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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF THE STABILITY, CONTROL, AND INDUCED ROLLING MOMENTS OF A CANARD MISSILE AIRFRAME AT A MACH NUMBER OF 1.7

By Robert S. Chubb

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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EXPERIMENTAL INVESTIGATION OF THE STABILITY, CONTROL, AND INDUCED ROLLING MOMENTS OF A CANARD MISSILE AIRFRAME AT A MACH NUMBER OF 1.7

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SUMMARY

This report presents the results of an investigation of the stability, control, and induced rolling moments of a canard missile having cruciform wings of rectangular plan form at a Mach number of 1.7. All data including the measured hinge moments of the canard control surfaces, the axial forces on the complete missile, and the forces and moments on the various combinations of the missile components are presented in tabular form. Data concerned with the longitudinal stability and the rolling moments of the complete missile are presented graphically. These data show that with the wings interdigitated 45° with respect to the forward fins the missile exhibits nearly linear normal-force and pitching-moment characteristics for most flight conditions and is statically stable in roll. However, interdigitation of the wings was not effective in reducing the rolling moments induced by the vertical canard controls such as would occur during lateral-acceleration maneuvers. Some method of roll control is necessary in order to reduce the roll rate to acceptable values.

INTRODUCTION

The plan form of the lifting surfaces and the external shape of missiles are dictated to a large extent by factors other than the aerodynamic properties of the missile. For reasons of storage and assembly, the body of the missile is usually divided into three general parts, including (1) the explosive charge, (2) the propellant charge or motor, and (3) the guidance system. This type of missile lends itself well to ease of manufacture since the component parts can be produced by different contractors.

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It is usually convenient to attach the aerodynamic control surfaces to the portion of the missile body containing the guidance system. As a result, the control surfaces are often placed forward of the main lifting surfaces. These surfaces are of cruciform arrangement in most cases to avoid the necessity of close control of the roll position and to obtain a more rapid missile response in lateral-acceleration maneuvers. Such an arrangement of components, while possessing desirable manufacturing and maintenance properties, very often exhibits some undesirable aerodynamic properties. For this reason, extensive aerodynamic investigations of such missiles are necessary. This report is concerned with one such missile.

The missile under investigation in the present tests is composed of a long cylindrical body fitted with a hemispherical nose, fixed rectangular cruciform wings, and small rectangular cruciform canard control fins. The purpose of the investigation is to determine the stability, control, and induced rolling-moment characteristics of the missile.

SYMBOLS

b span in the plane of two opposing wings (main lifting surfaces), feet

c chord of the wings, feet

c_F chord of the canard fins, feet

M Mach number

q free-stream dynamic pressure, pounds per square foot

S area of two opposing wings, including the area covered by the body, square feet

S_F exposed area of two opposing canard fins, square feet

α angle of attack, degrees

δ_H angle of deflection of the horizontal canard fins with respect to the plane passing through the hinge line and body axis (positive in the direction of increasing normal force), degrees

δ_V angle of deflection of the vertical canard fins with respect to the plane passing through the hinge line and body axis (positive in the direction of increasing side force toward the right, viewed from the rear), degrees

φ angle of bank about the body axis ($\varphi = 0^{\circ}$ with the undeflected vertical canard fins in the vertical plane), degrees

C_N normal-force coefficient $\left(\frac{\text{normal force}}{qS}\right)$

C_X axial-force coefficient $\left(\frac{\text{axial force}}{qS}\right)$

C_m pitching-moment coefficient about the center of gravity $\left(\frac{\text{pitching moment}}{qSc}\right)$

C_l rolling-moment coefficient about the body axis $\left(\frac{\text{rolling moment}}{qSb}\right)$

C_{l_u} uncorrected rolling-moment coefficient (measured rolling-moment coefficient uncorrected for effects of tunnel stream angularity)

C_h hinge-moment coefficient about the canard fin hinge line based on the combined moment of two opposing fins $\left(\frac{\text{hinge moment}}{qS_F c_F}\right)$

APPARATUS AND TESTS

Tunnel

The present investigation was conducted in the Ames 6- by 6-foot supersonic wind tunnel. This tunnel is of the single-return closed-throat type in which the stagnation pressure can be regulated to give a constant test Reynolds number. Further details of the tunnel and the results of flow studies in the asymmetric adjustable nozzle are reported in reference 1.

Model

The geometric characteristics of the model are shown in figure 1. The missile is composed of a cylindrical body of high fineness ratio (15.5) fitted with a hemispherical nose, fixed rectangular cruciform wings, and small rectangular cruciform canard control fins. The canard fins are mounted close behind the nose and are operated in pairs, the two horizontal fins giving control in the vertical plane and the two vertical fins giving control in the horizontal plane at zero angle of bank. The missile is roll-rate stabilized by use of small flap-type rollerons at each wing tip. Air-driven rate gyros automatically deflect the rollerons to oppose any rolling motions. The portions of these gyros which extend into the air stream at the wing tips were simulated on the present model. A photograph of the model mounted in the tunnel for testing is shown in figure 2.

Measurements and Corrections

The aerodynamic forces and moments on the model were measured by means of a four-component, electrical strain-gage balance contained within the body of the model and mounted on a sting-type support. The balance was calibrated prior to the investigation by applying known forces and moments to the model; corrections to the angle of attack due to deflection of the balance and support system under load were also applied.

As observed in reference 1, small deviations of stream pressure and direction from a uniform stream exist in the Ames 6- by 6-foot wind tunnel, causing forces and moments on the model not experienced in normal flight. Most of these stream irregularities can be minimized by proper test techniques as outlined in reference 1. For the present investigation, the effects of stream irregularities were limited to the rolling moments and axial forces on the model by pitching the model in the horizontal plane of the wind tunnel. Corrections for the effects of stream angularity on the rolling-moment data are discussed in a later section concerned with the measured rolling moments; corrections to the axial forces on the model due to a longitudinal pressure gradient in the tunnel were calculated from the flow studies of reference 1. The axial forces were adjusted to correspond to zero base drag (free-stream static pressure acting at the base) by utilizing the measured difference between the model base pressure and free-stream static pressure. Preliminary tests at the start of the investigation indicated that the effects of model asymmetry were negligible.

The combined hinge moment acting on either pair of opposing canard fins was measured by means of a strain gage mounted on a cantilever-type beam contained within the body of the model. The change in angle of the fins due to load was found to be within the accuracy of measurement of the fin angle and was therefore considered negligible.

The detached bow wave induced by the blunt hemispherical nose of the model was reflected from the tunnel walls and observed, by use of a schlieren system, to pass downstream of the model; hence no corrections due to tunnel-wall interference were necessary. All forces and moments calculated from the test data have been reduced to coefficient form as defined in the section entitled "Symbols".

Precision

The precision of the test data has been estimated from factors known to influence the accuracy of the results such as errors in reading pressures, recording strain-gage voltages and currents, hysteresis effects in the balance, and measurement of angles. The following table lists the estimated uncertainty associated with each given quantity:

	Uncertainty
Normal-force coefficient, C_N	0.005
Axial-force coefficient, C_X	.002
Pitching-moment coefficient, C_m	.010
Rolling-moment coefficient, C_l	.0005
Hinge-moment coefficient, C_h	.005
Angle of attack, α, degrees	.10
Angle of bank, φ, degrees	.20
Angle of fin deflection, δ, degrees	.25

Tests

The tests were conducted at a Mach number of 1.7 and a constant Reynolds number of 1.6 million (based on the chord of the wings) through an angle-of-attack range of -5° to 15°. Two model configurations were utilized: (1) wings in line with the canard fins, and (2) wings interdigitated 45° with respect to the canard fins. The tests included angles of bank between 0° and 45° in 11.25° increments with the canard fins undeflected. At 0° angle of bank, the vertical and horizontal canard fins were deflected at angles from -5° to 15° in 5° increments. Some tests were made of different combinations of the model components which included body-alone, body-wing, and body-fin arrangements. The various combinations of the test variables are listed in table I.

RESULTS AND DISCUSSION

The present discussion is concerned only with the normal-force, pitching-moment, and rolling-moment characteristics of the complete missile for the range of test variables listed in table I; however, during the investigation, axial forces on the model as well as hinge moments on the canard control fins were measured. All data obtained are presented in table II.

Normal Force and Pitching Moment

Experimental-data plots of the variations of normal-force coefficient with angle of attack and pitching-moment coefficient with normal-force coefficient are presented in figures 3 and 4, respectively, for both the in-line and interdigitated configurations at various bank angles with the canard fins undeflected. It is evident that the normal-force and pitching-moment characteristics are unchanged with roll position and are not affected by interdigitating the wings with respect to the canard fins. However, the important feature to note here is that the missile exhibits stable pitching-moment characteristics which vary nearly linearly with angle of attack; that is, with the canard fins undeflected, the downwash due to the horizontal canard fins on the wings does not cause nonlinear or unstable variations of pitching moment with angle of attack. This linearity of the pitching moments is one of the advantages of the canard control arrangement if the span of the foward surfaces is kept small compared to that of the wings. For instance, the missile reported in reference 2, having the forward fins slightly larger than the rear wings, exhibited extremely nonlinear, and in some cases destablizing, pitching-moment characteristics with angle of attack.

The data of figures 3 and 4 were obtained with the horizontal canard control fins undeflected; more often of course the missile is called upon for flight maneuvers wherein the forward fins are deflected. The normal force and pitching-moment characteristics of the missile at 0° bank angle are presented in figures 5 and 6, respectively, for both the in-line and interdigitated configurations with various horizontal-canard-fin deflections. It will be noted that as the angle of fin deflection increases, the normal-force and pitching-moment curves become somewhat nonlinear, the nonlinearity for the in-line configuration occurring at angles of attack near zero and that for the interdigitated configuration near the condition where balance is obtained ($C_m = 0$). The test condition for which the horizontal fins are deflected and the model is at zero angle of attack corresponds to an instantaneous flight maneuver wherein the missile is undergoing an accelerated pitching motion. The test condition for which the horizontal fins are deflected to balance the missile ($C_m = 0$) corresponds to steady flight. For the purpose of minimizing the nonlinearities for the more usual accelerated flight condition (small angles of attack), it appears that the interdigitated configuration may be somewhat superior to the in-line configuration.

