Theoretical Study of Self-Balancing Missiles

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A theoretical study based on linear theory is presented for two types of "self-balancing" missiles, designed to accelerate vertically or laterally without pitching or yawing. One type of missile had a variable-incidence wing and the other type had wing flaps to provide acceleration. The main objective of this investigation is to compare the maximum available acceleration for these self-balancing missiles with that of conventional pitching-type missiles. Ten different configurations were considered. The results indicate that self-balancing missiles with either variable wing incidence or wing flaps are feasible, but that the maximum available acceleration for these missiles is less than for a conventional pitching-type missile having the same wing and tail surfaces.

Nomenclature

a.c. = aerodynamic center
b_T = tailspan
b_W = wingspan
c = wing chord
c.g. = center of gravity
$\bar{c}$ = mean aerodynamic chord
$(c_R)_T$ = root chord of exposed tail
$(c_T)_T$ = tip chord of tail
$(c_R)_W$ = root chord of wing
$(c_T)_W$ = tip chord of wing
C_L = lift coefficient, lift/$q_\infty S_W$
$C_{L\text{DESIGN}}$ = design lift coefficient, design lift/$q_\infty S_W$
C_{Lf} = wing lift coefficient due to flap deflection including lift "carry over" on body, flap lift/$q_\infty S_W$
C_{LT} = tail lift coefficient including lift "carry over" on body, tail lift/$q_\infty S_T$
$C_{L\text{MAX}}$ = maximum lift coefficient available from a specified maximum control deflection or angle of attack
$C_{L\text{TOT}}$ = total lift including lift on the tail due to angle of attack, total lift/$q_\infty S_W$
C_{LW} = wing lift coefficient due to wing incidence including "carry over" on body, wing lift/$q_\infty S_W$
$C_{m_{c.g.}}$ = pitching-moment coefficient about the center of gravity, pitching moment/$q_\infty S_W \bar{c}$
$C_{m\text{-}0.57\bar{c}}$ = pitching-moment coefficient taken about a moment center located $0.57\bar{c}$ ahead of $0.25\bar{c}$
d = lateral distance from body centerline to the mean aerodynamic chord
g = acceleration due to gravity
L_T = longitudinal distance between center of lift for C_{LW} and C_{LT}
L_W = longitudinal distance between the center of gravity and the center of lift for C_{LW}
ΔL_W = longitudinal distance between center of lift for C_{LW} and center of lift for C_{Lf}
m = longitudinal distance between the leading edge of $\bar{c}$ and the intersection of the wing leading edge with the body centerline
M_∞ = freestream Mach number
$(n)_{\text{MAX}}$ = maximum normal acceleration factor, $(C_{L\text{MAX}}/C_{L\text{DESIGN}})-1$
q_T = average dynamic pressure just ahead of the tail surface
q_∞ = freestream dynamic pressure
r_N = body radius
S_T = tail area
S_W = wing area
x_{ac} = longitudinal distance from c.g. to the aerodynamic-center location
$x_{\bar{c}}$ = longitudinal distance from body nose to 0.25 $\bar{c}$
x_M = longitudinal distance from aerodynamic-center location to the center of lift for C_{LT}
x_N = length of body nose
x_T = longitudinal distance from body nose to the intersection of the tail leading edge with the body surface
x_W = longitudinal distance from body nose to the intersection of the wing leading edge with the body surface
α = angle of attack, degrees
δ_f = wing flap deflection, positive with its trailing edge down, degrees
δ_T = tail deflection, positive with its trailing edge down, degrees
$\delta_{T\text{TRIM}}$ = tail deflection for trim, degrees
$\delta_{W\text{TRIM}}$ = wing deflection for trim, positive with its trailing edge down, degrees
ϵ = downwash angle, degrees
Λ_T = leading-edge sweep of tail, degrees
Λ_W = leading-edge sweep of wing, degrees

Introduction

FOR a certain class of missiles having fixed target seekers for simplicity, there is a requirement that such missiles fly with their longitudinal axes aligned with the flight path in steady and maneuvering flight. When applied to horizontal flight, this flight condition can be accomplished by locating the center of gravity of the missile at a particular longitudinal position so that the aerodynamic pitching moment associated with the wing is equal and opposite to that associated with the horizontal tail produced by the downwash field from the wing. Provided the missile is symmetrical about its longitudinal axis and has cruxiform wing and tail surfaces, then the same center-of-gravity location would be required to perform lateral acceleration without yawing. This type of missile is hereinafter referred to as a "self-balancing missile."

