
- o Horizontal tail planform.
- o Horizontal tail vertical location.
- o Horizontal tail incidence.
- o Vertical and ventral fins.
- o Body cross section.

Examples of the large bank of data accumulated for this model are presented in references 10 through 12.

Supersonic Pitch-up.- Another major problem for supersonic airplanes was the phenomena of pitch-up, or longitudinal instability at high angles of attack. The problem at low speeds had already been encountered, particularly for the swept-wing designs. Other factors, many of which were investigated with the general stability research model, were the instability trend of long, slender forebodies and the loss of tail effectiveness that occurred when an aft-horizontal tail was immersed in the wing-flow field. These tests clearly showed the nature of supersonic interference flows that resulted in large losses in local dynamic pressure in the expansion field of a lifting surface and large increases in local dynamic pressure in the compression field. Designs in which the tail was high relative to the wing were especially susceptible to pitch-up--such as the Lockheed F-104, McDonnell F-101, and McDonnell F4. The F-104 saw only limited service in the U.S.; the F-101 flew within a somewhat restrictive flight envelope in performing reconnaissance missions; the F4, however, which was used extensively in a number of roles, underwent a number of modifications developed from wind-tunnel tests for the purpose of improving the stability characteristics. The wind-tunnel developed modifications included the leading-edge extension, turned-up wing tips, and tail anhedral.

Supersonic Control Effectiveness.- Another phenomena encountered in the testing of supersonic configurations was a loss in control power for conventional plain flap-type controls. This was found in roll control tests of the X-2 model when the aileron effectiveness reversed in the transonic region and remained very low at supersonic speeds (Fig. 17). The problem was caused by flow separation over the rather large trailing-edge angle of the 10-percent thick circular arc airfoil. Wind-tunnel tests indicated that the separation could be retarded and the reversal eliminated by thickening the aileron trailing edge to reduce the trailing-edge angle. Several thicknesses up to a full-slab aileron were tried and progressive increases in thickness progressively improved the effectiveness. A compromise fix adopted by the X-2 was an aileron having a trailing-edge thickness half that of the hinge-line thickness ($t = 0.5$). Recognition of this problem lead to greater application of spoilers for supersonic roll control and eventually to the use of differential deflection of horizontal tails for roll control. The latter solution was reasonably easy to adopt since the all-moving horizontal tail had already come into use as a needed more powerful surface for pitch control.

Canard Airplane Studies

Generic Research Model.- With the Air Force request for a new strategic bomber in the mid 1950's, some canard concepts (tail forward) were being considered. Up until that time the NACA research programs for supersonic airplanes had been for more conventional types and canard-type arrangements had received little attention. The general research stability model was quickly converted to serve as a generic canard research model in order to provide information that would be needed. One version of the model with 70-degree delta surfaces is shown in Figure 18. The model could be arranged to provide studies that included:

- Wing planform.
- Wing vertical location.
- Canard planform.
- Canard size.
- Forebody length.
- Tail arrangements, single and twin.

Some of the results of these studies are presented in references 13 through 15.

70-Degree Delta Canard.- Some effects of wing and vertical tail arrangement on the longitudinal trim characteristics for the 70-degree delta-canard airplane are shown in Figure 19 for $M = 2$. These results show a marked effect of wing vertical location with the low wing being substantially better than the high wing due to less interference at the wing from the canard flow field. The wing effects are essentially the same for the single or twin tails versions but the higher drag for the twin tails results in lower values of L/D.

The directional characteristics for the low wing canard arrangement at M = 2 are shown in Figure 20. With the single vertical tail, the directional stability decreases rapidly with increasing angle of attack and indicates some adverse effect from the presence of the canard. For the twin-tail arrangement, however, the directional stability is improved both with and without the canard. A substantial stabilizing increment due to the canards occurs at about $\alpha = 4^0$ as an indication that the twin tails are located outboard of the canard vortex and are in a favorable sidewash field.

60-Degree Delta Configuration.- Some results at M = 2 for a 60-degree delta-wing airplane show a comparison of the longitudinal trim characteristics with and without a canard surface (Fig. 21). The static margin (S.M.) is constant at 10 percent for this comparison. The canard arrangement illustrates the advantages of a lifting control surface with a long moment arm in that the control effectiveness is higher, higher trim lift is obtainable, and the maximum value of L/D is higher. The implications are that such a configuration, compared to the tailless delta, should be more maneuverable and, in addition, would retain the wing trailing edge for flaps.

X-2 Canard Configurations.- Because of the high stability levels and associated trimming problems of conventional aft-tail designs, consideration was given occasionally to the possibility of adding a canard surface as a third surface to such designs. Tunnel tests of the X-2 model with an added canard surface were made and the results (Fig. 22) at M = 1.9 indicated a substantial increase in trim lift compared to the basic configuration. What might have been one of the first three-surface configurations was never adapted to the airplane, however.

Area Ruling

Transonic Area Rule.- In the early 1950's, the wind tunnel was being used extensively in the development and verification of the transonic area rule. The problem of the transonic drag rise, caused by the compressibility of air, plagued many airplanes that were experiencing difficulty in achieving supersonic speeds. Richard T. Whitcomb, through some physics reasoning and wind tunnel experimentation, began to develop wing-body-tail shapes that, in aggregate, would present less of a disturbance to the surrounding air. This was done through a combination of contouring and surface shaping as well as through the judicious placement of components. The results of these experiments were somewhat revolutionary in that some designs that might have been abandoned were salvaged. The Convair F-102 is a classic example since, in its initial flight tests, it was found to be incapable of negotiating the transonic region and production was halted. Whitcomb applied some cut-and-try revisions to the shape and these revisions, together with some other modifications, succeeded in getting the airplane through the transonic region with relative ease some 117 days after the program had been halted.

Many designs of that era were revised to account for area ruling such as the Republic F-105, Convair F-106, Chance Vought F8U, and Grumman F11F. The feature was also incorporated in the Convair B-58 bomber.

Supersonic Area Rule.- The transonic area rule was followed closely by the supersonic area rule. With this revision, the area, or volume distribution, was determined along Mach planes for a specified Mach number so that the developed shape would be that as "seen" by the air stream. Since the advent of area ruling, essentially all designs, both here and abroad, have taken the concept into consideration early in the design cycle.

Missile Research

Much missile research information became available to the U.S., primarily from German sources, following World War II. Little or no experimental data was available from U.S. sources and some early U.S. designs such as the Nike Ajax air-defense missile were developed with only limited information. When flight tests of the Nike Ajax revealed some high-altitude control difficulties, referred to as low-q tumbling, a research missile model was assembled at NACA-Langley to study the problem. Some results at M = 2 for a model representative of the Nike Ajax revealed that the low-q tumbling was a case of pitch-up (Fig. 23) that occurred near $\alpha = 10^{0}$. The pitch-up was found to be predominately a result of the instability of the extremely long body.

The research model was used to study the effects of body length (Fig. 24). Other general research missile models were subsequently built and tested for extensive studies of such things as:

- o Wing planform and location.
- o Tail planform and location.
- o Forebody shape.
- o Body cross section.

An extensive data bank was established that is still in use.

Inlet Effects

Another item of importance is that of inlet flow simulation for models of air-breathing vehicles. Early supersonic wind tunnels were quite small and flow-through models with proper open inlets and exits were virtually impossible to build. An early indication of this potential problem came with the Chance Vought Regulus II supersonic cruise missile. The missile, which incorporated an underslung "sugar-scoop" inlet, was developed with the aid of wind-tunnel tests of a small-scale model in which the inlet was faired over. Flight tests subsequently indicated a need for greater longitudinal control power for trimming than had been anticipated from the tunnel tests. New tests were made in a larger tunnel at Langley using a new larger model with an open inlet and flow-through ducts. These tests indicated substantially greater negative values of pitching-moment for a given angle of attack than did the original tests and, hence, greater trimming requirements were imposed. With the inlets faired, the lower surface of the body was reshaped with a negative camber contour that resulted in positive increments of pitching moment.

An example is shown in Figure 25 of an air-breathing missile with a chin inlet. Tests with the inlet both opened and closed at M = 2.86 show a large positive shift in C_m when the inlet is faired because of an effective recontouring of the underside of the body. There is also an attendant increase in drag due to the pressure drag on the fairing.

There have been some cases in which fairing of inlets had only a minor effect on test results. These cases have occurred with simple nose inlets or with symmetrically-mounted side inlets. Generally speaking, however, extreme care should be taken in the manner by which model airflow is taken into account.

Optimum High-Speed Body Shapes

With the advent of the U.S. space program in the late 1950's (and the creation of NASA from NACA in 1958), an interest in optimum body shapes for efficent supersonic and hypersonic flight was renewed. Such shapes could be used for high-speed airplanes and missiles as well as for lifting-body reentry space concepts. A considerable amount of such data were generated in the late 1950's and during the 1960's with a view to developing concepts capable of operating over a wide range of speed and altitude (earth-to-orbit and return) with consideration given to aerodynamic efficiency, volumetric efficiency, structural integrity, and so on. Much of these data have been summarized and are contained in references 16 to 18. While being relevant to the basic research program of the mid 1960's, these data are relevant to some current development programs. Providing such lead time between basic research and potential application is one of the prime advantages of wind-tunnel testing.

EPILOGUE

The purpose of this paper was to recount some of the milestone events involving the use of wind tunnels in the development and analysis of airplanes and missiles since World War II. It would be presumptuous to think that all important events could be covered in one relatively short paper. However, it is believed that enough evidence is presented to indicate that wind-tunnel experimentation has played a very important part in discovering new phenomena, in explaining some phenomena, in developing new systems, and in providing early performance assessments for a wide variety of steadily improved airplanes and missiles.

Among the main developments resulting from wind-tunnel experimentation since World War II have been:

- o Understanding and application of swept wings.
- o Use of variable wing sweep.
- o Insight and resolution of problems related to supersonic flight such as inadequate directional stability; excessive longitudinal stability; trim

drag; inadequate control effectiveness; effects of interference flow fields; etc.

