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PREDICTION OF FORCES AND MOMENTS FOR FLIGHT VEHICLE CONTROL EFFECTORS: PROGRESS REPORT AND WORKPLAN

NASA Grant NAG 1-849

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I. SUMMARY

Two research activities directed at hypersonic vehicle configurations are currently underway. The first activity involves the validation of a number of classical local surface inclination methods commonly employed in preliminary design studies of hypersonic flight vehicles. Unlike several studies aimed at validating such methods for predicting overall vehicle aerodynamics, this effort emphasizes validating the prediction of forces and moments for flight control studies. Specifically, several vehicle configurations for which experimental or flight-test data are available are being examined. By comparing the theoretical predictions with these data, the strengths and weaknesses of the local surface inclination methods can be ascertained and possible improvements suggested. The second research thrust, of significance to control during take-off and landing of most proposed hypersonic vehicle configurations, is aimed at determining the change due to ground effect in control effectiveness of highly swept delta planforms. Central to this research is the development of a vortex-lattice computer program which incorporates an unforced trailing vortex sheet and an image ground plane. With this program, the change in pitching moment of the basic vehicle due to ground proximity, and whether or not there is sufficient control power available to trim, can be determined.

In addition to the current work, two different research directions are suggested for future study. The first would be aimed at developing an interactive computer program to assist the flight controls engineer in determining the forces and moments generated by different types of control effectors that might be used on hypersonic vehicles. The first phase of this work would deal in the subsonic portion of the flight envelope, while later efforts would explore the supersonic/hypersonic flight regimes. The second proposed research direction would explore methods for determining the aerodynamic trim drag of a generic hypersonic flight vehicle and ways in which it can be minimized through vehicle design and trajectory optimization. For proposed work, it is desired to select the research direction of the most value to NASA's ongoing and future activities.

II. ACTIVITIES IN PROGRESS

Validation of Methods for Predicting Hypersonic Flight Controls Forces and Moments

Before a great deal of activity is undertaken in assessing different types of flight control systems for hypersonic vehicles, it is important to understand the strengths and limitations of the prediction tools most likely to be used in this effort. Consequently, a number of supersonic/hypersonic methods are currently being evaluated. Specifically, because their inherent simplicity makes them ideally suited to preliminary design work, among the tools under examination are the classical local surface inclination methods, including Newtonian theory, tangent-wedge/tangent-cone methods, and shock expansion techniques. These methods are all part of an industry-standard computer program called the "Hypersonic Arbitrary Body Program (HABP)," originally prepared by Gentry[1] and now part of a more encompassing program, the "Aerodynamic Preliminary Analysis System (APAS)," detailed in Ref. 2. Although HABP has been widely used for preliminary design activities since the early 1970's and a number of studies have been undertaken to examine its ability to predict the overall vehicle aerodynamics, Ref. 3 and 4 for example, it is apparent that no comprehensive, systematic study has explored its ability to predict forces and moments generated by aerodynamic flight controls. Thus, the goal of the present activity is to determine the accuracy and range of validity of the simple local surface inclination methods for predicting control forces and moments for a variety of configurations.

The approach being used in this validation effort is to examine several vehicle configurations which cover a broad range of proposed hypersonic vehicle configurations and for which wind-tunnel and/or flight-test data are available. These configurations include the Space Shuttle, presented in Figure 1, the X-15, shown in Figure 2, a wing-body vehicle[5], as given in Figure 3, and possibly an all-body[6] or cone-body configuration.

Thus far, as represented by Appendix A, a literature search aimed at identifying appropriate configurations and available experimental data has been conducted, the APAS computer program has been implemented on the Penn State computer system, and the configurations of the first three vehicles to be considered have been input. Comparison of predicted control forces and moments with experimental values has begun and, along with a thorough evaluation of the local surface inclination methods for use in flight control evaluation efforts, is expected to be completed by late summer.

Control of Highly Swept Delta Planforms in Ground Effect

The second activity currently in progress is the prediction of control forces and moments of highly swept delta planforms in close proximity to the ground. Because of the possibility that such configurations suffer a large loss of control effectiveness in ground effect, this is an important area of concern for proposed hypersonic flight vehicles. Furthermore, any analysis of such configurations in ground effect must examine the coupling that exists between deflecting a control surface to achieve a proper moment for trim and the change that such a deflection causes in the total lift generated. In order to explore these issues, a vortex-lattice method, which includes a free-wake and a reflective image plane to model ground proximity, is currently being programmed. With this tool, it should be possible to examine the change in moment of the entire vehicle, as well as the change in control effectiveness, due to ground effect. In this way, it can be determined whether or not sufficient control power for trim in ground effect is available and if not, the vortex-lattice code should be useful in evaluating innovative ways of generating the required moments to trim.

The activity in this area thus far has included the completion of a literature review, summarized in Appendix B, addressing aerodynamic prediction methods applicable to highly swept delta wings. At present, a computer algorithm to implement the vortex-lattice method with a free-wake has been written and it remains to add the image plane capability to model the ground. As with the code validation efforts already discussed, it is anticipated that the study of highly swept delta planforms in ground effect will be concluded by late summer.

III. PROPOSED ACTIVITIES

Because there is more insight into the problems of the control of hypersonic vehicles now than was present at the beginning of this program, it seems appropriate to re-examine its original direction and goals. As a result of this re-examination, two different directions are proposed for the major thrust of future activities. It is hoped that a choice between these two options will be made which will result in the greatest benefit to all concerned.

Proposed Research, Option 1: Control Force and Moment Prediction for Hypersonic Vehicle Configurations

Because of the gains in performance that are made possible by modern controls technology, the configurations of advanced flight vehicles will be increasingly dictated by concerns of control rather than by those of classical aerodynamics. For this reason, it is important that the flight controls engineer be able to fully participate in preliminary design activities of new aircraft. To facilitate this, it is proposed to develop a design tool with which the controls engineer can estimate the forces and moments generated by different types of effectors used to control hypersonic vehicles configurations. The ultimate goal of this program is envisioned to be an interactive computer program which could be used by the controls engineer in preliminary design work to evaluate and consequently select appropriate control effectors to meet specific control requirements. This design tool would not help the engineer in identifying the hypersonic vehicle control requirements but would be of use once those requirements have been determined.

If this proposed direction is taken, the first phase of the research would deal with the control of hypersonic vehicle configurations at subsonic speeds. This phase would begin by cataloging existing effectors and the methods available for analyzing them. These methods would be assessed for accuracy by comparing predictions made using them with available experimental data. The existing methods would be improved when possible and new methods would be developed when necessary. Ultimately, this information would be incorporated into the interactive computer program for use by the controls engineer.

Once the subsonic phase of this work is completed, which is estimated to take approximately one year, future phases of the program would extend the range of capability of the program to supersonic and hypersonic speed ranges.

Proposed Research, Option 2: The Minimization of the Aerodynamic Trim Drag of Hypersonic Vehicles

In addition to the significant moments generated by the propulsion system, an aircraft accelerating through subsonic, transonic, supersonic, and hypersonic speeds will experience a large variation in the pitching moment required for trim due to Mach number effects on the aerodynamics. As a result, the drag created in trimming the vehicle for flight through such radically changing speed regimes can be significant. Unfortunately, based on present technology, the success of proposed hypersonic vehicles is critically dependent on achieving the highest performances possible in the areas of propulsion, materials, aerodynamics, and flight controls. Thus, the ability to minimize the trim drag may be one of the deciding factors in the success or failure of such a vehicle. The second proposed research program would investigate this problem. The proposed research would begin by determining the steady-state trim drag problem for a generic single-stage to orbit vehicle configuration. For this purpose, the control moments and associated trim drag for a generic hypersonic wing/body configuration, including the effects of the propulsion system, would be considered. One of the objectives of this research would be to determine ways to minimize the moments generated by the changing aerodynamic and propulsive forces.

Different control concepts such as thrust vectoring, center-of-gravity transfer, and variable geometry would be evaluated and a trade-off analysis of the different systems performed. The evaluation of each system would be largely dependent on maximizing the control moments generated while minimizing the drag that the system produces.

The ultimate goal of this research would be to develop strategies for vehicle design, and determine the optimum flight trajectories which would minimize the trim drag penalty over the entire phase of atmospheric flight for hypersonic vehicles.

Discussion of the Proposed Research Options

In considering the two research directions proposed, it is clear that while the force and moment prediction of control effectors is certainly more in line with the original plan for this research, the level of need for such a tool is not certain. Further, if not taken to the full measure of considering all effectors over the entire speed range, the usefulness of intermediate results is certainly limited. Consequently, contributing to the solution of the trim drag problem, one of the major problems confronting all hypersonic vehicles, might better serve NASA interests. Also, the level of research required in the analysis of the trim drag problem is more appropriate for graduate thesis work than is the cataloging of force and moment prediction methods. Thus, from our point of view, an effort directed at the trim drag problem is the more attractive of the two options.

IV. BUDGETARY CONSIDERATIONS

Although the formal starting date of the flight controls research grant was February 15, 1988, it is important to note that prior commitments and the mid-semester starting date of this work resulted in some delays before the effort was at full strength. In fact, from February until May the primary investigator and one graduate student worked on half the budgeted time fraction, and the second budgeted graduate student did not begin working until August 1988. Thus, with the budgeted funds not spent early in this program, it is possible to continue at current levels without additional funding for three months past the formal February 14, 1989 termination date. For this reason, a no-cost extension of this grant is requested until May 14, 1989. After that time, it is hoped that a follow-on grant would continue to support option 1 or 2 of the proposed activities, as well as the hypersonic configurations in ground effect study through its completion in July 1989. The code validation effort is funded internally through May 1989.

After completion of the code validation and ground effect research activities, it is desired to limit the scope of this program to a single topic. In this way, by reducing the amount of time required on administration and advising duties, it is felt that the principal investigator can contribute much more directly to the research effort.

The funding requirements for the program outlined above are tabulated on the following page with October 1 used as the starting date for future awards. As shown, $28,379 are required to conduct the program outlined from May 15, 1989 through September 30, 1989. Thereafter, the support required to continue one of the research options discussed in the previous section is reduced from the current level to approximately $56,425 per year.

Tentative Budget – Force and Moment Prediction of Control Effectors for Flight Vehicles

NASA Langley Research Center

	5/14/89 – 9/30/89	10/1/89 – 9/30/90
DIRECT COSTS		
Salaries (Category I)		
M .D. Maughmer		
15% academic year		
50% summer	9,011	15,933
Secretary		
7% academic year and summer	590	1,769
Subtotal	9,601	17,702
Salaries and Wages (Category II)		
Graduate Assistant I		
50% summer	2,394	–
Graduate Assistant II		
50% academic year and summer	3,408	10,837
Subtotal	5,802	10,837
Total Salaries and Wages	15,403	28,539
Fringe Benefits	2,818	5,207
Travel	500	1,500
Materials and Supplies	100	210
Publication Costs/Page Charges	0	210
Computer Services	1,000	2,000
Total Modified Direct Costs	19,821	37,666
Graduate Assistant Tuition	410	3,316
Total Direct Costs	20,231	40,982
INDIRECT COSTS		
Indirect Cost	8,148	15,443
TOTAL BUDGET ESTIMATE	28,379	56,425

V. REFERENCES

1. Gentry, A.E., "Hypersonic Arbitrary-Body Aerodynamic Computer Program (Mark III Version). Vol. 1 - User's Manual," Report DAC 61552, McDonnell-Douglas Corporation, April 1968.