It should be noted that due to symmetry of the cruciform arrangement these data are equally applicable to the directional stability.

Rolling Moment

Effects of bank angle.- The variation of uncorrected rolling-moment coefficient with angle of attack at various angles of bank from 0° to 45° is presented in figure 7 for both the in-line and interdigitated configurations. It will be noted that at both 0° and 45° angle of bank there is a rolling moment on the missile which due to symmetry of the cruciform arrangements should be zero; this rolling moment is due to the flow inclination of the wind-tunnel stream in the yaw plane. In order to arrive at a true result, it is necessary to apply a correction to these data. The influence of the stream flow deviation is twofold; first, the forward and rear lifting surfaces are actually at a different angle of bank than the geometric angle and this angle of bank due to stream inclination will vary with angle of attack; second, due to stream inclination, the canard fins develop components of normal force at right angles to the plane in which the model pitches and the resulting changes in the trailing vorticity induce spurious rolling moments on the rear wings. A study of the tabulated data shows that the second effect accounts for most of the rolling moments induced by stream inclination. It was assumed that the incremental rolling moments due to stream inclination are simply superimposed on the true rolling moments. Hence, for any given angle of attack, the correction to be applied at 0° and 45° bank angles was assumed equal to the measured rolling moment at those angles, and it was assumed further that the correction varied linearly with bank angle between 0° and 45°. The corrected rolling-moment coefficients are presented in figure 8 as a function of bank angle for several angles of attack.

The criterion for a stable variation of rolling moment with angle of bank is that the rolling moment should tend to rotate the missile back to the position from which it was displaced. It is seen in figure 8 that the bank angle for maximum static stability in roll occurs at a bank angle of 45° for the in-line configuration and at a bank angle of 0° for the interdigitated configuration; or, more generally, the missile is stable in roll for either configuration when the wings are rotated 45° with respect to the planes of pitch and yaw. It is seen also that the variation of rolling-moment coefficient with angle of bank is periodic[1] (period of 90°) and that the missile would tend to roll over to a wing position of 45° bank with either configuration.

Any differences in the order of magnitude of the rolling moments between in-line and interdigitated wings are due to the geometric location of the wings in the vortex wake shed by the canard fins. For the

[1]The periodic variation in the rolling-moment characteristics of multiplanar finned missiles with bank angle has been predicted theoretically by Maple and Synge in reference 3.

present missile, the magnitudes of the rolling moments for the in-line and interdigitated configurations are approximately equal at $\alpha = 4^{\circ}$ and $\alpha = 8^{\circ}$; however, at $\alpha = 12^{\circ}$ the rolling moments of the interdigitated configuration are considerably less than those of the in-line configuration.

Effects of canard fin deflection.- During accelerated pitching maneuvers, the vortices shed by the horizontal canard fins are symmetrically disposed over the rear wings and cause no induced rolling moments; however, during certain portions of lateral-acceleration maneuvers wherein the missile is at an angle of attack in the vertical plane and is undergoing accelerated yawing motions in the horizontal plane, the induced effects of the vortices trailing from the deflected vertical canard fins upon the rear wings cause large rolling moments which are a function of both fin deflection and angle of attack. In figure 9, the variation of rolling-moment coefficient with angle of attack is shown for several vertical-canard-fin deflections. It will be noted that when the vertical canard fins are undeflected ($\delta_V = 0^{\circ}$) there is a rolling moment on the missile which, as discussed previously, is due to the wind-tunnel stream inclination. A correction consisting of the measured rolling moments at $\delta_V = 0^{\circ}$ was applied to the data for all fin deflections for the same angle of attack. The corrected results are presented in figure 10. The validity of the correction is illustrated by a comparison of the rolling moments for $\delta_V = 5^{\circ}$ and $\delta_V = -5^{\circ}$.

As observed in figure 10, the maximum values of rolling moment occur at approximately 8° angle of attack for all fin deflections. At this angle of attack the vortex shed by the lower canard fin trails nearest the body juncture of the components of the cruciform lifting wings.

Of particular significance with regard to these induced rolling moments is the possibility of rolling motions of sufficient angular velocity to make significant the phase lag in the canard control servos with a consequent deterioration of the guidance properties. Hence, some method of roll control is necessary to suppress the roll rate to within acceptable limits.

As mentioned earlier, the missile of the present investigation is roll-rate stabilized by the use of flap-type rollerons at each wing tip. A small free-spinning wheel-type gyro sensitive to roll rate is mounted internally in each rolleron, and automatic deflection of the rollerons to oppose any rolling motions is obtained by utilizing the precession characteristics of the gyros. Calculations, based on linearized nonviscous theory of supersonic flow for wings and control surfaces (references 4, 5, and 6) were made of the effects of these rollerons in controlling the induced rolling motions experienced by the missile in lateral-acceleration maneuvers. The results of the calculations indicated that the rollerons were capable of restricting the induced rolling rates to within acceptable limits.

CONCLUDING REMARKS

The foregoing experimental results have shown that the normal-force and pitching-moment characteristics of the missile are unchanged with roll position and are nearly linear with angle of attack. The results have also shown that by interdigitating the wings 45° with respect to the forward fins the nonlinearities in the pitching-moment characteristics due to deflection of the horizontal canard controls can be avoided for flight maneuvers at small angles of attack.

With regard to the rolling-moment characteristics of the missile, it was found that the variation of rolling moment with angle of bank was periodic and that the missile was statically stable in roll with the wings banked or interdigitated 45° with respect to the vertical plane of pitch. However, during lateral-acceleration maneuvers, interdigitation of the wings was not effective in avoiding the induced rolling moments due to vertical-control deflections and some type of roll-rate control is necessary. Calculations based on linearized nonviscous theory of supersonic flow indicated that the rollerons would probably limit the missile roll rate to within acceptable values.

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TABLE I.- TEST CONDITIONS

Test No.	Configuration of model	Mach No.	Reynolds No.	δ_H (deg)	δ_V (deg)	φ (deg)	α (deg)
1	W_0BF	1.7	1.6×10^6	0	0	0	-5 to 15
2				0	0	11.25	
3				0	0	22.50	
4				0	0	33.75	
5				0	0	45	
6	$W_{45}BF$			0	0	0	
7				0	0	11.25	
8				0	0	22.50	
9				0	0	33.75	
10				0	0	45	
11	W_0BF			-5	0	0	
12				0	0	0	
13				5	0	0	
14				10	0	0	
15				15	0	0	
16	$W_{45}BF$			-5	0	0	
17				0	0	0	
18				5	0	0	
19				10	0	0	
20				15	0	0	
21	W_0BF			0	-5	0	
22				0	0	0	
23				0	5	0	
24				0	10	0	
25				0	15	0	
26	$W_{45}BF$			0	-5	0	
27				0	0	0	
28				0	5	0	
29				0	10	0	
30				0	15	0	
31	B			0	0	0	
32	W_0B			--	--	0	
33	$W_{45}B$			--	--	0	
34	BF			-5	0	0	
35				0	0	0	
36				5	0	0	
37				10	0	0	
38				15	0	0	

NOTE: W_0 Wings in line with forward canard fins
W_{45} Wings interdigitated 45° with respect to canard fins
B Body
F Canard fins

[redacted]