- o Importance of component arrangement as related to drag, stability, control, and so on.
- o Drag reduction and improved efficiency through area ruling.
- o Use of canard configurations.
- o Insight into missile aerodynamics.
- o Optimum high-speed body shaping.

Key to the success of the contribution of wind tunnels to the advancement of aerodynamics is, of course, the expertise of the researchers who develop tunnels and use them. The evidence is clear that the proper use of wind tunnels has advanced the science of aerodynamic research in a manner that could not otherwise be achieved. The record is such that there is no reason to doubt that the wind tunnel will continue to be vital to advancements yet to come.

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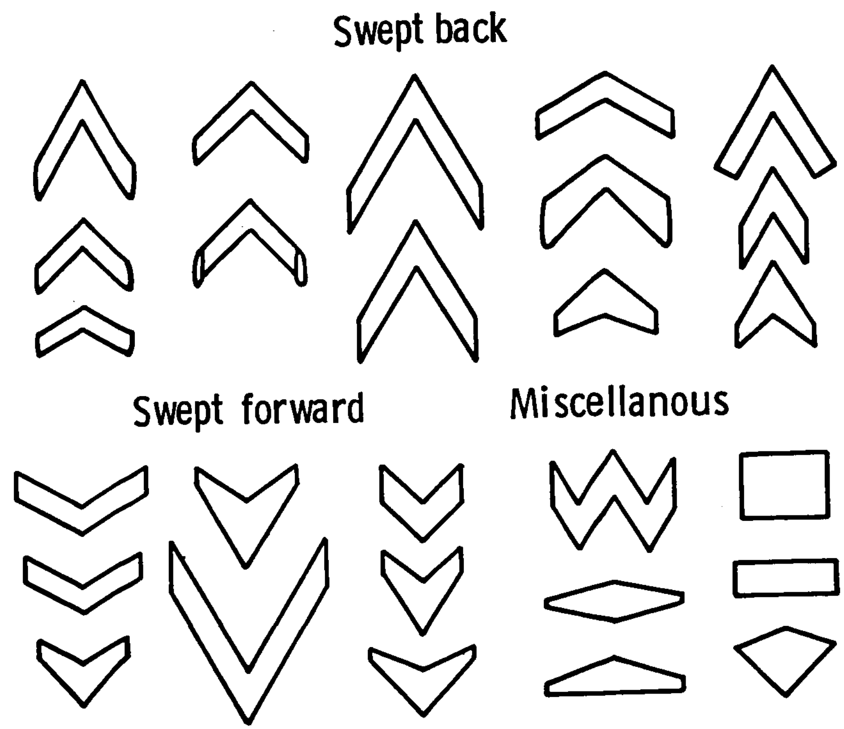

Figure 1.- Low speed planform models.

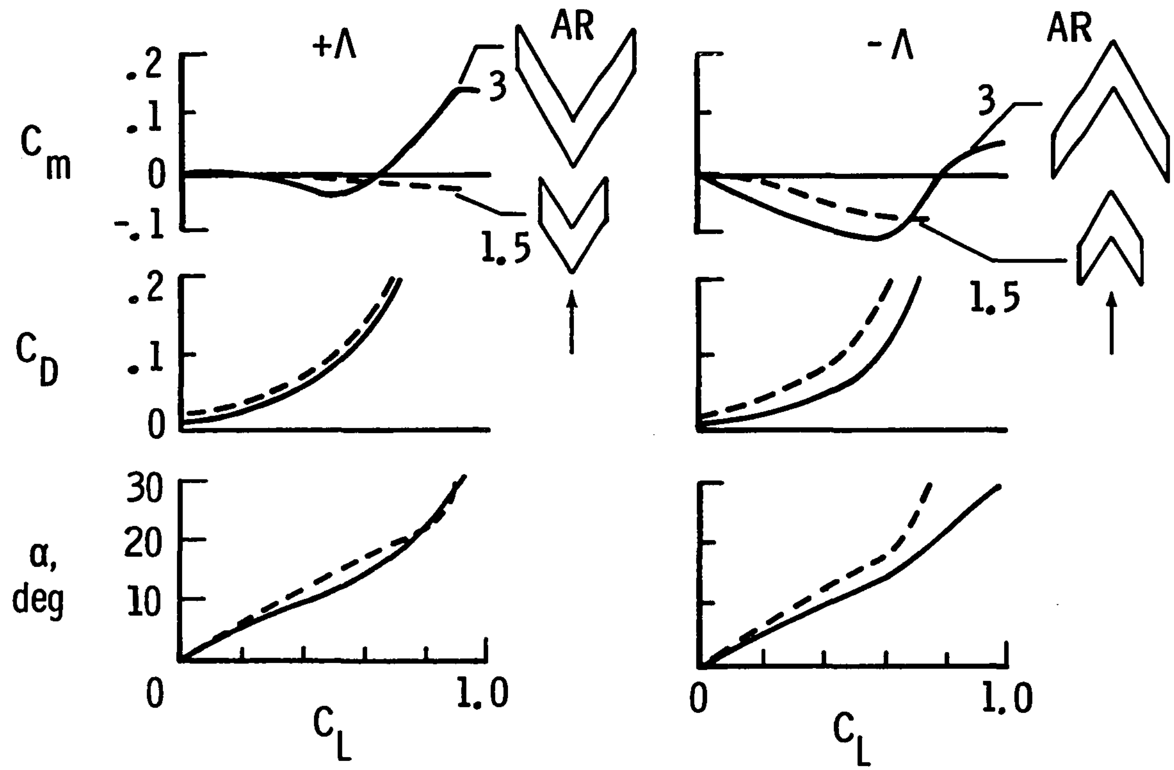

Figure 2.- Low speed longitudinal characteristics for 60° swept wings.
$\lambda = 1.0$.

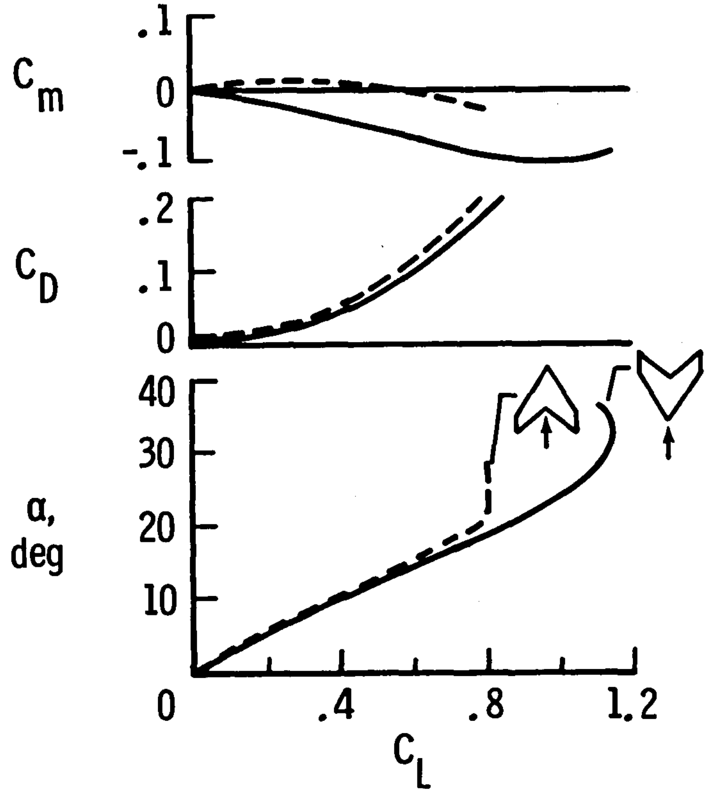

Figure 3.- Low speed longitudinal characteristics for a swept back and a swept forward wing. AR = 2.1, λ = 2.5.

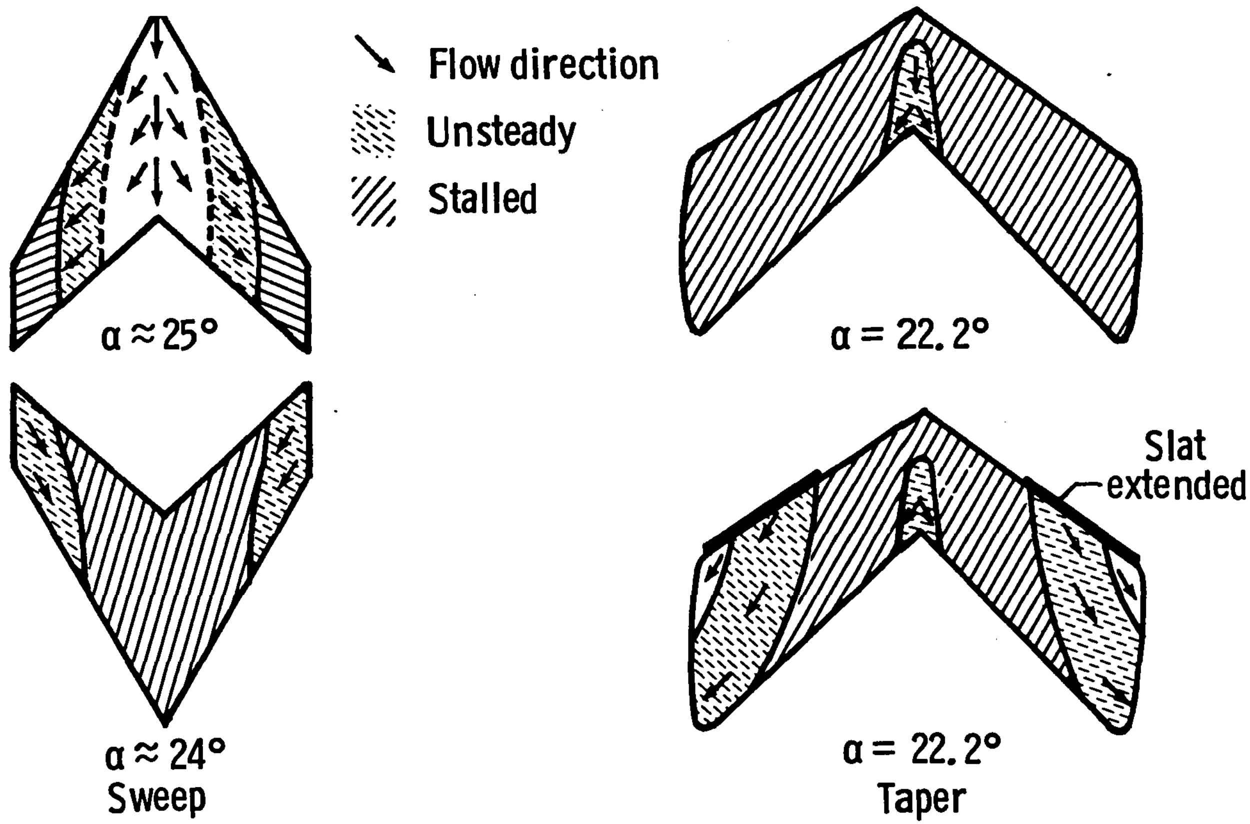

Figure 4.- Tuft studies of flow patterns for swept wings at low speed.