2. Bonner, E., Clever, W., and Dunn, K., "Aerodynamic Preliminary Analysis System II - Part I, Theory," North American Aircraft Operations, Rockwell International.

3. Middleton, W.D., Lundry, J.L., and Coleman, R.G., "A System for Aerodynamic Design and Analysis of Supersonic Aircraft, Part 1 - Development," NASA CR 3352, 1980.

4. Covell, P.F., Wood, R.M., Bauer, S.X., and Walker, I.J., "Configuration Trade and Code Validation Study on a Conical Hypersonic Vehicle," AIAA Paper 88–4505, September 1988.

5. Dillon, J.L. and Pittman, J.L., "Aerodynamic Characteristics at Mach 6 of a Wing-Body Concept for a Hypersonic Research Airplane," NASA TP 1249, August 1978.

6. Clark, L.E., "Hypersonic Aerodynamic Characteristics of an All-Body Research Aircraft Configuration," NASA TN D-7358, December 1973.

VI. APPENDIX A

Experimental Data for Hypersonic Vehicle Configurations
Literature Survey

1. Beeler, D.E., "The X-15 Research Program," AGARD Report 289, October 1960.

   Brief description of the X-15 research program. Comparison of wind tunnel tests and flight measured values of stability derivatives at Mach numbers from 0.0 to 8.0. Variation of control effectiveness with Mach number including horizontal tail, vertical tail and ailerons.

2. Bernot, P.T., "Effect of Modifications on Aerodynamic Characteristics of a Single-Stage-to Orbit Vehicle at Mach 5.9," NASA TM 84565, January 1983.

   The model was based on control-configured stability concepts. Results are presented for elevons, body flap, and wing tip fin controllers. Model similar to that in NASA TM X-3550 (item 3).

3. Bernot, P.T., "Aerodynamic Characteristics of Two Single-Stage-to-Orbit Vehicles at Mach 20.3," NASA TM X-3550, August 1977.

   Control deflection data are for elevons and a body flap. Most results are for high angles of attack (between 16° and 50°).

4. Boisseau,Peter C., "Investigation of the Low-speed Stability and Control Characteristics of a 1/7-Scale Model of the North American X-15 Airplane," NACA RM L57D09, 1957.

   Early X-15 data from free flying model tests. Purpose was to evaluate the use of the horizontal tail for roll control. Control deflection results are presented for the wing trailing edge flap, all moving vertical tail, and symmetrical and differential horizontal tail deflections.

5. Boyden, R.P. and Freeman, D.C. Jr., "Subsonic and Transonic Dynamic Stability Characteristics of a Space Shuttle Orbiter," NASA TN D-8042, November 1975.

   Dynamic and static stability are investigated. Dynamic results are presented to show the effect of rudder flare in combination with body flap deflection. The static lateral stability data show the effect of the vertical tail, combination body flap and rudder flare, and body flap alone.

6. Brooks, C.W. Jr. and Cone, C.D. Jr., "Hypersonic Aerodynamic Characteristics of Aircraft Configurations with Canard Controls," NASA TN D-3374, April 1966.

   The investigation was done on a wing-body configuration with a 70° swept delta wing at a Mach number of 10.03. Four different canards were each tested on various configurations. Results include canard effectiveness on longitudinal, lateral, and directional characteristics.

7. Brooks, C.W. Jr., "Interference Effects of Canard Controls on the Longitudinal Aerodynamic Characteristics of a Winged Body at Mach 10," NASA TN D-4436, April 1968.

    Effect of canard interference is studied by comparing body alone data with canard deflection data which appeared in NASA TN D-3374 (item 6) and TN D-3728 (item 44).

8. Clark, L.D., "Hypersonic Aerodynamic Characteristics of an All-Body Research Aircraft Configuration," NASA TN D-7358, December 1973.

    Experiment was done at Mach 6 on a lifting body configuration and compared with theoretical models. The horizontal wing-tip-type control surfaces were adjustable in 5° increments from +15° to −30°. HABP was used for theoretical predictions. The tangent-cone method gave the best agreement at control settings between +5° and −5° and at positive lift coefficients except for directional characteristics. None of the methods predicted characteristics well at negative lift coefficients and large control deflections.

9. Clark, L.E. and Richie, C.B., "Aerodynamic Characteristics at Mach 6 of a Hypersonic Research Airplane Concept Having a 70° Swept Delta Wing," NASA TM X-3475, May 1977.

    The study was a configuration build up and includes effect of elevon defleciton on trim characteristics. Elevon data are given for deflections of 10° to −20° in 5° increments for seven different configurations. Speed brake deflection data are also included.

10. Covell, P.F., Wood, R.M., Bauer, S.X., and Malker, I.J., "Configuration Trade and Code Validation Study on a Conical Hypersonic Vehicle," AIAA Paper 88-4505, September 1988.

    Test Mach numbers were between 2.5 and 4.5. Effect of canard shape, vertical tail shape, wing location, and wing incidence on aerodynamic characteristics included. A comparison is also made between the experimental results and three theoretical analysis programs: HABP, LT (Linear Theory), and SIMP (Supersonic Implicit Marching).

11. Decker, J.P. and Spencer, B. Jr., "Low-Subsonic Aerodynamic Characteristics of a Model of a Fixed-Wing Space Shuttle Concept at Angles of Attack to 76°," NASA TM X-1996, April 1970.

    These tests were done on an early shuttle concept at a Mach number of 0.25. Longitudinal stability and control are provided by a horizontal tail with an elevator. Elevator deflections of 20° to −20° were effective at low angles of attack where flow separation is not a major problem.

12. Dillon, J.L. and Creel, T.R. Jr., "Aerodynamic Characteristics at Mach Number 0.2 of a Wing Body Concept for a Hypersonic Research Airplane," NASA TP 1189, 1978.

    The experiment consisted of configuration buildup from the basic body by adding a wing, center vertical tail and scramjet engines. The test angle of attack range was approximately −5° to 30° at constant angles of sideslip of 0° and 4°. The elevons were deflected from 5° to −15°. Roll and yaw control were investigated. Also includes rudder deflection data.

13. Dillon, J.L. and Pittman, J.L., "Aerodynamic Characteristics at Mach Numbers from 0.33 to 1.20 of a Wing-Body Design Concept for a Hypersonic Research Airplane," NASA TP 1044, 1977.

    The tests were done at seven different transonic Mach numbers. Control deflection data includes: symmetrical elevon deflections of 0°, −10°, and −20°; differentially deflected elevons at ±20°; and rudder deflections of 0° and 15.6°.

14. Dillon, J.L. and Pittman, J.L., "Aerodynamic Characteristics at Mach 6 of a Wing-Body Concept for a Hypersonic Research Airplane," NASA TP 1249, August 1978.

    Similar configuration build-up of model in TP 1044 (item 13) and TP 1189 (item 12) at Mach 6. The elevons were deflected from 10° to −15° for pitch control and yaw and roll control were also investigated. HABP was used and gave good predictions for the longitudinal but not for the lateral-directional aerodynamic characteristics.

15. Ellison, J.C., "Investigation of the Aerodynamic Characteristics of a Hypersonic Transport Model at Mach Numbers to 6," NASA TN D-6191, April 1971.

    Tests were done at Mach numbers from 0.36 to 6.0. Results for elevon deflections from 5° to −20° are included for all Mach numbers. The configuration also had strakes which helped provide positive C_M.

16. Fetterman, D.E. Jr., Penland, J.A., "Static Longintudinal, Directional, and Lateral Stability and Control Data from an Investigation at a Mach Number of 6.83 of Two Developmental X-15 Airplane Configurations," NASA TM X-209, March 1960.

    Directional control data were obtained by testing vertical tail deflections of 0° and −5°, and lateral control data were obtained by testing differential horizontal tail deflections of 0°, −10°, and −20°. Results for speed brake deflections of 20° are also included.

17. Freeman, D.C. Jr., "Dynamic Stability Derivatives of Space Shuttle Orbiter Obtained from Wind-Tunnel and Approach and Landing Flight Tests," NASA TP 1634, April 1980.

    Wind tunnel and flight test data were compared with ADDB values at subsonic Mach numbers for the parameters of pitch, yaw and roll damping, as well as the yawing moment due to rolling velocity and the rolling moment due to yawing velocity.

18. Freeman, D.C. and Boyden, R.P., "Supersonic Dynamic Stability Characteristics of a Space Shuttle Orbiter," NASA TN D-8043, January 1976.

    Similar results to NASA TN D-8042 (item 5) except for different Mach numbers. Elevon data are also included.

19. Freeman, D.C. and Fournier, R.H., "Static Aerodynamic Characteristics of a Single-Stage-to-Orbit Vehicle With Low Planform Loading at Mach Numbers from 0.3 to 4.63," NASA TM 74056, November 1977.

    Tests were run at eight different Mach numbers. At a Mach number of 0.9, elevon deflections of 10° became completely ineffective at angles of attack above 6°. The resulting nonlinearity in $C_{M_{\delta_e}}$ was also seen in the Space Shuttle.

20. Freeman, D.C. and Fournier, R.H., "Static Aerodynamic Characteristics of a Winged Single-Stage-to-Orbit Vehicle at Mach Numbers from 0.3 to 4.63," NASA TP 1233, August 1978.

    Tests were done to determine the static longitudinal stability and trim, the static lateral-directional stability, and the aileron control effectiveness. Elevons were deflected from 0° to $-20°$ for all eight Mach numbers tested.

21. Freeman, D.C. and Jones, R.S., "Low -Speed Static Stability and Control Characteristics of Two Small-Scale, Hypersonic Cruise Configurations," NASA TM X-2021, June 1970.

    The first model was a distinct wing-body with a conventional rudder for directional control and differential deflections of the all-movable horizontal tail for roll control. The second model was a blended wing-body with elevons for both pitch and roll control and a center vertical rudder for directional control.

22. Freeman, D.C. and Spencer, B. Jr., "Comparison of Space Shuttle Orbiter Low-Speed Static Stability and Control Derivatives Obtained from Wind-Tunnel and Approach and Landing Flight Tests," NASA TP 1779, December 1980.

    The longitudinal stability, elevon effectiveness, lateral directional stability and aileron effectiveness derivatives were compared from wind tunnel tests, approach and landing flight tests and ADDB values. Body flap and speed brake deflections are included.

23. "Hypersonic Aerodynamic Characteristics of Two Delta-Wing X-15 Airplane Configurations," NASA TN D-5498, October 1969.

    The effects of wing geometry and longitudinal position, wing fins, nose cant, strakes, and speed brakes were looked at for elevon deflections to $-45°$. The experimental aerodynamic characteristics were compared with the analytical results from HABP. At the time of the investigation, HABP was very new and the results were not very good.

24. Kelly, M.W., "Wind-Tunnel Investigation of the Low-Speed Aerodynamic Characteristics of a Hypersonic Glider Configuration," NACA RM A58F03, September 1958.

    The tests were done to investigate the adequacy of the low speed stability and control characteristics for landing. Trailing-edge flaps at the wing tips supplied both yaw and roll control. The effect of wing tip droop on lateral and directional stabiltiy is also reported.

25. McCandless, R.S. and Cruz, C.I., "Hypersonic Characteristics of an Advanced Aerospace Plane," AIAA Paper 85-0346, January 1985.