TABLE II.- TEST DATA

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h	Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h	Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
1	-4.98	-0.311	0.29	0.142	0.0058	---	4	-5.00	-0.308	0.27	0.142	0.0060	---	7	-5.00	-0.308	0.26	0.139	0.0053	---
	-2.96	-.186	.17	.143	.0037	---		-2.97	-.185	.16	.142	.0044	---		-2.97	-.189	.16	.141	.0038	---
	-.92	-.061	.06	.144	.0010	---		-.93	-.064	.05	.144	.0020	---		-.93	-.066	.05	.142	.0016	---
	-.41	-.033	.03	.144	.0003	---		-.42	-.034	.02	.144	.0014	---		-.42	-.033	.03	.142	.0010	---
	.41	.014	-.01	.144	-.0011	---		.50	.011	-.02	.144	0	---		.50	.015	-.02	.143	-.0003	---
	.92	.044	-.03	.144	-.0020	---		.91	.042	-.04	.145	-.0008	---		.91	.047	-.05	.143	-.0008	---
	2.96	.168	-.14	.140	-.0050	---		2.95	.168	-.15	.140	-.0035	---		2.96	.172	-.16	.146	-.0033	---
	4.99	.295	-.26	.141	-.0079	---		4.98	.294	-.27	.140	-.0042	---		5.00	.290	-.24	.146	-.0070	---
	7.00	.427	-.39	.141	-.0102	---		7.00	.421	-.39	.140	-.0034	---		7.02	.417	-.36	.146	-.0091	---
	9.03	.562	-.50	.141	-.0107	---		9.03	.552	-.49	.141	-.0003	---		9.04	.557	-.48	.146	-.0108	---
	11.06	.702	-.62	.140	-.0102	---		11.07	.692	-.60	.140	.0046	---		11.06	.704	-.62	.144	-.0121	---
	13.09	.836	-.73	.137	-.0098	---		13.09	.839	-.73	.140	.0062	---		13.08	.852	-.76	.144	-.0138	---
	15.13	.974	-.84	.135	-.0082	---		15.14	.995	-.85	.139	.0031	---		14.09	.927	-.83	.143	-.0144	---
2	-4.99	-.310	.28	.140	.0067	---	5	-5.00	-.312	.27	.142	.0047	---	8	-4.99	-.311	.27	.143	.0045	---
	-2.96	-.186	.16	.143	.0044	---		-2.97	-.188	.16	.143	.0036	---		-2.97	-.190	.16	.143	.0034	---
	-.92	-.064	.06	.144	.0017	---		-.93	-.064	.04	.145	.0016	---		-.93	-.066	.05	.143	.0010	---
	-.41	-.036	.03	.145	.0009	---		-.42	-.036	.02	.147	.0008	---		-.42	-.035	.02	.144	.0005	---
	.41	.011	-.01	.145	-.0003	---		.49	.011	-.02	.146	-.0004	---		.49	.014	-.02	.144	-.0007	---
	.92	.041	-.03	.144	-.0013	---		.90	.042	-.05	.146	-.0013	---		.91	.047	-.05	.143	-.0013	---
	2.96	.167	-.15	.144	-.0044	---		2.95	.166	-.16	.145	-.0039	---		2.94	.161	-.16	.143	-.0042	---
	4.99	.296	-.27	.144	-.0062	---		4.98	.292	-.27	.144	-.0051	---		4.98	.274	-.25	.143	-.0084	---
	7.00	.429	-.39	.144	-.0059	---		7.00	.417	-.39	.144	-.0059	---		6.99	.393	-.36	.142	-.0129	---
	9.03	.565	-.51	.144	-.0043	---		9.04	.550	-.48	.143	-.0060	---		9.01	.523	-.48	.142	-.0165	---
	11.05	.702	-.63	.143	-.0013	---		11.07	.693	-.60	.142	-.0053	---		11.07	.700	-.61	.140	-.0158	---
	13.08	.841	-.75	.142	.0007	---		13.10	.842	-.73	.142	-.0063	---		13.09	.843	-.73	.139	-.0170	---
	15.12	.983	-.86	.139	.0003	---		15.15	.997	-.83	.141	-.0078	---		14.73	.964	-.83	.137	-.0196	---
3	-4.99	-.308	.27	.141	.0067	---	6	-5.00	-.298	.25	.137	.0068	---	9	-4.99	-.313	.27	.145	.0053	---
	-2.97	-.185	.16	.141	.0048	---		-2.97	-.183	.16	.138	.0042	---		-2.97	-.192	.16	.146	.0038	---
	-.93	-.064	.05	.143	.0021	---		-.92	-.062	.06	.139	.0019	---		-.93	-.067	.05	.146	.0013	---
	-.41	-.034	.03	.144	.0013	---		-.41	-.030	.03	.138	.0013	---		-.42	-.036	.02	.146	.0005	---
	.40	.011	-.01	.145	-.0003	---		.41	.018	-.02	.140	-.0002	---		.49	.013	-.02	.146	-.0005	---
	.91	.042	-.04	.145	-.0009	---		.91	.049	-.05	.139	-.0010	---		.90	.045	-.05	.145	-.0012	---
	2.96	.167	-.15	.141	-.0038	---		2.97	.172	-.15	.137	-.0027	---		2.95	.170	-.16	.143	-.0044	---
	4.98	.296	-.27	.141	-.0049	---		5.01	.289	-.24	.138	-.0053	---		4.99	.290	-.26	.142	-.0078	---
	7.00	.423	-.39	.141	-.0035	---		7.03	.417	-.35	.138	-.0065	---		7.00	.420	-.38	.142	-.0112	---
	9.03	.559	-.50	.141	.0003	---		9.04	.550	-.47	.139	-.0070	---		9.03	.559	-.49	.141	-.0145	---
	11.06	.692	-.61	.140	.0076	---		11.06	.699	-.61	.138	-.0087	---		11.07	.703	-.61	.139	-.0136	---
	13.08	.836	-.74	.139	.0111	---		13.08	.846	-.76	.137	-.0103	---		13.11	.845	-.72	.137	-.0153	---
	15.12	.987	-.85	.137	.0067	---		15.12	.971	-.86	.137	-.0087	---		15.16	.990	-.81	.133	-.0193	---

TABLE II.- CONTINUED

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
10	-5.00	-0.314	0.27	0.138	0.0059	---
	-2.98	-.193	.16	.139	.0039	---
	-.93	-.070	.05	.141	.0013	---
	-.42	-.038	.02	.141	.0007	---
	.49	.010	-.02	.141	-.0003	---
	.90	.043	-.05	.141	-.0010	---
	2.95	.167	-.16	.144	-.0040	---
	4.98	.290	-.27	.143	-.0065	---
	6.99	.422	-.39	.142	-.0080	---
	9.02	.559	-.51	.140	-.0082	---
	11.06	.705	-.62	.139	-.0073	---
	13.10	.842	-.72	.135	-.0076	---
	15.16	.991	-.82	.132	-.0085	---
11	-5.16	-.356	.13	.148	---	---
	-3.15	-.226	0	.147	.0032	0.109
	-1.22	-.102	-.12	.147	.0006	.078
	-.70	-.070	-.15	.147	-.0001	.069
	.32	-.012	-.19	.147	-.0014	.055
	.83	.015	-.21	.146	-.0024	.046
	2.88	.136	-.31	.145	-.0055	.012
	4.91	.261	-.42	.143	-.0083	-.020
	6.84	.390	-.54	.142	-.0105	-.052
	8.86	.524	-.65	.140	-.0101	-.085
	10.90	.666	-.77	.138	-.0086	-.116
	12.93	.799	-.87	.134	-.0076	-.146
12	-4.98	-.311	.29	.142	.0058	.082
	-2.96	-.186	.17	.143	.0037	.050
	-.92	-.061	.06	.144	.0010	.016
	-.41	-.033	.03	.144	.0003	.009
	.41	.014	-.01	.144	-.0011	-.004
	.92	.044	-.03	.144	-.0020	-.012
	2.96	.168	-.14	.140	-.0050	-.046
	4.99	.295	-.26	.141	-.0079	-.079
	7.00	.427	-.39	.141	-.0102	-.110
	9.03	.562	-.51	.141	-.0107	-.141
	11.06	.702	-.62	.140	-.0102	-.171
	13.09	.836	-.73	.137	-.0098	-.199
	15.13	.974	-.84	.135	-.0082	-.227

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
13	-4.91	-0.280	0.46	0.129	0.0073	0.023
	-2.88	-.159	.34	.133	.0053	-.009
	-.83	-.037	.25	.137	.0027	-.043
	-.31	-.005	.22	.140	.0019	-.052
	.71	.046	.18	.142	.0005	-.067
	1.22	.079	.15	.143	-.0003	-.096
	3.26	.209	.04	.148	-.0035	-.109
	5.17	.337	-.10	.152	-.0066	-.139
	7.18	.468	-.23	.154	-.0094	-.168
	9.19	.607	-.36	.154	-.0112	-.198
	11.21	.747	-.49	.154	-.0110	-.226
	13.24	.885	-.60	.152	-.0098	-.254
	15.27	1.025	-.72	.148	-.0088	-.279
14	-4.76	-.247	.59	.125	.0082	-.034
	-2.71	-.128	.50	.131	.0061	-.068
	-.65	-.007	.42	.137	.0035	-.102
	-.14	.015	.40	.138	.0027	-.110
	.89	.066	.36	.140	.0013	-.124
	1.41	.097	.34	.141	.0005	-.132
	3.44	.234	.20	.150	-.0027	-.163
	5.44	.372	.05	.157	-.0063	-.194
	7.33	.505	-.09	.164	-.0094	-.222
	9.34	.645	-.24	.169	-.0110	-.249
	11.33	.778	-.38	.171	-.0108	-.275
	13.35	.912	-.50	.172	-.0086	-.300
	15.39	---	-.62	.171	-.0088	-.326
15	-4.61	-.210	.73	.155	.0092	-.089
	-2.56	-.095	.63	.159	.0071	-.123
	-.51	.013	.55	.160	.0044	-.155
	.01	.038	.54	.161	.0035	-.163
	1.05	.087	.52	.163	.0021	-.178
	1.56	.112	.50	.164	.0014	-.186
	3.59	.250	.35	.170	-.0026	-.215
	5.57	.397	.17	.177	-.0060	-.244
	7.46	.536	.01	.183	-.0093	-.270
	9.46	.673	-.14	.187	-.0115	-.296
	11.45	.810	-.30	.189	-.0117	-.321
	13.46	.940	-.43	.190	-.0111	-.344
	13.97	.977	-.46	.189	-.0101	-.352

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
16	-5.13	-0.326	0.07	0.153	0.0060	---
	-3.10	-.218	-.01	.152	.0035	---
	-1.21	-.108	-.10	.148	.0010	---
	-.70	-.077	-.13	.147	.0002	---
	.32	-.018	-.17	.145	-.0011	---
	.83	.008	-.20	.144	-.0017	---
	2.87	.130	-.31	---	-.0044	---
	4.90	.250	-.42	---	-.0067	---
	6.93	.375	-.53	.142	-.0081	---
	8.79	.510	-.65	.139	-.0085	---
	10.82	.649	-.77	.138	-.0097	---
	11.73	.721	-.84	.137	-.0102	---
17	-4.94	-.301	.26	.145	.0073	---
	-2.90	-.181	.16	.141	.0044	---
	-.86	---	---	---	---	---
	-.35	-.027	.03	.152	.0015	---
	.34	.017	-.02	.154	---	---
	.85	.046	-.04	.152	-.0009	---
	2.90	.168	-.15	.152	-.0036	---
	4.94	.287	-.24	.152	-.0067	---
	6.96	.412	-.35	.151	-.0083	---
	8.98	.554	-.49	.149	-.0084	---
	10.99	.703	-.63	.151	-.0100	---
	13.01	.856	-.78	.150	-.0103	---
	14.22	.931	-.84	.149	-.0104	---
18	-4.90	-.280	.46	.145	.0080	---
	-2.88	-.156	.34	.145	.0056	---
	-.83	-.027	.23	.146	.0030	---
	-.33	.005	.20	.150	.0023	---
	.70	.062	.14	.152	.0010	---
	1.21	.094	.12	.152	-.0001	---
	3.10	.213	.02	.162	-.0028	---
	5.14	.322	-.05	.165	-.0060	---
	7.16	.446	-.16	.162	-.0080	---
	9.17	.591	-.31	.168	-.0085	---
	11.16	.737	-.48	.164	-.0093	---
	13.17	.893	-.64	.164	-.0102	---
	15.20	---	-.77	.163	-.0096	---