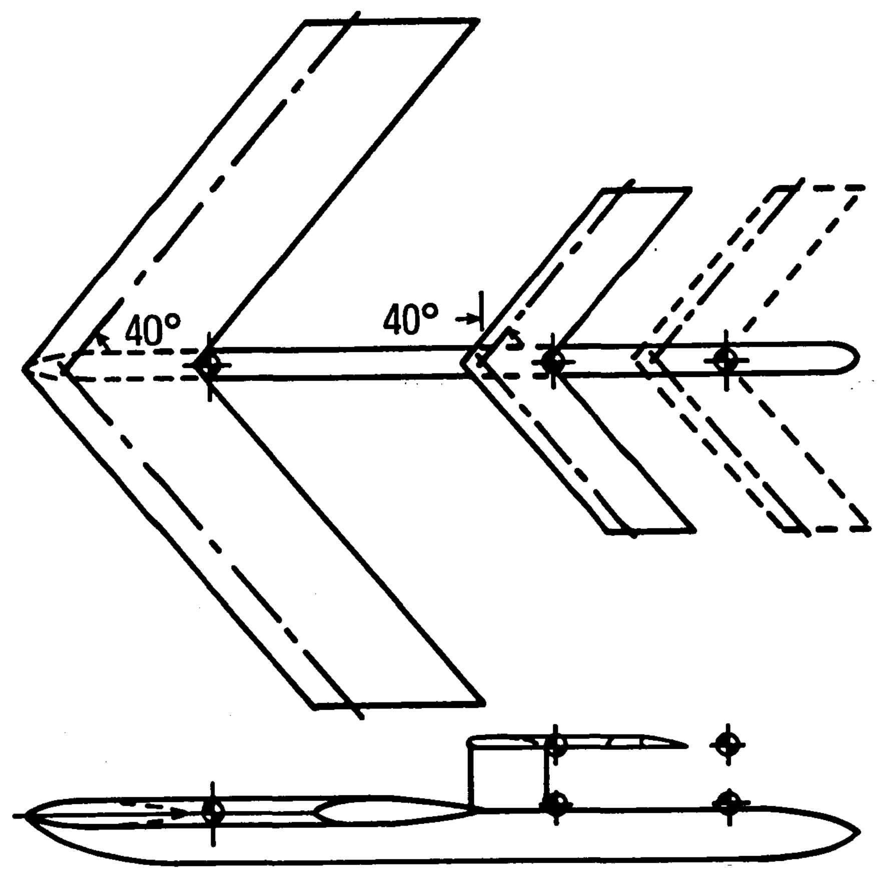

Figure 5.- Low speed tail position study model.

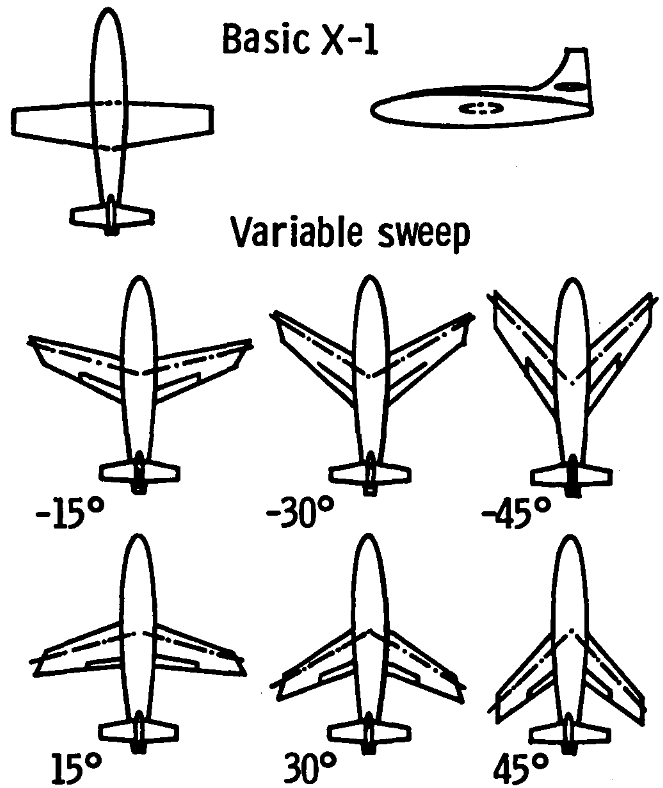

Figure 6.- Low speed wind tunnel model of the X-1 airplane with variable sweep wing.

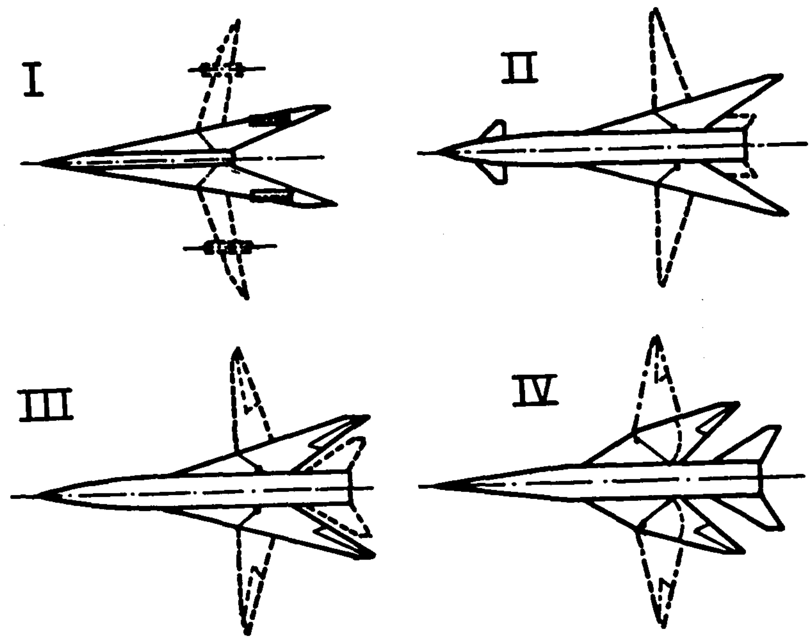

Figure 7.- Variable sweep configuration study models.

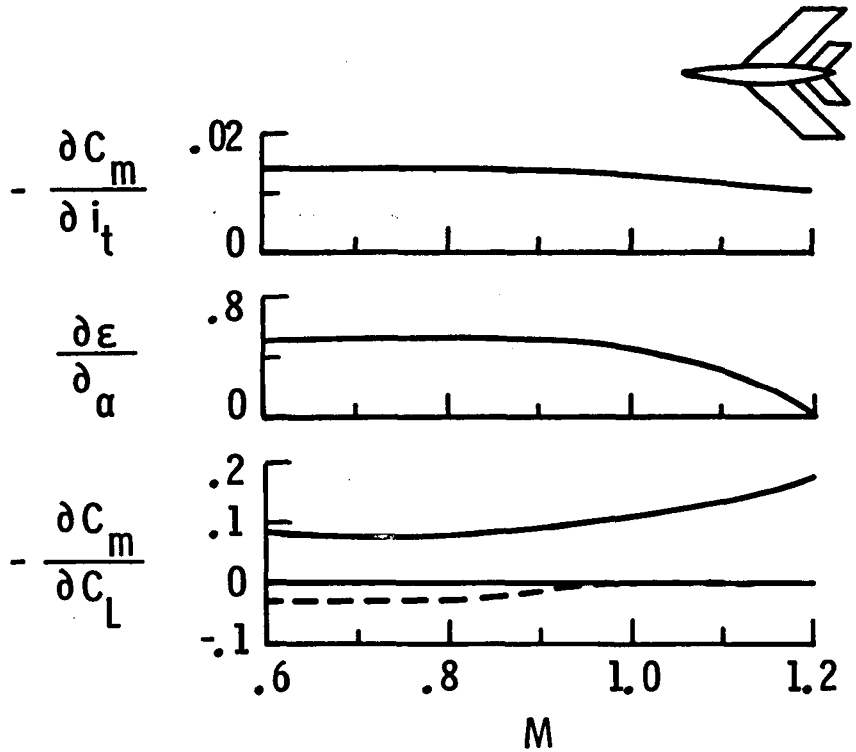

Figure 8.- Longitudinal characteristics for a 45° wing-tail airplane model from transonic bump tests.