This paper analytically examines 10 arbitrary designs of self-balancing missiles from the standpoint of maximum acceleration that can be produced with, first, variable wing incidence, and then, wing trailing-edge flaps. In addition, the maximum available acceleration for each of these designs is

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compared with that of a geometrically similar but conventional pitching-missile design having an all-movable tail surface. The expected tradeoff for self-balancing missiles is the loss of some maximum possible acceleration in return for the simplicity of not requiring a gimballed target seeker. For the calculations, wing-body and tail-body mutual interference factors from the method of Pitts, Nielsen, and Kaattari[1] are used with lift from linear theory to determine the center-of-gravity locations for self-balance, trim surface angles, static longitudinal stability, and maximum available accelerations. Finally, the analytical results are compared with the experimental results for the Dart missile[2] (a self-balancing missile).

Theoretical Methods

In the equations for self-balancing missiles which are subsequently developed, all derivatives are considered to be constant for a given Mach number, and the force and moment curves are considered to be linear. These assumptions are particularly valid for small surface and flap deflections and for deriving the required center-of-gravity locations for a self-balancing missile. For larger surface and flap deflections required for the calculation of maximum vertical or lateral accelerations, these assumptions are less valid, but it is believed that the relative values of acceleration calculated for the various missile designs are comparable. It should be understood that the equations to be given for calculating the center-of-gravity location required for self-balance in pitch are equally valid for self-balance in yaw, provided the missile is symmetrical about its longitudinal axis and has symmetrical cruxiform wing and tail surfaces. Maximum acceleration in the lateral direction should be greater than in the vertical direction, since part of the available control deflection is not required for trim for the 1-g level-flight condition.

For a self-balancing missile with variable wing incidence (Fig. 1), the pitching moment must be zero for all values of wing incidence (δ_W); therefore, the tail incidence must be zero and the pitching moment equation is

$$\sum C_{m_{c.g.}} = 0 = (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_W) \cdot (\delta_W)(L_T+L_W)/\bar{c} - (\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)(\delta_W)(L_W/\bar{c}) \tag{1}$$

Solving Eq. (1) for the unknown longitudinal distance to the center-of-gravity location ($L_W/\bar{c}$), we obtain

$$L_W/\bar{c} = (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_W)(L_T/\bar{c}) / (\mathrm{d}C_{L_W}/\mathrm{d}\delta_W) - (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_W) \tag{2}$$

Since the angle of attack and tail incidence are zero, the wing incidence for trim at the assumed design lift coefficient for level flight (no vertical acceleration) is

$$\delta_{W_{\mathrm{TRIM}}} = (C_{L_{\mathrm{DESIGN}}}) / [(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W) - (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_W)] \tag{3}$$

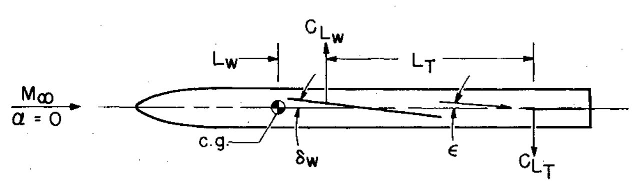

Fig. 1 Self-balancing missile with variable wing incidence.

It was found[3] for wing-body combinations having all-movable trapezoidal wings (variable wing incidence) that maximum lift generally occurred when the sum of angle of attack and wing incidence equals about 14°. In the analysis of self-balancing missiles with variable wing incidence, therefore, the maximum normal acceleration factor (in g's) is

$$(n)_{\mathrm{MAX}} = [(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W) - (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W) \cdot (q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_W)](14 - \delta_{W_{\mathrm{TRIM}}}) / C_{L_{\mathrm{DESIGN}}} \tag{4}$$

For a self-balancing missile with trailing-edge flaps (Fig. 2), it is assumed that acceleration will be produced by trailing-edge wing-flap deflection alone and that a fixed wing incidence combined with a fixed tail incidence will provide trim at the desired design lift coefficient. The pitching-moment equation which defines the required center-of-gravity location for the missile is

$$\sum C_{m_{c.g.}} = 0 = (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_f) (\delta_f)(L_W+L_T)/\bar{c} - (\mathrm{d}C_{L_f}/\mathrm{d}\delta_f)(\delta_f)(L_W+\Delta L_W)/\bar{c} \tag{5}$$

