SUMMARY REPORT

A THEORETICAL STUDY OF THE AERODYNAMIC CHARACTERISTICS OF LIFTING-BODY ENTRY VEHICLES

NOR 66-72
May 1966

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by

NORTHROP CORPORATION
NORAIR DIVISION
3901 West Broadway
Hawthorne, California 90250

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Ames Research Center
Moffett Field, California

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FOREWORD

This report was prepared by the Norair Division of Northrop Corporation, Hawthorne, California, on NASA AMES Research Center Contract NAS2-2671, "Theoretical Study of the Aerodynamic Characteristics of Lifting Body Entry Vehicles." The studies presented here began in March 1965 and were concluded in March 1966. They represent an effort by members of the Research and Technology Section of Northrop Norair.

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H. R. Wasson	Viscous Crossflow and Vortex Tracking Theory
J. E. Brickman	Area Rule and Shock Expansion
S. A. Powers	Three-Dimensional Method of Characteristics
W. E. Grahame	Empirical Correlations
J. R. Garcia	Assistance in Studies and Final Report.

The technical monitors for the NASA AMES Research Center were Mr. J. L. Jones and Mr. E. R. Keener.

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ILLUSTRATIONS

INTRODUCTION

To complement NASA's extensive experimental research effort in lifting entry bodies, corresponding theoretical analyses of the aerodynamic characteristics of the Ames M-2 and Langley HL-10 have been conducted by Norair. Such analyses are required to assist in the interpretation of wind tunnel and flight test results and, in general, to complete the scope of the research program related to lifting bodies. One purpose of the present study is to provide such theoretical analyses; however, a more basic purpose is to evolve and evaluate theoretical methods applicable to the lifting-body class of vehicles in general. Emphasis is placed on the evolution of simplified methods representing an engineering approach. The following theoretical methods are presented in Sections 1 through 8.

1. Lifting Surface Theory
2. Slender Body Theory Using Apparent Mass Methods
3. Viscous Crossflow and Vortex Tracking Theory
4. Shock-Expansion Theory
5. Area Rule Wave Drag
6. Modified Newtonian and Exponential Flow Theory
7. Three-Dimensional Method of Characteristics
8. Empirical Correlations.

The results shown in each section present both an evaluation of applicable aerodynamic theories and general methods for computing the aerodynamic characteristics of lifting-body entry vehicles as derived from these theories. A Mach number range from incompressible to hypersonic is covered. Longitudinal, lateral-directional, and dynamic forces were studied. Theoretical estimates of the aerodynamic characteristics of the M-2 or the HL-10 lifting body were compared with experimental test results. Conclusions are based on the comparisons.

The material appearing in each of the subsequent sections is condensed and emphasizes the major contributions made, the conclusions or concluding remarks, and the recommendations for future studies. A comprehensive detailed presentation of the work in each section appears in the Final Report (NOR 66-71).

The charts shown in Figures 1 and 2 summarize this study.

SPEED REGIME:

1. SUBSONIC INCOMPRESSIBLE
2. SUBSONIC COMPRESSIBLE
3. TRANSONIC
4. SUPERSONIC
5. HYPERSONIC

ACCURACY OR APPLICABILITY OF METHOD:

A - GOOD F - FEASIBLE, FURTHER WORK REQUIRED
B - FAIR I - IMPRACTICAL OR INVALID
C - POOR L - LIFTING BODY DATA COMPILED

EASE OF APPLICATION:

EEE - EASY
EE - MODERATE
E - INVOLVED

	DRAG	LIFTING FORCES		MOMENTS			CONTROL EFFECTS: BASIC			CONTROL EFFECTS: COUPLED	
	1	2	3	4	5	6	7	8	9	10	11
	DRAG	LIFT / ANGLE OF ATTACK	SIDE FORCE / SIDE SLIP	PITCH MOM. / ANGLE OF ATTACK	YAW MOM. / SIDE SLIP	ROLL MOM. / SIDE SLIP	PITCH MOM. / ELEV. DEFL.	YAW MOM. / RUDDER DEFL.	ROLL MOM. / AILERON DEFL.	ROLL MOM. / RUDDER DEFL.	YAW MOM. / AILERON DEFL.
LONGITUDINAL	C_D	C_L		C_m			$C_{m_{\delta_e}}$				
LATERAL-DIRECTIONAL			c_{y_β}		C_{n_β}	C_{ℓ_β}		$C_{n_{\delta_r}}$	$C_{\ell_{\delta_a}}$	$C_{\ell_{\delta_r}}$	$C_{n_{\delta_a}}$
DYNAMIC DERIVATIVES											