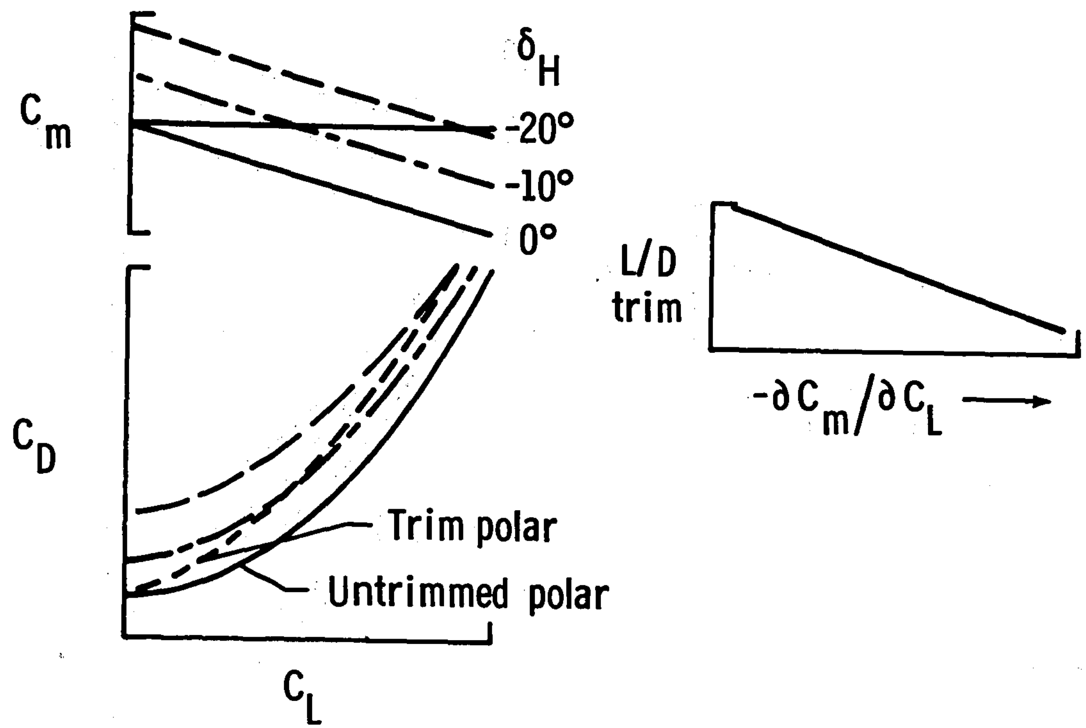

Figure 9.- Supersonic trim drag.

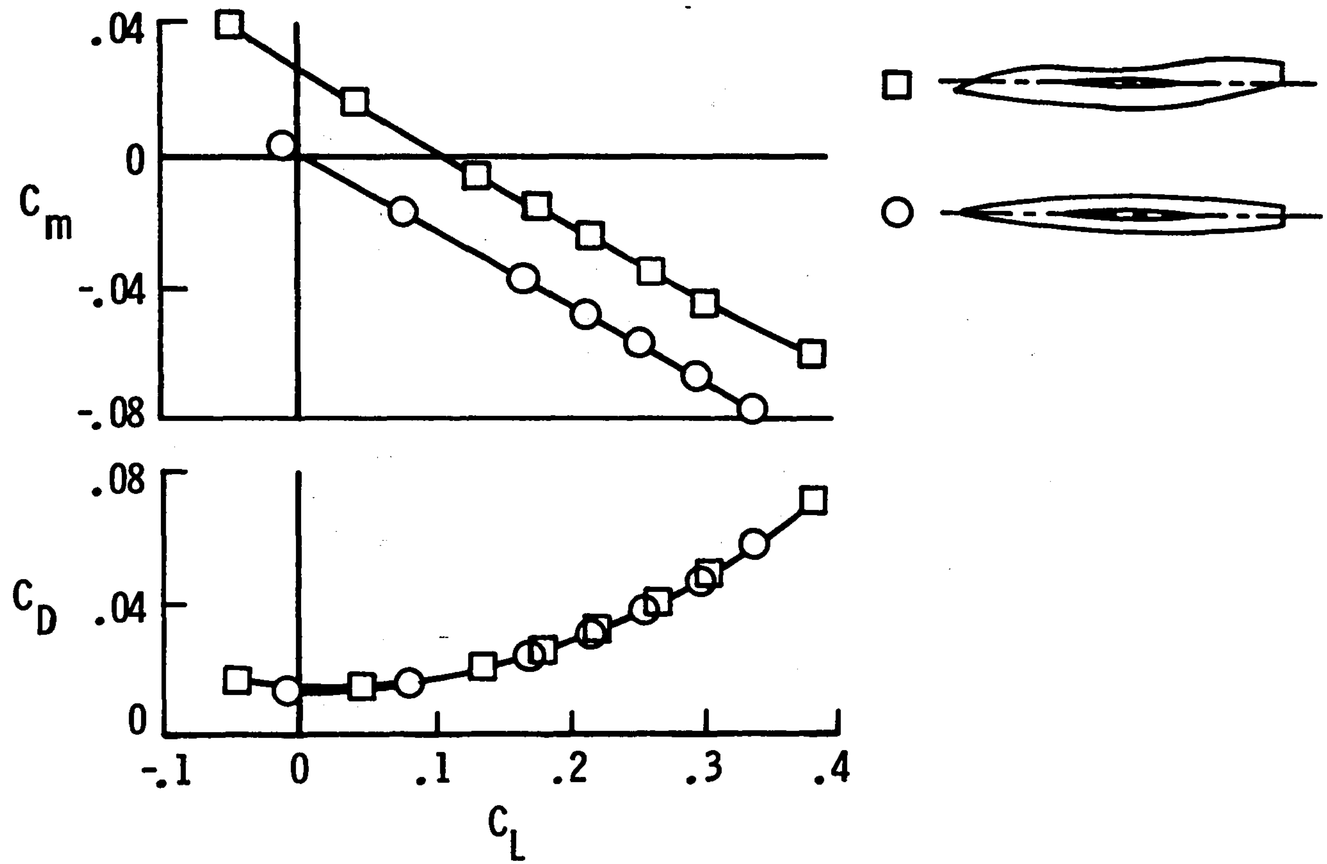

Figure 10.- Effect of body camber on longitudinal trim, M = 1.6.

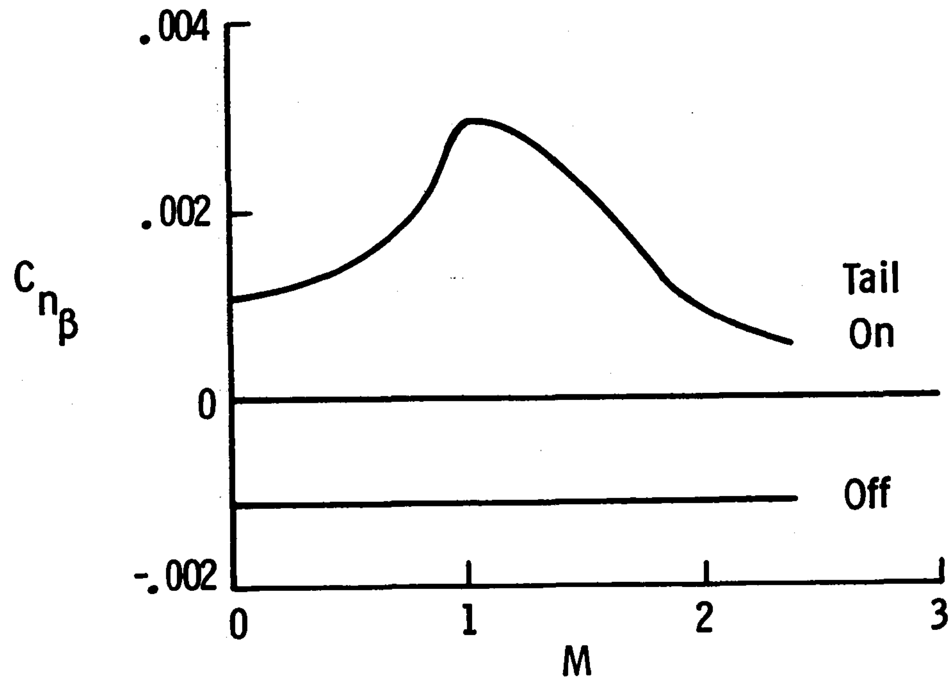

Figure 11.- Directional stability characteristics for the X-2, $\alpha = 0^0$.

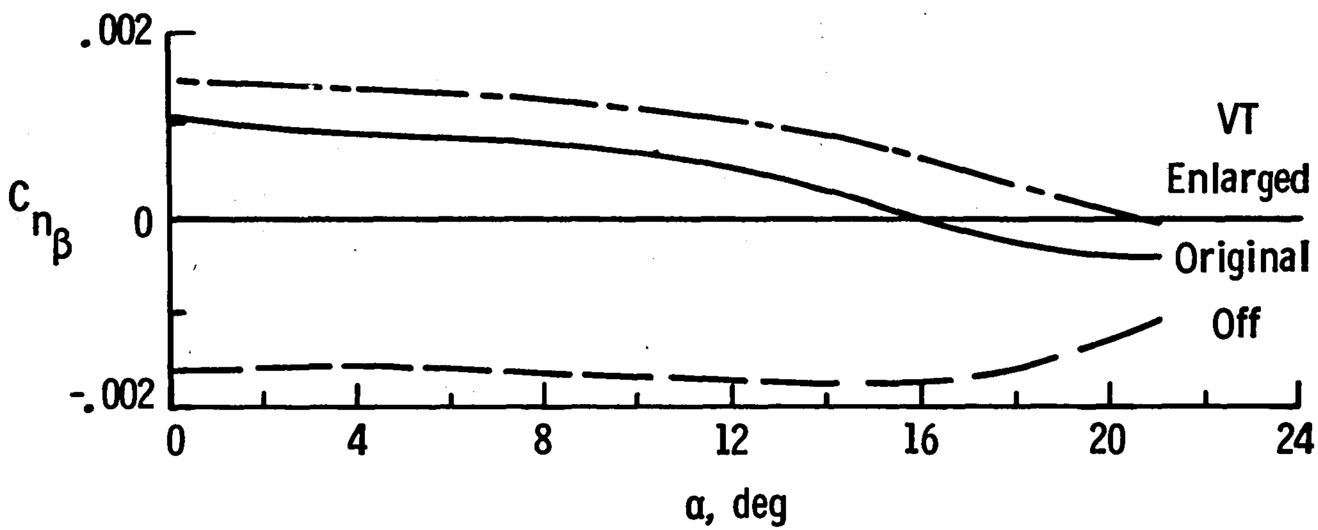

Figure 12.- Directional stability characteristics for the F-100, M = 1.6.

