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MEMORANDUM REPORT ARBRL-MR-03020

ALGORITHM FOR ESTIMATING AERODYNAMIC
STATIC MOMENTS OF LONG ROD
PENETRATORS AT $2 < M < 5$

William F. Donovan

May 1980



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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TABLE OF CONTENTS

	Page
LIST OF ILLUSTRATIONS.	5
I. INTRODUCTION	7
II. PROCEDURE.	7
III. RESULTS AND CONCLUSIONS.	8
REFERENCES	15
APPENDIX A	17
APPENDIX B	29
APPENDIX C	39
APPENDIX D	43
APPENDIX E	47
LIST OF SYMBOL	55
DISTRIBUTION LIST.	59

LIST OF ILLUSTRATIONS

Figure		Page
1-a	Long Rod Penetrator Outline.	9
1-b	Input Data for Sample Problem	10
2-a	Static Moment Coefficient for Hypothetical Projectile. .	11
2-b	Normal Force Coefficient for Hypothetical Projectile . .	12
2-c	Aerodynamic Jump Factor for Hypothetical Projectile. . .	13
2-d	Initial Yaw Period for Hypothetical Projectile	14

I. INTRODUCTION

An insight into the influence of aerodynamics on the overall performance of the long rod projectile is obviously necessary to the mechanical analyst and to the terminal ballisticians in the concept phase of design consideration. For the unfinned projectile, in the absence of righting moments in the form of gyroscopic reaction or direct aerodynamic contributions of tailfins, the static moment will normally increase the yaw in the plane of the angle of attack and destabilize the flight projectile. Since the gyroscopic correction is bounded by the possibility of dynamic instability¹, a tailfin system is invariably selected to control the flight of long rod projectiles. The designer must then estimate the static moment in compromise with the drag, weight, length/diameter and penetration parameters. For this purpose the projectile is considered as a forebody (total projectile without fins) plus a complete aerodynamic wing plan form. An "interference factor" correction allows the free flight wing characteristic to be coupled to the forebody performance. Reference 2 offers a combined graphical-tabular calculation technique by which C_D , the drag coefficient, $C_{N\alpha}$, the normal force lift coefficient, and $C_{M\alpha}$, the static moment coefficient can be determined over the Mach range from subsonic to $M = 5$. In the lower velocity regime, the forebody values are determined from slender body theory wherein second order effects are neglected; while in the true supersonic flow, the data are from open literature reported experimentation. Similarly, the lower Mach number fin performance is based on thin airfoil theory and the higher range data is experimental. Using the graph-tables, however, requires about eight manhours to estimate the aerodynamic performance of one projectile. By restricting the Mach envelope through linearization of critical graphs and by neglecting the effects of wing profile it is possible to simplify the presentation to desk top calculator (HP-97, Appendix B) utility. Linearization consists of the substitution of a straight line for a curved or undulating characteristic.

II. PROCEDURE

Figure 1-a is an outline diagram of a typical fin stabilized long rod projectile. In conjunction with Table A-1, the $C_{N\alpha}$, $C_{M\alpha}$, $C_{L\alpha}$, the aerodynamic jump factor and the initial yaw period may be calculated. To use the table it is necessary to separately determine the physical properties of the projectile and C_D . A step-by-step sample calculation, as indicated in Table A-1 will illustrate the procedure for the projectile dimensions of Figure 1-b. The geometric limitations, algebraic specifications, etc., for the column entries are given in Appendix A.

¹C.H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD 442757).

²AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets", 1968.

A similar, and much more elaborate, procedure based on the same formulation has been published³ but is not reduced to CDC presentation locally. This current interim report presents the algorithm for determining $C_{N\alpha}$ and $C_{M\alpha}$. From Reference 4, C_D can be estimated and $C_{L\alpha}$ is therefore available. With the known physical properties of the projectile, the aerodynamic jump factor⁵ and the initial yaw period¹ are established and, in caliber dimensions, comparison with all other flight vehicles postulated.

III. RESULTS AND CONCLUSIONS

Figures 2-a through 2-d show the comparison performance of the hypothetical projectile with the curve trends in reasonable agreement over the region of interest. An additional example is presented in Appendix E, Figures E-1 through E-4. These plots compare algebraically determined performance and experimental range data⁶ for the XM 110 projectile which has been exhaustively tested at BRL. The data indicate agreement in magnitude as well as direction.

Future work in this area will include:

- o Analysis of range data as available.
- o A comprehensive Fortran/CDC programming effort to present the results in mapped context.
- o Extension of the synthesis to higher Mach numbers.

³W.D. Washington, "Computer Program, for Estimating Stability Derivatives of Missile Configurations", U.S. Army Missile Command Report RD7625, May 1976, (AD #1473).

⁴W.F. Donovan and B.B. Grollman "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978, (AD #A054326).

⁵W.F. Donovan "One Factor Affecting the Dispersion of Long Rod Penetrator", ARBRL MR 02846, June 1978, (AD #A058596).

⁶M.J. Piddington, "The Aerodynamic Characteristics of a SPIW Projectile (U)", BRL Memorandum Report 1594, September 1964, (AD #355679).

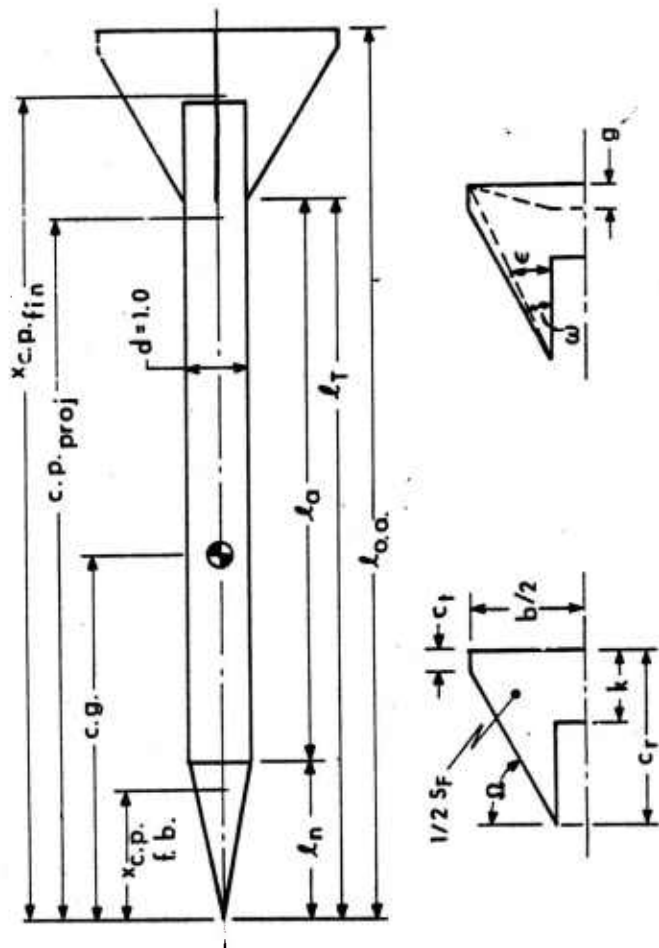
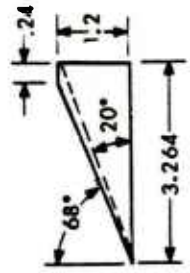
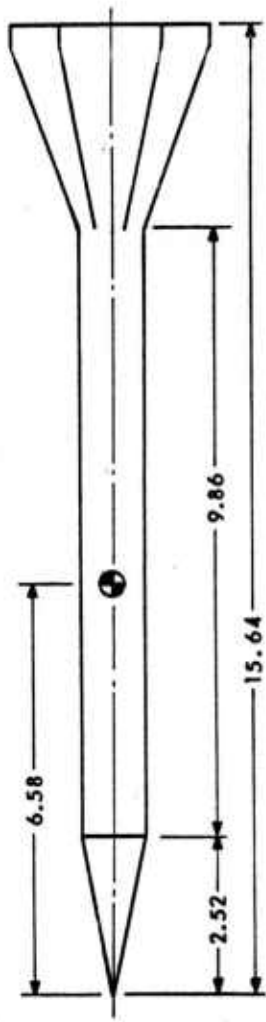