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TABLE II.- CONTINUED

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
19	-4.74	-0.258	0.63	0.145	0.0087	---
	-2.70	-.130	.51	.145	.0064	---
	-.66	.002	.39	.148	.0040	---
	-.15	.038	.35	.153	.0032	---
	.87	.096	.30	.154	.0020	---
	1.38	.126	.28	.157	.0012	---
	3.43	.245	.18	.163	-.0021	---
	5.47	.357	.11	.168	-.0059	---
	7.43	.470	0	.175	-.0078	---
	9.32	.618	-.17	.181	-.0087	---
	11.30	.771	-.35	.182	-.0092	---
	13.30	.922	-.52	.185	-.0095	---
	15.32	---	-.66	.184	-.0101	---
20	-4.56	-.236	.81	.156	.0094	---
	-2.53	-.110	.68	.154	.0072	---
	-.50	.033	.53	.158	.0046	---
	.01	.068	.50	.160	.0038	---
	1.02	.127	.44	.166	.0030	---
	1.53	.160	.40	.168	.0023	---
	3.56	.277	.30	.176	-.0016	---
	5.60	.380	.24	.181	-.0056	---
	7.62	.490	.14	.188	-.0076	---
	9.44	.638	-.05	.200	-.0086	---
	11.41	.795	-.25	.205	-.0096	---
	13.40	.949	-.43	.207	-.0115	---
	15.40	---	-.59	.207	-.0098	---
21	-5.34	---	---	.143	-.0175	0.089
	-3.34	---	---	.146	-.0114	.088
	-1.34	---	---	.148	-.0038	.089
	-.84	---	---	.148	-.0018	.089
	.15	---	---	.149	.0019	.090
	.65	---	---	.149	.0040	.090
	2.65	---	---	.149	.0119	.090
	4.64	---	---	.149	.0180	.092
	6.63	---	---	.150	.0237	.094
	8.63	---	---	.149	.0232	.096
	10.64	---	---	.150	.0188	.098
	12.63	---	---	.149	.0150	.100
	14.62	---	---	.148	.0094	.105

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
22	-5.15	---	---	0.139	-0.0054	0.028
	-3.15	---	---	.140	-.0036	.028
	-1.15	---	---	.141	-.0016	.029
	-.65	---	---	.142	-.0012	.029
	.35	---	---	.142	---	.029
	.85	---	---	.142	.0007	.029
	2.84	---	---	.143	.0031	.030
	4.84	---	---	.144	.0053	.032
	6.83	---	---	.145	.0080	.033
	8.82	---	---	.145	.0092	.035
	10.82	---	---	.143	.0097	.036
	12.81	---	---	.142	.0082	.039
	14.80	---	---	.141	.0071	.041
23	-5.06	---	---	.142	.0068	-.035
	-3.06	---	---	.143	.0043	-.033
	-1.06	---	---	.143	.0008	-.033
	-.56	---	---	.144	-.0004	-.032
	.44	---	---	.144	-.0019	-.032
	.94	---	---	.144	-.0028	-.032
	2.93	---	---	.146	-.0057	-.032
	4.93	---	---	.147	-.0073	-.032
	6.92	---	---	.147	-.0076	-.032
	8.92	---	---	.148	-.0048	-.031
	10.91	---	---	.148	-.0022	-.029
	12.91	---	---	.146	.0001	-.029
	14.91	---	---	.145	.0023	-.026
24	-4.78	---	---	.142	.0166	-.096
	-2.78	---	---	.141	.0106	-.094
	-.78	---	---	.140	.0026	-.093
	-.28	---	---	.141	.0003	-.092
	.72	---	---	.141	-.0034	-.092
	1.22	---	---	.142	-.0055	-.092
	3.22	---	---	.143	-.0125	-.093
	5.21	---	---	.144	-.0178	-.093
	7.21	---	---	.146	-.0211	-.093
	9.19	---	---	.147	-.0151	-.092
	11.07	---	---	.147	-.0078	-.092
	13.07	---	---	.147	-.0026	-.091
	15.08	---	---	.145	.0018	-.091

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
25	-4.62	---	---	0.149	0.0228	-0.151
	-2.62	---	---	.149	---	-.149
	-.62	---	---	.149	.0038	-.147
	-.12	---	---	.150	.0007	-.146
	.88	---	---	.150	-.0046	-.147
	1.38	---	---	.150	-.0075	-.146
	3.38	---	---	.152	-.0177	-.147
	5.38	---	---	.152	-.0251	-.148
	7.37	---	---	.154	-.0307	-.150
	9.34	---	---	.156	-.0234	-.151
	11.32	---	---	.159	---	-.155
	13.29	---	---	.159	-.0002	-.150
	15.29	---	---	.157	.0096	-.150
26	-5.00	---	---	.154	-.0157	---
	-3.00	---	---	.154	-.0101	---
	-1.00	---	---	.154	-.0035	---
	-.50	---	---	.154	-.0019	---
	.50	---	---	.154	.0012	---
	1.00	---	---	.153	.0029	---
	3.00	---	---	.151	.0096	---
	5.00	---	---	.150	.0162	---
	7.00	---	---	.150	.0184	---
	9.00	---	---	.149	.0186	---
	11.00	---	---	.148	.0187	---
	13.00	---	---	.146	.0179	---
	15.00	---	---	.144	.0140	---
27	-5.00	---	---	.152	-.0050	---
	-3.00	---	---	.152	-.0033	---
	-1.00	---	---	.153	-.0016	---
	-.50	---	---	.153	-.0012	---
	.50	---	---	.155	-.0003	---
	1.00	---	---	.155	.0003	---
	3.00	---	---	.153	.0024	---
	5.00	---	---	.151	.0047	---
	7.00	---	---	.150	.0057	---
	9.00	---	---	.148	.0057	---
	11.00	---	---	.145	.0072	---
	13.00	---	---	.142	.0084	---
	15.00	---	---	.141	.0081	---

TABLE II.- CONTINUED

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
28	-5.00	---	---	0.154	0.0061	---
	-3.00	---	---	.155	.0037	---
	-1.00	---	---	.155	.0002	---
	-.50	---	---	.155	-.0003	---
	.50	---	---	.156	-.0016	---
	1.00	---	---	.156	-.0022	---
	3.00	---	---	.153	-.0052	---
	5.00	---	---	.151	-.0075	---
	7.00	---	---	.148	-.0073	---
	9.00	---	---	.146	-.0065	---
	11.00	---	---	.144	-.0037	---
	13.00	---	---	.142	.0001	---
	15.00	---	---	.142	.0017	---
29	-5.00	---	---	.147	.0168	---
	-3.00	---	---	.149	.0102	---
	-1.00	---	---	.154	.0023	---
	-.50	---	---	.156	.0005	---
	.50	---	---	.157	-.0027	---
	1.00	---	---	.157	-.0044	---
	3.00	---	---	.153	-.0119	---
	5.00	---	---	.151	-.0189	---
	7.00	---	---	.148	-.0192	---
	9.00	---	---	.146	-.0172	---
	11.00	---	---	.144	-.0115	---
	13.00	---	---	.146	-.0024	---
	15.00	---	---	.143	.0019	---
30	-5.00	---	---	.161	.0232	---
	-3.00	---	---	.163	.0157	---
	-1.00	---	---	.169	.0044	---
	-.50	---	---	.171	.0016	---
	.50	---	---	.173	-.0038	---
	1.00	---	---	.173	-.0070	---
	3.00	---	---	.171	-.0185	---
	5.00	---	---	.170	-.0271	---
	7.00	---	---	.168	-.0291	---
	9.00	---	---	.165	-.0266	---
	11.00	---	---	.163	-.0173	---
	13.00	---	---	.161	-.0031	---
	15.00	---	---	.159	.0055	---

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
31	-5.11	-0.030	-0.08	.085	.0002	---
	-3.06	-.016	-.05	.084	.0002	---
	-1.02	-.005	-.02	.084	.0002	---
	-.51	-.003	-.01	.084	.0002	---
	.51	.001	0	.084	.0001	---
	1.01	.003	.01	.084	0	---
	3.05	.014	.05	.084	-.0001	---
	5.10	.028	.08	.084	-.0002	---
	7.15	.047	.11	.087	-.0002	---
	9.21	.071	.15	.082	-.0003	---
	11.28	.098	.20	.080	-.0003	---
	13.37	.131	.26	.080	-.0003	---
	15.49	.176	.34	.079	-.0005	---
32	-4.92	-.275	.50	.133	.0028	---
	-2.92	-.167	.31	.135	.0018	---
	-.91	-.059	.11	.137	.0009	---
	-.40	-.031	.06	.138	.0007	---
	.40	.010	-.02	.138	.0002	---
	.90	.036	-.07	.137	-.0001	---
	2.93	.149	-.27	.135	-.0009	---
	4.93	.261	-.48	.134	-.0017	---
	6.92	.272	-.67	.132	-.0029	---
	8.91	.483	-.87	.130	-.0039	---
33	-4.86	-.275	.51	.134	.0036	---
	-2.92	-.162	.30	.136	.0025	---
	-.97	-.053	.10	.139	.0017	---
	-.49	-.027	.05	.140	.0015	---
	.49	.012	-.03	.138	.0010	---
	.98	.040	-.08	.138	.0009	---
	2.92	.148	-.28	.136	-.0002	---
	4.86	.260	-.49	.135	-.0013	---
	6.79	.376	-.69	.135	-.0028	---
	8.72	.492	-.90	.132	-.0043	---