METHOD		1: 1	1: 2	1: 3	1: 4	1: 5	2: 1	2: 2	2: 3	2: 4	2: 5	3: 1	3: 2	3: 3	3: 4	3: 5	4: 1	4: 2	4: 3	4: 4	4: 5	5: 1	5: 2	5: 3	5: 4	5: 5
1. LIFTING SURFACE	(EE)	A[1]	B[1]	F[1]	A[1]	F[1]	A	B	F	A	F	F	F	F	F	F	C	C	C	C	C	I	I	I	I	I
2. SLENDER BODY THEORY USING APPARENT MASS METHODS	(EEE)	I	I	I	I	I	B	B	B	B	I	B	B	B	B	I	B	B	B	B	I	B	B	B	B	I
3a. VISCOUS CROSSFLOW	(EEE)	I	I	I	I	I	B	B	B	B	I	B	B	B	B	I	B	B	B	B	I	B	B	B	B	I
3b. VORTEX TRACKING METHOD	(EE)	I	I	I	I	I	A	A	F	F	I	F	F	F	F	I	A	A	F	F	I	F	F	F	F	I
4. SHOCK-EXPANSION	(EEE)	I	I	A[2]	A[2]	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
5. AREA RULE	(EEE)	I	I	A	A	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
6. MODIFIED NEWTONIAN AND EXPONENTIAL FLOW	(EE)	I	I	I	F	A	I	I	I	F	A	I	I	I	F	A	I	I	I	F	B	I	I	I	F	C
7. 3-D METHOD OF CHARACTERISTICS	(E)	I	I	I	A[3]	A[3]	I	I	I	A[3]	A[3]	I	I	I	A[3]	A[3]	I	I	I	F	F	I	I	I	F	F
8. EMPIRICAL CORRELATIONS	(EEE)	L	L	L	A[4]	A[4]	L	L	L	A[4]	A[4]	L	L	L	A[4]	A[4]	L	L	L	B[4]	B[4]	L	L	L	L	L

METHOD		6: 1	6: 2	6: 3	6: 4	6: 5	7: 1	7: 2	7: 3	7: 4	7: 5	8: 1	8: 2	8: 3	8: 4	8: 5	9: 1	9: 2	9: 3	9: 4	9: 5	10: 1	10: 2	10: 3	10: 4	10: 5	11: 1	11: 2	11: 3	11: 4	11: 5
1. LIFTING SURFACE	(EE)	F	F	I	F	F	F	F	I	F	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
2. SLENDER BODY THEORY USING APPARENT MASS METHODS	(EEE)	F	F	F	F	I	F	F	F	F	F	F	F	F	F	F	F	F	F	F	I	F	F	F	F	F	F	F	F	F	I
3a. VISCOUS CROSSFLOW	(EEE)	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
3b. VORTEX TRACKING METHOD	(EE)	F	F	F	F	I	F	F	F	F	I	F	F	F	F	I	F	F	F	F	I	F	F	F	F	I	F	F	F	F	I
4. SHOCK-EXPANSION	(EEE)	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
5. AREA RULE	(EEE)	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
6. MODIFIED NEWTONIAN AND EXPONENTIAL FLOW	(EE)	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F
7. 3-D METHOD OF CHARACTERISTICS	(E)	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F
8. EMPIRICAL CORRELATIONS	(EEE)	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

[1] REFERS TO DRAG DUE TO LIFT

[2] APPLIED TO EQUIVALENT BODIES OF REVOLUTION

[3] NOT APPLIED TO LIFTING BODIES

[4] REFERS TO ZERO LIFT

DYNAMIC DERIVATIVES																																		
STEADY																									UNSTEADY									
BASIC															ROTARY																			
12					13					14					15					16					17					18				
ROLL MOM. / ROLL RATE					PITCH MOM. / PITCH RATE					YAW MOM. / YAW RATE					YAW MOM. / ROLL RATE					ROLL MOM. / YAW RATE					PITCH MOM. / ANG. ATT. RATE					YAW MOM. / SIDE-SLIP RATE				
C_{ℓ_p}					C_{m_q}					C_{n_r}					C_{n_p}					C_{ℓ_r}					$C_{m_{\dot{\alpha}}}$					$C_{n_{\dot{\beta}}}$				
1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
F	F	I	F	I	F	F	I	F	I	I	I	I	I	I	F	F	I	F	I	F	F	I	F	I	I	I	I	I	I	I	I	I	I	I
F	F	F	F	I	B	B	B	B	I	B	B	B	B	I	F	F	F	F	I	F	F	F	F	F	B	B	B	B	I	B	B	B	B	I
I I	I I	I I	I I	I I	I F	I F	I F	I F	I I	I F	I F	I F	I F	I I	I I	I I	I I	I I	I I	I F	I F	I F	I F	I I	I I	I I	I I	I I	I I	I I	I I	I I	I I	I I
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F
I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F	I	I	I	F	F
L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L	L