Figure 1-a Long Rod Penetrator Outline



Wt	145.1 cal ³
I _x	16.02 cal ⁵
I _y	1982 cal ⁵
d	1.0 cal
S.G. _{ave}	12.96
N	6

M	CD
2.0	.719
2.5	.638
3.0	.559
3.5	.481
4.0	.405
4.5	.329
5.0	.253

*APPENDIX D

Figure 1-b Input Data for Sample Problem

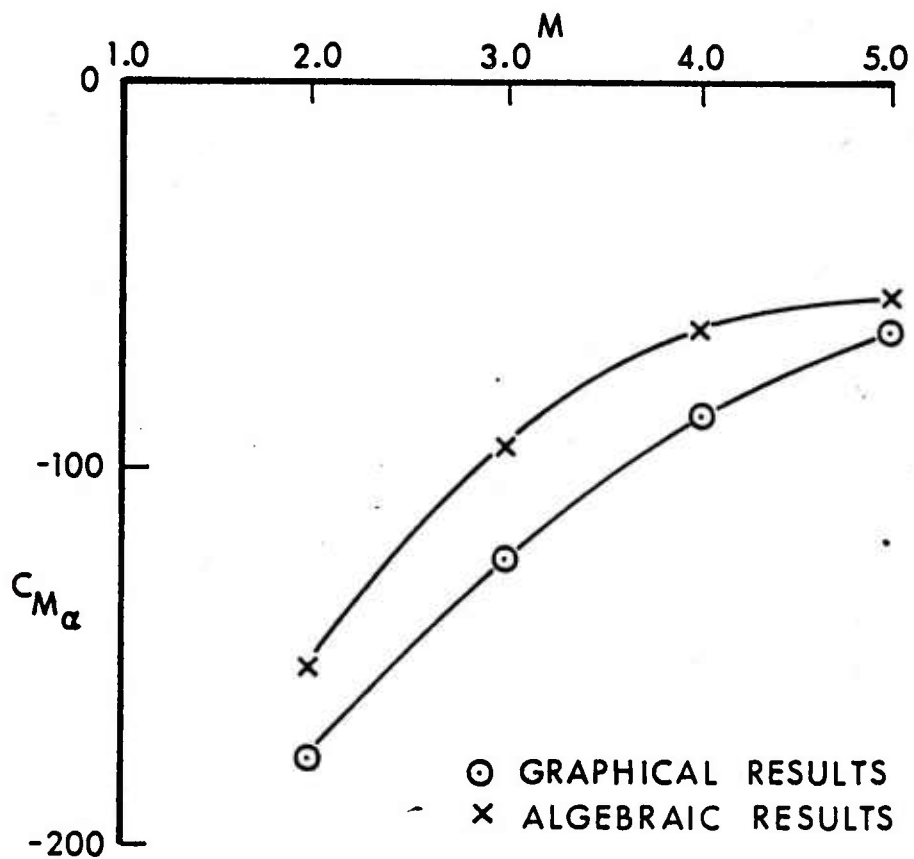


Figure 2-a Static Moment Coefficient for Hypothetical Projectile

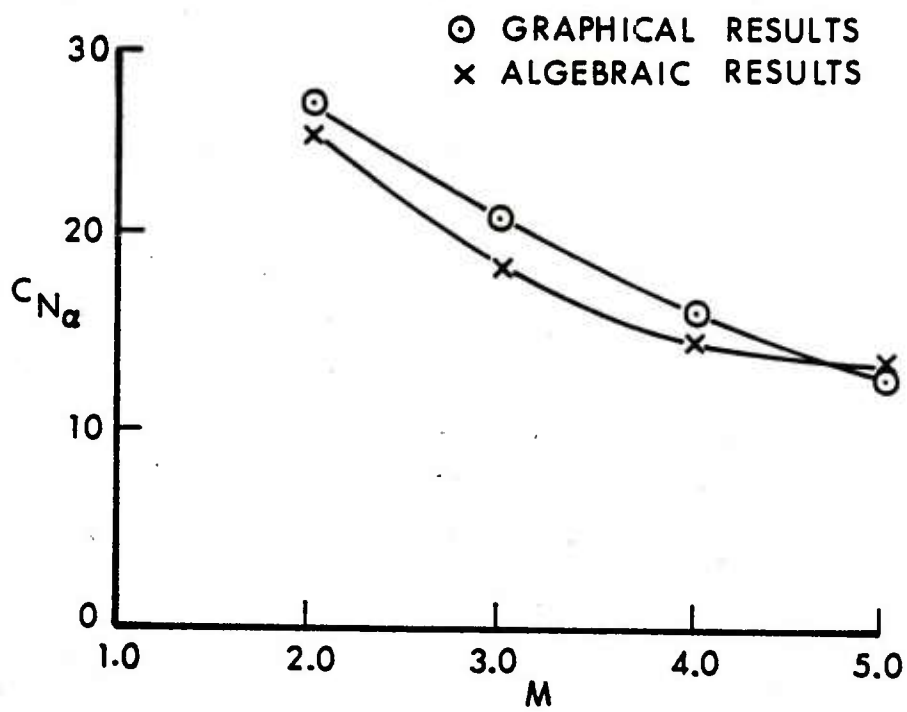


Figure 2-b Normal Force Coefficient for Hypothetical Projectile

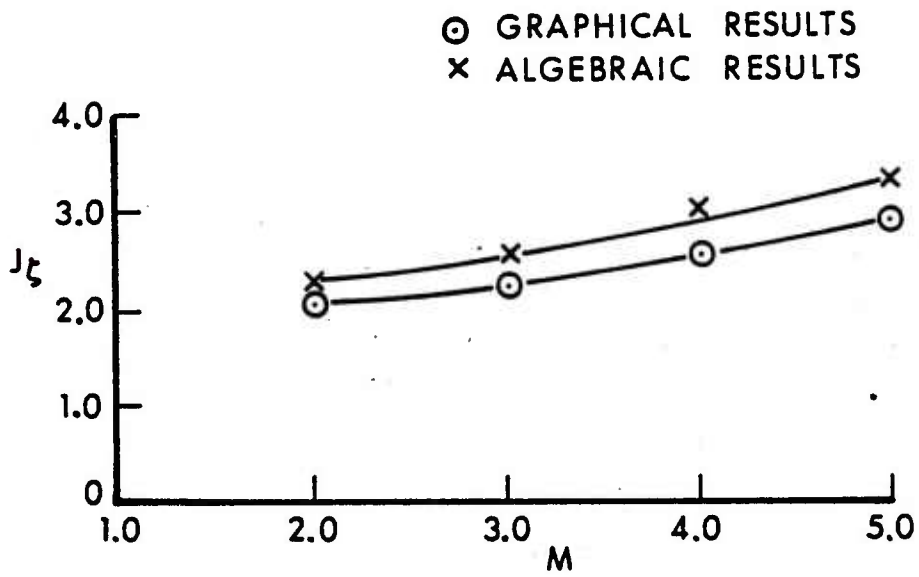


Figure 2-c Aerodynamic Jump Factor for Hypothetical Projectile

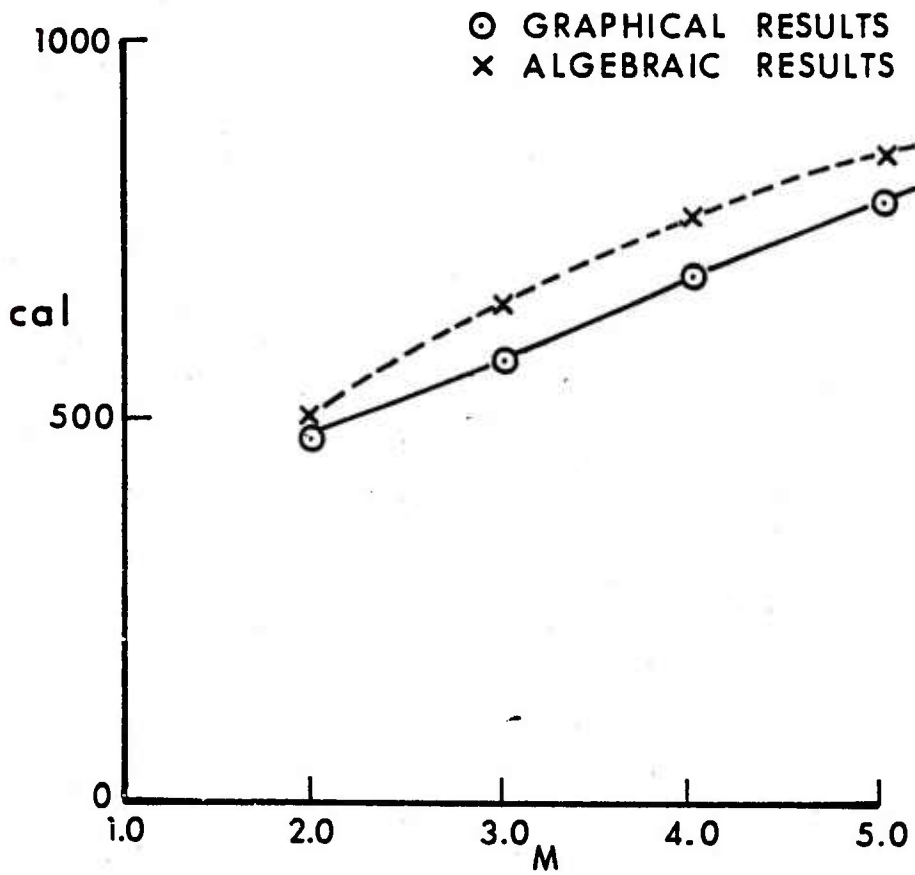


Figure 2-d Initial Yaw Period for Hypothetical Projectile

REFERENCES

1. C.H. Murphy, "Free Flight Motion of Symmetric Missiles", BRL Report No. 1216, July 1963, (AD #442757).
2. AMCP 706-280, "Design of Aerodynamically Stabilized Free Rockets", 1968.
3. W.D. Washington, "Computer Program for Estimating Stability Derivatives of Missile Configurations", U. S. Army Missile Command Report RD-76-25, May 1976, (AD #1473).
4. W.F. Donovan and B.B. Grollman, "Procedure for Estimating Zero Yaw Drag Coefficients for Long Rod Projectiles at Mach Numbers from 2 to 5", ARBRL MR 02819, March 1978, (AD #A054326).
5. W.F. Donovan, "One Factor Affecting the Dispersion of Long Rod Penetrators", ARBRL MR 02846, June 1978, (AD #A058596).
6. M.J. Piddington, "The Aerodynamic Characteristics of a SPIW Projectile (U)", BRL Memorandum Report 1594, September 1964, (AD #355679).

APPENDIX A
TABULATED VALUES

TABLE A-1 FOREBODY

	$\beta = (M^2 - 1)^{1/2}$			(2/3)	(4/2)	Fig. 8-4, Ref. 2 or Eq. (1), Appendix A	Fig. 8-5, Ref. 2 or Eq. (2), Appendix A	(7)(8)
1	2	3	4	5	6	7	8	9