Solving Eq. (5) for the unknown longitudinal distance to the center of gravity $L_W/\bar{c}$, we obtain

$$L_W/\bar{c} = (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_f)(L_T/\bar{c}) - (\mathrm{d}C_{L_f}/\mathrm{d}\delta_f)(\Delta L_W/\bar{c}) / (\mathrm{d}C_{L_f}/\mathrm{d}\delta_f) - (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T) \cdot (S_T/S_W)(q_T/q_\infty)(\mathrm{d}\epsilon/\mathrm{d}\delta_f) \tag{6}$$

To find the trim angles of incidence for the wing and tail corresponding to a given design lift coefficient, it is necessary to write equations for the pitching moment and the lift as

$$\sum C_{m_{c.g.}} = 0 = (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)[(\mathrm{d}\epsilon/\mathrm{d}\delta_W) \cdot (\delta_{T_{TRIM}} - \delta_{T_{\mathrm{TRIM}}}](L_W+L_T)/\bar{c} - (\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)(\delta_{W_{\mathrm{TRIM}}}) \times (L_W/\bar{c}) \tag{7}$$

and

$$C_{L_{\mathrm{DESIGN}}} = (\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)(\delta_{W_{\mathrm{TRIM}}}) + (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)[\delta_{T_{\mathrm{TRIM}}} - (d\epsilon/\mathrm{d}\delta_W) \times (\delta_{W_{\mathrm{TRIM}}})] \tag{8}$$

A simultaneous solution of Eqs. (7) and (8) for $\delta_{W_{\mathrm{TRIM}}}$ and $\delta_{T_{\mathrm{TRIM}}}$ leads to

$$\delta_{W_{\mathrm{TRIM}}} = [C_{L_{\mathrm{DESIGN}}}/(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)][1 + (L_W/L_T)] \tag{9}$$

and

$$\delta_{T_{\mathrm{TRIM}}} = C_{L_{\mathrm{DESIGN}}}\{(\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty) \cdot (\mathrm{d}\epsilon/\mathrm{d}\delta_w)[1 + (L_W/L_T)] - (\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)(L_W/L_T)\} / (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)(S_T/S_W)(q_T/q_\infty)(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W) \tag{10}$$

Maximum vertical acceleration for a self-balancing missile which derives its acceleration from deflection of wing trailing-edge flaps is dependent upon the maximum flap deflection necessary to produce wing stall with consideration given to $\delta_{W_{\mathrm{TRIM}}}$. For the present analysis, a constant value of

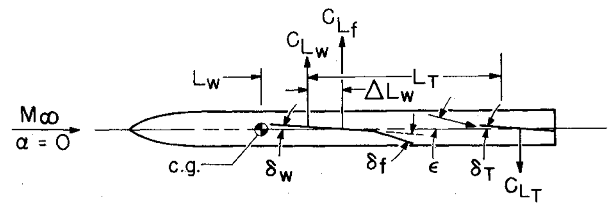

Fig. 2 Self-balancing missile with trailing-edge wing flaps.

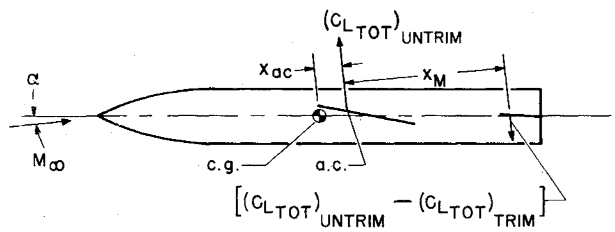

Fig. 3 Conventional missile with variable tail incidence.