METHOD	STATUS	CONCLUSIONS	RECOMMENDATIONS
1. Lifting Surface	• Applied subsonic and supersonic lifting surface computer programs to approximations of the M-2 and HL-10. • Applied the theory to a delta planform lifting body configuration.	• Lifting surface theory provides an adequate prediction method for determining lift and drag due to lift but not pitching moment at subsonic and supersonic speeds. • At supersonic speeds, pitching moment slope prediction is acceptable with end plate factors but the magnitude is in error.	• Component build-up wind tunnel tests with control surfaces at zero degrees are desired for configuration analysis and development. • The subsonic program should be extended to non-planar lifting surface theory to include tip fin effects. • A design option applied to lifting bodies should be developed.
2. Slender Body Theory Using Apparent Mass Methods	• Developed simple desk top electrical analogy method to obtain apparent masses for arbitrary cross sections. • Applied electrically measured apparent masses to get static and dynamic stability derivatives for M-2 and HL-10.	• The simple measurement of overall resistance of electrically conducting paper with arbitrary shapes cut out can be used to determine apparent masses with good accuracy. • Slender body theory gives fair approximations of average values of most coefficients in the subsonic and lower supersonic speed ranges.	• Determine rotational apparent masses by electrical analogy. • Determine 3-D apparent masses with electrical tank analog. • Obtain apparent masses by fluid immersion. • Study supersonic apparent masses by radar cross-section.
3. Viscous Crossflow and Vortex Tracking	• Investigated the applicability of the viscous crossflow method to arbitrary lifting bodies. • Developed a vortex tracking computer program to compute forces and moments caused by vorticity for arbitrary lifting bodies.	• The viscous crossflow method is limited to pitch plane forces and moments, and to circular and/or elliptical and near elliptical shapes. • The feasibility of predicting forces and moments on arbitrary bodies by tracking vortices has been shown.	• Further effort should be applied to complete the checkout of the computer program and compare results with test data. • Determine parameters which define the lines of vortex separation by correlation with test data. • Develop the program to predict static and dynamic derivatives.
4. Shock Expansion	• Coupled an adjusted modified Newtonian equation with second-order shock-expansion method to obtain a blunt-body pressure distribution. • Applied the method to an equivalent axisymmetric area ruled body to obtain the wave drag at zero lift in Method 5.	• Application of second-order shock-expansion method to the M-2 and HL-10 lifting bodies does not appear practical. • Ideal method for estimating wave drag of equivalent area ruled body.	• A continued effort to apply this method to other equivalent lifting body configurations should be conducted.
5. Area Rule Wave Drag	• Incorporated shock expansion method to determine wave drag according to area rule theory. • Applied method to equivalent M2-F2, HL-10 bodies.	• Zero lift wave drag of M2-F2 and HL-10 as determined from experiment compares quite well with that predicted by second-order shock-expansion method. • Design analyses of lifting bodies are facilitated by use of transonic area rule.	• Application of this method would be particularly useful in future lifting body design studies. • Development of an Area Rule computer program using shock expansion theory.
6. Modified Newtonian and Exponential Flow Theory	• Developed a modified Newtonian and exponential flow program which calculates forces and moments on a three-dimensional body. • The program has the option of computing forces and moments which include the effects of laminar or turbulent skin friction.	• The three-dimensional force and moment program has been applied to both the M2-F2 and HL-10 configurations. Close agreement with test results was achieved.	• In order to gain added flexibility, the computer program should include changes involving general body cross sections and the effect of fins.
7. Three-Dimensional Method of Characteristics	• Initiated cooperative computer program with Ames Research Center and repeated results obtained at Wright Field.	• The program is working properly and indications are that reasonable results can be obtained.	• The program should be used to determine the entire flow field over the M-2 and HL-10 bodies for comparison with experimental data.
8. Empirical Correlations	• Compiled and correlated aerodynamic characteristics of thirty-five representative lifting body shapes. • Developed methods of analysis using correlated data in the supersonic-hypersonic speed regime.	• The parameter $\frac{Vol^{2/3}}{S}$ holds promise as a design tool for predicting lift curve slope but not forebody drag. • Developed a method whereby lift curve slope, pitching moment slope of arbitrary lifting body shapes could be obtained by conversion to an equivalent lifting body shape.	• A continued effort to compile additional aerodynamic characteristics (particularly dynamic derivatives) should be pursued. • Further emphasis is required to determine effects of control surfaces, control surface deflection and canopies on lifting body aerodynamics. • The development of a lifting body aerodynamic handbook is necessary.