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
34	-5.53	-0.133	-0.45	0.085	0.0008	0.150
	-3.39	-.097	-.34	.090	.0005	.117
	-1.25	-.061	-.22	.091	.0004	.082
	-.72	-.053	-.20	.092	.0004	.074
	.34	-.036	-.14	.093	.0004	.057
	.88	-.028	-.11	.094	.0003	.048
	3.03	.011	.02	.095	.0004	.006
	5.17	.048	.14	.093	.0003	-.028
	7.32	.088	.25	.090	.0002	-.063
	9.47	.130	.37	.087	0	-.097
	11.64	.180	.50	.084	0	-.131
	13.80	.234	.62	.080	-.0003	-.163
	15.99	.302	.77	.076	-.0003	-.193
35	-5.35	-.090	-.30	.086	.0004	.091
	-3.21	-.054	-.18	.088	.0003	.056
	-1.08	-.019	-.07	.092	.0002	.021
	-.54	-.010	-.04	.093	.0001	.012
	.52	.008	.02	.093	.0001	-.006
	1.06	.017	.05	.093	.0001	-.016
	3.20	.053	.17	.092	-.0001	-.053
	5.35	.091	.29	.091	-.0003	-.089
	7.49	.129	.41	.090	-.0003	-.123
	9.64	.173	.53	.089	-.0006	-.156
	11.79	.218	.64	.087	-.0007	-.188
	13.94	.270	.76	.085	-.0008	-.219
	16.12	.332	.89	.083	-.0006	-.247
36	-5.18	-.048	-.15	.089	.0004	.033
	-3.04	-.012	-.04	.093	.0003	-.002
	-.89	.028	.09	.095	.0001	-.042
	-.36	.035	.12	.096	0	-.051
	.70	.051	.17	.096	0	-.067
	1.24	.060	.21	.096	0	-.077
	3.38	.096	.32	.096	0	-.112
	5.52	.134	.44	.095	-.0002	-.146
	7.66	.171	.55	.095	-.0003	-.179
	9.81	.212	.67	.095	-.0004	-.211
	11.95	.256	.78	.094	-.0004	-.242
	14.09	.305	.89	.094	-.0006	-.270
	16.26	.364	---	.093	-.0006	-.297

TABLE II.- CONCLUDED

Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h	Test No.	α (deg)	C_N	C_m	C_X	C_{l_u}	C_h
37	-5.01	-0.010	0	0.098	0.0003	-0.026	38	-4.85	0.032	0.14	0.100	0.0003	-0.088
	-2.86	.031	.12	.099	.0001	-.065		-2.71	.067	.26	.101	.0002	-.123
	-.72	.064	.24	.100	0	-.101		-.58	.099	.37	.103	0	-.156
	-.19	.073	.27	.100	-.0001	-.109		-.05	.107	.40	.104	-.0001	-.166
	.87	.088	.32	.100	-.0002	-.124		1.01	.121	.45	.105	-.0001	-.180
	1.41	.097	.35	.100	-.0002	-.133		1.54	.130	.48	.106	-.0002	-.190
	3.55	.134	.47	.101	-.0004	-.167		3.67	.166	.57	.109	-.0003	-.222
	5.68	.171	.57	.101	-.0006	-.201		5.80	.201	.68	.112	-.0003	-.252
	7.82	.207	.68	.102	-.0006	-.232		7.92	.235	.78	.113	-.0005	-.280
	9.95	.243	.79	.102	-.0005	-.260		10.05	.271	.88	.115	-.0006	-.309
	12.08	.285	.90	.103	-.0007	-.290		12.17	.310	.98	.117	-.0007	-.336
	14.22	.333	---	.104	-.0008	-.317							

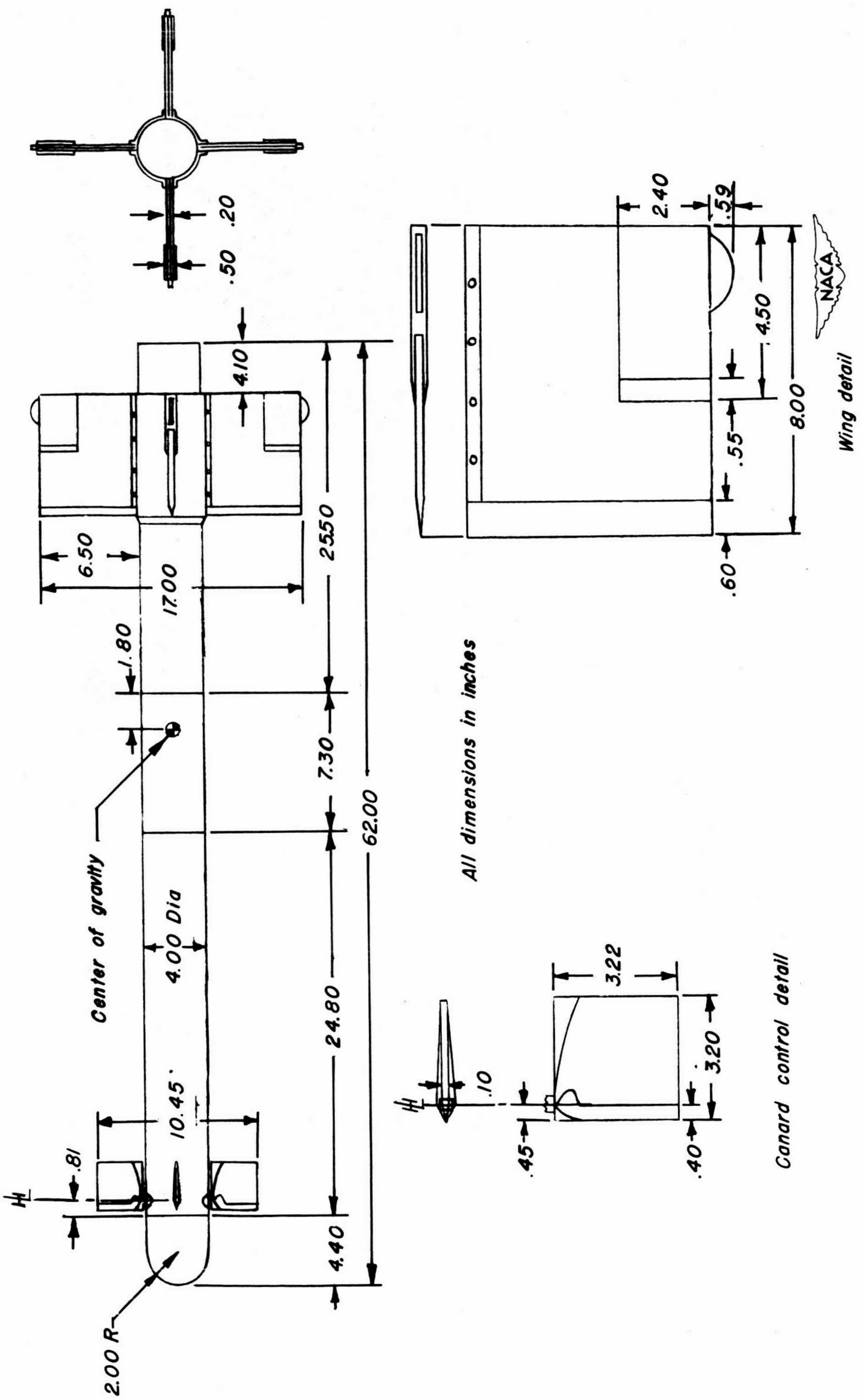


Figure 1.- Geometric characteristics of the model.

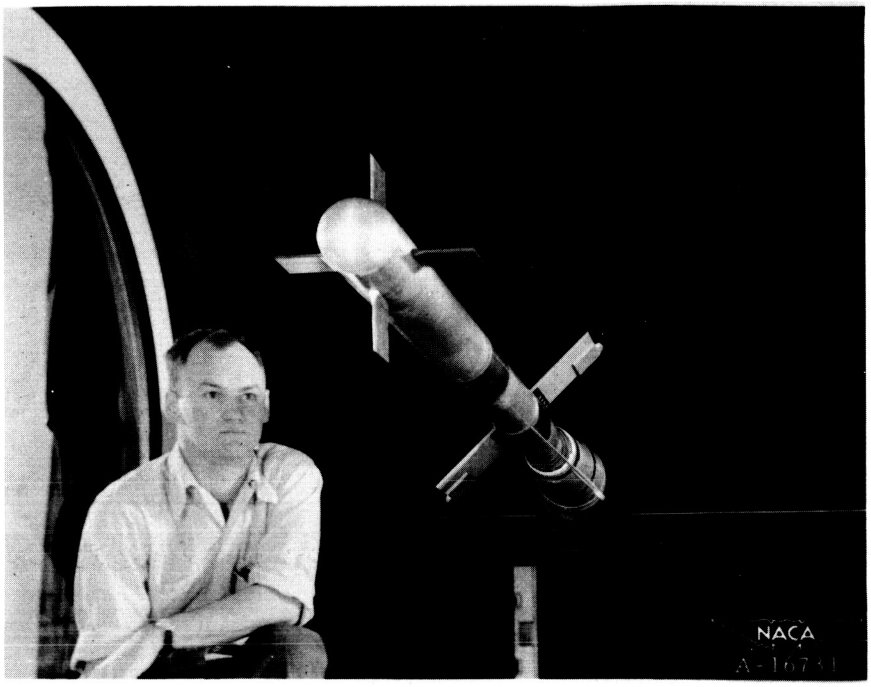


Figure 2.- Photograph of the model mounted in the Ames 6- by 6-foot supersonic wind tunnel.