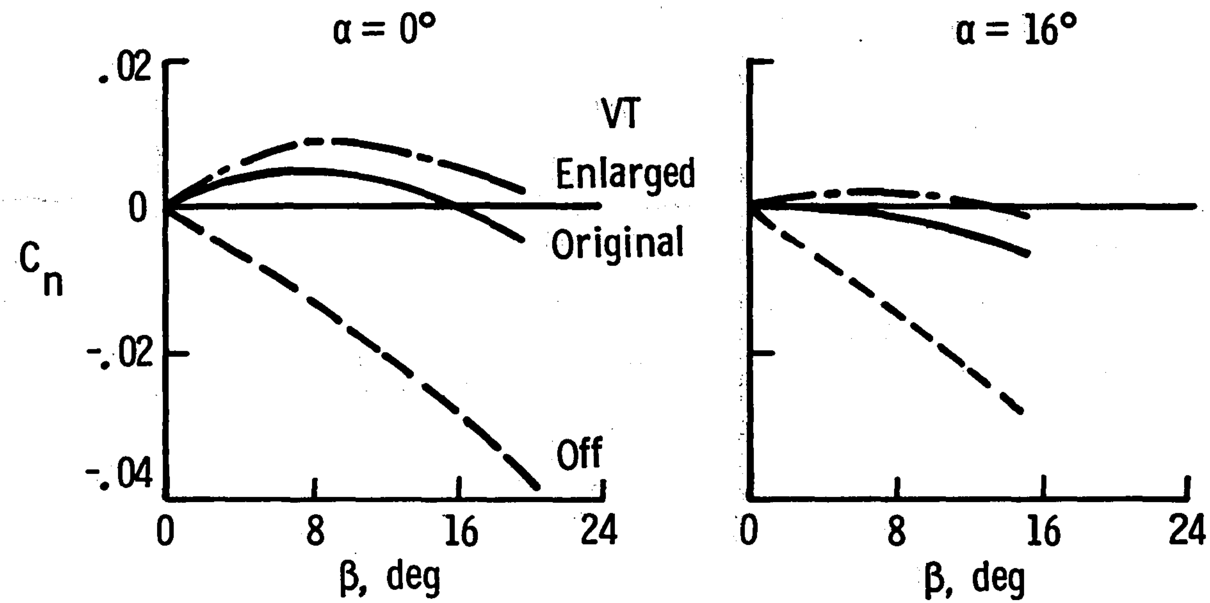

Figure 13.- Variation of C_n with β for the F-100, M = 1.6.

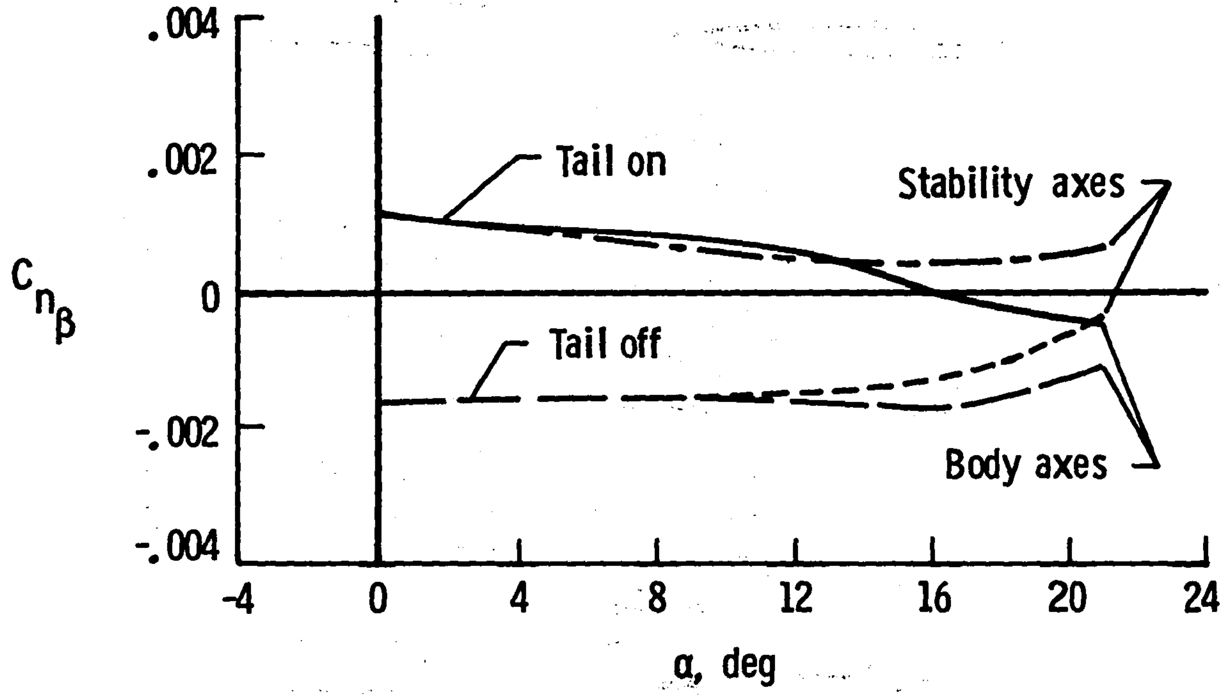

Figure 14.- Effect of axis system on directional stability characteristics of the F-100, M = 1.6.

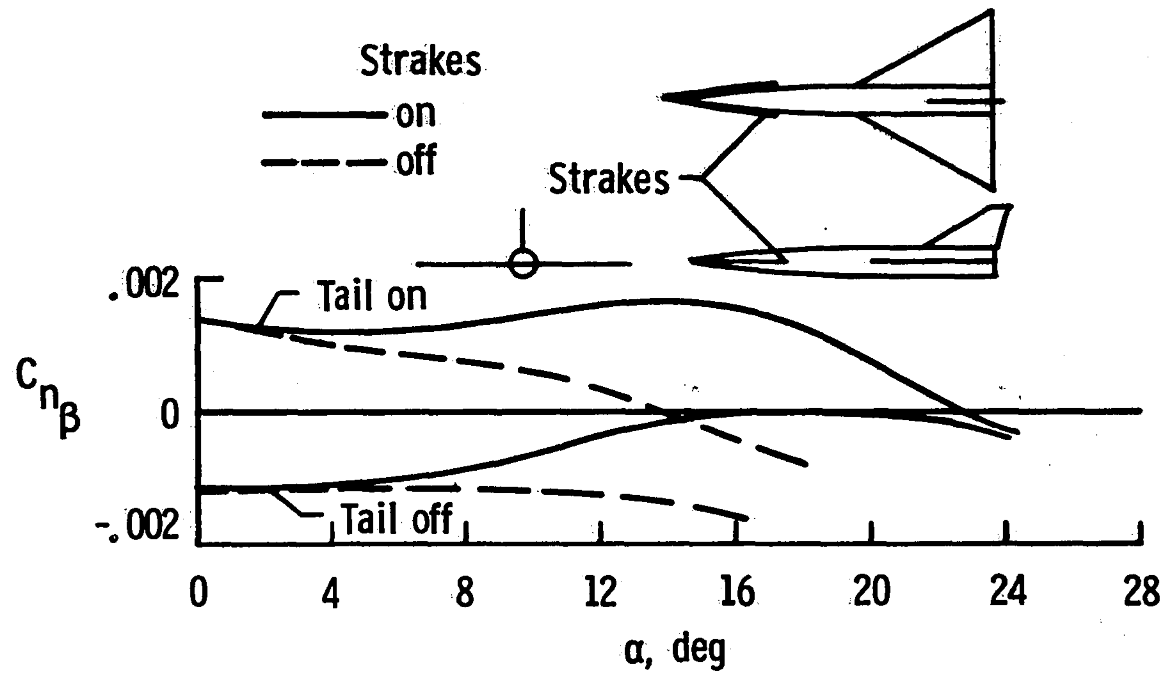

Figure 15.- Effect of forebody strakes on directional stability, M = 2.

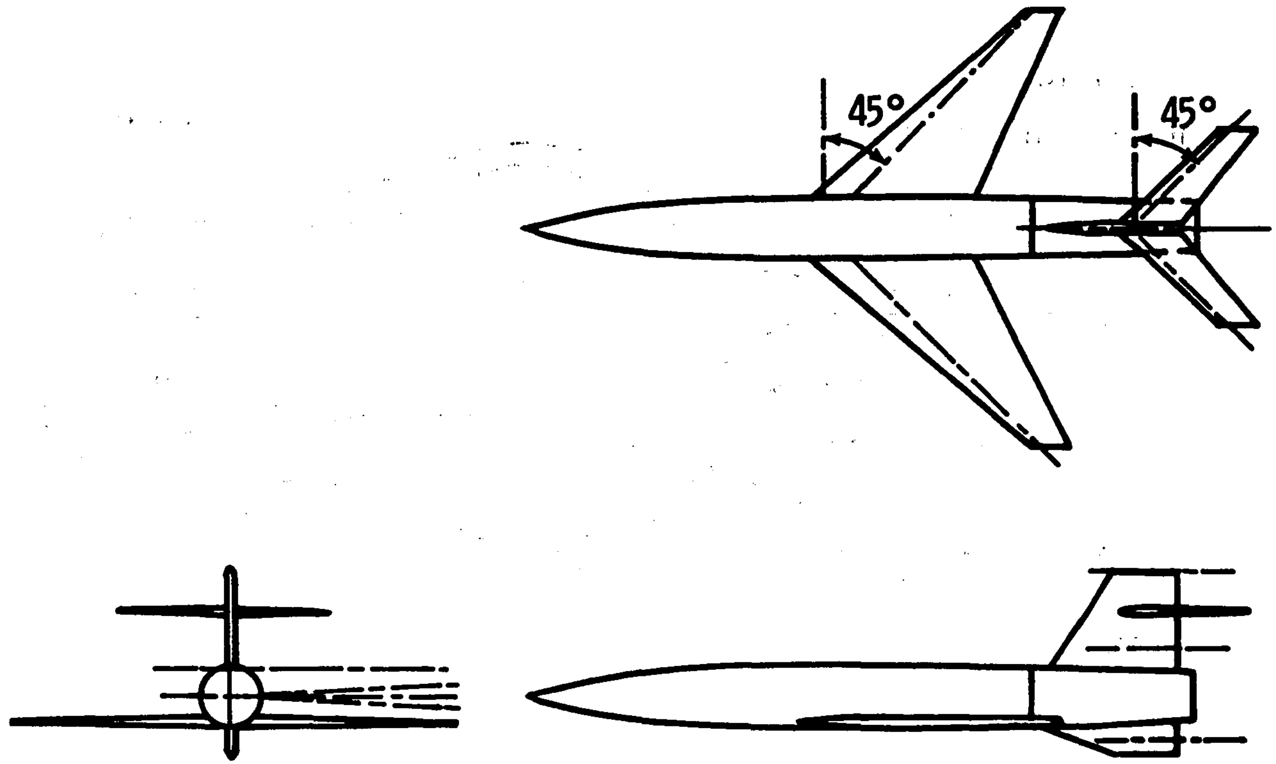

Figure 16.- General stability research model.