$\delta_{f\text{MAX}} = 15°$ was chosen, since $\delta_{W_{\text{TRIM}}}$ varied only from 4° to 7.5° for all configurations studied. Maximum normal acceleration factor (in g's) is

$$(n)_{\text{MAX}} = [\,(\mathrm{d}C_{L_f}/\mathrm{d}\delta_f) - (\mathrm{d}C_{L_T}/\mathrm{d}\delta_T)\,(S_T/S_W)\,(q_T/q_\infty) \cdot (\mathrm{d}\epsilon/\mathrm{d}\delta_f)\,]\,(\delta_{f\text{MAX}})\,/\,C_{L\text{DESIGN}} \tag{11}$$

For the conventional missile controlled in pitch by an all-movable horizontal tail (variable tail incidence), as indicated in Fig. 3, the pitching-moment equation is

$$\sum C_{m_{\text{c.g.}}} = 0 = [\,(C_{L_{\text{TOT}}})_{\text{UNTRIM}} - (C_{L_{\text{TOT}}})_{\text{TRIM}}\,]\,(x_M/\bar{c}) - (C_{L_{\text{TOT}}})_{\text{TRIM}} \times (x_{ac}/\bar{c}) \tag{12}$$

and the trimmed lift-curve slope becomes

$$(\mathrm{d}C_{L_{\text{TOT}}}/\mathrm{d}\alpha)_{\text{TRIM}} = (\mathrm{d}C_{L_{\text{TOT}}}/\mathrm{d}\alpha)_{\text{UNTRIM}}\,[x_M/(x_{ac}+x_M)\,] \tag{13}$$

If, again, maximum lift is considered to occur at an angle of attack equal to 14° minus the wing incidence angle, then the maximum normal acceleration factor (in g's) for the conventional missile is

$$(n)_{\text{MAX}} = \frac{(\mathrm{d}C_{L_{\text{TOT}}}/\mathrm{d}\alpha)_{\text{TRIM}}\,(14-\delta_{W_{\text{TRIM}}})}{C_{L\text{DESIGN}}} \tag{14}$$

Analysis of 10 Self-Balancing Missiles

Equations (1-14) were used to analyze 10 self-balancing missiles. Details of the nomenclature and the dimensions for these missiles are presented in Fig. 4 and Table 1, respectively. In addition to the assumptions already stated, the following assumptions were made to simplify the analysis: a) $q_T/q_\infty = 1.0$; b) center of additional lift from wing flap deflection is at 0.50c; c) $\mathrm{d}\epsilon/\mathrm{d}\delta_f = (\mathrm{d}\epsilon/\mathrm{d}\delta_W)\;[\,(\mathrm{d}C_{L_f}/\mathrm{d}\delta_f)\,/\,(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)\,]$ $\mathrm{d}C_{L_f}/\mathrm{d}\delta_f =$ (0.75) $(\mathrm{d}C_{L_W}/\mathrm{d}\delta_W)$; and e) gap effects from movable surfaces are considered to be negligible. These assumptions should not invalidate the relative evaluation of these 10 self-balancing missiles, since the same assumptions were made for each missile.

Each of the self-balancing missiles was analyzed for acceleration assumed to be produced first by a) variable wing in-

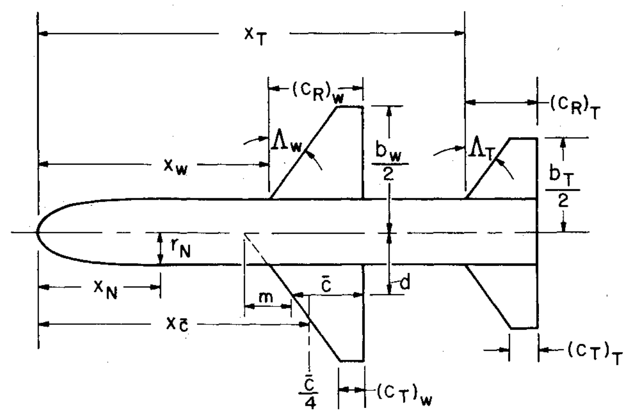

Fig. 4 Nomenclature.