M	β	l_n	l_a	β/l_n	l_a/β	$C_{N\alpha}$ f.b.	$x_{c.p.}$ f.b.	$C_{M\alpha}$ f.b.
		cal	cal	1/cal	cal	1/rad	cal	1/rad
2.	1.732	2.52	9.86	.687	5.690	3.0	2.52	7.56
						3.2	1.94	6.24
3.	2.828	2.52	9.86	1.122	3.487	3.75	3.06	11.48
						3.65	2.19	8.04
4.	3.873	2.52	9.86	1.557	2.546	3.80	3.14	11.93
						3.99	2.43	9.71
5.	4.899	2.52	9.86	1.944	2.013	3.70	3.28	12.14
						4.26	2.65	11.31

* Graphical values from Ref. 2

** Algebraic values from Appendix B

TABLE A-2 FINS

	$\lambda = c_v/c_f$		$\frac{(2)}{(11)}$	$\frac{(11)}{(2)}$	b^2/s_f	$\frac{(11) \times (14)}{(11)}$
N	10	11	12	13	14	15
	λ	TAN α	$\beta/TAN \alpha$	TAN α/β	AR	AR TAN α
2.	.074	2.52	.687		1.37	3.45
					1.37	
3.	.074	2.52		.891	1.37	3.45
					1.37	
4.	.074	2.52		.651	1.37	3.45
					1.37	
5.	.074	2.52		.514	1.37	3.45
					1.37	

TABLE A-3 FINS (COMPLETED)

	Fig. 8-13, Ref. 2	Fig. 8-13, Ref. 2	(16) (11), (17) (2) or Eq. (3), Appendix A	$\frac{N S_F}{\pi} \times (18)$ (based on reference area)	Fig. 8-14, Ref. 2	(19) x (20) (nose fulcrum)
	16	17	18	19	20	21
M	$\beta \tan \alpha$	$\beta C_{N\alpha}$	$C_{N\alpha}$ fin	$C_{N\alpha}$ fin	$x_{c.p.}$ fin	$C_{M\alpha}$ fin
		1/rad	1/rad	1/rad	cal	1/rad
2.	4.56		1.81	14.53	14.4	209
			1.18	9.47		221
3.		3.85	1.36	10.92	14.4	157
			1.10	8.84		133
4.		3.87	1.00	8.03	14.4	115
			1.11	8.88		101
5.		3.90	.80	6.42	14.4	92
			1.14	9.17		84

TABLE A-4 INTERFERENCE FACTOR

		$a = \beta \text{ TAN } \omega$	$z = \frac{\text{TAN } \omega}{\text{TAN } \epsilon}$	Fig. 8-21, Ref. 2 or Eq. (4), Appendix A
	22	23	24	25
M	$d / (1+b)$	a	a/z	K
2.	.29	.63	.95	1.69
				1.65
3.	.29	1.03	.95	1.62
				1.58
4.	.29	1.41	.95	1.59
				1.47
5.	.29	1.78	.95	1.55
				1.39

