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CRANFIELD

THE INITIAL PREDICTION OF GUIDED MISSILE WEIGHT

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SUMMARY

In the initial design stages of a guided missile it is essential to predict the weight as accurately as is possible, and this note is intended to be a guide in this process.

The information has been presented in a form which is applicable to two definite stages in the evaluation of the missile. These, for the sake of convenience, have been called the weapon system and project design stages, and correspond to the procedures of formulating the requirements for a particular missile and the initial interpretation of them.

The note is intended to be as complete as is possible and the weight prediction methods suggested apply to equipment and systems as well as to structure. In some instances the formulae quoted are derived from published work, but much of the information is the result of original investigation. Whilst much of this investigation has been of an empirical nature, in some cases a theoretical approach has been used.

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Notation

A	Net Aspect Ratio	(Outside body)
b	Net Wing Span (ft)	(Outside body)
d	Maximum body diameter (inches)	
d_c	Ramjet combustion chamber diameter (ft)	
d_r	Homing set reflector diameter (inches)	
D	Term in formula for wing weight - see Eq.(1)	
E	Youngs Modulus (lb/sq.in.)	
F	Ratio of Ultimate Tensile Strength of wing material at 15°C to that at temperature corresponding to M	
f	Body fundamental 'free-free' bending frequency (cycles/sec.)	
g	Location of Inertia axis aft of leading edge as ratio of the chord, but not less than 0.4.	
H	$\frac{\cos \Lambda}{0.9(1+\frac{0.8}{A})}$ for $\leqslant 3$ or $\cos 3/2\, \Lambda$ for $A > 3$	
k	Taper ratio correction = $0.87 + 0.265\,\lambda$	
l	Overall body length (inches)	
L	Ratio of Shear Modulus of wing material at 15°C, to that at temperature corresponding to M	
M	Mach Number corresponding to V_D	
n	Number of body joints and major cutouts	
N	Maximum factored normal acceleration in wing plane	
P	Missile Range (ft)	
Q	Factor in wing weight formula - see paragraph 2.1	
r	Wing relief factor = $1 - R/W_N$ (approx. equals 0.9 when wing is not used to house fuel or equipment)	
R	First Moment of Wing Relief loads divided by $0.2b$ (lbs)	
S	Net Wing Area (sq.ft.)	(Outside body)
t	Flight time (seconds)	
(t/c)	Wing thickness chord ratio	
T	Engine thrust (lbs)	

V_D	Maximum Equivalent Airspeed (ft.per sec.)
W	Coasting Weight of Missile (lbs)
W_B	Total body weight (lbs.)
W_c	Solid Rocket Charge weight (lbs)
W_M	Weight of Propellant (lbs.)
W_N	Proportion of Missile Weight carried by wings under '1g' flight conditions
W_W	Wing Weight (lbs)
Y	Length of Blast Pipe (ft.)
γ	Sweepback of wing structure
Λ	Leading edge sweepback
ϕ	Sweepback of 0.25 chord line
λ	Tip chord/Root chord
ρ	Density of body structural material (lb/cu.in.)

1.0. Introduction

Guided missiles are a relatively recent innovation and as a result of this there is very little information upon which to base the weight prediction of a new project. One exception is the case of missiles which bear a marked resemblance to conventional aircraft, for instance the long range aerodynamic cruise type, and which can be dealt with by existing methods. In the more general case however, such methods have not been readily available, and the present note is an attempt to remedy this situation.

In many instances it is possible to use very approximate values which are typical of current trends, and this is particularly true during the process of formulating the requirements for a particular missile. Rather more accurate methods, which give some indication of the effect of changes in shape and configuration are desirable when the requirements are being interpreted and a missile projected. The final stage of course is the detailed weight estimation from the finally designed component.

2.0. Structures.

Fortunately the structure weight of a missile is usually a smaller percentage of the total weight than is the case with a manned aircraft, and consequently errors in weight prediction are not likely to be as critical. It is, nevertheless, essential to reduce the structure weight to an absolute minimum and any aid in this direction is worthy of consideration.