SECTION 1

LIFTING SURFACE THEORY

DESCRIPTION OF METHOD

By describing the sources and doublets on the planform of a thin, finite wing, it is possible to calculate the flow past the wings of arbitrary planforms. The strength of these sources and doublets is adjusted so that the flow is parallel to the slope of the wing surface. This process is called lifting surface theory.

Using lifting surface theory, Northrop developed an analytical procedure for designing and analyzing subsonic lifting surfaces, under BuWEPS Contract NOw 63-0726-c. This contract covered two programs: a design program (which included two separate options) and an analysis program. The programs apply to continuous surfaces of arbitrary planforms only, and do not include such interference effects as slots, ground effects, large dihedral angles, or end plates. The two options of the design program, however, provide a flexible choice of design loadings: (1) the lifting surfaces can be designed to produce elliptic spanwise loadings for independently specified design conditions, or (2) the surfaces can be designed to produce an arbitrarily specified load distribution. The procedure, using IBM 7090 computer programs, determines:

1. The angle of attack and camber distribution on a given arbitrary wing planform to provide a specified load distribution, or to provide specified lift and pitching moment coefficients with an elliptic spanwise load distribution. The latter is the optimized load distribution.

2. The load distribution and aerodynamic coefficients for a given arbitrary planform and distribution of camber and angle of attack.

APPLICATION OF METHOD

Subsonic

The Northrop Norair analytical lifting surface procedures utilize a trigonometric series multiplied by a polynomial to describe the pressure loading on the wing. This series is substituted into the lifting surface integral equation which is solved at selected downwash control points, and thus generates a matrix equation from which either the unknown coefficients of the loading series or the downwash velocities at the collocation points can be determined, depending on which is specified.

Supersonic

The values of C_L, C_{D_L}, C_M in the low angle-of-attack range at supersonic speeds are calculated by a digital program similar to that described for subsonic flow, except that the program is equipped to handle asymmetric loadings. The program allows for a discontinuity in the planform distribution of camber. This discontinuity may be used for either an outboard control surface or the body-vertical tail junction.

CONCLUSIONS

This study using the lifting surface theory has led to the following conclusions:

1. Lifting surface theory provides an adequate prediction method for preliminary design purposes of the drag and lift characteristics of lifting bodies.

2. The prediction of the subsonic pitching moments cannot be relied upon for configurations with fins and blunt bases.

3. At supersonic speeds, the prediction of the slope of the pitching moment with lift coefficients is acceptable with end plate factors included but the magnitude of the pitching moment coefficients will be in error.

4. Lifting surface theory will not calculate acceptable pitching moment characteristics at hypersonic speeds.

RECOMMENDATIONS

The following items are recommended for further study.

1. Component build-up wind tunnel tests, including runs with control surfaces set at zero deflection, are desired for configuration analysis and development.

2. The subsonic lifting surface program should be extended to nonplanar lifting surface theory to allow analysis with tip fins.

3. The theory should be applied to the analysis of configurations with various control deflections to determine:

   a. Whether the level of pitching moments can be improved.

   b. The accuracy of the theory in predicting the variation in aerodynamic characteristics with control deflection.

4. The generally acceptable results in lift and drag obtained from the application of the analysis option of the theory provide a strong indication that the design option also might be applied profitably to lifting bodies.

SECTION 2

SLENDER BODY THEORY USING APPARENT MASS METHODS

Apparent mass measurements can be used with slender body theory to obtain aerodynamic forces. The basic idea of slender body theory is that each body cross section can be studied independently of other cross sections, and the aerodynamic force contribution of each can be summed over the body length to obtain aerodynamic stability derivatives. The important parameter of each cross section which allows computation of these derivatives is the apparent mass.

Apparent masses are obtained by utilizing the electrical analogy for fluid flow. The apparent electrical resistance of an arbitrary cross section can be shown to be directly related to the apparent mass for fluid flow. This apparent resistance is readily measured, and these measured values have been shown to be close to theoretical values for simple shapes. Stability derivatives determined from these measurements have shown good agreement with test data in the several cases where good test data are available.