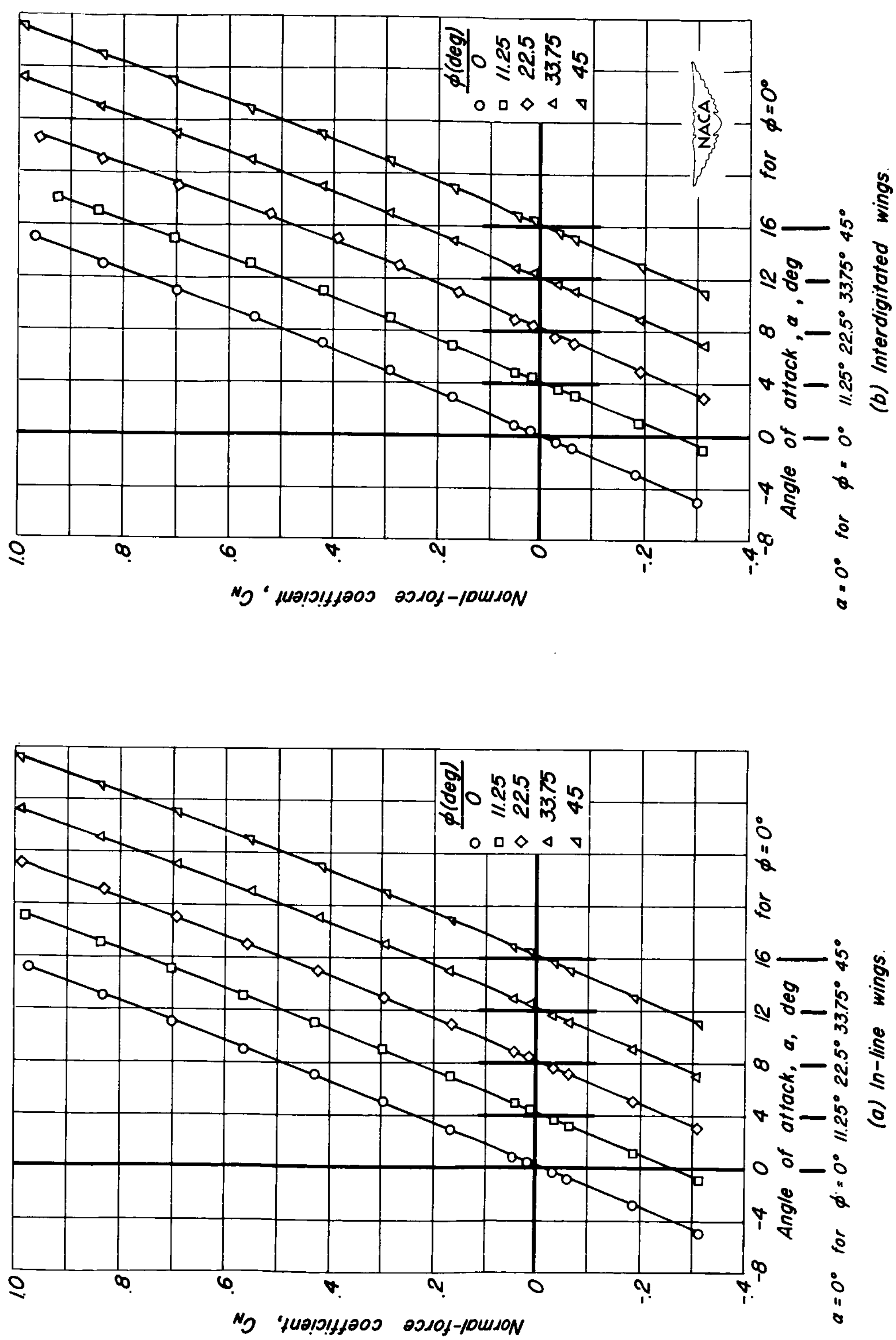
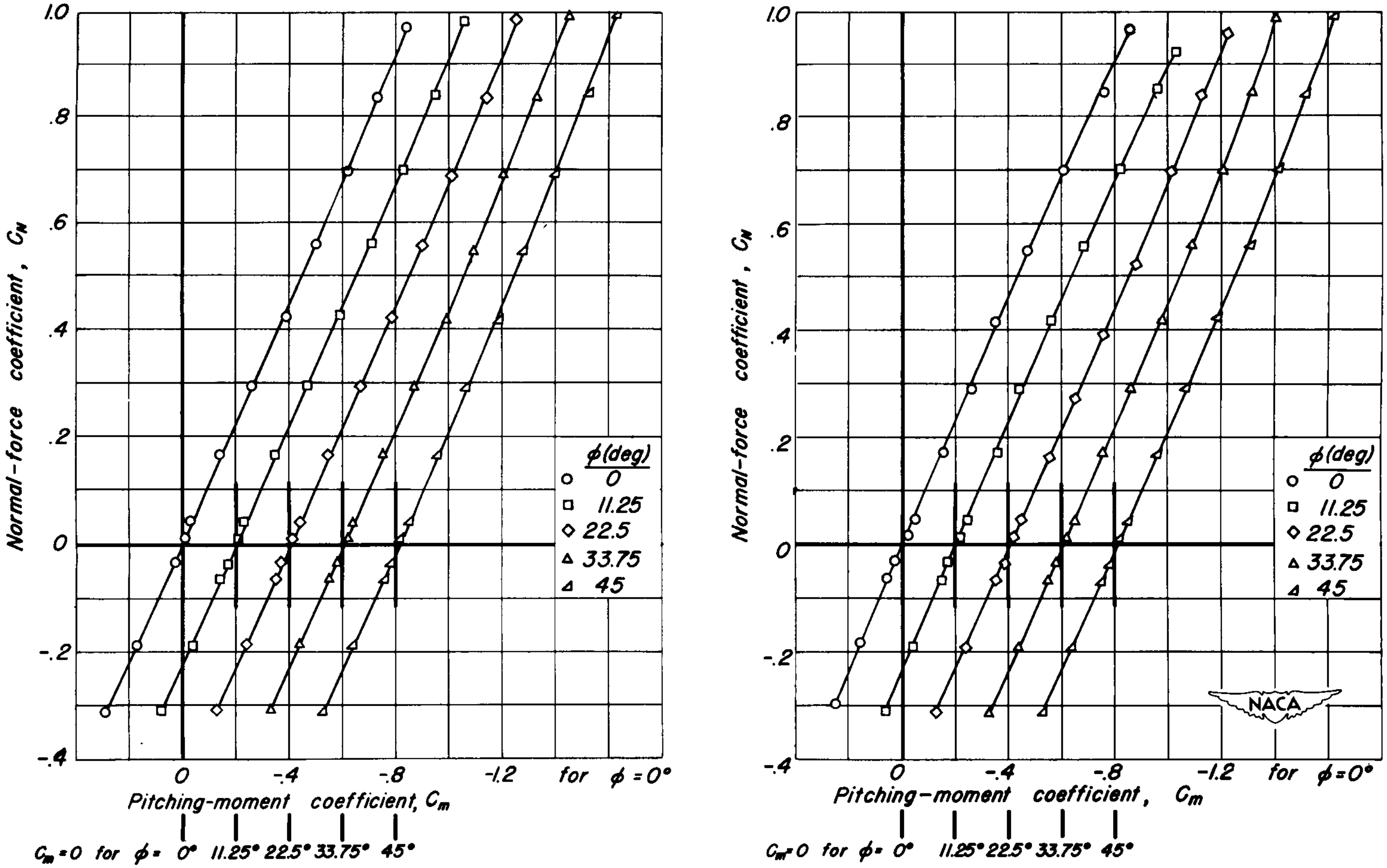


Figure 3.- Variation of normal-force coefficient with angle of attack at various angles of bank, $M=1.7$, $\delta_v=0°$, $\delta_H=0°$.



(a) In-line wings.

(b) Interdigitated wings.

Figure 4.- Variation of normal-force coefficient with pitching-moment coefficient at various angles of bank, $M = 1.7$, $\delta_v = 0°$, $\delta_h = 0°$.