    Tests were run at Mach numbers of 6, 10, and 20. Results include elevator, elevon and rudder deflection data. The experimental data were then compared with APAS II predicted values.

26. McCandless, R.S., "Hypersonic Characteristics of an Advanced Aerospace Plane at Mach 20.3," NASA TM 86435.

    Aerodynamic control effectiveness was determined by deflecting the elevators, the elevons, and the rudder. Tests were run at a Mach number of 20.3 at various Reynolds numbers.

27. McKinney, R.L. and Lancaster, J.A., "Investigation of the Aerodynamic Characteristics of a 0.02-Scale Model of the X-15 Airplane at Mach Numbers of 2.96, 3.96, and 4.65 at High Angles of Attack," NASA TM X-820, June 1963.

    Supersonic tests on the final X-15 configuration. Results include deflections of the horizontal tail, asymmetric deflections of the upper and lower verticals, and deflections of upper and lower speed brakes.

28. Mellinger, G.R., "Design and Operation of the X-15," *Shell Aviation News*, April 1961, pp 14–21.

    Includes a description of the X-15 design. The article discusses design decisions such the need for the wedge airfoil for the upper and lower vertical tails.

29. Moore, M.E. and Williams, J.E., "Aerodynamic Prediction Rationale for Analyses of Hypersonic Configurations," AIAA Paper 89-0525, January 1989.

    A method selection rationale was developed for S/HABP. They suggest braking the configuration into three basic parts: nose, body, and aerodynamic surfaces. Analyses were done on the Space Shuttle, the FDL-7, and the X-24C-10D. No comparisons for control deflections.

30. Nelms, W.P. and Ames, J.A., "Longitudinal Aerodynamic Characteristics of Three Representative Hypersonic Cruise Configurations at Mach Numbers from 0.65 to 10.70," NASA TM X-2113, October 1970.

    Two configurations were discrete wing-body concepts and the third was a blended wing-body design. Effects of varying angle of attack, Mach number, and configuration build-up were considered. There are no control deflection data in this report.

31. Nelms, W.P. and Thomas, C.L., "Aerodynamic Characteristics of an All-Body Hypersonic Aircraft Configuration at Mach Numbers from 0.65 to 10.6," NASA TN D-6577, November 1971.

    The effectiveness of horizontal tail, vertical tail and canard stabilizing and control surfaces were investigated. The horizontal tail was deflected both symmetrically and differentially. The rudder was deflected asymmetrically and flared as a speed brake.

32. Osbourne, R.S., "Aerodynamic Characteristics of a 0.0667 Scale Model of the N.A. X-15 Research Airplane at Transonic Speeds," NASA TM X-24, 1959.

    Tests were run at eight Mach numbers between 0.6 and 21.43. The tests were not run on the final X-15 configuration (does not include vertical wedge airfoil). Results are presented for symmetrical and differential deflections of the horizontal tail.

33. Penland, J.A., "Low-Speed Aerodynamic Characteristics for a Hypersonic Research Airplane Concept Having a 70° Swept Delta Wing," NASA TM X-71974, August 1974.

    Tests were conducted at a Mach number of 0.06 on a model like that in NASA reports: TP 1252 (item 38), TP 1552 (item 39), TM X-3475 (item 9), and TN D-8065 (item 37). Eight model configurations were tested with various elevon and aileron deflections.

34. Penland, J.A. and Fetterman, D.E. Jr., "Static Longitudinal, Directional, and Lateral Stability and Control Data at a Mach Number of 6.83 of the Final Configuration of the X-15 Research Airplane," NASA TM X-236, April 1960.

    Data are presented in comparison plots to show the effects of component breakdown and control deflection. Control surfaces include: vertical tail, horizontal tail (symmetrical and differential deflections), speed brakes. The configuration geometry is well documented in the report (0.02 scale model).

35. Penland, J.A. and Creel, T.R. Jr., "Low-Speed Aerodynamic Characteristics of a Lifting-Body Hypersonic Research Aircraft Configuration," NASA TN D-7851, February 1975.

    Configuration is similar to that of NASA TN D-7358. The model was tested with two sets of horizontal and vertical tip controls, a center vertical tail, and two sets of canard controls.

36. Penland, J.A., Creel, T.R. Jr., and Howard, "Experimental Low-Speed and Calculated High-Speed Aerodynamic Characteristics of a Hypersonic Research Airplane Concept Having a 65° Swept Delta Wing," NASA TN D-7633, August 1974.

    Experimental low speed tests were done to determine lift and stability during landing. Calculated results using HABP are presented for Mach numbers from 3 to 12. Results are given for elevon, aileron, and wing tip rudder deflections.

37. Penland, J.A., Fournier, R.H., and Marcum, D.C. Jr., "Aerodynamic Characteristics of a Hypersonic Reseach Airplane Concept Having a 70° Swept Double-Delta Wing at Mach Numbers from 1.50 to 2.86," NASA TN D-8065, December 1975.

    A configuration build-up was done as well as the effect of elevon deflections. Data for elevon deflections of 0°, −10°, and −20° are presented at four supersonic Mach numbers. Aileron effectiveness data are also presented.

38. Penland, J.A., Creel, T.R. Jr., and Dillon, J.L., "Aerodynamic Characteristics of a Hypersonic Research Airplane Concept Having a 70° Swept Double-Delta Wing at Mach Number 0.2," NASA TP 1252, September 1978.

    Tests were done at a Mach number of 0.2 for various Reynolds numbers. The elevons were deflected from 0° to −20° in 5° increments. Roll control was also investigated.

39. Penland, J.A., Hallissy, and Dillon, J.L., "Aerodynamic Characteristics of a Hypersonic Research Airplane Concept Having a 70° Swept Double-Delta Wing at Mach Numbers from 0.80 to 1.20, With Summary of Data from 0.20 to 6.0," NASA TP 1552, December 1979.

    Wind tunnel data of static longitudinal, lateral, and directional stabilty characteristics of a hypersonic research airplane, for angles of attack from −4° to 23°, and at angles of sideslip of 0° and 5°. The configuration variables included wing planform, tip fins, and the center vertical tail. The second area is a summary of the variations of the more important aerodynamic parameters with $M = 0.2$ to 6.0. Elevon deflections are included.

40. Pittman, J.L and Riebe, G.D., "Experimental and Theoretical Aerodynamic Characteristics of Two Hypersonic Cruise Aircraft Concepts at Mach Numbers of 2.96, 3.96, and 4.63," NASA TP 1767, December 1980.

    Comparison of wind tunnel tests with results from various theoretical methods includeng HABP. The control deflections studied were for horizontal and vertical tails.

41. Powell, R.W. and Freeman, D.C., Jr., "Application of a Tip-Fin Controller to the Shuttle Orbiter for Improved Yaw Control," *Journal of Guidance and Control*, AIAA Paper 81-0074R, 1982.

    Looks at possibility of implementing tip-fins on the Shuttle Orbiter for imnproved yaw control. Results compared effectiveness of speed brakes on the two configurations.

42. Powell, R.W. and Freeman, D.C. Jr., "Aerodynamic Control of the Space Shuttle Orbiter with Tip-Fin Controllers," *Journal of Spacecraft*, AIAA Paper 84-0488, September–October 1985.

    Results show that the orbiter with tip-fin controllers can successfully perform the required maneuvers during entry. They do however exhibit less control authority in some flight regimes than the current configuration.

43. Putman, L.E. and Trescot, C.D. Jr., "Hypersonic Aerodynamic Characteristics of Plain and Ported Elevon Controls on a 75° Swept Modified Delta-Wing Configuration," NASA TM X-987, July 1964.

    The tests were run at a Mach numbr of 10.03 and at various Reynolds numbers. The relative effectiveness of plain and ported elevons and the effect of wing position on elevon effectiveness were reported. Newtonian impact theory was used to predict the control characteristics but was not adequate for this configuration.

44. Putnam, L.E. and Brooks, C.W. Jr., "Hypersonic Aerodynamic Characteristics of Wing-Body Configurations with Canard Controls," NASA TN D-3728, December 1966.

    Similar to work in NASA TN D-3374 (item 6) but with different canards.

45. Rainey, R.W., Fetterman,D.E. Jr., and Smith, R., "Summary of the Static Stability and Control Results of a Hypersonic Glider Investigation," NASA TM X-277, May 1960.

    Test Mach numbers of 6.7 to 18.4. Wing trailing edge flaps provided longitudinal and lateral control, and the wing-tip fins with rudders provided directinal stability and control. Other control surfaces tested include delta tripanel tip controls, pyramidal tip controls, and conical tip controls.

46. Romere, P.D. and Young, J.C., "Space Shuttle Entry Aerodynamic Comparisons of Flight 2 with Preflight Predictions," AIAA Paper 82-0565, March 1982.

    Control deflection data given only for the speed brakes.

47. Ross, A.J. and Thomas, H.H.B.M, "A Survey of Experimental Data on the Aerodynamics of Controls, in the Light of Future Needs," *Aerodynamics of Controls – Paper 2*, AGARD CP 262.

    This paper is a good overview of both conventional and unconventional motivators. A bibliography of control data for pitch, roll, yaw, and lift motivators is included. They are further broken down into different speed regimes.

48. Shuttle Performance: Lessons Learned, "Space Shuttle Entry Longitudinal Aerodynamic Comparisons of Flights 1-4 with Prefight Predictions," NASA CP 2283, March 8-10, 1983.

    Analysis results of the STS 2 and 4 maneuvers during entry indicate that the hypersonic trim discrepancy is due to an error in the prediciton of the basic vehicle pitching moment and not an error in prediction of the elevon and body flap effectiveness. Speed brake data are included.

49. Small W.J., Kirkham, F.S., and Fetterman, D.E., "Aerodynamic Characteristics of a Hypersonic Transport Configuration at Mach 6.86," NASA TN D-5885, June 1970.

    Configuration was a low-wing, distinct wing-body with a vertical tail. Elevon deflection data are included. The analytical prediction methods used were found to be inadequate. At $\alpha = 6.85°$ the vertical tail became ineffective due to interference and shielding effects.

50. Spearman, M.L. and Driver, C., "Longitudinal and Lateral Stability and Control Characteristics at a Mach Number of 2.01 of a 60° Delta-Wing Airplane Configuration Equipped with a Canard Control and with Wing Trailing-Edge Flap Controls," NACA RM L58A20, March 1958.

51. Spencer, B. Jr., "Effects of Stabilizer Configuration on Transonic Aerodynamic Characteristics of a Variable-Geometry High-Hypersonic-Performance Spacecraft," NASA TM X-1865, September 1969.

    The configuration has an adjustable wing which is stowed at high speeds and is deployed at low speeds. Elevon controls were deflected 0°, $-10°$, and $-20°$ for pitch control and differentially for roll control. The results are given for various horizontal stabilizer configurations.

52. Spencer, B. Jr., Henry, B.Z. Jr., and Putnam, L.E., "The Transonic Longitudinal and Lateral Aerodynamic Characteristics of a Low-Fineness-Ratio Elliptic Hypersonic Configuration Employing Variable-Sweep Wing Panels for Improving Subsonic Lift and Performance," NASA TM X-768, March 1963.

    Results are given for body-base flap deflections at various transonic Mach numbers. The wing leading edge sweep angle was also varied with body flap deflections.