To obtain the apparent masses, all that is needed is conducting paper and a Wheatstone bridge box. Electric resistance of a sheet of conducting paper from which a body cross section has been cut is compared with resistance of an identical paper without the cutout.

CONCLUSIONS

1. The simple measurement of overall resistance of a sheet of conducting paper with arbitrary shapes cut out can be used to determine apparent masses with good accuracy.

2. The electrical analogy method for determining apparent masses is a useful yet simple tool for obtaining static and dynamic aerodynamic stability derivatives.

3. Slender body theory gives fair approximations of average values of most coefficients in the subsonic and lower supersonic speed ranges.

RECOMMENDATIONS

This study has revealed that the determination of static and dynamic stability derivatives can be estimated easily if the appropriate apparent masses are determined. Because of the possible application of the method to all aircraft, further study should be applied to this problem. Future effort should be directed under the following four categories.

1. Determination of Rotational Apparent Masses by Electric Analogy

   Experimental resistance measurements to obtain rotational apparent masses for 2-D shapes should be made on known simple shapes using several methods and the results compared with the actual answers. From this combination experimental and theoretical approach, the simplest method for the determination of rotational apparent mass would result. The most direct method should be studied and refined to the point where it can be used easily by design engineers.

2. Determination of Three-Dimensional Apparent Masses with Electrical Tank Analog

   It can be shown that for a three-dimensional flow of electricity around an arbitrary shape in an electrically conducting fluid, all of the pure translational apparent masses can be determined by the same procedure described above for two-dimensional flow. This proof is the result of using the basic definition of apparent mass which is:

$$A = \iint \Phi \frac{\partial \Phi}{\partial n} ds. \qquad (1)$$

Since the above integral can be determined on conducting plates at either end of a tank, and is zero over all insulated surfaces, determination of apparent masses is a simple matter.

This technique for arbitrary three-dimensional configurations using an electrically conducting tank should be developed. The three-dimensional apparent masses would be determined by measuring resistances before and after an insulating model is immersed in the tank. The results of the three-dimensional measurements can be used to obtain static and dynamic coefficients for aerodynamic bodies directly, without the need for resorting to the slender body theory limiting assumptions.

3. <u>Apparent Mass by Fluid Immersion</u>

Apparent masses and apparent rotary inertias of a body can be evaluated empirically by observing transients or oscillatory motions of the body immersed in a liquid and noting its acceleration. The apparent mass is equal to the apparent volume times the fluid density. Repeating the same experiment, with the same body in air and in water, would be a simple direct way of measuring all the apparent masses.

This is probably the simplest and most direct method for measuring apparent masses to get stability derivatives. Such tests can be performed very inexpensively and a little effort in this area should produce much useful information on aircraft stability in general.

4. <u>Supersonic Apparent Masses by Radar Cross Section</u>

Much research has been conducted on the determination of radar cross sections for various configurations. A study of the equations required to obtain these radar cross sections shows that the equations are identical with the equations for linearized supersonic flow. The variation of radar cross sections with frequency bears a striking resemblance to the variation of aerodynamic coefficients with Mach number.

Therefore, a detailed study of these relations along with some experimental work might result in a method for determining aerodynamic coefficients throughout the Mach number range by measuring radar cross section of arbitrary bodies. It is recommended that an analysis of the relationships between radar cross sections and supersonic apparent masses be conducted. This might lead to a simplified method of estimating stability derivatives for supersonic aircraft of arbitrary shapes.

SECTION 3

VISCOUS CROSS FLOW AND VORTEX TRACKING THEORY

DESCRIPTION OF METHOD

Data comparison between viscous cross flow methods and tests reveals shortcomings of the viscous cross flow method. Consequently, a vortex tracking computer program has been written which tracks vortex pairs separating from the body. The innermost pair is fed from the body by feeding sheets. The program is designed to compute forces and moments caused by these vortices for an arbitrary body, and is not limited to symmetrical flow conditions. The program, which is also capable of estimating the effects of pitching and yawing velocities, requires that a mapping function be known which maps the arbitrary body sections into a circle. A method of accomplishing this has been devised using the electrical analog method which relates voltage differences measured at various points about a body section cut out of Teledeltos paper to angular distances about a circle.

CONCLUSIONS

The program is not as yet operational but insights obtained during its development indicate that the method can be used to refine estimates of aerodynamic coefficients if the model chosen is workable and sufficiently general.