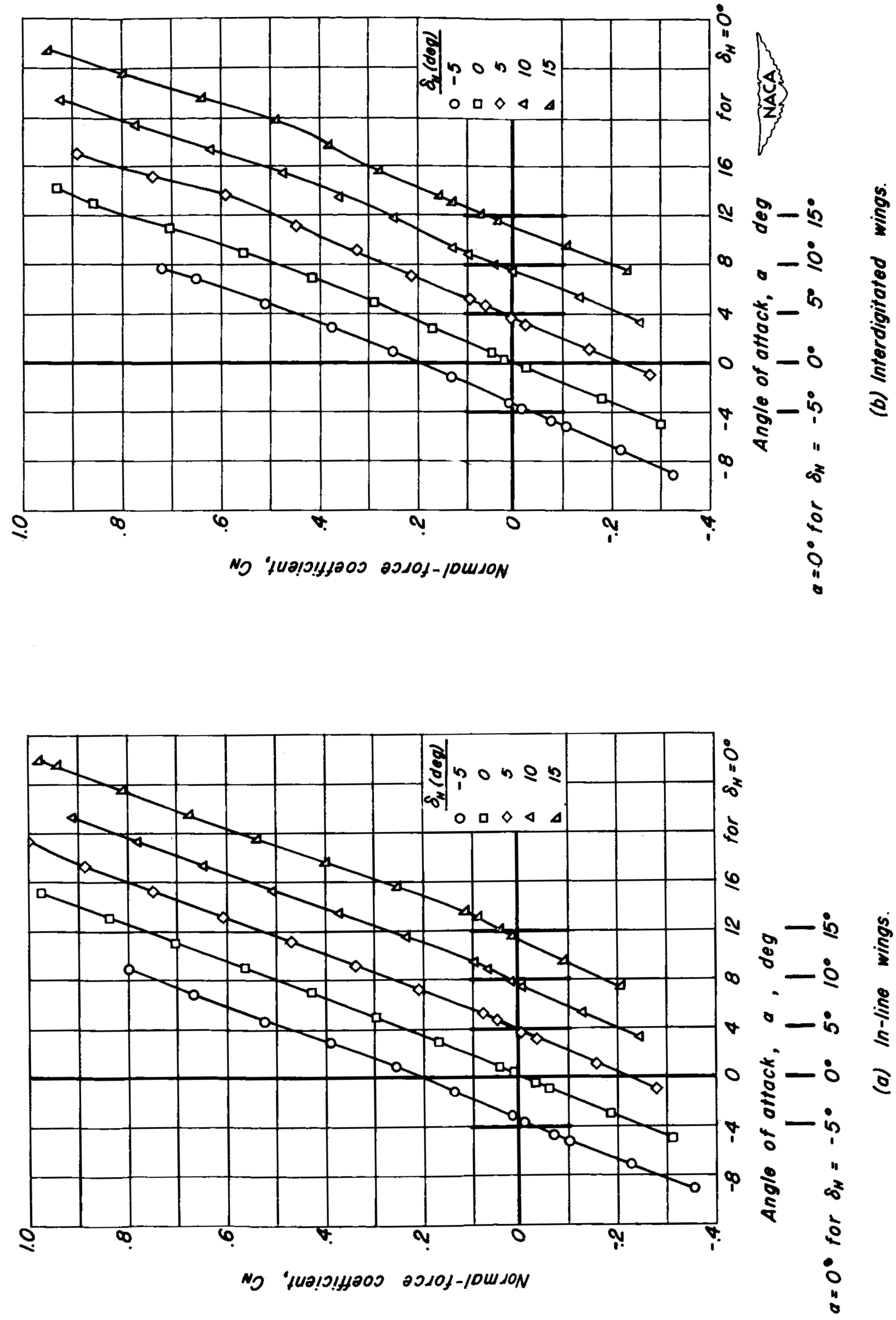
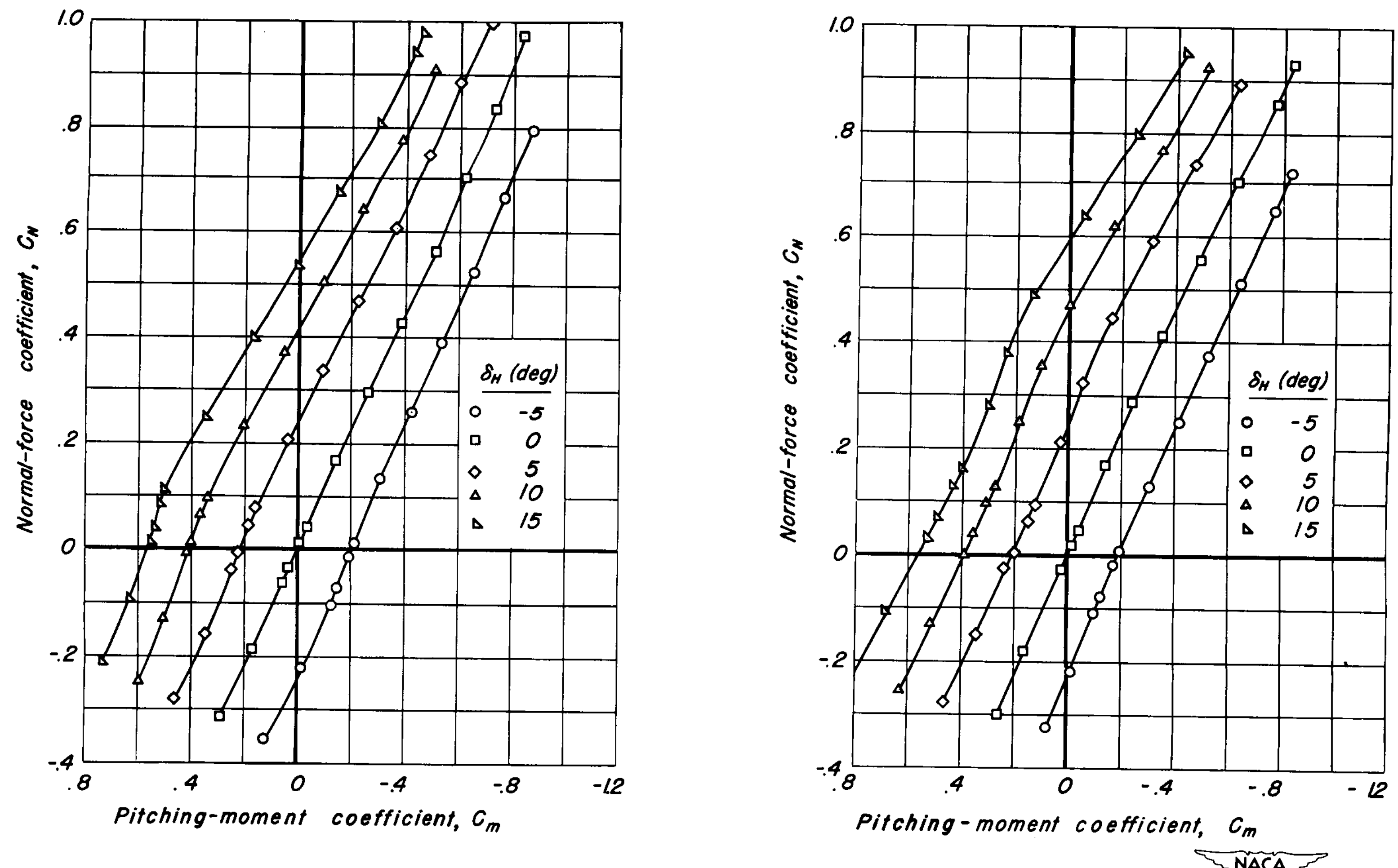


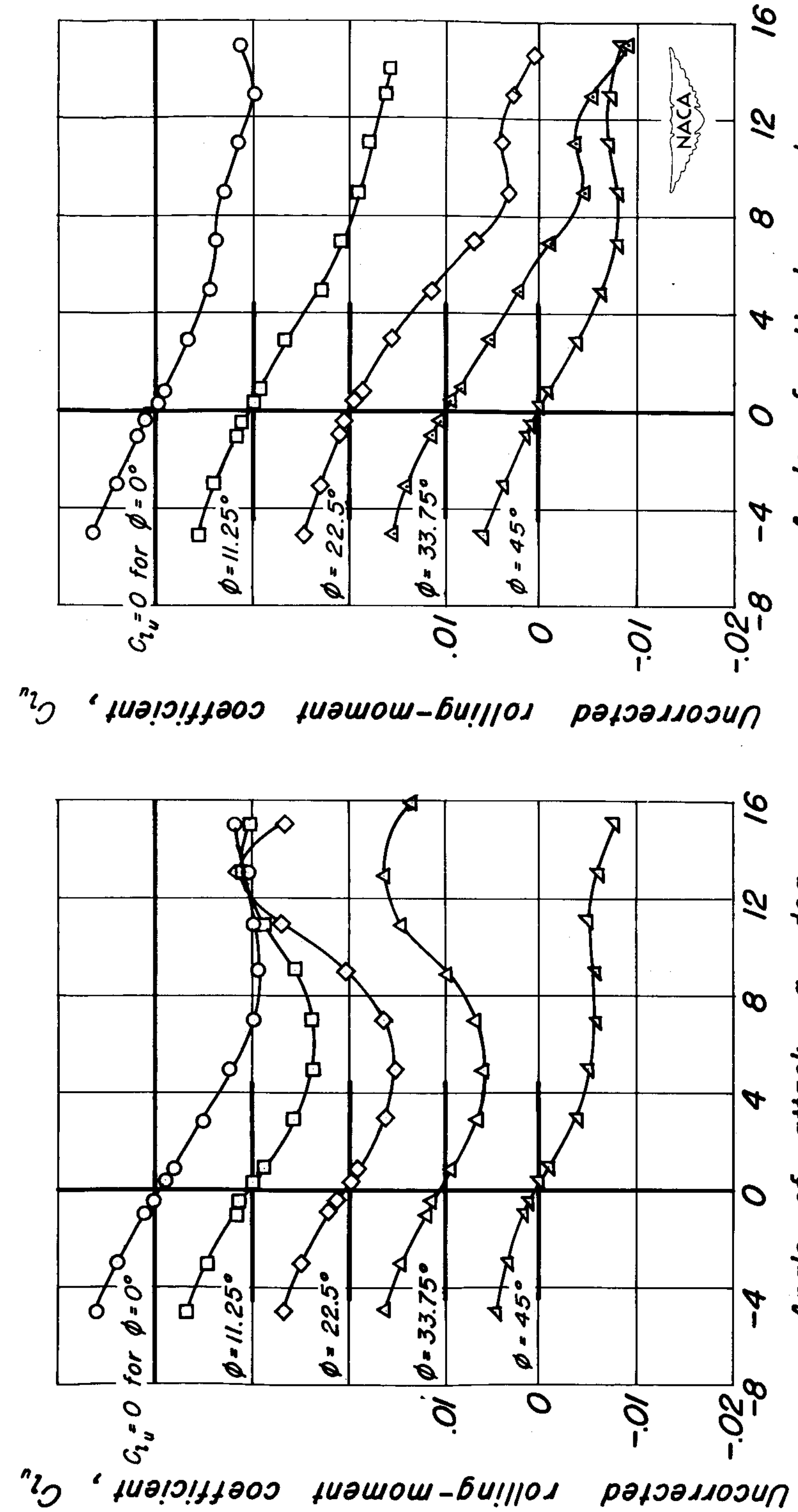
Figure 5.- Variation of normal-force coefficient with angle of attack at various horizontal-canard-fin deflections, $M = 1.7, \phi = 0°$.



(a) In-line wings.

(b) Interdigitated wings.

Figure 6.- Variation of normal-force coefficient with pitching-moment coefficient at various horizontal-canard-fin deflections, $M = 1.7$, $\phi=0°$.

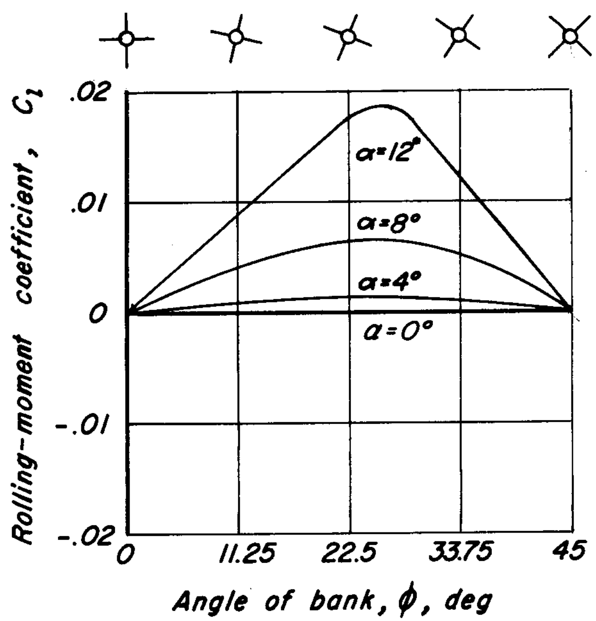


(a) In-line wings.