53. Suit, W.T. and Schiess, J.R., "Lateral and Longitudinal Stability and Control Parameters for the Space Shuttle *Discovery* as Determined from Flight test Data," NASA TM 100555, February 1988.

    Comparison of flight test data with predictions. Results include: rolling and yawing moments due to aileron deflection; rolling and yawing moments due to rudder deflection; and pitching moment due to elevon deflection. These results are given versus Mach number from 25.0 to 0.

54. Syvertson, C.A., Gloria, H.R., and Sarabia, M.F., "Aerodynamic Performance and Static Stability and Control for Flat-Top Hypersonic Gliders at Mach Numbers from 0.6 to 18," NACA RM A58G17, September 1958.

    The model was a 77.4° swept arrow wing with deflected wing tips, a retractable ventral fin, plain trailing edge flaps, a rudder on the ventral fin, and body flaps that could also be used for speed brakes. All of the test results are presented in tabular form.

55. Trescot, C.D. and Spencer, B. Jr., "Hypersonic Aerodynamic Characteristics of a Lifting Reentry Vehicle Model with Four Types of Longitudinal Control Surfaces," NASA TM X-1173, November 1965.

    Tests were at a Mach number of 10.03. The baseline configuration is that of TM X-768 (item 52) with the wing in the 75° leading edge sweep position. The four types of controls tested were aft-mounted fins, a canard, a chin flap, and two body trailing edge flaps (one each on upper and lower surfaces).

56. Underwood, J.M. and Cooke, D.R., "A Preliminary Correlation of the Orbiter Stability and Control Aerodynamics from the First Two Space Shuttle Flights (STS 1 and 2) with Preflight Predictions," AIAA Paper 82-0564, March 1982.

Data from STS-1 and STS-2 are compared with Shuttle Data Book values. Results are presented for aileron and rudder effectiveness.

57. Walker, H.J. and Wolowicz, C.H., "Stability and Control Derivative Characteristics of the X-15 Airplane," NASA TM X-714, March 1962.

Results compare actual flight test data with wind tunnel test predictions. Control deflections include horizontal tail, upper vertical tail rudder, and speed brakes.

58. Yancy, R.B., Rediess, H.A., and Robinson, G.H., "Aerodynamic Derivative Characteristics of the X-15 Research Airplane as Determined from Flight Tests for Mach Numbers from 0.6 to 3.4," NASA TN D-1060, January 1962.

Flight test results are derived from pulse, pull-up and sideslip maneuvers and are compared to wind tunnel results for corresponding conditions. Results are given for aileron, vertical tail and horizontal stabilizer deflections.

APPENDIX B

Aerodynamic Prediction Methods for Highly-Swept Delta Planforms
Literature Survey

1. Barsby, J.E., "Flow Past Conically-Cambered Delta Wings With Leading-Edge Separation," ARC R&M 3748, 1972.

   The efficiency of a conically cambered wing can be better than a flat wing.

2. Boyden, R.P., "Theoretical and Experiental Studies of the Effects of L.E. Vortex Flow on the Roll Damping of Slender Wings," AIAA Paper 70-540, 1970.

   Increments in roll damping due to vortex flow is not too dependent on AR, but it is a function of notch ratio. At high α, the vortex migrates inboard and away from the wing, while the rolling moment decreases.

3. Campbell, B.A. and Riebe, G.D., "An Investigation of the Subsonic Maneuver Characteristics of Two Supersonic Fighter Wing Concepts," NASA CP 2417, Paper 10.

4. Carey K.M. and Erickson, G.E., "Vortex Flap Technology: A Stability and Control Assessment," NASA CR 172439, November 1984.

   Deflected vortex flaps reduce C_L at a given α, increase $C_{L_{max}}$, decrease drag due to lift, and produce a nose-down increment in the pitching moment with little change in stability. Drag reduction decreases with sweep angle from 45% less for a 45° delta to 16% less for a 70° delta. A part-span vortex flap doesn't reduce C_{D_i} as much because of vortex interaction. The vortex migrates off flap more quickly for larger sweep. The actual thrust component is less for high leading edge sweep angles. Pitch due to sideslip is reduced by vortex flaps. The cropped arrow wing is best wing for lift generation. In all sweep cases, as the trailing edge flap deflection increases, its longitudinal control effectiveness decreases. Asymmetric trailing edge flap deflections can cause large rolling moments (they act as elevons).

5. Carlson, H.W. and Darden, C.M., "Attached Flow Numerical Methods for the Aerodynamics Design and Analysis of Vortex Flaps," NASA CP 2417, Paper 6.

   If separation is confined to the leading edge flap, its effects on the overall flow patterns and loadings are small, and this approximates an attached flow. Linearized attached flow theory should therefore be capable of predicting efficient flap systems, since efficient flaps produce minimal flow separation.

6. Carlson, H.W. and Darden, C.M., "Applicability of Linearized-Theory Attached-Flow Methods to Design and Analysis of Flap Systems at Low Speeds for Thin Swept Wings With Sharp Leading Edges," NASA TP 2653, January 1987.

   The highest levels of flap-system aerodynamic performance require a flow that is as nearly attached as circumstances allow. Trailing edge flaps are necessary to reduce the amount of flow turning at the wing leading edge. Otherwise, separation at the leading edge hinge line. Separation at the trailing edge flap hinge line is not as detrimental as separation at the leading edge flap hinge line. A severely deflected leading edge flap is useful for maintaining smooth flow, but most likely, this case will lead to a highly loaded leading edge and cause separation at the leading edge hinge line. For this reason, it is best to use trailing edge flaps to reduce the severe flow turning requirements.

7. Carlson, H.W. and Mack, R.J., "Estimation of Attainable Leading-Edge Thrust for Supersonic Wings of Arbitrary Planform," NASA TP 1270, October 1976.

8. Carlson, H.W. and Walkly, K.B., "A Computer Program for Wing Subsonic Aerodynamic Performance Estimates Including Attainable Thrust and Vortex Lift Effects," NASA CR 3515.

   This report describes the numerical methods which are used to analyze twisted and cambered wings of arbitrary planform, with attainable thrust taken into account. A superposition of independent solutions for cambered, twisted, and flat wings allows for accurate integration of the pressure distributions.

9. Carlson, H.W. and Walkly, K.B., "An Aerodynamic Analysis Computer Program and Design Notes for Low-Speed Wing Flap Systems," NASA CR 3675, 1986.

   This program has the additional capability of analyzing simple hinged leading and trailing edge flaps. The Reynolds number can affect aerodynamic performance of twisted and cambered wings as well as wings with leading and trailing edge flaps. An increased Re yields an increased value of the limiting C_p. An increased Mach number decreases the limiting value of C_p.

10. Carlson, H.W. and Walkly, K.B., "Numerical Methods and a Computer Program for Subsonic and Supersonic Aerodynamic Design and Analysis of Wings with Attainable Thrust Considerations," NASA CR 3808, August 1984.

    This paper presents some ideas about the types of wing camber and flap systems one might use in design. There are not many results.

11. Carlson, H.W., "The Design and Analysis of Simple Low-Speed Flap Systems with the Aid of Linearized Theory Computer Programs," NASA CR 3913, 1987.

    This report demonstrates how CR 3675 (item 9) and CR 3808 (item 10) can be used to design wing-flap combinations. The major assumption is that the flow over the wing must remain as nearly attached as possible. A vortex flap is a good way to limit the amount of flow separation and recover some leading edge thrust. It is applicable to subsonic or supersonic flow with round or sharp leading edges. Most of the distributed leading edge thrust acts on the outboard wing stations.

12. Carlson, H.W., "Application of an Aerodynamic Analysis Method Including Attainable Thrust Estimates to Low Speed Leading Edge Flap Design for Supersonic Cruise Vehicles," NASA CR 165843, March 1982.

    Flaps can be designed smaller and simpler than conventional methods when the actual attainable leading edge thrust is considered.

13. Carlson, H.W., Mack, R.J., and Barger, R.L., "Estimation of Attainable Leading-Edge Thrust for Wings at Subsonic and Supersonic Speeds," NASA TP 1500, October 1979.

    Empirical method is presented to estimate the theoretical leading edge thrust. The method is based on a simple 2-D sweep theory and accounts for twist and camber.

14. Coe, P.L. Jr. and Weston, R.P., "Effects of Wing Leading-Edge Deflection on Low-Speed Aerodynamic Characteristics of a Low-Aspect-Ratio Highly Swept Arrow-Wing Configuration," NASA TP 1434, June 1979.

    The minimum induced drag occurs with 100% leading edge suction. In all observed cases, it was necesary to use a continuous flap deflection. Segmented deflections lead to separation even with fairings in place. This is similar to TP 1777 (item 15), but opposite to TP 1351 (item 42). Leading edge flap deflections which promote attached flow improve aileron and trailing edge flap efficiency. The leading edge deflection is most important for outboard portions of the wing.

15. Coe, P.L. Jr., Huffman, J.K., and Fenbert, J.W., "Leading-Edge Deflection Optimization for a Highly Swept Arrow Wing Configuration," NASA TP 1777, December 1980.

    Ninety percent suction was recovered with a 16° root and a 50° tip deflection of the leading edge for a continuously warped wing. Attempts to approximate continuous warp/camber with multi-segmented leading edge flaps resulted in a large drag increase. Leading edge suction can be increased with increasing Re for attached flow.

16. Coe, P.L. Jr., Thomas, J.L., Huffman, J.K., Weston, R.P., Schoonover, W.E. Jr. and Gentry, G.L. Jr., "Overview of the Langley Subsonic Research Effort on SCR Configurations," NASA CP 2108, N81-17982, March 1980.

    The most significant advance during this period is the development of leading edge deflection concepts which reduce leading edge flow separation. This significantly delays pitch-up, increases trailing edge flap effectiveness, and increases lateral control capability. Some attached flow methods may be impractical for supersonic wings, which are typically thin.

17. Coe, P.L. and Graham, A.B., "Results of Recent NASA Research on Low-Speed Aerodynamic Characteristics of Supersonic Cruise Aircraft," NASA CP 001, Paper 6, November 1976.

    Some limited information on directional stability with and without strakes, C_{M_α} for apex flaps with Kruger flaps on the outboard panel, and C_{L_α} for some limited trailing edge flap deflections is presented.

18. Coe, P.L. and Huffman, J.K., "Influence of Optimized Leading Edge Deflection and Geometric Anhedral on the Low Speed Aerodynamic Characteristics of a Low Aspect Ratio Highly Swept Arrow-Wing Configuration," NASA TM 80083, June 1979.

    Leading edge deflections provided a favorable reduction in the inherently high level of C_{L_β}. The paper investigates the effects of varying the deflection of the leading edge across the span to match the local upwash angle. Some of these results are also in NASA TP 1434 (item 14).

19. Coe, P.L. and Johnson, T.D., "Effect of Outboard Vertical-Fin Position and Orientation on the Low Speed Aerodynamic Performance of Highly Swept Wings," NASA TM 80142, September 1979.

    Outboard vertical fins improve the lateral stability and can act as winglets by producing forward thrust when properly oriented.

20. Covell, P.F., Wood, R.M. and Miller, D.S., "An Evaluation of Leading Edge Flap Performance on Delta and Double Delta Wings at Supersonic Speeds," AIAA Paper 86-0315, 1986.