RECOMMENDATIONS

Further effort is recommended to fully develop and perfect the method. The areas considered most profitable for further study are:

1. Complete the checkout of the computer program and compare estimates obtained from it with test data available for a variety of bodies.

2. Develop the electrical analog technique either by refining the test methods and techniques, or by developing an analytical method to improve the mapping obtained from the electrical analog. The Theodorsen method is a possible means of doing this.

3. Determine the parameters which define the lines of vortex separation by using the method of this study and existing test data which gives information on vortex separation and the forces and moments associated with them. This determination can be accomplished by correlating the existing test data using the present method of vortex tracking. The data can be correlated by determining which vortex separation line best reproduces the test forces and moments, as well as the location of the vortices as seen in tests.

4. Develop the computer program to provide both static and dynamic derivatives associated with viscous cross flow.

SECTION 4

SHOCK-EXPANSION THEORY

A direct application of the second-order shock-expansion method to three-dimensional lifting body configurations, such as the M-2 and HL-10, does not appear practical due to the complexity of defining surface streamlines over the body. By removing the pointed-nose restriction, however, the second-order shock-expansion method can be used to calculate equivalent body drag coefficients in accordance with the area rule concept presented in Section 5.

DESCRIPTION OF METHOD

The second-order shock-expansion method provides a relatively simple but accurate solution for calculating flow characteristics over rotationally symmetric bodies at supersonic speeds. Although this method was originally restricted to bodies having pointed noses, the governing equations can be applied downstream of a blunted nose provided the local surface properties including pressure gradient are known at the nose-body junction.

Based on experimental results of a spherically-blunted cylinder it was determined that an adjusted form of the modified Newtonian equation,

$$C_p = C_{p_n}\left[1 - \left(\frac{M_\infty^{3.5}}{M_\infty^{3.5} - 0.3}\right)\cos^2\delta\right] + \frac{0.167 - M_\infty^{-1.5}}{10.^{0.066\,\delta} + 1.4} \quad (\delta \text{ in degrees}), \qquad (2)$$

provides accurate pressure coefficients over the entire nose surface for supersonic speeds down to and including Mach 1.0. Equation (2), therefore, is an ideal blunt nose solution for the second-order shock-expansion method.

The accuracy of the second-order shock-expansion method using the blunt-nose adjustment has been substantiated by comparing theoretical pressure distributions with experimental results for a spherically-blunted, 10-degree, cone-cylinder body. The comparisons showed close agreement for free stream Mach numbers of 1.17, 1.41, and 1.80. Further substantiation was obtained during the wave drag analysis presented in Section 5, where the M2-F2 equivalent body drag coefficient obtained using the second-order shock-expansion method with the blunt-nose adjustment agreed exceptionally well with the method of characteristics solution at Mach 2.0.

CONCLUSIONS AND RECOMMENDATIONS

A direct application of shock-expansion theory to three-dimensional lifting entry bodies does not appear practical at this time. Combined with the blunt-nose solution of this section, however, the second-order shock-expansion method is ideal for calculating equivalent body drag coefficients in accordance with the area rule concept presented in Section 5. It is recommended, therefore, that future lifting body wave drag analyses be conducted using the second-order shock-expansion method with the blunt-nose adjustment.

SECTION 5

AREA RULE THEORY

Area rule theory provides a simple method for reducing and predicting the zero lift wave drag characteristics of complex three-dimensional bodies. This theory has been applied successfully to such designs as the Northrop T-38/F-5 aircraft.

DESCRIPTION OF METHOD

The area rule concept was developed through systematic experiments which established that the zero lift wave drag of a low aspect ratio body can be related to that of an equivalent body of revolution having the same distribution of cross-sectional area. Thus, the wave drag of a complex three-dimensional shape can be approximated by calculating the drag of its equivalent area body.

This theory is generally applied using the Kármán wave drag equation. Lifting entry bodies, however, are characterized by blunt noses and small fineness ratios which violate the assumptions of linear potential theory. In this analysis, therefore, the equivalent body drag coefficients have been calculated using the second-order shock-expansion method as discussed in Section 4.

DISCUSSION OF RESULTS

Wave drag analyses were performed for both the M2-F2 and HL-10 lifting bodies using normal body cuts. The results were compared with available test data and, in both cases, accurate wave drag coefficients were obtained over the entire supersonic Mach number range. Accuracy obtained at the higher Mach numbers helped to substantiate the validity of using normal body cuts in this region.