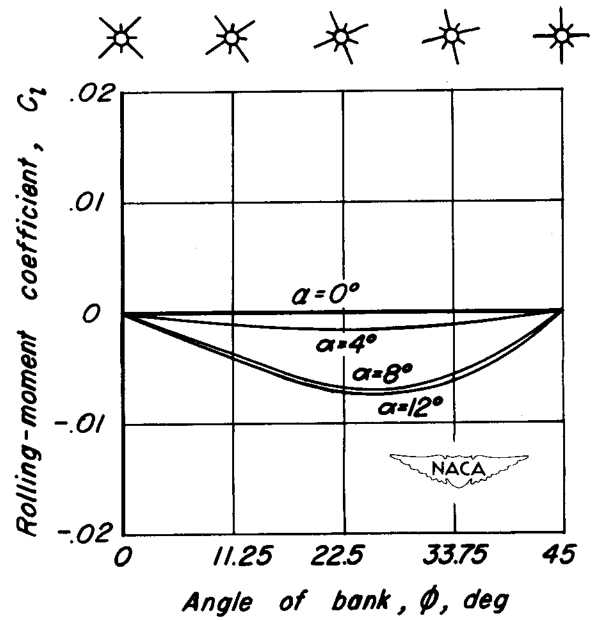
(b) Interdigitated wings.

Figure 7.- Variation of uncorrected rolling-moment coefficient with angle of attack at various angles of bank, $M=1.7, \delta_V=0°, \delta_H=0°$.

[redacted]

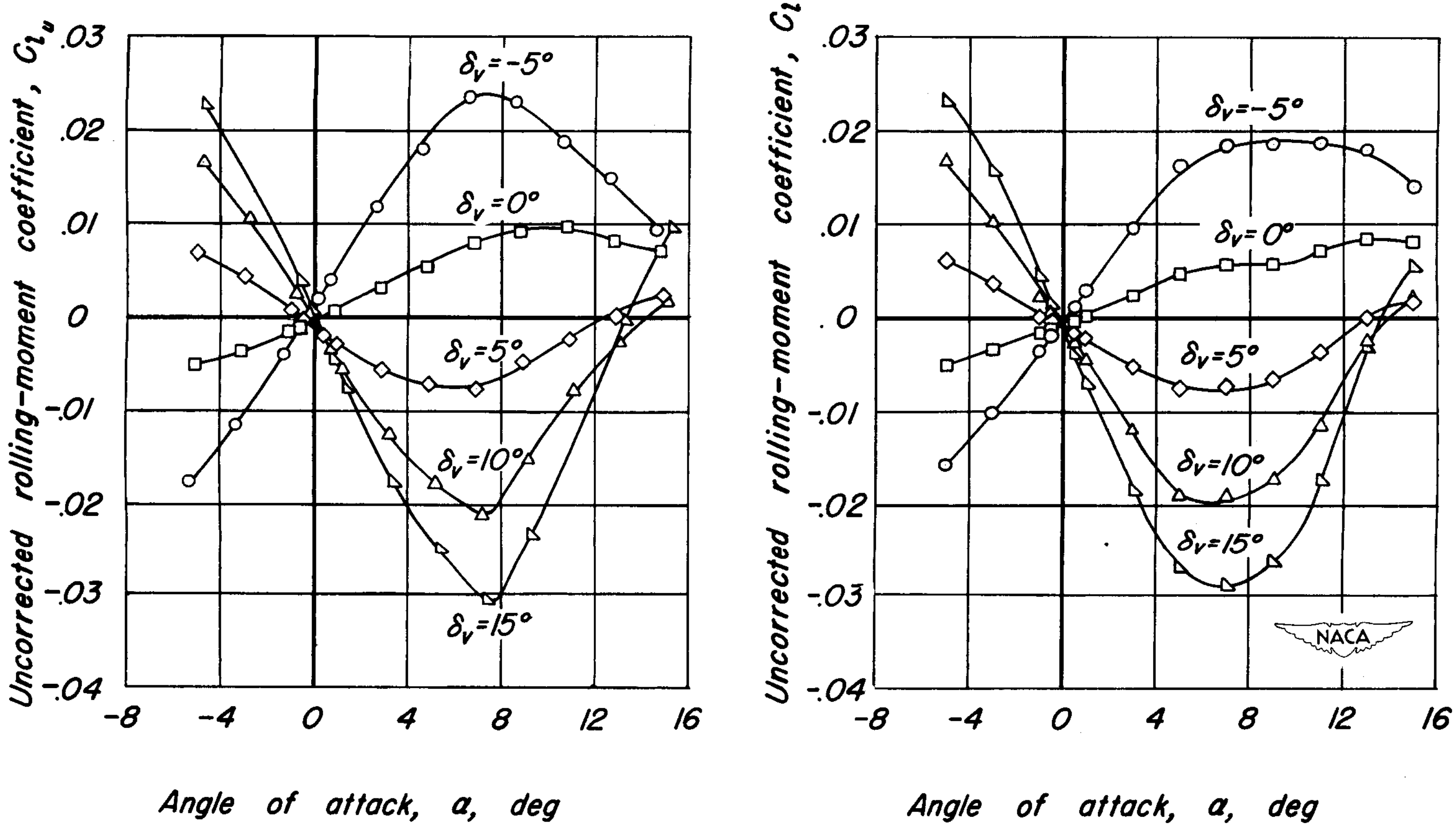


(a) In-line wings.



(b) Interdigitated wings.

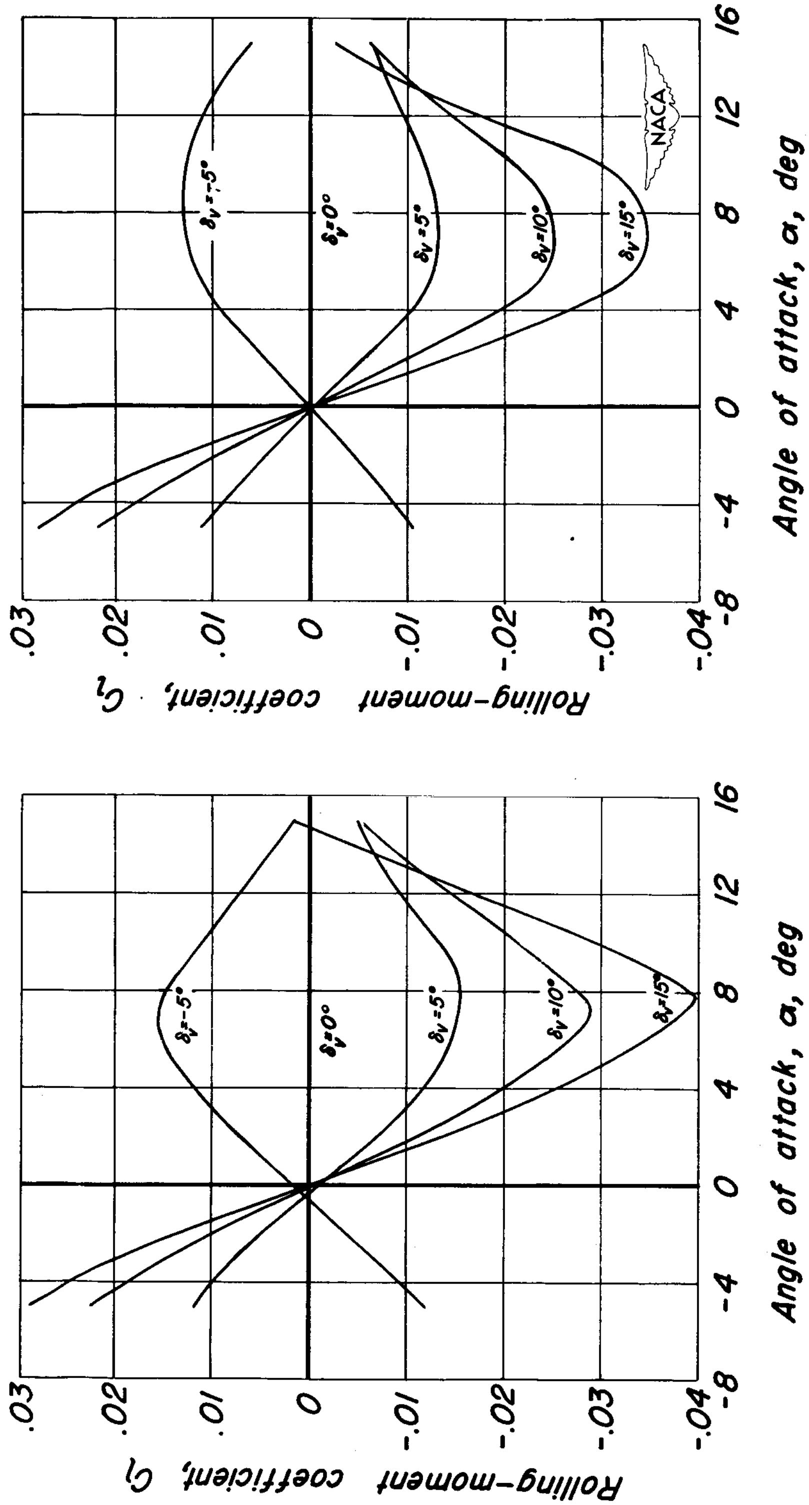
Figure 8.- Variation of rolling-moment coefficient with angle of bank at various angles of attack, M=1.7, δ_V=0°, δ_H=0°.



(a) In-line wings.

(b) Interdigitated wings.

Figure 9.- Variation of uncorrected rolling-moment coefficient with angle of attack for various vertical-canard-fin deflections, $M = 1.7, \delta_H = 0°, \phi = 0°$.



(a) In-line wings.

(b) Interdigitated wings.

Figure 10.- Variation of rolling-moment coefficient with angle of attack for various vertical—canard—fin deflections, $M = 1.7, \delta_H = 0°, \phi = 0°$.

[redacted]