    This paper presents an experimental investigation of the effects of AR, planform, and leading edge flap planform on the supersonic performance of simple wing/body configurations.

21. Davenport, E.E. and Huffman, J.K, "Experimental and Analytical Investigation of Subsonic Longitudinal and Lateral Aerodynamic Characteristics of Slender Sharp-Edge 74° Swept Wings," NASA TN D-6344, July 1971.

    Aerodynamic characteristics are only moderately effected by Mach numbers from .2 to .8 . The longitudinal characteristics with β less than 4° remain about unchanged.

22. Davenport, E.E., "Aerodynamic Characteristics of Three Slender Sharp-Edge 74° Swept Wings at Subsonic, Transonic, and Supersonic Mach Numbers," NASA TN D-7631, August 1974.

    The slope of the pitching moment curve becomes more negative with increasing M. Typically, a decrease in stability occurs at supersonic Mach numbers.

23. Decker, J.P. and Jacobs, P.F., "Stability and Performance Characteristics of a Fixed Arrow Wing Supersonic Transport Configuration (SCAT15F-9898) at Mach Numbers From .6 to 1.2," NASA TM 78726, June 1978.

    Wing tip Kruger flap deflections of 20° and an outboard wing sweep angle of 60° alleviated the higher-angle-of-attack pitch-up. Ventral fins, as well as leading and trailing edge flaps were considered. This is a complete and probably quite useful report.

24. Dollyhigh, S.M., "Theoretical Evaluation of High-Speed Aerodynamics for Arrow-Wing Configurations," NASA TP 1358, 1979.

    This paper is about the applicability of three computer programs which NASA Langley used at the time. The configuration was tested at Mach numbers of 0.8 to 2.70.

25. Edwards, J.B.W., "Free-Flight Measurements of Control Effectiveness on Three Wing Planforms at Transonic Speeds," ARC CP 572, March 1961.

26. Ellison, J.C., "Investigation of the Aerodynamic Characteristics of a Hypersonic Transport Model at Mach Numbers to 6," NASA TN D-6191, April 1971.

    This is primarily a data-gathering report, but some comparisons with theory are presented. It also considers elevon deflections and vertical tails.

27. Erickson, G.E., "Application of Free Vortex Sheet Theory to Slender Wings With Leading-Edge Vortex Flaps," AIAA Paper 83-1813, 1983.

    FVS is a non-conical flow model since the Kutta Condition is applied at all appropriate wing edges. FVS is good for preliminary design of flaps. Cranked delta wings can create vortex flap desing difficulties since two vorticies are formed for cranks greater than 10°.

28. Erickson, G.E. and Campbell, J.F., "Improvement of Maneuver Aerodynamics by Spanwise Blowing," NASA TP 1065, 1977.

    Some good data for blowing on vs. blowing off. There are conclusions regarding benefit of blowing such as: good at high α and high M, and increased trailing edge flap effectiveness.

29. Erickson, G.E., and Rogers, L.W., "Experimental Investigation at Low and High Subsonic Speeds of a Moderately Swept Fighter Wing With Deflected Leading-Edge Flaps," NASA CP 2417, Paper 8.

    Mainly presents low leading edge sweep angle results. Compressibility reduces the upwash at the leading edge for a given α . Ninety percent suction recovery at maneuvering $C_L s$ is achieved.

30. Feryn, M.O. and Cambell, .J.F., "Effects of Wing Dihedral and Planform on Stability Characteristics of a Research Model at Mach Numbers From 1.80 to 4.63," NASA TN D-2914, 1965.

    This paper presents the effects of planform, horizontal tail, and dihedral; there are no control deflections.

31. Fox, C.H. Jr., "Predicting Lift and Drag for Delta Wings in Ground Effect," NASA TN D-4891, January 1969.

    If potential theory or the suction analogy predicts free-air coefficients, it will predict ground effect coefficients accurately. ($AR < 2$).

32. Fox, C.H. and Lamar, J.E., " Theoretical and Experimental Longitudinal Aerodynamic Characteristics of an Aspect Ratio .25 Sharp-Edged Delta Wing at Subsonic, Supersonic, and Hypersonic Speeds," NASA TN D-7651, August 1974.

    As M increases, the Mach cone approaches the leading edge and the upwash field is reduced, causing smaller, weaker leading edge vorticies. K_v becomes a function of α for $M > 1$. The Tangent Cone Hypersonic Method is valid for $M > 3$.

33. Frink, N.T., "Analytical Study of Vortex Flaps on Highly Swept Delta Wings," ICAS 82 6.7.2.

    Description of VLM-SA, WVLM-SA, and FVS computer programs. There are comparisons with experiment. Trailing edge flaps increase circulation.

34. Frink, N.T., "Critical Evaluation of a Vortex Flap Design Concept Using a 74° Delta Configuration," NASA CP 2417, Paper 2.

    It can be difficult to use VLM-SA for highly deflected leading edge vortex flaps (40°) since it applies linear boundary conditions. The Free Vortex Sheet (FVS) method applies non-linear boundary conditions. Again, the percentage increase in L/D for vortex flaps is greatest for wings with lower sweep.

35. Frink, N.T., Huffman, J.K. and Johnson, T.D. Jr., "Vortex Flap Flow Reattachment Line and Subsonic Longitudinal Aerodynamic Data on 50° to 74° Delta Wings With Common Fuselage," NASA TM 84618, 1983.

    This study investigates how the reattachment line is affected by canards, trailing edge flaps, and wing sweep.

36. Goebel, T.P., Bonner, E. and Robinson, D.A., "A Study of Wing Body Blending for an Advanced Supersonic Transport," NASA CP 2108, N81-17987, March 1980.

    This paper compares the attainable leading edge thrust which is predicted by H.W. Carlson (item 13) to APAS.

37. Grantham, W.D. and Nguyen, L.T., "Recent Ground Based and In-Flight Simulator Studies of Low-Speed Handling Characteristics of Supersonic Cruise Transport Aircraft," AIAA Paper 77-1144, 1977.

    Low speed handling problems of an arrow wing supersonic cruise transport were solved by using a small lifting canard and small horizontal tail by Boeing, but NASA was able to solve them with careful attention to wing planform, wing leading edge design, and high lift devices. So, it is possible that many aerodynamic stability problems of delta wing aircraft designed for supersonic speeds may be solved without extra control surfaces if the aerodynamicist use some ingenuity.

38. Grantham, W.D., Nguyen, L.T., Deal, P.L., Neubauer, M.J. Jr., Gregory, F.D. and Smith, P.M., "Ground Based and In Flight Simulator STudies of Low-Speed Handling Characteristics of Two Supersonic Cruise Transport Concepts," NASA TP 1240, July 1978.

    The results of a study of the amount of control augmentation necessary to permit acceptable stability and flying qualities are presented.

39. Grantz, A.C., "The Lateral-Directional Characteristics of a 74° Delta Wing Employing Gothic Planform Vortex Flaps," NASA CP 2417, Paper 3.

    For $\alpha > 15°$, the configuration's stability decreases despite the improved vertical tail effectiveness. Asymmetric leading edge deflections are shown to be inferior to conventional ailerons in generating rolling moments. Lan's empirical formulas for predicting vortex burst and its effects did not work.

40. Hardy, B.C. and Fiddes, S.P., "Prediction of Vortex Lift of Non-Planar Wings By the Suction Analogy," *Aeronautical Journal*, April 1988.

    A 3-D panel method is used to calculate the edge-suction forces for thin sharp-edged wings. The suction forces are then used to estimate the vortex lift by using the suction analogy.

41. Henderson, J.M., "Low Speed Handling of a Slender Delta (HP115)," *Journal of the Royal Aeronautical Society*, Vol. 69, 1965, p. 311.

    One requirement for avoiding pitch-up may be streamwise wing-tips. Elevons of 80% span were used for lateral control power. A qualitative paper, it contains a test pilot's comments.

42. Henderson, "Effects of Wing Leading-Edge Flap Deflections on Subsonic Longitudinal Aerodynamic Characteristics of a Wing-Fuselage Configuration With 44° Swept Wing," NASA TP 1351, November 1978.

    Deflecting simple leading edge flaps recovered a significant portion of the leading edge thrust. With strakes, less was recovered. Segmented leading edge flaps were used.

43. Hoffler, "Investigation of the Vortex Tab," M.S. Thesis, N.C. State Univ., NASA CR 172586, May 1985.

    Increases in L/D obtained with a vortex tab are small and may be offset by the increased mechanical complexity and probable extra weight.

44. Hoffman, S., "Bibliography of Supersonic Cruise Research (SCR) Program From 1977 to Mid-1980," NASA RP-1063, December 1980.

    Pages 75-90 contain approximately 100 abstracts of reports about the aerodynamic data gathered during the period. The relevant papers were read and summarized.

45. Hoffman, S., "Bibliography of Supersonic Cruise Research (SCR) Program From 1980 to 1983," NASA RP-1117, July 1984.

    This is the final report about the completed SCR program. The relevant papers were read and summarized.

46. Huebner, L.B. and Lamar, J.E., "Performance Analysis and Supersonic Design of Wing Leading Edge Vortex Flaps for the Convair F-106B," NASA CP 2417, Paper 7.

    The effects of the fuselage on the pitching moment must be included in an analysis program, or the pitching moment information is useless.

47. Huntley, E., "Wind Tunnel Tests at Transonic and Supersonic Speeds to Investigate the Longitudinal Stability of a Model of the AVRO 720 Aircraft," ARC CP 1140, May 1960.

    This paper contains mostly experimental results of the longitudinal stability of an airplane.

48. Johnson, T.D. and Huffman, J.K., "Experimental Study of Vortex Flaps on a Delta Wing Sweep Series at High Angle of Attack," NASA CP 2417, Paper 9.

    Lateral and longitudinal stability decreased for all flap deflections as the wing sweep angle increased.

49. Kirby, D.A., "An Experimental Investigation of the Effect of Planform Shape on the Subsonic Longitudinal Stability Characteristics of Slender Wings," ARC R&M 3568, June 1967.

    There are no control deflections, but there is some interesting information about the planform effects on longitudinal aerodynamic characteristics.

50. Kirby, D.A. and Kirkpatrick, D.L.I., "An Experimental Investigation of the Effect of Thickness on the Subsonic Longitudinal Stability Characteristics of Delta Wings of 70° Sweepback," ARC R&M 3673, November 1969.

    An increase of the wing thickness causes losses in lift, improvement in longitudinal stability, and reductions in lift-dependent drag. For bi-convex airfoils with thickness ratios of 4, 8, 12, and 16% at angles-of-attack between $\alpha = 2^\circ$ and 4°, laminar separation occurred and caused nose-down pitching moments. The lift is always less than $a = \pi AR/2$ as predicted by slender body theory. This is expected in a subsonic flow because the theory fails to satisfy the Kutta-Joukowski condition of no-load at the trailing edge. The point of action of $C_{N_{linear}}$ moves forward with increasing thickness, while that of $C_{N_{non-linear}}$ moves rearward.

51. Kirkpatrick, D.L.I. and Hepworth, A.G., "Experimental Investigation of the Effect of Trailing Edge Sweepback on the Subsonic Longitudinal Characteristics of Slender Wings," ARC CP 1130, March 1970.

    There is not much difference in the aerodynamic characteristics of arrow wings with small notch ratios.