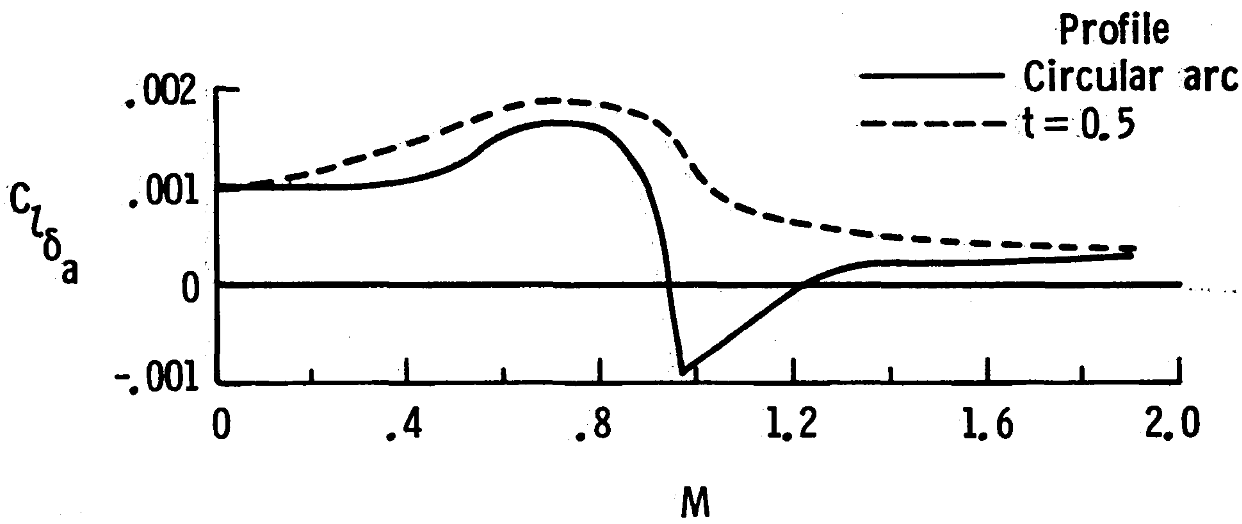

Figure 17.- Roll control effectiveness for the X-2 model, $\alpha = 0^{0}$.

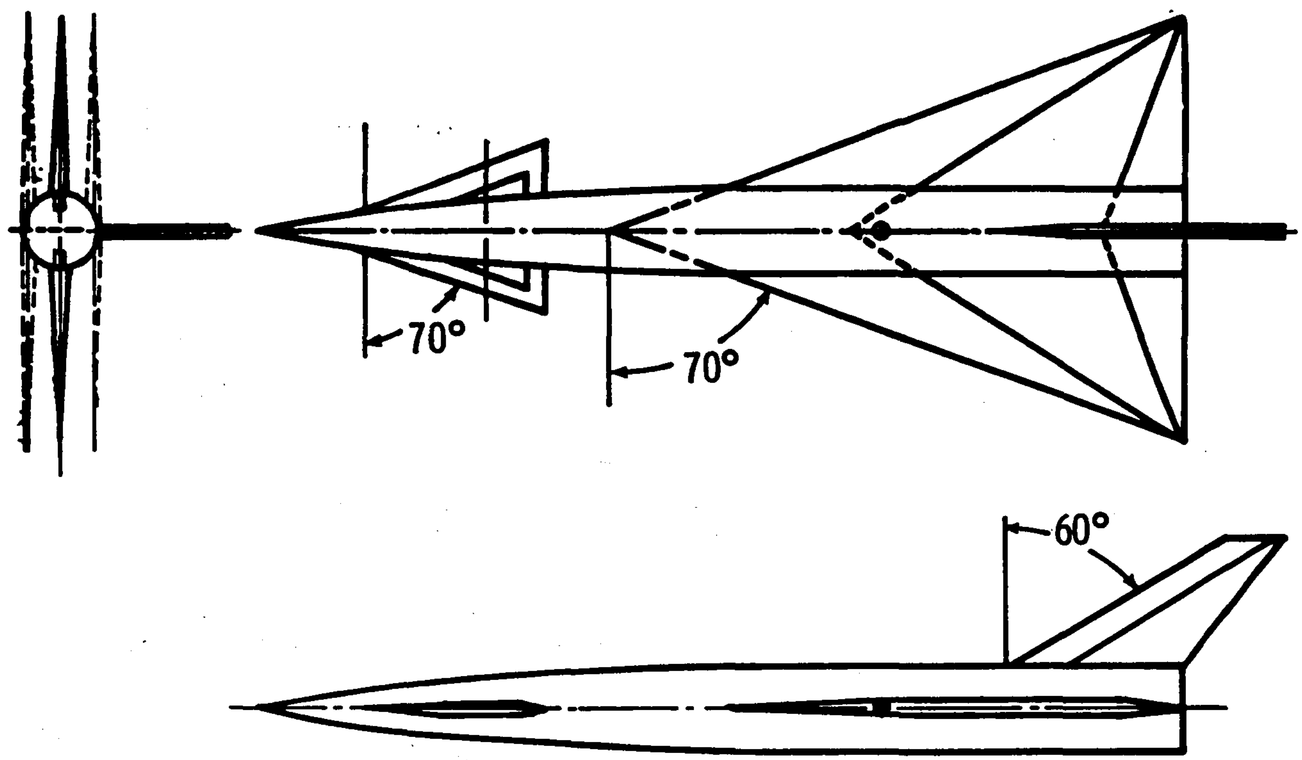

Figure 18.- Canard research model.

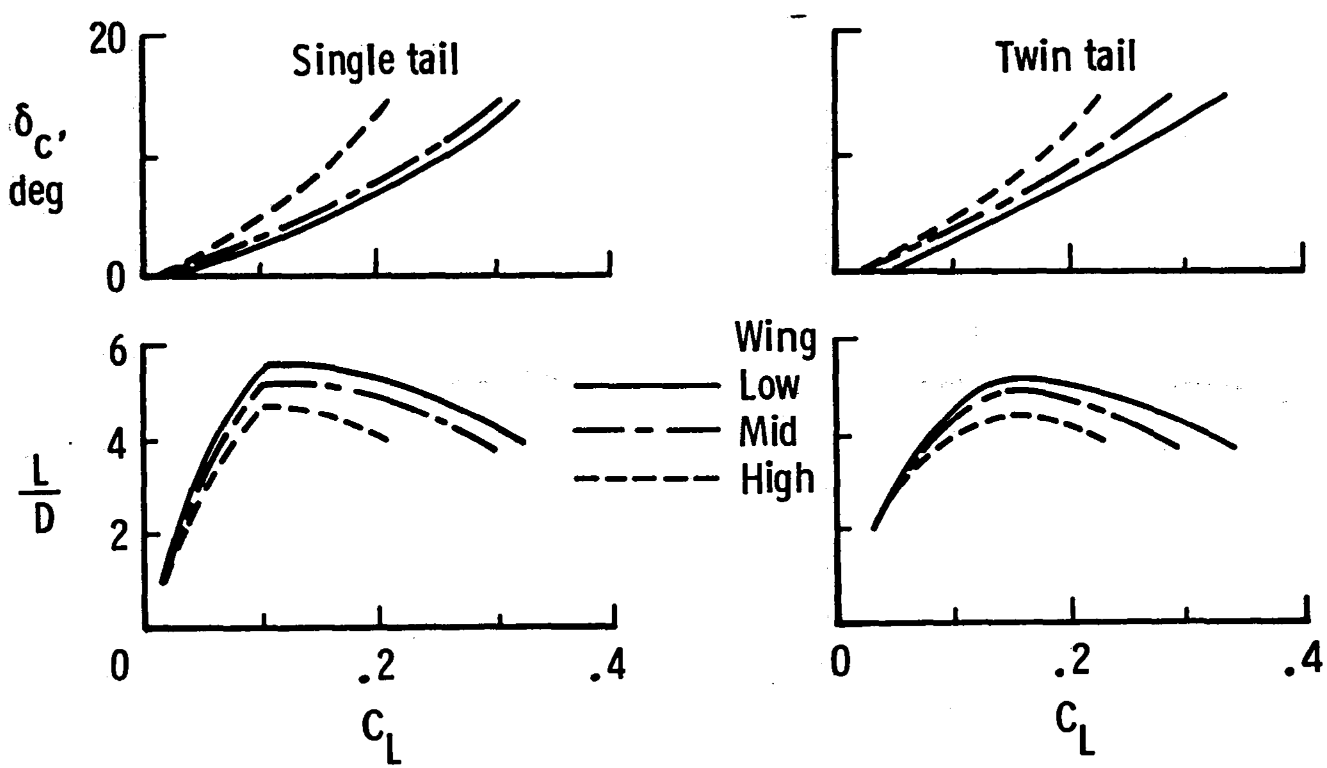

Figure 19.- Longitudinal trim characteristics for a 70° delta canard airplane model, M = 2.