TABLE A-5 SUMMARY

	7	19 (interference free)	25 x 27	26 + 28	9	21 (interference free)	25 x 31	30 + 32 (nose fulcrum)	33 29 (nose datum)	(34 - c.g.) x 29 (c.g. fulcrum)
	26	27	28	29	30	31	32	33	34	35
M	$C_{N\alpha}$ f.b.	$C_{N\alpha}$ fin	$C_{N\alpha}$ fin	$C_{N\alpha T}$ proj.	$C_{M\alpha}$ f.b.	$C_{M\alpha}$ fin	$C_{M\alpha}$ fin	$C_{M\alpha T}$ proj.	c.p. proj.	$C_{M\alpha T}$
	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	1/rad	cal	1/rad
2.	3.00	14.53	24.56	27.56	7.56	209	353	358	12.98	-177
	3.2	9.47	22.75	25.95	6.24	193	318	324	12.49	-153
3.	3.75	10.92	17.69	21.44	11.48	157	254	266	12.40	-125
	3.65	9.84	15.2	18.85	8.04	134	212	220	11.67	-96
4.	3.80	8.03	12.76	16.57	11.93	115	183	195	11.76	-86
	3.99	8.88	11.04	15.03	9.71	104	154	164	10.89	-65
5.	3.70	6.42	9.95	13.65	12.14	92	143	155	11.35	-65
	4.26	9.17	10.0	14.26	11.31	101	140	151	10.61	-58

TABLE A-6 AERODYNAMIC JUMP FACTOR

	Separate schedule	$\textcircled{29} - \textcircled{36}$	$\textcircled{37} / \textcircled{35}$	Separate schedule	$\textcircled{38} \times \textcircled{39}$	$144.6 \left[\frac{I_y}{\textcircled{41}} \right]^{1/2}$ Eq. C-1, Appendix C
	36	37	38	39	40	41
M	C_D	$C_{L\alpha}$	$C_{L\alpha} / C_{Mac}$	I_y/m	J	s
		1/rad				cal
2.	.72	26.84	.152	13.66	2.08	484
		25.23	.165		2.25	520
3.	.56	20.88	.167	13.66	2.28	576
		18.29	.191		2.60	657
4.	.41	16.16	.188	13.66	2.57	694
		14.62	.224		3.07	798
5.	.25	13.4	.206	13.66	2.82	798
		14.01	.242		3.29	845

NOTES ON COLUMN ENTRIES

Column 1	The Mach number range is restricted to $2 < M < 5$ due to linearization of the characteristics.
Column 2	--
Column 3	The given example refers to a cone-cylinder forebody. An ogive nose would increase the normal force about 10%; Figures 8-2 and 8-4 of Reference 2. $2 < \ell_n < 6$.
Column 4	$5 < \ell_a < 20$
Column 5	--
Column 6	--
Column 7	$(C_{N\alpha})_{f.b.} = \left(1.9 + 1.3 \frac{\beta}{\ell_n} + .0149 \frac{\ell_a}{\beta} \right) \left(\beta^{-.7} \right) \left(-.0675 \ell_T + 2.3 \right) \quad (1)$
	This equation is a fitted approximation to the curves of Figure 8-4 of Reference 2. It applies to cone-cylinders only.
Column 8	$(X_{c.p.})_{f.b.} = \left(.69 + .65 \frac{\beta}{\ell_n} + .5 \frac{\ell_a}{\beta} \right) \left(\beta^{-.46} \right) \quad (2)$
	This equation is obtained by fitting Figure 8-5 of Reference 2. It also applies to cone-cylinders only.
Column 9	Moment is referred to nose.
Column 10	--
Column 11	--
Column 12	--
Column 13	--
Column 14	--
Column 15	--
Column 16	Figures 8-13, Reference 2.
Column 17	Figures 8-13 of Reference 2.

Column 18

$$C_{N\alpha} = \frac{1}{\beta} \left[4 + \left(.9\lambda + 1.25\ell_n \frac{ARTAN\Omega}{4} \right) \left(\frac{TAN\Omega}{\beta} \right) \right] + \frac{1}{TAN\Omega} \left[\left(.6AR - 1 \right) \left(1 - \frac{\beta}{TAN\Omega} \right) \right] \left(\frac{.541}{M} \right) \left(\beta^{-.58} \right) \quad (3)$$

where the first term is used for $\frac{TAN\Omega}{\beta} < 1$ and both terms are used for $\frac{TAN\Omega}{\beta} > 1$. $C_{N\alpha}$ is based on the plan form area.

This expression is determined by empirical data as fitted from Figures 8-13 (A) through (C) of Reference 2. It includes a term to represent the complete expanse of tip/root ratios, as well as the fin aspect ratio and leading edge sweep angle as affected by Mach number.

Column 19 $C_{N\alpha}$ is converted to a reference area value (bourelet).

The effect of the fin solidity is established by Reference 2, p. 8-41.

Column 20 For the algebraic formulation, the c.p. is taken at the mid point of the total fin length. The error introduced, in comparison with Figures 8-14 of Reference 2, is quite small.

Column 21 Moment is referred to nose.

Column 22 --

Column 23 --

Column 24 --

Column 25 $K = (-.167 a + 1.334)e^{d/d+b} \quad (4)$

The rather minor contribution of "z" has not been included in this equation. This is a sweep angle compensation and would be significant for rectangular fin designs. The equation represents the curves given as Figures 8-21 (C) through (E) of Reference 2.

Column 26 Transcription of column 7

Column 27 Interference free $C_{N\alpha}$

Column 28 Complete empennage

Column 29 --
Column 30 --
Column 31 Interference free fins
Column 32 Complete empennage

Note that with columns 28 and 32, the capacity of the HP-97 has been exceeded. The table is then completed by individual operations.

Column 33 Complete projectile, nose datum.
Column 34 --
Column 35 c.g. must be separately determined
Column 36 C_D must be separately determined
Column 37 --
Column 38 --
Column 39 --
Column 40 --
Column 41 I_y must be separately determined

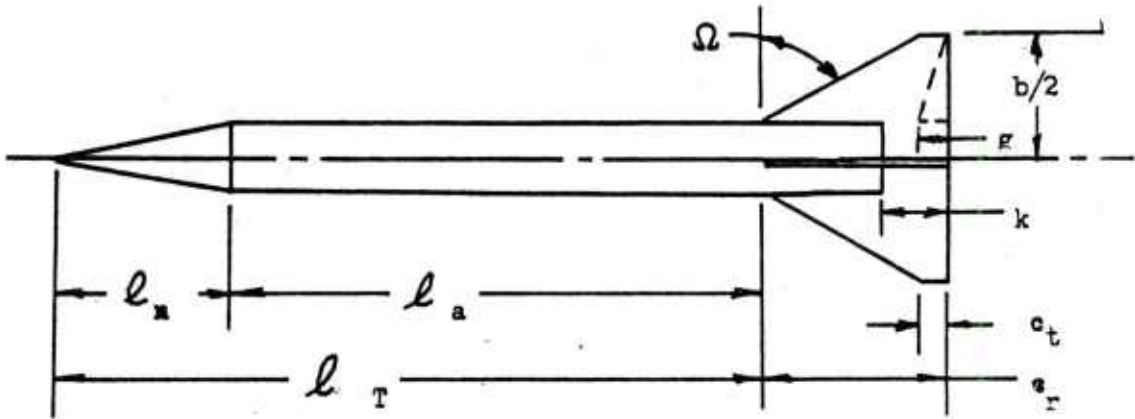
APPENDIX B

DESKTOP CALCULATOR PROGRAMS FOR $C_{N\alpha}$, $C_{M\alpha}$ and C_D

APPENDIX B

DESKTOP CALCULATOR PROGRAMS FOR $C_{N\alpha}$, $C_{M\alpha}$ and C_D

1. HP-97 Listing for $C_{M\alpha}$ and $C_{N\alpha}$.



Listing for Nose/Body $C_{N\alpha}$ and $C_{M\alpha}$

Input Storage Registers

0 l_a cylindrical body length

9 l_n nose length

A M initial Mach number

Printed Output

Mach number M
 Normal Force coefficient $C_{N\alpha}$
 Static Moment coefficient $C_{M\alpha}$
 Center of pressure (nose datum)