52. Klein, J.R., Chu, J., and Frink, N.T., "Aerodynamic Assessment of Vortex Flaps on Two Fighter Aircraft Configurations at Transonic Speeds," NASA CP 2417, Paper 4.

    Partial span flaps are significantly less effective than full span flaps. Most of the drag reduction associated with l.e. flap deflections was achieved with 15° of deflection and greater deflections didn't reduce drag proportionally. Shorter chord flaps are as effective in drag reduction as longer chord flaps at $C_L = .45$. At greater C_Ls they are not as effective, but are still better in terms of drag reduction per unit flap area. Inboard panel vortex flap effectiveness was decreased when the outboard crank was reduced from 66° to 30°.

53. Kuchemann, D., *The Aerodynamic Design of Aircraft*, Pergamon Press, 1978.

    2-D airfoil type flow is the degenerate case of conical flow. Secondary separation causes additional outboard pressure peaks, resulting in non-conical flow. The load at the trailing edge doesn't vanish for a supersonic wing. Vortex breakdown occurs earliest on thicker wings and fuller planforms. Camber is one way to obtain vortex thrust.

54. Kuchemann, D. and Weber, "An Analysis of Some Performance Aspects of Various Types of Aircraft Designed to Fly Over Different Ranges at Different Speeds," *Progress in Aeronautical Science*, Vol. 9, pp. 329–456.

    The report contains general preliminary design information. There is no specific data about controls.

55. Kulfan, R.M., "Wing Geometry Effects on Leading Edge Vorticies," AIAA Paper 79-1872, August 1979.

    A straightforward method to predict geometry effects on the spanwise progression of the leading edge vorticies is presented. Sweep, camber, twist, flaps, planform, and airfoil shapes are all considered.

56. Kulfan, R.M., "Prediction of Nacelle Aerodynamic Interference Effects at Low Supersonic Mach Numbers," NASA CP 2108, N81-17988, March 1980.

    Theory predicts an aerodynamic center which is aft of experimental locations.

57. Lamar, J.E., "Prediction of Vortex Flow Characteristics of Wings at Subsonic and Supersonic Speeds," *Journal of Aircraft*, Vol. 13, No. 7, July 1976.

    Tip raking has been shown to be an effective roll control method.

58. Lamar, J., "Recent Studies of Subsonic Vortex Lift Including Parameters Affecting Stable Leading Edge Vortex Flow," *Journal of Aircraft*, Vol. 14, No. 12, December 1977.

    Vortex lift is generated at the leading edge, but also around the side edges. Furthermore, if there is a side edge, then the leading edge vortex will augment the lift over the rear part of the wing.

59. Lamar, J. and Campbell, J.F., "Recent Studies at NASA-Langley of Vortical Flows Interacting With Neighboring Surfaces," AGARD CP 342, No. 10, 1983.

    A round leading edge can recover "residual suction" even after the flow separates at the leading edge. Apparently there is such a thing as "conservation of suction", meaning that the vortex normal force plus the residual suction force equals the thin wing leading edge suction. Segmented flaps achieve the same L/D but with less flap area (Rao). Appears to be a reduction in roll damping at high α causing wing rock. Secondary separation may be estimated by Smith's conical flow theory.

60. Lan, C.E. and Chang, J.F., "Calculation of Vortex Lift Effect for Cambered Wings by the Suction Analogy," NASA CR 3449, July 1981.

    The leading edge suction force direction depends on the local camber and α. It is not always normal to the surface at the leading edge. Basic prediciton methods are presented and verified.

61. Lan, C.E. and Hsu, C.H., "Effects of Vortex Breakdown on Longitudinal, Lateral, and Directional Aerodynamics of Slinder Wings by th Suction Analogy," AIAA Paper 82-1385, August 1982.

    Empirical corrections for the change in the vortex lift with vortex burst are presented. There is also information about the effect of breakdown on $C_{L\beta}$ and $C_{Y\beta}$.

62. Lan, C.E., and Hsing, C.C., "Subsonic Analysis and Design of Vortex Flaps," NASA CP 2417, Paper 5.

63. Lockwood, V.E.,"Effect of Leading Edge Contour and Vertical Tail Configuration on the Low Speed Stability Characteristics of a Supersonic Transport Model Having a Highly Swept Delta Wing," NASA TM 78683, March 1978.

    A leading edge flap with a large leading edge radius practically eliminated the pitch-up tendency. Leading edge deflection and camber delayed the pitch-up from 11° to 19°.

64. Mack, R.J., "Wind Tunnel Investigation of Leading Edge Thrust on Arrow Wings in Supersonic Flow," NASA TP 2167, 1983.

    The axial force increments were in poor agreement with the theory of TP 1500 for very sharp and very blunt airfoils. For standard sections, however, at Mach 1.8, only slightly more leading edge thrust than the theoretical maximum was obtained.

65. Maltby, R.L., "The Development of the Slender Delta Concept," *Aircraft Engineering*, March 1968, p. 12.

    AR is not the suitable parameter to compare different wing planforms. The average sweep, expressed as the semi-span to length ratio is the crucial parameter. In order to minimize drags around M = 2, a semi-span to length ratio around 1/4 is needed. Trailing edge controls are effective and linear.

66. Manro, M.E., "Transonic Pressure Measurements and Comparison of Theory to Experiment ffor Three Arrow-Wing Configurations—Summary Report," NASA CR 3434, 1982.

    Full and partial span trailing edge flaps and wing fins were evaluated for their effects on the spanwise variation of the normal force on the wing.

67. Manro, M.E., Bobbit, P.J. and Kulfan, R.M., "The Prediction of Pressure Distributions on an Arrow-Wing Configuration Including the Effect of Camber, Twist, and a Wing Fin," NASA CP 2108, N81-17984, March 1980.

    The conditions when attached or separated flow theories should be used are evaluated.

68. McLemore, H.C. and Parlett, L.P., "Low-Speed Wind-Tunnel Tests of a 1/10-Scale Model of a Blended-Arrow Supersonic Cruise Aircraft," NASA TN D-8410, 1977.

    This paper reports the effects of combinations of canards, leading edge flaps, trailing edge flaps (segmented), and a vertical tail on longitudinal and lateral stability.

69. Mercer, C.E. and Carson, G.T. Jr.,"Transonic Aerodynamic Characteristics of a Supersonic Cruise Aircraft Research Model With the Engines Suspended Above the Wing," NASA TM 80145, December 1979.

    This is an investigation of how upper surface blowing affects the longitudinal aerodynamic characteristics of an arrow-wing aircraft.

70. Middleton, W.D. and Lundry, J.L., "A System for Aerodynamic Design and Analysis of Supersonic Aircraft, Part 1–General Description and Theoretical Development" NASA CR 3351, 1980.

    The program was updated to contain the near-field wave drag, fuselage and nacelle effects, and pressure limiting terms to constrain linear theory vortex lift solution. NASA CR 3352, NASA CR 3353, and NASA CR 3354 contain the user's manual, the computer program description, and test cases; respectively.

71. Miller, D.S. and Wood, R.M., "Leeside Flows Over Delta Wings at Supersonic Speeds," *Journal of Aircraft*, Vol. 21, No. 9, September 1984.

    The experimental vortex-induced normal force varies linearly with α , but theoretically, it should vary with α^4.

72. Morris, O.A., Fuller, D.E. and Watson, C.B., "Aerodynamic Characteristics of a Fixed Arrow-Wing Supersonic Cruise Aircraft at Mach Numbers of 2.30, 2.70, and 2.95," NASA TM 78706, August 1978.

    An investigation of the controls which can be used to change the stability of the aircraft was conducted. Elevons, canards, spoilers, and horizontal tails are considered.

73. Nangia, R.K. and Hancock, G.J.. "Delta Wings with Longitudinal Camber at Low Speed," ARC CP 1129, September 1969.

    The Polhamus suction analogy allows a linear treatment of the non-linear lift effects on slender delta wings. (Carlson uses this in his flap design- superposition of effects).

74. Peckham, D.H., "Low Speed Wind-Tunnel Tests on a Series of Uncambered Slender Pointed Wings With Sharp Edges," ARC R&M 3186, December 1958.

    No control deflections are included.

75. Penland, J.A., "Maximum L/D Characteristics of Rectangular and Delta Wings at M=6.9," NASA TN D-2925, August 1965.

    There are no control deflections, but there is some information about the L/D predicted for delta and rectangular wedge-shaped (pyramidal) wings.

76. Pinsker, W.J.G., " The Lateral Motion of Aircraft and in Particular of Inertially Slender Configurations," ARC-3334, September 1961.

    A thorough discussion of cross-coupling effects, particularly in regard to lateral-directional aerodynamics is presented.

77. Pinsker, W.J.G., "The Effect of Variations in Local Gravity and of Aircraft Speed on the Effective Weight of Aircraft in High Performance Cruise," ARC-3680, December 1969.

    For $M = 4.0$ at 80,000 ft, the weight of aircraft is reduced 5.1% in eastbound flight and 1.5% in westbound flight. The Concorde's weight is reduced 2.3% eastbound. This is substantial and shouldn't be ignored.

78. Pinsker, W.J.G., "The Aerodynamic Effect of Ground Proximity on Lateral Control of Slender Aircraft in the Landing Approach," ARC CP 1152, 1970.

    Ground effect exerts such a powerful constraint on bank angle disturbances for slender aircraft, that lateral turbulence is almost eliminated as a control problem.

79. Pinsker, W.J.G., "Critical Flight Conditions and Loads Resulting From Inertia Cross-Coupling and Aerodynamic Stability Deficiencies," ARC CP 404, March 1957.

    An aircraft is liable to experience divergent pitching and yawing motions during rolling maneuvers if the inertia in roll is small when compared to the inertia in pitch. Gyroscopic forces generated by aircraft with large inertias can lead to autorotational rolling states (easily predicted). A loss of directional stability may occur at high supersonic Mach numbers or high α .

80. *Proceedings of the SCAR Conference Part 1*, NASA CP 001, November 1976.

    This is mostly an overview of the basic research done since SCAR began in the early 1970s. It includes conceptual and preliminary configuration studies as well as some computer program validations.

81. Quinto, P.F. and Paulson, J.W. Jr., "Flap Effectiveness on Subsonic Longitudinal Aerodynamic Characteristics on a Modified Arrow Wing," NASA TM 84582, March 1982.

    Significant improvements in drag-due-to-lift resulted from combined leading edge and trailing edge deflections. Suction recovery of 84° at $C_L=.47$ was noted.

82. Rao, D.M., "Vortical Flow Management for Improved Configuration Aerodynamics–Recent Experiences," AGARD CP 342, No. 30, 1983.

    Lost linear lift caused by deflecting l.e. vortex flaps can be recovered by using extended planform flaps. Structural difficulty can be encountered when flaps are used on thin wings. Apex flap characteristics are discussed.

83. Rao, D.M., "Shock Interaction Effect on a Flapped Delta Wing at $M = 8.2$," *AIAA Journal*, Vol. 9, January 1971.

    Outboard portions of the trailing edge flaps on a hypersonic delta wing are less effective than inboard portions. Shock interactions decrease the normal and axial forces, and make C_M less negative.

84. Rao, D.M., "Upper Vortex Flap - A Versatile Surface for Highly Swept Wings". ICAS 82 6.7.1.

    Trailing edge flaps produce large pitching moments on delta wings. The UVF may be a lift augmentor at low α and a drag reducer at high α. The absence of pitch variation when these flaps are used is good for braking.