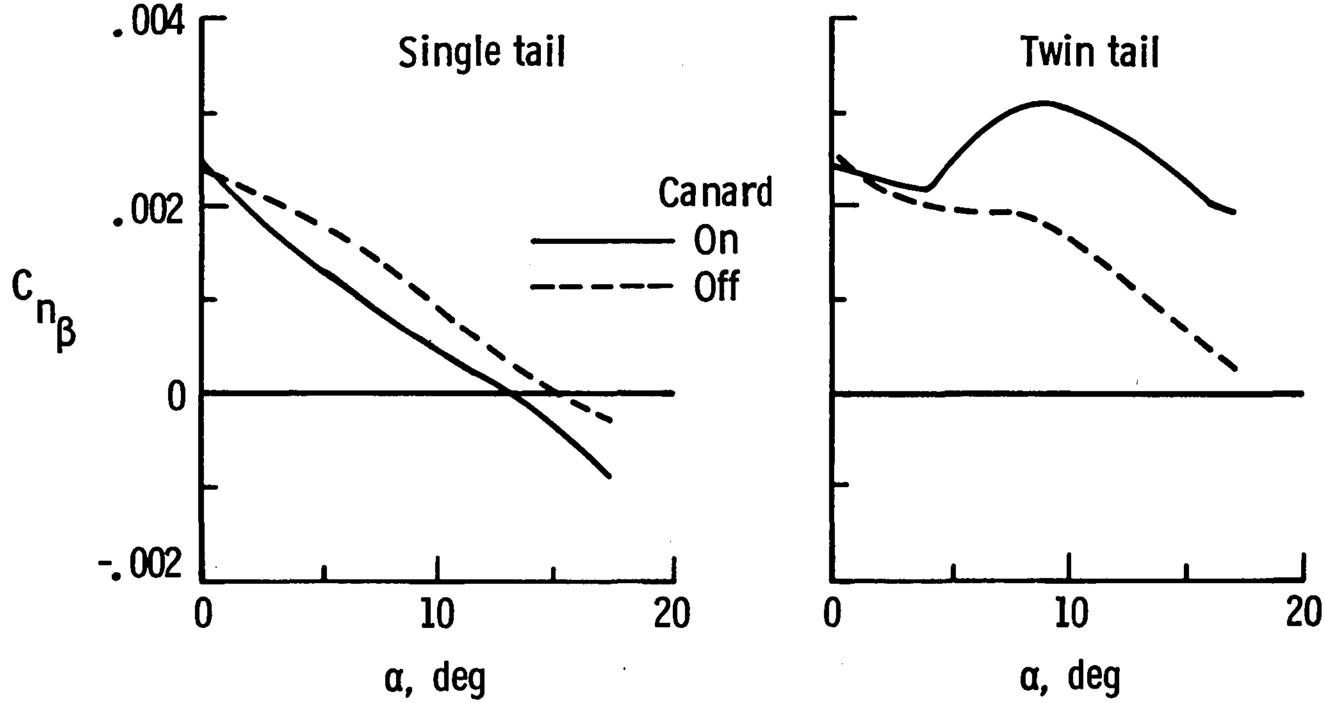

Figure 20.- Directional stability characteristics for a 70° delta canard airplane model, M = 2, low wing.

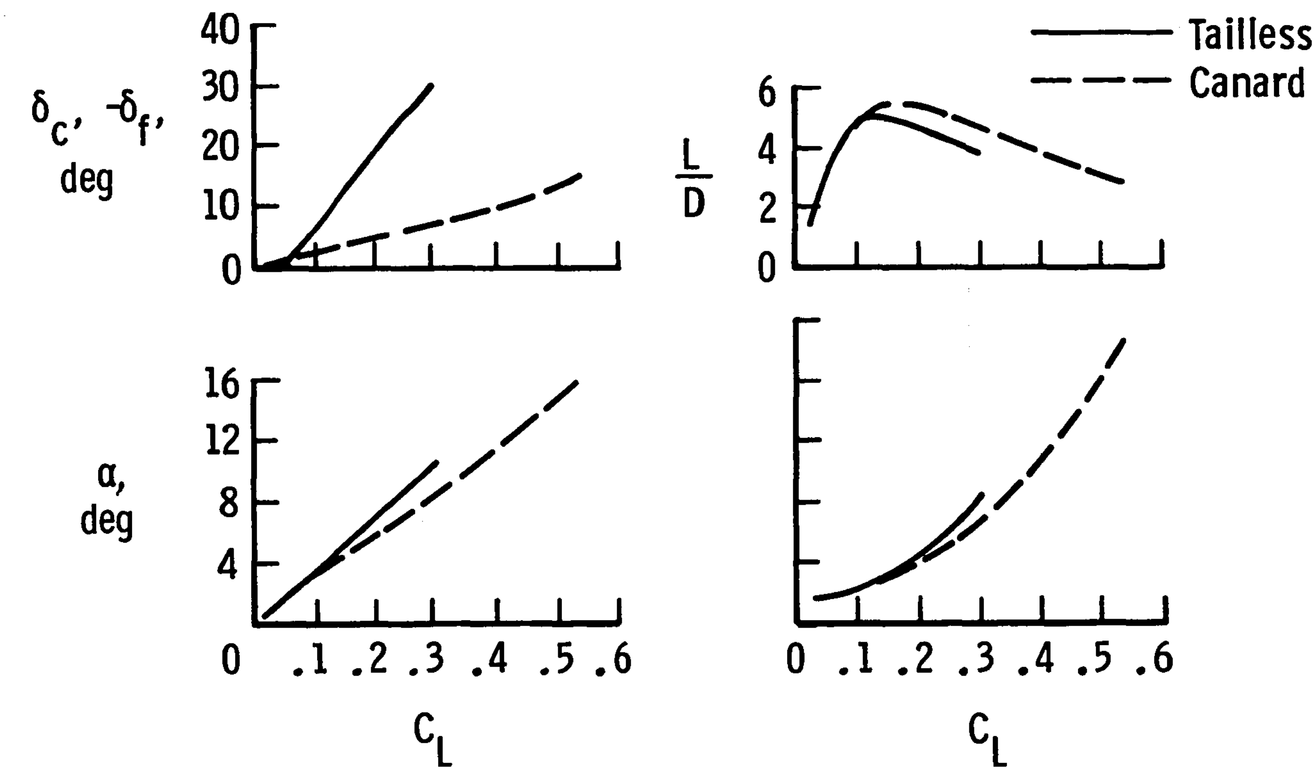

Figure 21.- Longitudinal trim characteristics for tailless and canard 60° delta wing airplane model, M = 2, static margin of 10 percent.

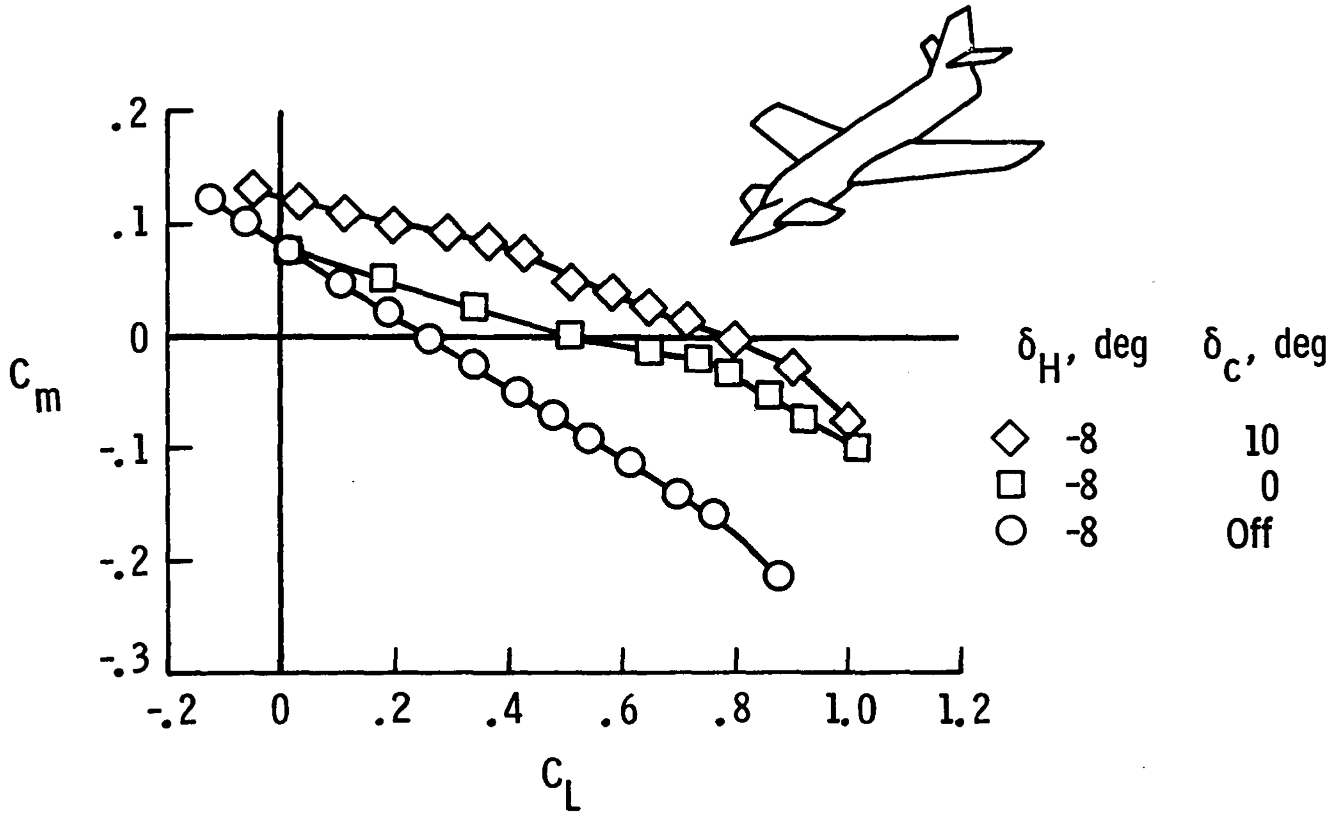

Figure 22.- Effect of canard on longitudinal trim for X-2 model, M = 1.9.