CONCLUSIONS

From the results of this analysis, it is concluded that:

1. The transonic area rule concept is a valuable tool for the design and analysis of lifting body vehicles.

2. The second-order shock-expansion method, in conjunction with the simplified blunt-nose solution covered in this report, is an ideal approach for calculating the equivalent body wave drag coefficients.

RECOMMENDATIONS

It is recommended, therefore, that the above method be applied in future lifting body design and analysis studies. An area rule computer program using shock-expansion theory should be developed to facilitate this application.

SECTION 6

MODIFIED NEWTONIAN AND EXPONENTIAL FLOW THEORY

DESCRIPTION OF METHOD

Modified Newtonian flow theory is used to determine the aerodynamic characteristics of vehicles at high supersonic and hypersonic speeds. This theory is easy to apply and yields satisfactory results for most engineering purposes.

The basic equation of this theory is the modified Newtonian equation,

$$C_p = C_{p_{max.}} \sin^2 \delta , \tag{3}$$

where δ is the flow deflection angle which predicts accurate pressures on body surfaces of large flow deflection angles. At small deflection angles, however, the accuracy of Equation (3) diminishes, and it is often necessary to employ a more accurate method.

Based on results obtained from the method of characteristics solution for a sphere, an exponential curve has been developed which fairs smoothly with Equation (3) at a deflection angle of 45 degrees, and agrees more closely with the characteristics solution at the smaller angles as follows:

$$\frac{C_p}{C_{p_{max.}}} = \frac{1}{1 + \exp \left[4(\theta - \frac{\pi}{4})\right]} , \tag{4}$$

where θ is the complement of the flow deflection angle in radians.

In this application of modified Newtonian theory, therefore, Equation (3) is used for angles greater than 45 degrees, while Equation (4) is used for the smaller angles.

APPLICATION OF METHOD

The forces and moments for a three-dimensional body are calculated by a computer program. Pressure coefficients are calculated using a Newtonian plus exponential method. The body is defined by a series of cross sections consisting of a rectangular center section and two elliptical leading edges. The cross sections are defined by four body geometry subroutines which must be changed for each new configuration to be analyzed. The four body geometry parameters may be defined by numerical or analytical data. The program has the option for computing the forces and moments considering turbulent or laminar skin friction effects. It has been determined that the addition of skin friction did not change results significantly. When skin friction effects were considered, the computing time increased by about 35 percent. The program does not have the capability to analyze a configuration with fins.

CONCLUSIONS AND RECOMMENDATIONS

Static longitudinal characteristics have been calculated for two lifting bodies at different Mach Numbers. Close agreement with experimental results was obtained in both cases. It is concluded that this program is an adequate tool for predicting these characteristics for lifting bodies in general.

To obtain a program with greater flexibility, two modifications are suggested: (1) change the body description equations to consider cross sections of a general rather than elliptical nature, and (2) consider fin effects.

SECTION 7

THREE-DIMENSIONAL METHOD OF CHARACTERISTICS

DESCRIPTION OF METHOD

Northrop has developed a generalized computer program for determining the real and ideal gas flow fields about a class of hypersonic lifting body reentry configurations. This program evaluates the complete viscid and inviscid flow fields and their interactions.

The program will determine the hypersonic flow (Mach number greater than approximately 5.0) about a class of bodies at arbitrary angles of attack, but zero yaw. The class of bodies treated consists of blunt leading edge delta wings with variable width of the flats, variable thickness, and variable leading edge eccentricity, but with continuous slopes everywhere. The initial portion of the body must, however, be spherical. Included in this class are smooth bodies of revolution, since these are merely circularly blunted leading edge delta wings with zero flat width.

The program can calculate the flow fields using either an ideal gas (with a constant but arbitrary specific heat ratio), or a real equilibrium gas. The gas model used for the equilibrium calculations is valid for temperatures up to 15,000 degrees K and pressures less than 10 atmospheres. Ion-electron concentrations are available from the calculations but, since the nitric oxide ionization is not included, the ionization level can be off by an order of magnitude.

APPLICATION OF METHOD

The input data required for this program is divided into four groups: (1) general data, (2) viscous data, (3) inviscid data, and (4) body description data. The general data and body description data must be supplied for each case whereas the viscous data is supplied as required by the option, viscid and/or inviscid, being used. The body can be described either numerically or analytically.

RESULTS AND DISCUSSION

The work on this program, utilizing the Ames Research Center computer, has resulted in the achievement of the following.

1. A small portion of the data generated at Wright Field was repeated. This shows that the program, as set up on the ARC computer, is working properly.