85. Rao, D.M., "Hypersonic Aerodynamic Characteristics of Flat Delta and Caret Wing Models at High Incidence Angles," *Journal of Spacecraft and Rockets*, Vol. 7, December 1970, p1475.

    Caret wings are superior to flat delta wings for hypersonic lift generation.

86. Rao, D.M., "Exploratory Subsonic investigation of Vortex-Flap Concept on Arrow Wing Configuration,", NASA CP 2108, N81-17985, March 1980.

    Leading edge vortex flaps can reduce the intensity of pitch-up.

87. Rao, D.M. and Johnson, T.D., "Investigation of L.E. Devices for Dtag Reduction of 60° Delta Wings at High Angle of Attack," AIAA Paper 80-0310, January 1980.

    It is desirable to design the outboard sections of the wing to recover the most possible thrust. This is where the leading edge upwash is greatest.

88. Reddy, C.S., "Effect of Leading Edge Vortex Flaps on Aerodynamic Performance of Delta Wings," *Journal of Aircraft*, Vol. 18, No. 9., September 1981.

    The forward movement of vortex lift with increased α causes longitudinal instability.

89. Riebe, G.D., "Aerodynamic Characteristics Including the Effect of Body Shape, of a Mach 6 Aircraft Concept," NASA TP 2235, December 1983.

    Contrary to impact theory predictions, the body cross sectional shape for the range of geometries studied, appears to have little effect on the configuration's L/D. As much fuselage area as possible should be located below the wing rather than above the wing for best L/D.

90. Riebe, G.D. and Fox,C.H. Jr., "Subsonic Maneuver Capability of a Supersonic Cruise Fighter Wing Concept," NASA TP 2642, 1987.

    There is little variation of the experimental results between $M = .3$ to $.7$. Trailing edge flap deflection alone gives greater aerodynamic improvement than leading edge flap deflection alone, but simultaneous deflection is best. Ninety percent of the leading edge thrust is recovered for this cambered, twisted, and round leading edge wing. Inboard, larger flaps cause higher nose-down moments and the same drag as small flaps.

91. Robins, A.W. and Carlson, H.W., "High-Performance Wings With Significant L.E. Thrust at Supersonic Speeds," *Journal of Aircraft*, Vol. 17, No. 6, June 1980.

    Until recently, the amount of leading edge thrust at cruise in configurations suitable for extended supersonic cruising had generally been thought to be insignificant. The basic idea is that thickness outboard can recover the suction due to the strong outboard upwash without compromising performance.

92. Robins, A.H., Carlson, H.W. and Mack, R.J., "Supersonic Wings With Significant Leading-Edge Thrust at Cruise," NASA TP 1632, 1980.

    Experimental and theoretical correlations are presented which show that significant levels of leading edge thrust are possible at supersonic speeds for certain wings.

93. Robins, A.W., Carlson, H.W. and Mack, R.J., "Supersonic Wings With Significant Leading-Edge Thrust at Cruise," NASA CP 2108, N81-17990, March 1980.

    It is possible to exploit the leading edge suction phenomenon at supersonic speeds with the proper wing design.

94. Robins, A.W., Lamb, H., and Miller, D.S., "Aerodynamic Characteristics at Mach Numbers of 1.5, 1.8, and 2.0 of a Blended Wing-Body Configuration With and Without Integral Canards," NASA TP 1427, May 1979.

    At low C_Ls in the supersonic regime, any reduction in the vortex drag through the use of a canard is outweighed either by the additional wave- or viscous-drag. The benefits can also be outweighed by the canard-induced reduction of the leading edge upwash which gives rise to leading edge thrust in first place. The configuration was designed for attached flow at a $C_L = .07$.

95. Roensch, R.L. and Page, G.S., "Analytical Development of an Improved Supersonic Cruise Aircraft Based on Wind Tunnel Data," NASA CP 2108, N81-17989, March 1980.

    The configuration wave drag-due-to-volume increases with high trailing edge notch ratios, which cancels the notch ratio's beneficial effect of decreasing the drag-due-to-lift. The optimal notch ratio corresponds to a notch angle of about one-half the Mach cone angle.

96. Roensch, R.L., Felix, J.E., Welge, H.R., Yip, L.P. and Parlett, L.P., "Results of a Low-Speed Wind Tunnel Test of the MDC 2.2M Supersonic Cruise Aircraft Configuration,", NASA CP 2108, N81-17983, March 1980.

    Leading edge flaps are required for maximum performance. Eighty-five percent suction can be obtained at C_L=.65 . Leading edge flaps have less of an effect on C_D or C_L when the trailing edge flaps are deflected.

97. Ross, A.J. and Beechan, L.J., "An Approximate Analysis of th Non-Linear Lateral Motion of a Slender Aircraft (HP115) at Low Speeds," ARC R&M 3674.

98. Runyan, L.J., Middleton, W.D. and Paulson, J.A., "Wind Tunnel Test Results of a New Leading Edge Flap Design fo Highly Swept Wings—A Vortex Flap," NASA CP 2108, N81-17986, March 1980.

    This paper presents an investigation of a leading edge flap which has a small tab on the leading edge to force separation. An increase in both lift and drag, typical of leading edge vortex formation, is found.

99. Schoonover, W.E. and Ohlson, W.E., "Wind Tunnel Investigation of Vortex Flaps on a Highly Swept Interceptor Configuration,"ICAS 82 6.7.3.

The amount of vortex flap deflection has very little effect on the amount of suction recovered (30° and 45° are about the same). Higher flap deflections do, however, decrease α and upwash. Vortex flaps delay and moderate pitch-up. Trailing edge flaps increase performance and can generate pitching moments effectively. Full span flaps can recover most of the suction (approximately 80 percent). A vertical stabilizer can influence the leading edge vortex migration such that pitching moments are dramatically effected.

100. Shrout, B.L. and Fournier, R.H., "Aerodynamic Characteristics of a Supersonic Cruise Aircraft Configuration at Mach Numbers of 2.3, 2.96, and 3.30," NASA TM 78792, 1979.

A chine destabilizes pitch stability, but increases roll and directional stability at an angle of attack greater than 4°. The effects of nacelles and outboard vertical tails are also included.

101. Shrout, B.L., Corlet, W.A. and Collins, I.K., "Surface Pressure Data for a Supersonic Cruise Airplane Configuration at Mach Numbers of 2.30, 2.96, and 3.30," NASA TM 80061, 1979.

Tabulated results are presented without any analysis.

102. Small, W.J., Kirkham, F.S. and Fetterman, D.E. Jr.,"Aerodynamic Characteristics of a Hypersonic Transport Configuration at Mach 6.86," NASA TN D-5885, June 1970.

A distinct wing-body hypersonic transport was tested. Theoretical and Experimental evaluations of C_{N_β}, C_{L_β}, C_{L_α}, and δ_e to trim are included.

103. Smith, J.H.B., Beasley, J.A., and Stevens, A., "Calculations of the Lift Slope and Aerodynamic Centre of Cropped Delta Wings at Supersonic Speeds," ARC CP 562, July 1960.

104. Smith, P.H., "Low Speed Aerodynamic Characteristics from Wind Tunnel Tests of a Large Scale Advanced Arrow Wing Supersonic Cruise Transport Concept," NASA CR 145280, April 1978.

The principle configuration variables were leading edge flap deflections, trailing edge flap deflections, horizontal tail effectiveness, strakes, and a slotted trailing edge flap program. Lateral and longitudinal characteristics included. A good amount of data is contained in this report.

105. Snyder, M.H. and Lamar, J.E., "Applicaotion of the Leading-Edge-Sucion Analogy to Prediction of Longitudinal Load Distribution and Pitching Moment for Sharp-Edged Delta Wings," NASA TN D-6994, October 1972.

The suction analogy can't predict the pitching moment because of a real-life loss of lift at wing tips. The vortex migrates inward and upward.

106. *Supersonic Cruise Research 1979, Part 1*, NASA CP 2108, (Contains Papers N81-17981 to N81-18004), March 1980.

107. Wahls,R.A., Vess,R.J., and Moskovitz,C.J., "An Experimental Investigation of Apex Fence Flaps on Delta Wings". AIAA Paper 85-4055.

Apex fence flaps were tested for lift and lateral control.

108. Wentz, W.H. Jr., "Effects of L.E. Camber on Low Speed Characteristics of Slender Delta Wings," NASA CR 2002, 1972.

Leading edge camber near the apex is effective in controlling the pitch-up of slender delta wings. The aerodynamic center is located at .40 MAC (typically). For a flap deflection of 36°, the performace benefits nearly duplicate those of an apex-camber wing. With cambered leading edges, substantial side forces and yawing moments are generated, which differs from a flat plate delta (at high C_L and sideslip).

109. Whitcofski, R.D. and Marcum, D.C. Jr., "Wing Sweep and Blunting Effects on Delta Planforms at M=20," *AIAA Journal*, Vol. 3, March 1965, p. 547.

Basic delta planforms were investigated for longitudinal stability characteristics and L/D. A thin wing of 80° sweep combined with a blunt balance-housing-body produced the highest L/D.

110. Whitehead, A.H. and Keyes, J.W., "Flow Phenomena and Separation over Delta Wings With Trailing Edge Flaps at Mach 6," *AIAA Journal*, Vol. 6, December 1968, p. 2380.

The paper is primarily about the flow physics and boundary layers of highly swept delta wings with trailing edge flaps.

111. Wood, R.M., "Supersonic Aerodynamics of Delta Wings," NASA TP 2771, March 1988.

The geometric characteristics and flow conditions which should be used in assessing the supersonic aerodynamics of delta wings are presented.

112. Wood, R.M. and Covell, P.F., "Experimental and Theoretical Study of the Longitudinal Aerodynamics Characteristics of Delta and Double Delta Wings at Mach Numbers of 1.6, 1.9, and 2.16," NASA TP 2433, July 1985.

Deflecting trailing edge flaps for pitch control revealed that the induced aerodynamic forces are only a function of the flap planform and were independent of the wing planform for $M = 1.6$ to 2.16. A delta wing has better drag due to lift than a cranked delta, but worse zero-lift wave drag. It is important to have a subsonic leading edge to decrease drag. Usually, an upward trailing edge flap deflection is necessary for pitch stability at supersonic speeds. This causes significant drag and a decrease in lift.

113. Wood, R.M. and Miller, D.S., "Experimental Investigation of Leading Edge Thrust at Supersonic Speeds," NASA TP 2204, September 1983.

There is no deflection information. For sharp and varying leading edge geometries, there were large differences between experiment and the theory from NASA TP 1500. For standard NACA-type sections, the theory was a useful predictor.

114. Yip, L.P.,"Low-Speed Wind Tunnel Tests of a 1/10 Scale Model of an Advanced Arrow-Wing Supersonic Cruise Configuration Designed for Cruise at Mach 2.2," NASA TM 80152, August 1979.

A wealth of information is contained about the effects of leading edge and trailing edge flaps and their effects on vortex lift, pitch instability, L/D, and more. Lateral information is also provided.