2.1. Wings

For initial systems work it is sufficient to use 4 lb/sq.ft for fixed wing and 5.5 lb/sq.ft for moving wing structures. Very often the wings are small in comparison with the body and no great error results from using the above figures for initial project investigations also. However, when the wings are of appreciable size, or if it is required to investigate the effect of such parameters as aspect ratio or thickness, the following formulae can be used.

$$\frac{W_W}{S} = k\left\{\frac{0.16b(^t/_c)}{A} + \frac{QW_N \times 10^{-2}}{S} + D + 0.6\right\} \text{ lb/sq.ft.} \qquad (1)$$

$$\text{where } D = \frac{Fb}{S}\ (W_N Nr) \times 10^{-6}\left\{\frac{3A\sec^2\phi}{(^t/_c)} + 70\sec\phi + 15\right\}$$

if the wing is designed by strength condiserations

$$\text{or } D = \frac{3Lb^3}{S}\cos\gamma \times 10^{-10}\left\{\frac{V_D gH}{(^t/_c)\,(1-0.166M\cos\Lambda)}\right\}^2$$

if the wing is designed by stiffness.

The larger value of D obtained should be used.

Q is a factor depending upon the type of construction and has the following values :-

Q = 1.75 for rivetted fixed wings
Q = 1.50 for bonded fixed wings
Q = 3.0 for rivetted moving wings
Q = 2.60 for bonded moving wings

The other symbols are explained in the notation.

This formula is based upon one which has long been used in conventional aircraft practice, but considerable modification has been made to incorporate revised stiffness criteria and guided missile techniques.

2.2. Bodies

The body shell weight is usually about 2 lb/sq.ft of surface area for medium size missiles, with an additional penalty of 0.5 to 1.0 lb/sq.ft for mountings, attachments, jury structure, cut outs and the like. This weight does not include the substantial rings used for control surface attachments, for which see paragraph 2.4. Larger ballistic missiles tend to have a body shell weight per unit area which is less than that quoted above, especially when pressurised integral fuel tanks are used to stabilise the skins. In this case

1.0 lb/sq.ft is likely to be more accurate.

Radomes weigh on average about 3.9 lb/sq.ft of surface area.

One of the important body design criteria is the stiffness required to avoid undue control system structural feed back. The following formula, which is based on the 'free-free' vibration frequency of a beam is aimed at estimating the weight required to ensure a given body fundamental frequency :-

$$W_B = 1.4 \left(\frac{f}{66}\right)^2 \frac{W \rho l^4}{E(1 - 0.1n) d^{3/2}} \text{ lbs.} \qquad (2)$$

f is the body bending frequency and should be about 1.5 times the designed control response frequency. The term (1 - 0.1n) has been introduced to allow for the loss in stiffness due to body joints, large cutouts, etc., and is usually equal to about 0.6.

The formula includes a factor to allow for miscellaneous fittings, fin rings, etc., and gives the total body structure weight.

2.3. Controls

An average weight for control fins of medium size is 8 lb/sq.ft., although the value may vary considerably due to different aspect ratio, thickness, load and type of construction. The total weight is not likely to be very great however.

An estimate of control load should be available quite early in the design programme and a more accurate estimation of fin weight can then be made. The way that this is done is dependent upon the form of construction. For a solid control surface, engineers beam theory can be used to check the required root thickness and an estimate of volume can then be made. For a built up structure a modified form of Equation (1) can be used, replacing the term ($W_N Nr$) by the maximum control load. Both forms of construction should also be checked for stiffness.

Where movable jet vanes are used for control the little information available indicates that they weigh about 0.75% of the maximum thrust in lbs.

2.4. Control Attachment Rings and Actuators

Attempts have been made to derive formulae for combined control ring and actuator weight but they are rather complex. The accuracy is probably very little greater than assuming the weight to be equal to that of the moving surfaces based on 8 lb/sq.ft of surface area.

2.5. Boost Fins

Again a value of 4 lb/sq.ft is an average weight, but if the loading cases are sufficiently well defined and a more accurate prediction is desired, then a modified form of Equation (1) similar to that suggested in paragraph 2.3 could be used.