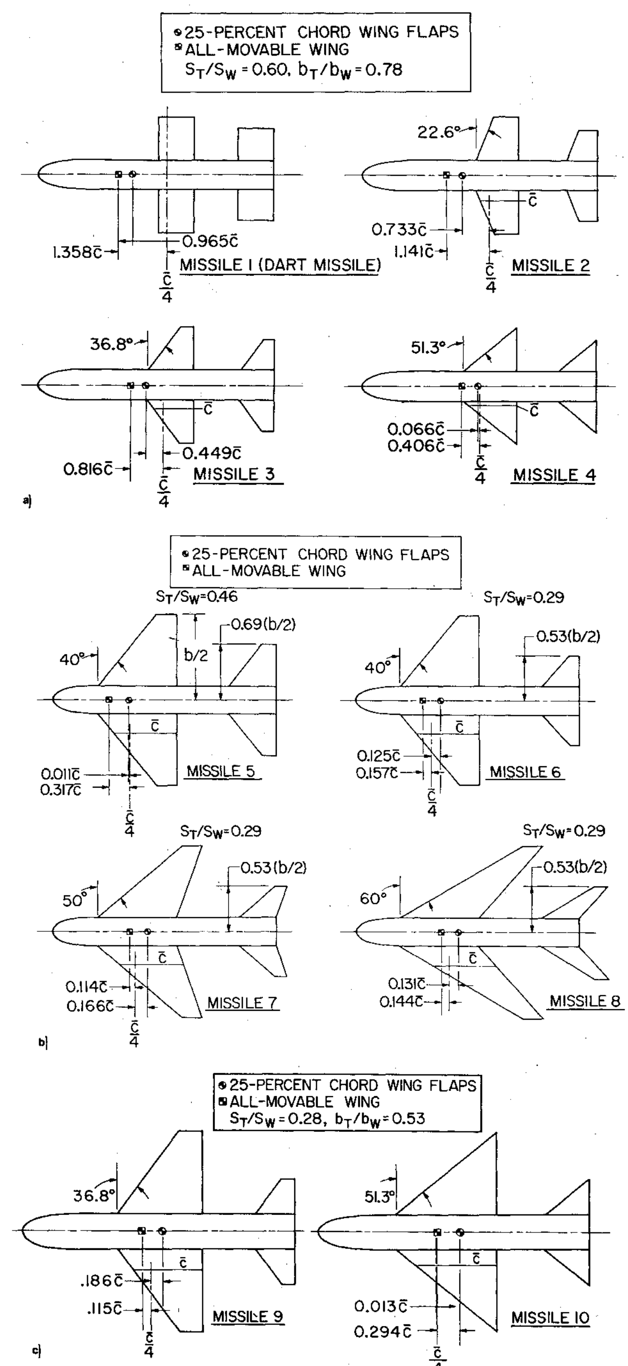

Fig. 5 Center-of-gravity locations required for self-balance, $M_\infty = 0.31$; a) missiles 1-4, b) missiles 5-8, c) missiles 9-10.

Table 1 Dimensional data (see Fig. 4 for nomenclature)

Model	$\frac{b_W}{2}$, cm	$(c_R)_W$, cm	$(c_T)_W$, cm	Λ_T, and Λ_W, deg	x_W, cm	$\frac{b_T}{2}$, cm	$(c_R)_T$, cm	$(c_T)_T$, cm	x_T, cm	r_N, cm	x_N, cm	V_N, cm^3	S_W, cm^2	$\bar{c}$, cm	$x_{\bar{c}}$, cm	d, cm	m, cm
1	43.18	26.92	26.92	0.0	89.00	33.48	20.88	20.88	154.4	10.80	43.18	10,538	2,325	26.92	95.73	21.59	0.0
2	43.18	31.42	17.96	22.60	84.51	33.48	23.67	13.92	151.6	10.80	43.18	10,538	2,325	27.93	94.97	19.19	7.99
3	43.18	35.00	10.77	36.81	80.92	33.48	25.91	8.36	149.3	10.80	43.18	10,538	2,325	30.15	93.31	17.27	12.93
4	43.18	40.39	0.0	51.27	75.54	33.48	29.26	0.0	146.0	10.80	43.18	10,538	2,325	35.89	88.99	14.40	12.95
5	67.28	63.32	15.93	40.0	35.56	44.45	37.85	11.86	140.0	10.80	35.56	7,751	5,942	50.17	61.26	26.47	22.21
6	67.28	63.32	15.93	40.0	35.56	35.56	30.28	9.50	147.6	10.80	35.56	7,751	5,942	50.17	61.26	26.47	22.21
7	67.28	63.32	15.93	50.0	35.56	35.56	30.28	9.50	147.6	10.80	35.56	7,751	5,942	50.17	66.79	26.47	31.55
8	67.28	63.32	15.93	60.0	35.56	35.56	30.28	9.50	147.6	10.80	35.56	7,751	5,942	50.17	75.20	26.47	45.85
9	63.50	55.25	15.82	36.80	60.68	33.48	27.18	8.36	149.4	10.80	43.18	10,538	5,028	44.32	82.09	24.60	18.41
10	63.50	65.74	0.0	51.27	50.19	33.48	29.26	0.0	146.0	10.80	43.18	10,538	5,028	52.80	76.33	21.17	26.40