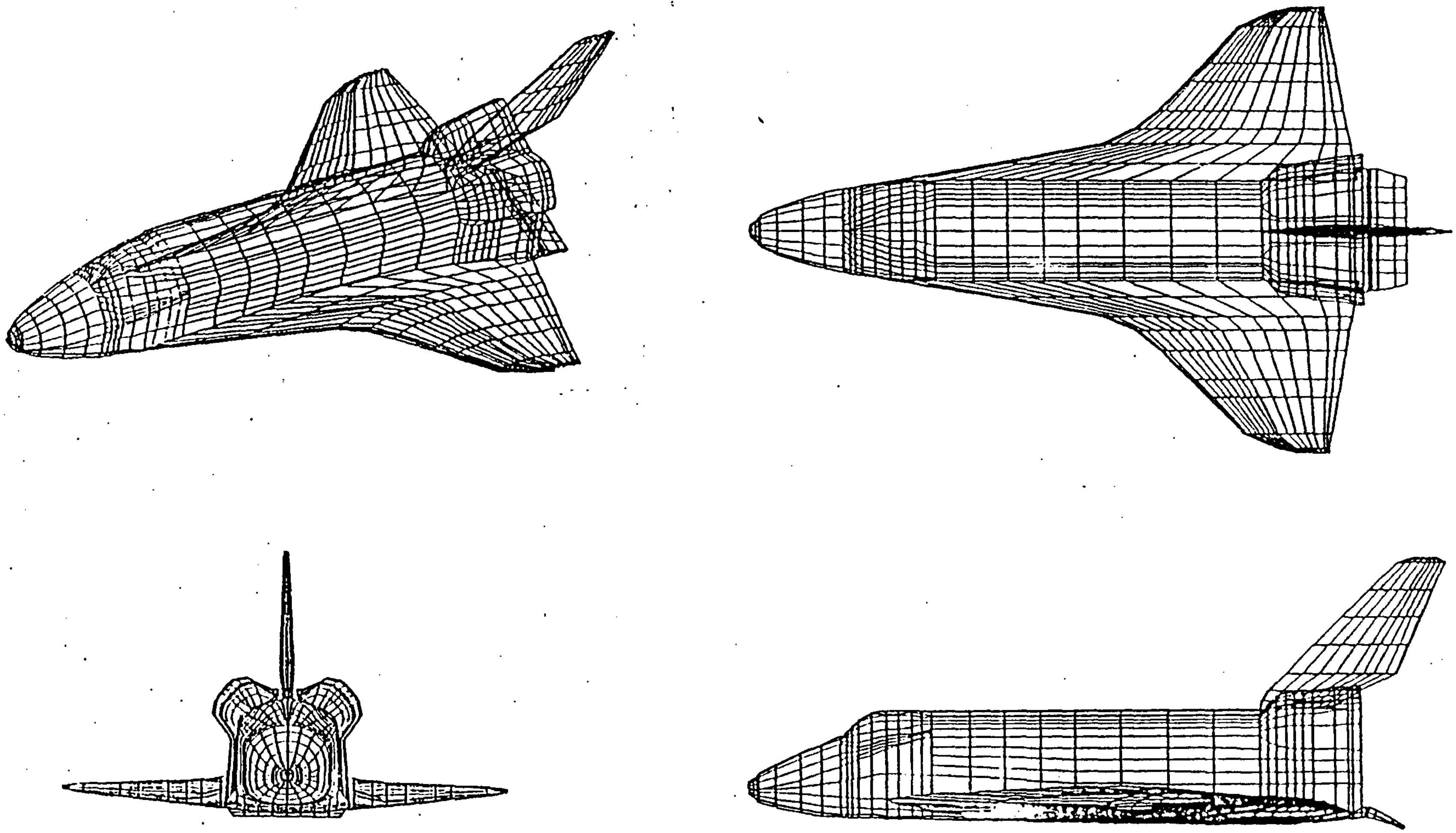

Figure 1: Space Shuttle configuration.

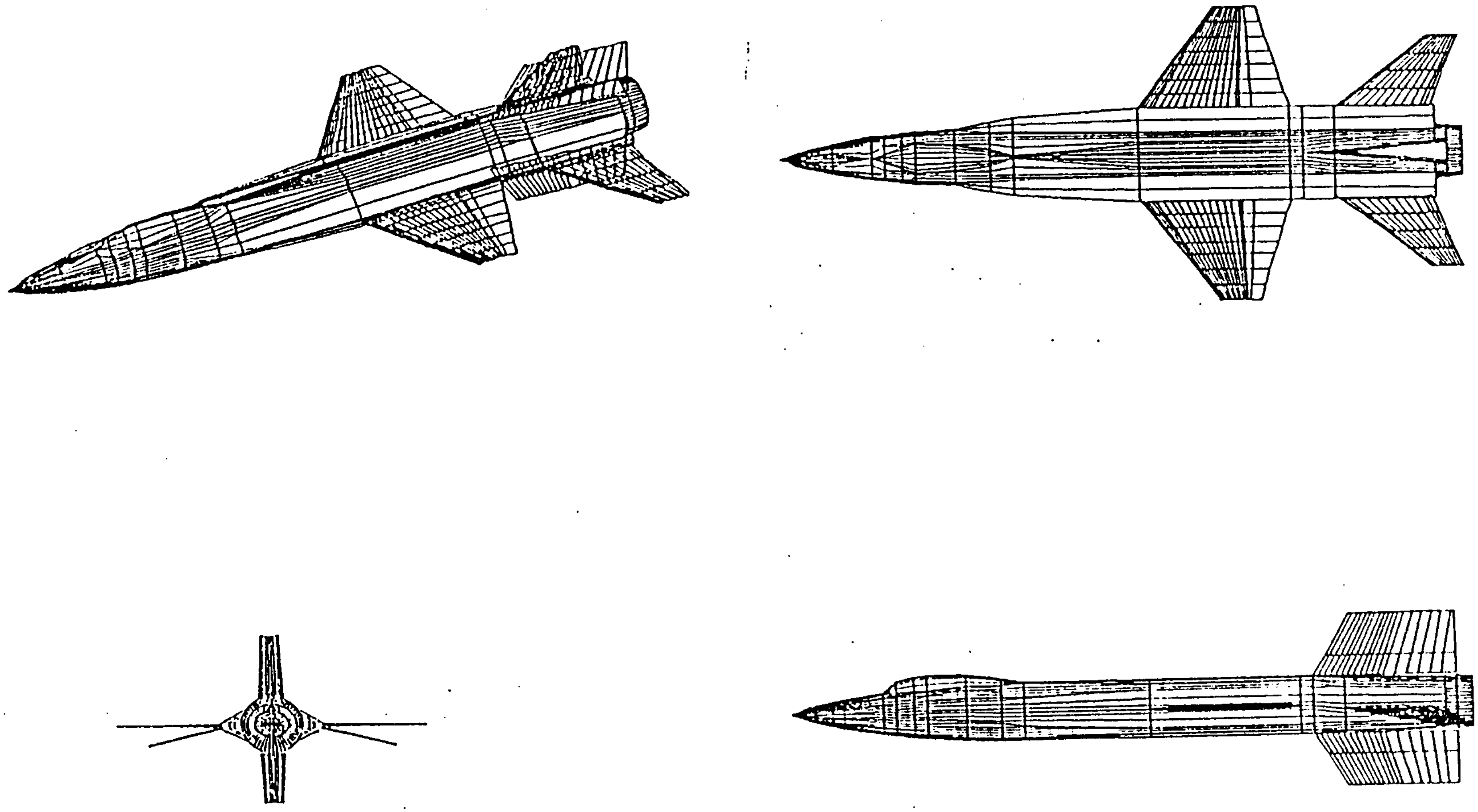

Figure 2: X – 15 configuration.

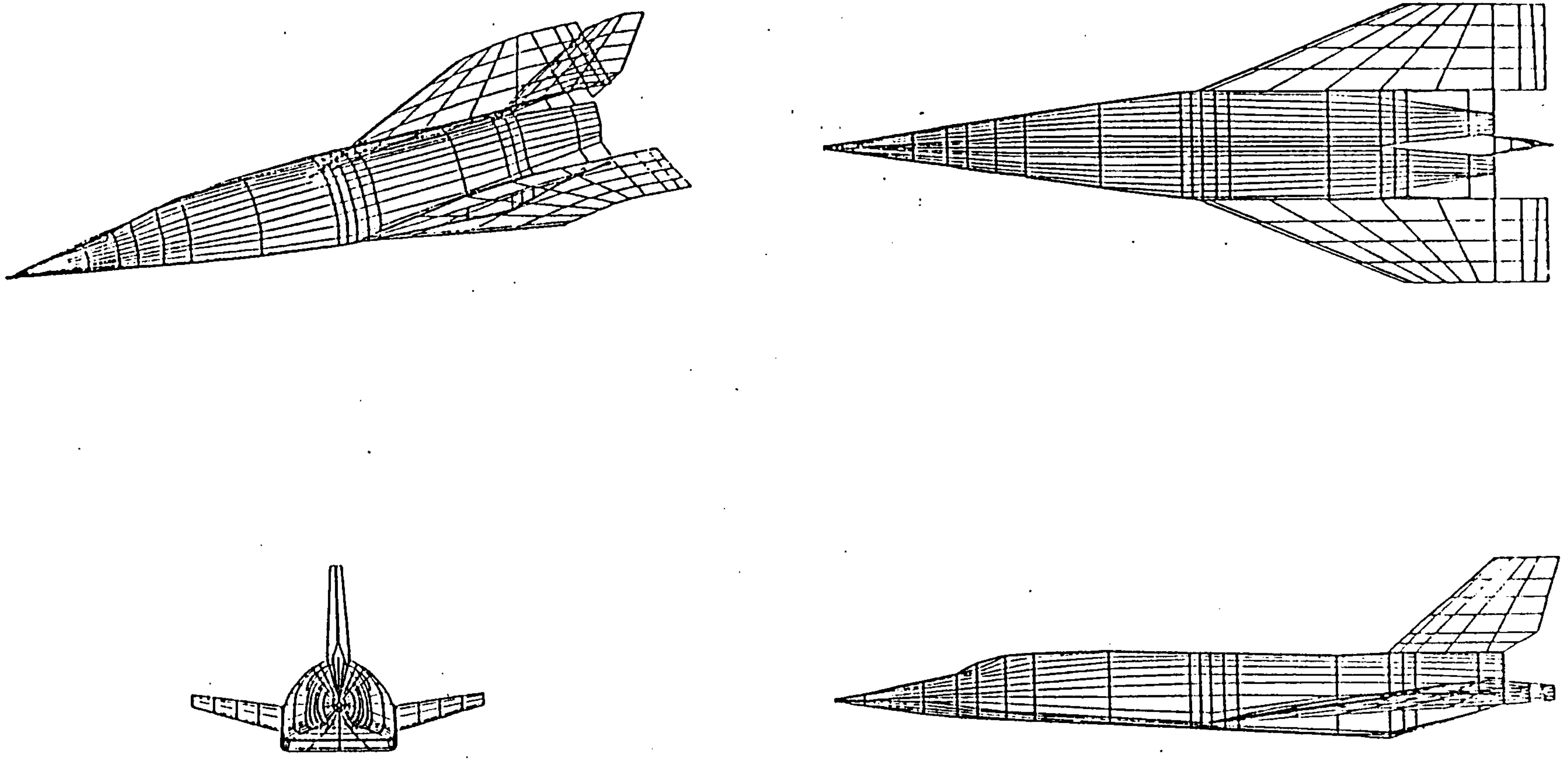

Figure 3: Hypersonic Wing – Body configuration