001	*LBLA	21	11
002	RCLH	36	11
003	FRTM	-14	
004	X	53	
005	.	01	
006	-	-45	
007	TM	54	
008	STOC	35	01
009	CLM	-51	
010	RCL1	36	01
011	RCLP	36	09
012	=	-24	
013	1	01	
014	.	-62	
015	3	03	
016	X	-35	
017	STOC	35	15
018	CLM	-51	
019	RCLC	36	00
020	0	08	
021	=	-24	
022	RCL1	36	01
023	X	-35	
024	STOD	35	12
025	.	-62	
026	1	01	
027	1	01	
028	9	09	
029	+	-55	
030	RCLC	36	15
031	+	-55	
032	RCL1	36	01
033	LM	32	
034	.	-62	
035	7	07	
036	X	-35	
037	e^y	33	
038	=	-24	
039	STOD	35	14
040	CLM	-51	
041	RCLC	36	00
042	RCLP	36	09
043	+	-55	
044	.	-62	
045	0	00	
046	6	06	
047	5	05	
048	CHS	-22	
049	X	-35	
050	2	02	

051	.	-62	
052	3	03	
053	+	-55	
054	STOC	35	02
055	RCLC	36	14
056	X	-35	
057	FRTM	-14	
058	STOD	35	14
059	CLM	-51	
060	RCLC	36	15
061	2	02	
062	=	-24	
063	STOC	35	13
064	RCLC	36	12
065	.	-62	
066	4	04	
067	X	-35	
068	RCLC	36	13
069	+	-55	
070	.	-62	
071	6	06	
072	9	09	
073	=	-55	
074	2	02	
075	=	-24	
076	RCLP	36	09
077	X	-35	
078	RCLC	36	14
079	X	-35	
080	RCL1	36	01
081	LM	32	
082	.	-62	
083	4	04	
084	6	06	
085	X	-35	
086	e^x	33	
087	=	-24	
088	FRTM	-14	
089	RCLC	36	14
090	=	-24	
091	FRTM	-14	
092	CLM	-51	
093	SFC	16-11	
094	.	-62	
095	5	05	
096	RCLA	36	11
097	-	-55	
098	STDA	35	11
099	CSBA	23	11
100	RTN	24	
101	FRTM	-14	
102	R/C	51	

Listing for Fin/Emppennage $C_{N\alpha}$ and $C_{M\alpha}$

Input Primary Storage Registers

0	$b/2$	fin blade height
1	c_r	fin blade length at root
2	$\tan \Omega$	tangent of fin sweepback angle
3	g	fin dimension
4	k	fin dimension
5	c_t	fin blade length at tip
6	ΔM	Mach number increment
7	N	number of fin blades

Secondary Storage

1	l_T	complete body length
2	l_a	body length
3	l_n	nose length
6	c.g.	center of mass (nose datum)
I	M	initial Mach number

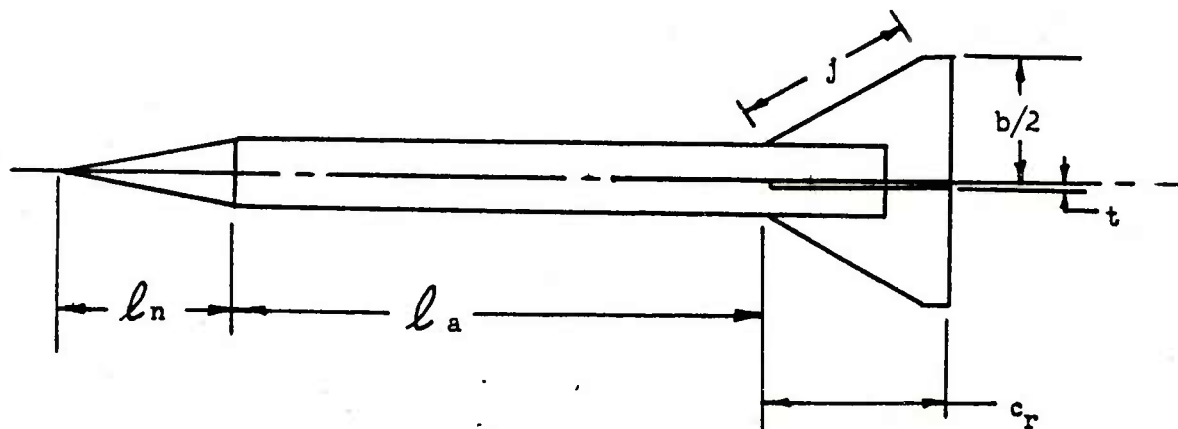
Printed Output

Mach number	M
Static Moment coefficient	$C_{M\alpha}$
Normal Force coefficient	$C_{N\alpha}$

001	4LELE	21 15	051	STOI	35 46
002	RCL0	36 00	052	W	53
003	2	02	053	:	01
004	*	-35	054	-	-45
005	W	53	055	W	54
006	STOA	35 11	056	STOA	35 11
007	CLX	-51	057	CLX	-51
008	RCL0	36 00	058	RCL0	36 02
009	RCL1	36 01	059	RCLB	36 12
010	*	-35	060	*	-35
011	STOB	35 12	061	4	04
012	CLX	-51	062	=	-24
013	RCL2	36 02	063	LX	32
014	RCL0	36 00	064	5	05
015	W	53	065	*	-35
016	*	-35	066	4	04
017	2	02	067	=	-24
018	=	-24	068	XW	-41
019	RCL0	36 12	069	RCL5	36 05
020	-	-45	070	RCL1	36 01
021	CHS	-22	071	=	-24
022	STOB	35 12	072	.	-62
023	CLX	-51	073	9	09
024	RCL0	36 00	074	.	-35
025	RCL0	36 03	075	+	-55
026	*	-35	076	XW	-41
027	2	02	077	RCL2	36 02
028	=	-24	078	*	-35
029	RCL0	36 12	079	RCLA	36 11
030	-	-45	080	=	-24
031	CHS	-22	081	STOB	35 08
032	STOB	35 12	082	4	04
033	CLX	-51	083	+	-55
034	RCL4	36 04	084	RCLA	36 11
035	.	-62	085	:	-24
036	5	05	086	STOC	35 13
037	*	-35	087	CLX	-51
038	RCLB	36 12	088	RCLA	36 11
039	+	-55	089	RCL2	36 02
040	2	02	090	=	-24
041	*	-35	091	1	01
042	RCLA	36 11	092	-	-45
043	XW	-41	093	CHS	-22
044	=	-24	094	STOC	35 14
045	STOB	35 12	095	CLX	-51
046	CLX	-51	096	RCL5	36 12
047	RCL1	36 46	097	.	-62
048	RCL5	36 06	098	6	06
049	+	-55	099	*	-35
050	PRTX	-14	100	1	01