Table 2 Summary of theoretical results

$M_\infty = 0.31$, $C_{L_{DESIGN}} = 0.2$, $(\alpha_W + \delta_W)_{MAX} = 14$ DEG, $(\delta_f)_{MAX} = 15$ DEG

MISSILE NO.	1		2		3		4		5		6		7		8		9		10	
WING VARIABLE	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f	δ_W	δ_f
$\delta_{W_{TRIM}}$, DEG.	7.11	6.36	6.98	6.16	7.06	6.22	7.30	6.28	5.37	4.64	4.94	4.30	5.29	4.57	6.05	5.21	4.78	4.02	5.19	4.28
$\delta_{T_{TRIM}}$, DEG.	0.0	0.82	0.0	0.96	0.0	1.03	0.0	1.36	0.0	1.53	0.0	2.50	0.0	2.77	0.0	3.27	0.0	2.98	0.0	3.69
dC_m/dC_L SELF-BAL. MISSILE	−1.50	−1.10	−1.34	−0.93	−1.12	−0.76	−0.82	−0.47	−0.72	−0.42	−0.42	−0.14	−0.39	−0.11	−0.36	−0.08	−0.34	−0.04	−0.26	0.02
$(n)_{MAX}$ in g's $\alpha = 0$ SELF-BAL. MISSILE	0.97	1.19	1.01	1.11	0.98	1.02	0.92	0.87	1.61	1.58	1.84	1.72	1.65	1.60	1.31	1.40	1.93	1.75	1.70	1.49
$(n)_{MAX}$ in g's α AND δ_T VAR. $dC_m/dC_L = -0.1$	2.89		2.86		2.74		2.49		3.21		3.09		2.79		2.25		3.24		2.82	
$(dC_L/d\alpha)_{UNTRIM}$	0.0765		0.0745		0.0728		0.0686		0.0716		0.0652		0.0611		0.0536		0.0677		0.0619	
$(dC_L/d\alpha)_{TRIM}$ $dC_m/dC_L = -0.1$	0.0733		0.0712		0.0689		0.0646		0.0667		0.0615		0.0575		0.0504		0.0634		0.0575	
$dC_m/d\alpha$ SELF-BAL. MISSILE	−0.1144	−0.0844	−0.1005	−0.0699	−0.0819	−0.0552	−0.0559	−0.0325	−0.0519	0.0301	−0.0276	−0.0093	−0.0238	−0.0068	−0.0191	−0.0044	−0.0231	−0.0027	−0.0161	0.0013
$dC_m/d\alpha$ α AND δ_T VAR. $dC_m/dC_L = -0.1$	−0.0076		−0.0075		−0.0073		−0.0069		−0.0072		−0.0065		−0.0061		−0.0054		−0.0068		−0.0062	

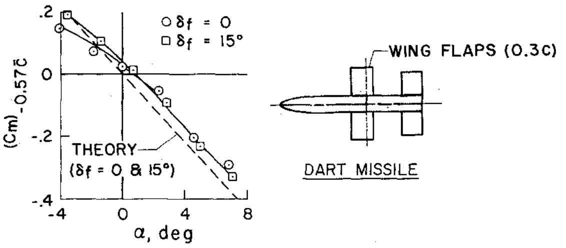

Fig. 6 Pitching-moment results for the self-balancing missile 1 (the Dart missile) equipped with full-span flaps, $M_\infty = 0.31$.

cidence and then by b) full-span trailing-edge wing flaps. The center-of-gravity locations required for each of these assumptions to satisfy the requirement of self balance at $M_\infty = 0.31$ are shown in Fig. 5. This analysis was restricted to $M_\infty = 0.31$, the Mach number of the Dart missile (missile 1), so that comparisons could be made with known experimental results. However, the effects of Mach number can be easily assessed theoretically by use of quantities affected by Mach number such as lift-curve slope and aerodynamic center location in the equations given under Theoretical Methods.