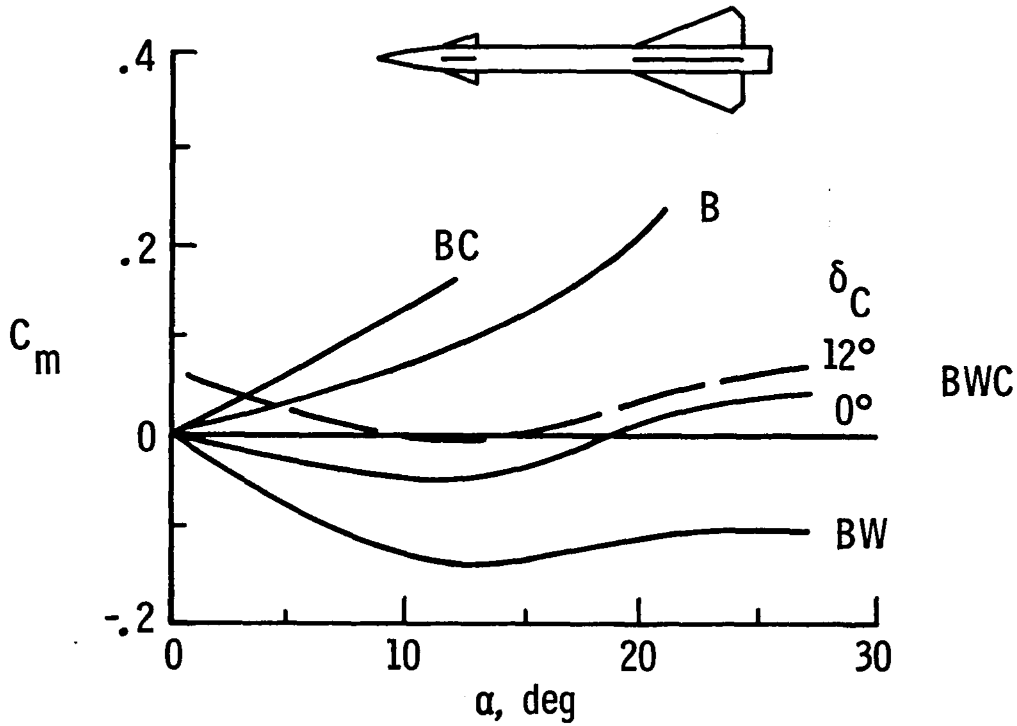

Figure 23.- Pitching moment characteristics for delta-wing-canard missile model, M = 2, l/d = 19.1, c.g. = 0.67l.

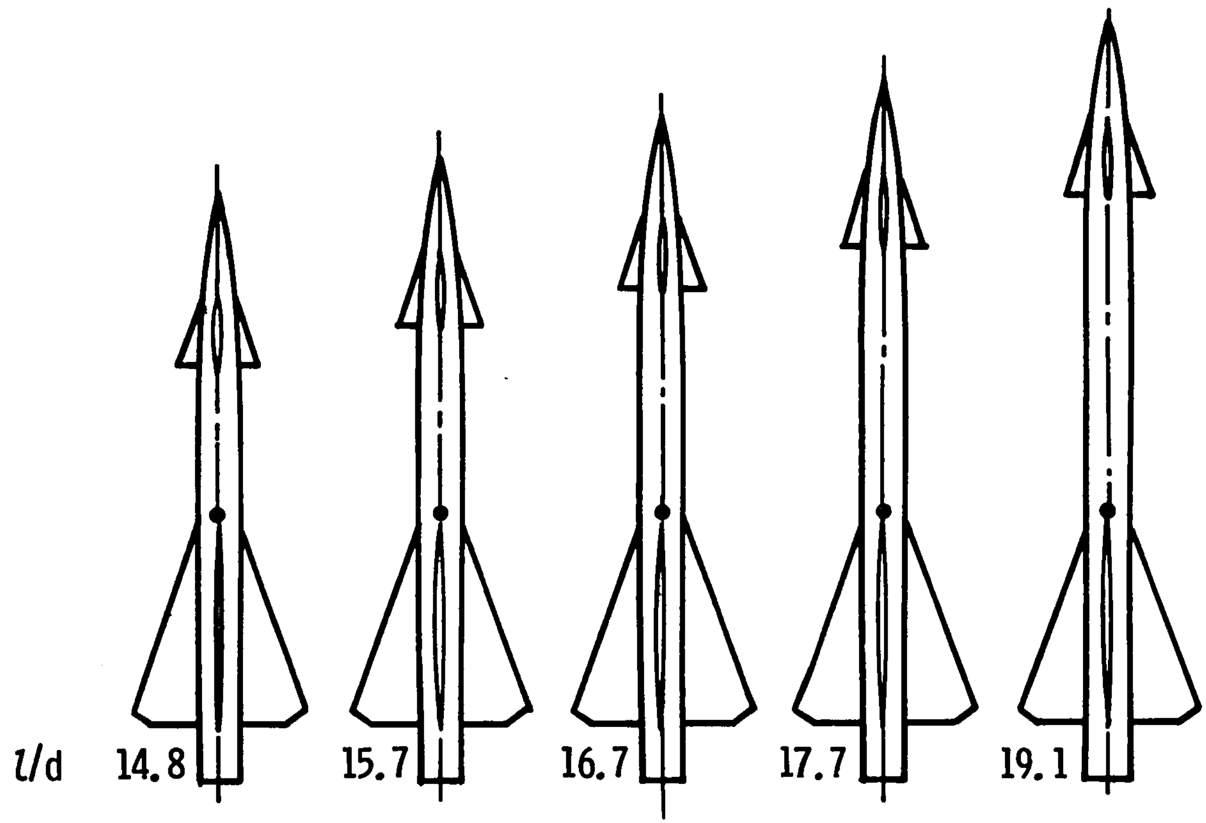

Figure 24.- Canard missile body length study model.

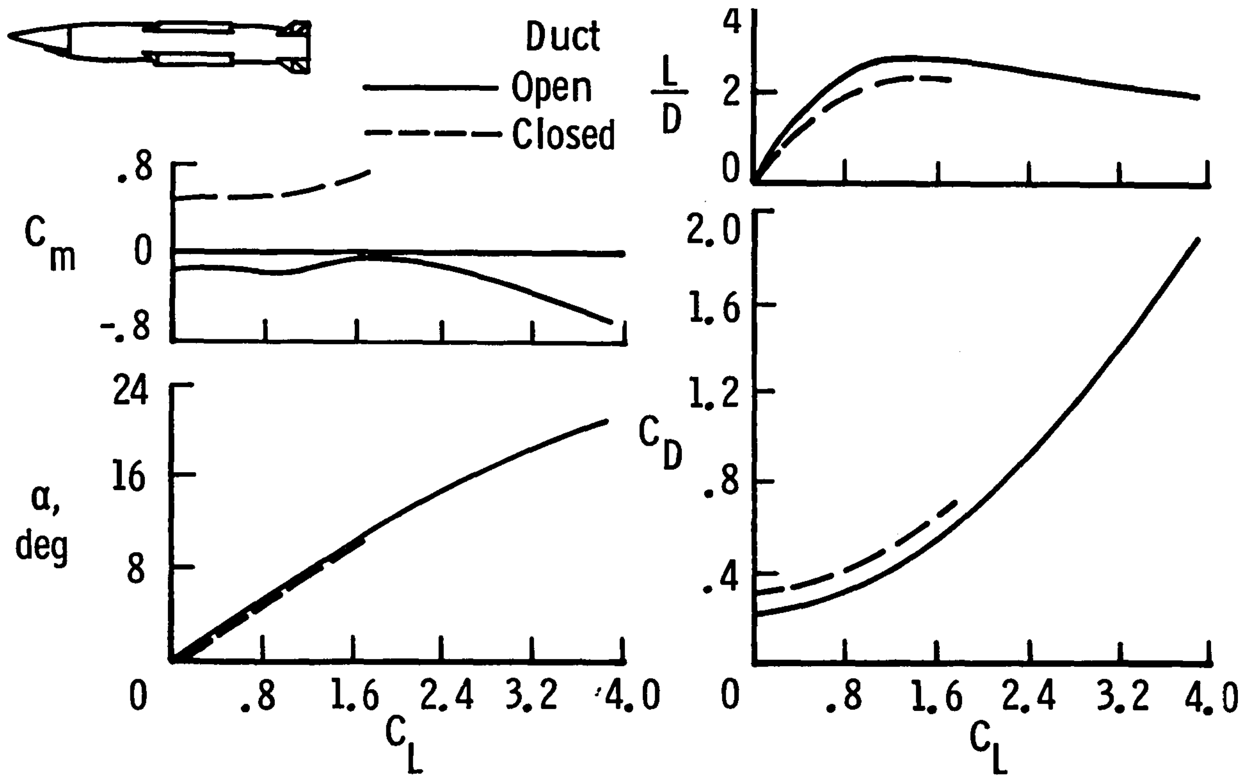

Figure 25.- Effect of duct fairing on missile longitudinal characteristics, M = 2.86.

Standard Bibliographic Page

1. Report No. NASA TM-87710	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SOME LESSONS LEARNED WITH WIND TUNNELS		5. Report Date March 1986
		6. Performing Organization Code 505-69-71-03
7. Author(s) M. Leroy Spearman		8. Performing Organization Report No.
9. Performing Organization Name and Address NASA Langley Research Center Hampton, Virginia 23665-5225		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546-0001		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code

15. Supplementary Notes

Colateral release with paper presented at the AIAA 14th Aerodynamic Testing Conference, West Palm Beach, Florida, March 5-7, 1986.

16. Abstract

A review is presented of some of the lessons learned from wind tunnel tests since World War II. Wind tunnels achieved a very high productivity rate during the war due in part to development testing of numerous military aircraft concepts. Following the war, in addition to development testing, a rapid increase in basic research testing occurred in order to explore areas of interest revealed by the conduct of war and to expand on advanced technology that became available from Germany and Italy. The research test areas discussed are those primarily related to the transition from subsonic flight to supersonic flight.

17. Key Words (Suggested by Authors(s)) Wind Tunnels; Aerodynamic characteristics; Research and Development		18. Distribution Statement Unclassified - Unlimited; Subject Category 01	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 39	22. Price A03

For sale by the National Technical Information Service, Springfield, Virginia 22161

NASA Langley Form 63 (June 1985)

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