151	.	-62	101	-	-45	201	.	-35
152	5	05	102	RCLD	36 14	202	PRTM	-14
153	9	08	103	*	-35	203	CLM	-51
154	*	-35	104	RCLZ	36 02	204	RCLD	36 14
155	e ^y	33	105	+	-24	205	RCLZ	36 09
156	+	-24	106	STOE	35 14	206	*	-35
157	STOD	35 14	107	CLM	-51	207	PRTM	-14
158	STOE	35 15	108	1	01	208	CLM	-51
159	RCL1	36 01	109	WZY	-41	209	WZY	-41
160	.	-62	110	RCLA	36 11	210	CLM	-51
161	5	05	111	+	-24	211	SFD	16-11
162	*	-35	112	STOS	35 09	212	GTGE	22 15
163	FPS	16-51	113	WZY?	16-35	213	RTH	24
164	RCL1	36 01	114	*LBLD	21 14	214	R/S	51
165	+	-55	115	RCLC	36 08			
166	RCLZ	36 15	116	RCL9	36 09			
167	FPS	16-51	117	*	-35			
168	*	-35	118	4	04			
169	STOE	35 15	119	+	-55			
170	CLM	-51	120	RCLA	36 11			
171	RCLZ	36 15	121	+	-24			
172	STOE	35 15	122	STOC	35 13			
173	RCLZ	36 00	123	CLM	-51			
174	RCL1	36 01	124	RCLC	36 13			
175	+	-24	125	RCLC	36 14			
176	RCLA	36 11	126	+	-55			
177	*	-35	127	RCL1	36 46			
178	.	-62	128	3	03			
179	1	01	129	.	-62			
180	6	06	130	7	07			
181	7	07	131	+	-24			
182	CHS	-22	132	*	-35			
183	.	-35	133	STOE	35 15			
184	1	01	134	CLM	-51			
185	.	-62	135	RCL0	36 00			
186	3	03	136	2	02			
187	3	03	137	.	-35			
188	4	04	138	WZ	53			
189	+	-55	139	RCLB	36 12			
190	RCLZ	36 00	140	+	-24			
191	2	02	141	Fi	16-24			
192	*	-35	142	+	-24			
193	1	01	143	RCL7	36 07			
194	+	-55	144	*	-35			
195	1W	52	145	RCLZ	36 15			
196	e ^y	33	146	*	-35			
197	WZY	-41	147	2	02			
198	*	-35	148	.	-35			
199	STOS	35 09	149	RCLA	36 11			
200	RCLZ	36 15	150	LK	32			

Program for C_D



Input Storage Registers

- 1 l_n nose length
- 2 l_a cylindrical body length
- 3 $b/2$ fin blade height at trailing edge
- 4 t fin thickness
- 5 c_r fin blade length at root
- 6 j fin leading edge length
- 7 N number of fin blades
- I M Mach number

Printed Output

- Mach number M
- Body wave C_D
- Body base C_D
- Body viscous C_D
- Body total C_D
- Fin wave C_D
- Fin base C_D
- Fin viscous C_D
- Fin total C_D
- Combined C_D

001	*LBLE	21	13
002	RCL1	36	46
003	PRTX	-14	
004	LK	32	
005	.	-62	
006	2	02	
007	3	00	
008	CHS	-22	
009	*	-35	
010	EX	32	
011	STOA	35	11
012	CLX	-51	
013	RCL1	36	01
014	LK	32	
015	1	01	
016	.	-62	
017	7	07	
018	3	02	
019	CHS	-22	
020	*	-35	
021	EX	32	
022	RCLA	36	11
023	*	-35	
024	.	-62	
025	7	07	
026	*	-35	
027	PRTX	-14	
028	STOA	35	11
029	CLX	-51	
030	RCL1	36	46
031	.	-62	
032	0	00	
033	4	04	
034	8	08	
035	CHS	-22	
036	*	-35	
037	.	-62	
038	2	02	
039	5	05	
040	5	05	
041	+	-55	
042	PRTX	-14	
043	STOE	35	12
044	CLX	-51	
045	RCL1	36	01
046	X²	53	

047	.	-62	
048	5	05	
049	X²	53	
050	+	-55	
051	∇	54	
052	.	-62	
053	5	05	
054	*	-35	
055	RCL2	36	02
056	+	-55	
057	F1	16-24	
058	x	-35	
059	STO9	35	02
060	F1	16-24	
061	=	-24	
062	4	04	
063	x	-35	
064	.	-62	
065	0	00	
066	0	00	
067	0	00	
068	1	01	
069	7	07	
070	3	03	
071	*	-35	
072	STO0	35	13
073	CLX	-51	
074	RCL1	36	46
075	4	04	
076	.	-62	
077	1	01	
078	6	06	
079	6	06	
080	CHS	-22	
081	x	-35	
082	2	02	
083	8	08	
084	.	-62	
085	7	07	
086	5	05	
087	+	-55	
088	RCL2	36	13
089	*	-35	
090	PRTX	-14	
091	STO0	35	13
092	RCLA	36	11
093	+	55	
094	RCLB	36	12

095	+	-55	143	FX	54	191	GTCC	22 13
096	PRTX	-14	144	RCLC	36 15	192	RTH	24
097	STOB	35 08	145	÷	-24	193	GSBC	23 13
098	CLX	-51	146	1/2X	52	194	RCLC	36 15
099	RCL3	36 03	147	PRTX	-14	195	6	06
100	RCL6	36 06	148	STOD	35 14	196	.	-62
101	÷	-24	149	RCLB	36 12	197	5	05
102	3/4X	16 41	150	RCL7	36 07	198	STOI	35 46
103	TAN	43	151	.	-25	199	+	-55
104	STOE	35 15	152	RCL3	36 03	200	RCLC	36 14
105	RCL3	36 03	153	x	-35	201	+	-55
106	X²	53	154	RCL4	36 04	202	PRTX	-14
107	RCLC	36 15	155	x	-35	203	RCLB	36 08
108	÷	-24	156	Fi	16-24	204	+	-55
109	2	02	157	÷	-24	205	PRTX	-14
110	÷	-24	158	4	0*	206	.	-25
111	STOE	35 15	159	x	-35	207	aX	33
112	RCL3	36 03	160	PRTX	-14	208	STOB	35 08
113	÷	-24	161	STOE	35 15	209	CLX	-51
114	2	02	162	CLX	-51	210	RCLB	36 11
115	x	-35	163	RCLA	36 11	211	2	02
116	CHS	-22	164	2	02	212	.	-25
117	RCL5	36 05	165	x	-35	213	RCLB	36 09
118	+	-55	166	RCL9	35 09	214	÷	-24
119	RCL3	36 03	167	÷	-24	215	RCLC	36 13
120	x	-35	168	RCLC	36 13	216	x	-35
121	RCLC	36 15	169	x	-35	217	RCL7	36 07
122	+	-55	170	RCL7	36 07	218	x	-35
123	STOB	35 11	171	x	-35	219	.	01
124	Fi	16-24	172	1	01	220	.	-62
125	÷	-24	173	.	-62	221	1	01
126	4	04	174	1	01	222	5	05
127	.	-25	175	5	05	223	÷	-24
128	STOE	35 15	176	÷	-24	224	PRTX	-14
129	RCL4	36 04	177	PRTX	-14			
130	RCL6	36 06	178	RCLC	36 15			
131	÷	-24	179	+	-55			
132	X²	53	180	RCLD	36 14			
133	RCLC	36 15	181	+	-55			
134	x	-35	182	PRTX	-14			
135	RCL7	36 07	183	RCLB	36 08			
136	x	-35	184	+	-55			
137	STOE	35 15	185	PRTX	-14			
138	CLX	-51	186	SFC	16-11			
139	RCL1	36 46	187	DSZI	16 25 46			
140	X²	53	188	GTCC	22 13			
141	1	01	189	RTH	24			
142	-	-45	190	SPC	16-11			