For all missiles in Fig. 5, a more forward center-of-gravity location is required for missiles with all-movable wings than with wing flaps. A comparison of missile 5 with missile 6 indicates that the center-of-gravity location is more rearward and more practical for the missile with the smaller tail. This result is not unexpected because a missile without a tail would be required to have its center-of-gravity location coincident with the aerodynamic center of the wind-body combination. Inspection of missiles 5-8 indicates that increased sweepback also moves the center-of-gravity location rearward to more practical locations.

The main theoretical results for the 10 self-balancing missiles are summarized in Table 2. For each case, the maximum normal acceleration factor $(n)_{MAX}$ is based on an assumed $C_{L_{DES}} = 0.2$. A comparison between the $(n)_{MAX}$ for the self-balancing missiles and conventional pitching-type missiles is also presented in Table 2. Note that $(n)_{MAX}$ for the conventional missiles is based on an assumed static longitudinal stability margin of $0.10\bar{c}$ or $dC_m/dC_L = -0.10$, a typical margin for this type missile. Also, these results are based on an assumed maximum flap angle of 15° and an assumed combination of angle of attack and wing incidence of 14°, the latter assumption being less appropriate for the wing with leading-edge sweepback greater than 50°.

The self-balancing missiles analyzed have one third to one half the maximum acceleration of that for a conventional pitching-type missile having an all-movable horizontal tail. Depending on the self-balancing missile design, there is a large difference in the amount of static longitudinal stability. For example, compare dC_m/dC_L for missile 1 with that for missile 10.

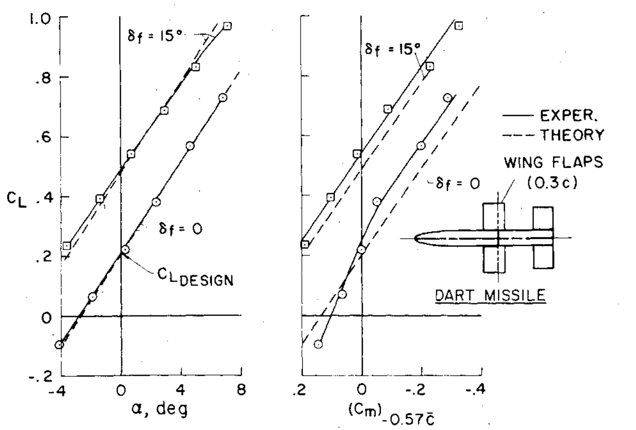

Fig. 7 Lift and pitching-moment results for the self-balancing missile 1 (the Dart missile) equipped with full-span flaps, $M_\infty = 0.31$.

Missile 1 (the Dart Missile)

Experimental and theoretical results for the self-balancing missile 1 (the Dart missile) equipped with full-span trailing-edge flaps are presented for a $M_\infty = 0.31$ in Figs. 6 and 7. For positive angles of attack, a flap deflection of either 0° or 15° gave almost identical experimental moment curves (Fig. 6). With the theoretical results adjusted to the experimentally determined moment center, located $0.57\bar{c}$ ahead of $0.25\bar{c}$, the slopes of the moment curves were correctly predicted at positive angles of attack. The actual theoretical location of the center of gravity to satisfy the condition of self-balance was about $0.40\bar{c}$ forward of the experimental location. It is believed that this difference in the experimental and theoretical center-of-gravity locations is related to the over-simplified, two-wing vortex model used in the theory. For angles of attack greater than about 2°, the slopes of the lift and pitching-moment curves were correctly predicted (Fig. 7); however, some nonlinearity exists in the experimental pitching-moment curve near an angle of attack of 0° with the flap undeflected.

Conclusions

Simplified equations based on linear theory are presented for predicting the center-of-gravity locations, trim wing and tail incidences, and normal acceleration factors for self-balancing missiles. The analytical results indicate that self-balancing missiles are feasible, but they will have less maximum acceleration available than conventional pitching-type missiles with all-movable tail surfaces. Employment of wing trailing-edge flaps rather than variable wing incidence to attain acceleration resulted in more reasonable center-of-gravity locations. Linear theory gave a good estimate of the experimental pitching-moment and lift-curve slopes for the Dart missile.

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