2. The step size used in Item 1 was increased by factors of two and three, with only small decreases in accuracy. This indicates that reasonable results can be obtained with the larger mesh sizes, at large savings in computer time.

3. The M-2 body description was used to generate the initial data on the computer, up through starting the three-dimensional method of characteristics calculations.

CONCLUDING REMARKS AND RECOMMENDATIONS

The Northrop Norair three-dimensional method of characteristics program developed under Contract AF33(657)-8673 has been made available to NASA-Ames. A cooperative effort now is under way to apply the program to a blunted cone and to the M-2 vehicle.

It is recommended that future work consist of:

1. Proving out the start-and-stop features of the program in order to reduce the computer time required over a long period of time to run a problem.

2. Carrying out large-scale calculations over the M-2 body.

3. Carrying out large-scale calculations over blunted cones at angle of attack for comparison with existing NASA experimental data.

4. Investigating at Norair the possibilities of using the more accurate description of the M-2 body.

SECTION 8

EMPIRICAL CORRELATIONS

DESCRIPTION OF METHOD

Northrop Norair's approach was to compile aerodynamic data on lifting shapes, ranging from thick delta wings to blunt bodies of large volume, to provide a basic reference for the prediction of aerodynamic characteristics of lifting entry vehicles. Accordingly, data from 35 representative lifting shapes are presented in this report in the form of tabular comparisons and graph plots.

The aerodynamic characteristics presented include longitudinal, lateral-directional, control and dynamic derivatives. Correlation of these characteristics, by means of similarity rule and by other methods, has been limited to the longitudinal and lateral cases.

OBJECTIVES

The objectives sought are threefold:

1. Compile and correlate aerodynamic characteristics of basic lifting body shapes throughout the speed regime.

2. Develop methods of analysis using the correlated data for the prediction of arbitrary lifting body shapes.

3. Provide basic aerodynamic data of lifting bodies as a reference for comparison with various theoretical methods.

DISCUSSION

The geometric characteristics of 35 lifting entry configurations, which include thick wings ($t/c_{AVG} = 19\%$) and blunt bodies $\left(\frac{d^*}{D} = 0.4 \text{ to } 0.7\right)$, were compiled to establish a base from which correlating parameters could be developed. The thickness parameter $Vol^{2/3}/S_{Plan}$ was employed to correlate lift curve slope C_{L_α}, side force slope C_{y_β}, and forebody drag C_{D_F} at zero lift at a Mach number of 4.5. This compilation of characteristics also enabled forebody drag C_{D_F} to be correlated according to the hypersonic similarity rule $\frac{M}{1/D}$. It was shown that this rule applies to blunt bodies despite certain restrictive assumptions, i.e., slender, pointed bodies and high Mach numbers.

Further correlations based on geometric characteristics and the Allen-Perkins potential equations were developed for lift curve slope C_{L_α}, and pitching moment slope C_{m_α}.

The equivalent body method, whereby arbitrary lifting shapes are converted to axisymmetric shapes, was applied successfully in this work. This resulted in obtaining equivalent fineness ratio 1/D which was applied in the hypersonic area rule, and an aspect ratio correction which was applied to lift curve slope.

Other aerodynamic characteristics are presented in detail in the main body of the Final Report (NOR 66-71), including lateral directional force and moment coefficients, control deflection effects and dynamic derivatives.

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* $\frac{d}{D}$ = ratio of nose diameter to equivalent base diameter.

CONCLUSIONS

The following conclusions are drawn as a result of the work described in this section:

1. Parameter, $\frac{Vol^{2/3}}{S_{Plan}}$, holds promise for the prediction of lift curve slope of lifting entry shapes in the supersonic-hypersonic speed regime.

2. Forebody drag, C_{D_F}, is predicted better by the hypersonic similarity law than by the parameter $\frac{Vol^{2/3}}{S_{Plan}}$ at supersonic-hypersonic speeds.

3. Analysis of lift curve slope, pitching moment slope, and forebody drag of lifting entry body shapes is simplified by conversion to equivalent axisymmetric shapes.

RECOMMENDATIONS

Recommendations for future work are:

1. Continued effort to compile aerodynamic data on lifting body shapes (particularly dynamic derivatives) would be of importance for correlation purposes.

2. Further emphasis is required to determine the effects of control surfaces, control surface deflection, and canopies on the aerodynamic characteristics of lifting bodies.

3. Development of an aerodynamic handbook, to predict the aerodynamic characteristics of any lifting body shape throughout the Mach number regime, is a logical extension of the work performed.