APPENDIX C
DETERMINATION OF INITIAL YAWING PERIOD

APPENDIX C

DETERMINATION OF INITIAL YAWING PERIOD

The initial yawing period for a fin stabilized missile where the epicyclic arm rates are self compensating may be approximated as

$$s = \pi \left(\frac{2 I_y}{\rho S d C_{M\alpha}} \right)^{1/2} \quad (C-1)$$

where

s = yaw distance between successive maxima or between successive minima, cal

ρ = Air density, $.075/62.4 = .00120$

S = Reference area, $\pi/4 \text{ cal}^2$

d = 1.0 cal

$I_y = 1982 \text{ cal}^5$, Figure 1-a.

Thus:

$$s = \pi \left(\frac{2 \times 1982}{.00120 \times .7854 \times 1.0} \right)^{1/2} \left(C_{M\alpha} \right)^{-1/2}$$

APPENDIX D
CALIBER NOMENCLATURE

APPENDIX D

CALIBER NOMENCLATURE

Caliber nomenclature is widely used in aerodynamic expression as a dimensional convenience to compare performance parameters of geometrically similar models. It is usually referred to a linear scale representing the arithmetic ratio of a linear dimension to an arbitrary standard - most often the body diameter at the forward bourrelet - but has been employed to identify volumes*. Only a simple extension of the reasoning is required then to simultaneously de-dimensionalize the "mass" factor in a given expression and deduce a normalized system of mechanical units which permits a rational comparison of the dynamic properties of even geometrically dissimilar elements of machinery. Usually the context of discussion identifies the quantities as "mass cal", "inertia cal" "length cal", etc., although a complete lexicon of explicit and descriptive terms is available for this purpose.

For this report, the following correlation is employed:

$$\text{Length (cal)} = \frac{\text{linear dimension}}{\text{diametral dimension}}$$

$$\begin{aligned} \text{Weight (cal}^3) &= \frac{\text{weight}}{\text{weight of unit volume of water}} \\ &= \text{S.G.N.} \end{aligned}$$

$$\text{Mass (cal}^2 \text{ sec}^2) = \frac{\text{S.G.N.}}{\text{gravity acceleration}}$$

Thus, with force equal to mass times acceleration:

$$(\text{cal}^3) = (\text{cal}^2 \text{ sec}^2) \left(\frac{\text{cal}}{\text{sec}^2} \right)$$

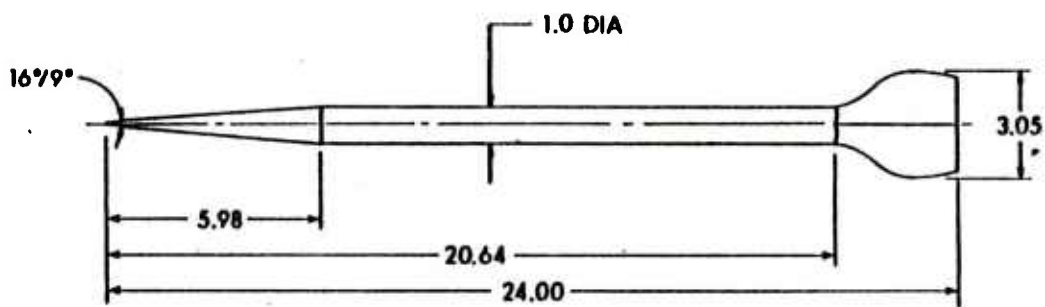
* MacAllister, et al., "A Compendium of Ballistic Properties of Projectiles of Possible Interest in Small Arms", BRL Report No. 1532, February 1971, (AD #882117).

APPENDIX E
ANALYSIS OF THE XM-110 PROJECTILE

APPENDIX E

ANALYSIS OF THE XM-110 PROJECTILE

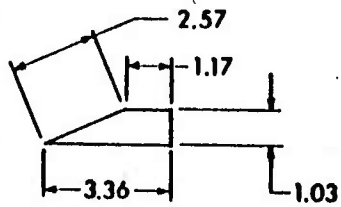
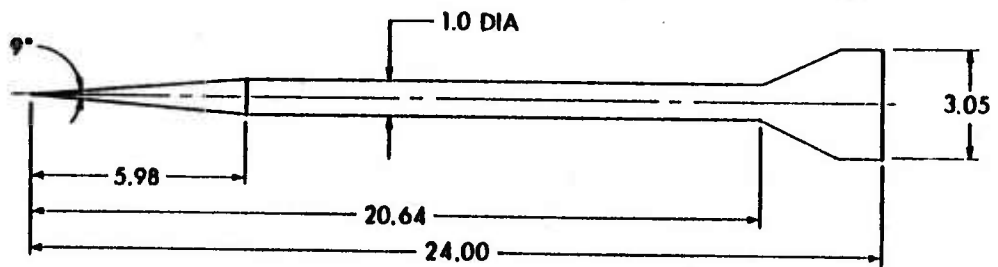
The static moment and normal force coefficients for the XM-110 projectile, a flechette (Figures E-1 and E-2), were determined by the techniques described in this report and compared with range test data as shown on Figures E-3 and E-4. Agreement is satisfactory, the algebraic values being roughly 15% low for the normal force coefficient and within 10% for the static moment coefficient over the velocity range $2 < M < 5$.



WT.	115 CAL ³
I _x	CAL ⁵
I _y	2452 CAL ⁵
DIA	1.0 CAL
P	7.86

•• APPENDIX D

Figure E-1. Outline of XM-110 Projectile



WT.	115 CAL ³
I _x	CAL ⁵
I _y	2452 CAL ⁵
DIA	1.0 CAL
P	7.86

•• APPENDIX D

Figure E-2. Outline of Idealized Model of XM-110 Projectile

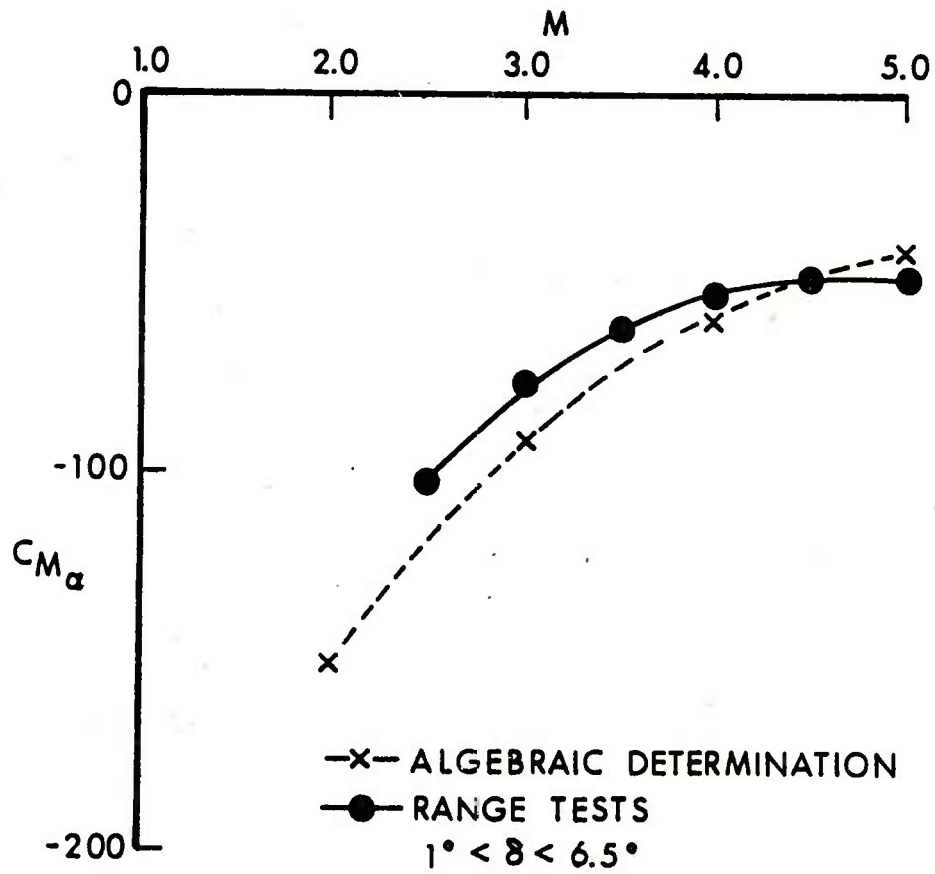


Figure E-3 Static Moment Coefficient of the XM-110 Projectile

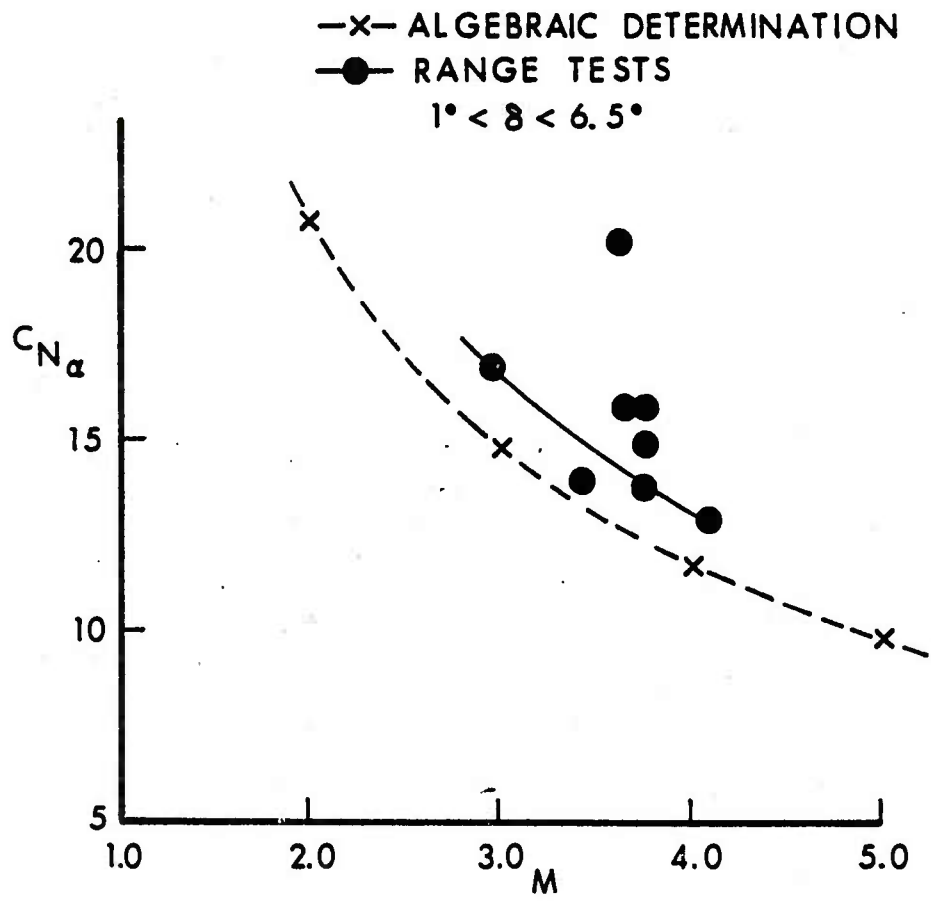


Figure E-4 Normal Force Coefficient of the XM-110 Projectile

LIST OF SYMBOLS

a.	= $\beta \text{ TAN } \omega$, operational parameter
b/2	Fin blade height
c_r	Fin blade length at root
c_t	Fin blade length at tip
c.g.	Center of gravity of projectile, nose datum
c.p.	Center of pressure of normal force
d	= 1.0 cal , reference diameter
g	Fin dimension
k	Fin dimension
l_a	Cylindrical body length
l_n	Nose length
$l_{o.a.}$	Overall length of projectile
l_T	= $l_a + l_n$
m	Mass of projectile
s	Length of initial yaw period
v	Velocity of projectile
x	Distance along projectile, nose datum
z	Operational parameter
α, γ	Angle of attack, sideslip
α_T	= $(\alpha^2 + \gamma^2)^{\frac{1}{2}}$ = arc sin δ , total angle of attack
β	= $(M^2 - 1)^{\frac{1}{2}}$, operational parameter
δ	= sin α_T , operational parameter
δ'	Initial yawing rate
ϵ	= arc tan (b/2)/($C_r + g$) , fin shade angle
λ	= C_t/C_r , fin tip ratio

Ω	Fin sweep back angle
ρ	Density of air
ω	$= \frac{\Pi}{2} - \Omega$, fin leading edge angle taken from axis of rotation.
AR	$= \frac{b^2}{S_F}$, Aspect ratio of fin planform
C_D	$= \frac{\text{Drag Force}}{\frac{1}{2} \rho v^2 S}$, zero-yaw drag coefficient
$C_{L\alpha}$	$= \frac{\text{Lift Force}}{\frac{1}{2} \rho v^2 S \delta}$, aerodynamic lift slope coefficient, $\delta = \sin \alpha_T$
$C_{M\alpha}$	$= \frac{\text{Static Moment}}{\frac{1}{2} \rho v^2 S d \delta}$, aerodynamic moment slope coefficient
$C_{N\alpha}$	$= \frac{\text{Normal Force}}{\frac{1}{2} \rho v^2 S \delta}$, aerodynamic normal force slope coefficient
I_x	Axial moment of inertia
I_y	Transverse moment of inertia
J	$= J_\zeta \delta'$, aerodynamic jump term
J_ζ	$= \frac{I_y}{m d^2} \frac{C_{L\alpha}}{C_{M\alpha}}$, aerodynamic jump factor
K	Interference factor
M	Mach number
N	Number of fin blades
S	$= \frac{\Pi}{4} d^2$, reference area
S.G.N. _{ave.}	Specific gravity of projectile as normalized
S_F	Fin planform area

Supernumerary Subscripts

f.b. Forebody

T Total quantity

Abbreviations

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HP-97 Hewlett-Packard - 97

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