2.6. Boost Attachment and Release Mechanism

Typical values of the penalty incurred for the boost attachment and release are 5% of the boost weight for tandem boosts and 8% of the boost weight for wrap round boosts. The boost attachment weight excludes any boost fins which may be used.

3.0. Power Plants.

The power plant weight of a missile, expressed as a percentage of the total weight, can vary enormously, since it is often a function of the time of operation as well as the thrust developed. This is particularly true of short range missiles using rocket engines, and it is therefore desirable to express the power plant weight in terms of thrust and time, or parameters dependent upon them.

3.1. Solid Rocket Motors

The charge weight, W_c, determines the total impulse and hence is a function of both thrust and time. Case weight can be estimated approximately by :-

$$\text{Case Weight} = 0.22\, W_c + 4Y \text{ lbs.} \tag{3}$$

where Y is the blast tube length in feet.

3.2. Liquid Rocket Motors

An approximate expression for the weight of the motor, together with fuel pumps, pipes and tanks is

$$0.028T + 0.125W_M \tag{4}$$

T being the maximum thrust and W_M the propellant weight.

3.3. Ramjets

The weight of a high performance expendable ramjet is given by the following formula which has been suggested by the R.A.E. :-

$$\text{Weight} = 60d_c + 48d_c^2 \qquad (5)$$

d_c is the combustion chamber diameter in feet.

Pumps and valves add 30% to this weight. When a stub wing is used for mounting the ramjet, a further weight penalty of approximately 15% of the basic weight is incurred.

3.4. Turbojets

An expendable turbojet engine designed for operation over a range of altitudes, will have a weight which is approximately 13% of the sea level static thrust. The installed weight will probably be nearer 15% of the sea level static thrust.

4.0. Services

As is the case with manned aircraft, the accurate prediction of the weights of the various services is a difficult task, but certain recommendations can be made.

4.1. Power Supplies
Actuation, Fuel Expulsion, etc.

These services normally account for 3% to 4% of the unboosted missile weight, except on small weapons. In this latter case, the weight of the actuation is likely to be nearer 5% of the unboosted missile weight or up to 7% if some form of homing is used.

4.2. Power Supplies
Electronics.

The longer the missile flight duration, the more complex the guidance and control systems tend to be, and more power is required. It is therefore convenient to express the weight of the electrical power supplies as a function of duration. The approximate weight is given by :-

$$\text{Weight of Electric Power System} = 4t^{1/2} \text{ lbs.} \qquad (6)$$

where t is the flight time in seconds.

4.3. Fuel System

This has largely been covered in the power plant section, paragraph 3, but it may be necessary to estimate tank weights in certain instances.

Lightweight Flexible Tanks weigh approximately $10 + 0.015W_M$ lbs, W_M being the fuel weight.

5.0. Guidance and Control

This item has been deliberately isolated from the other systems as it is almost impossible to make any definite predictions of guidance weight. In a few cases, however, it is possible to indicate certain very approximate trends. The figures include control instruments and electronics.

5.1. Command Guidance

Wire link :- $(8 + 3.3P \times 10^{-4})$ lb

where P is the range of missile in feet.

Radio Link :- About 25 - 30 lb

5.2. Beam Riding

Weight $= 0.3P^{1/2}$ lb, approximately.

5.3. Homing

Active :- $16d_r$ lb approximately.

Semi-active :- $10d_r$ lb approximately

Passive :- $8d_r$ lb approximately

where d_r is the reflector diameter in inches.

6.0. Miscellaneous Items

There is usually a weight equal to approximately 2% of the unboosted weight which is accounted for by such items as miscellaneous pipes, cables, insulation, paint, etc. It should be emphasised that this does not include all pipe and cable weight which is allowed for in the appropriate system.

Appendix

Approximate densities of some guided missile components.

Warheads :- Blast 100 lb/cu.ft
Fragmenting 150-250 lb/cu.ft

Power Supplies and Actuation :- 20 lb/cu.ft
Control and Guidance Electronics :- 30-35 lb/cu.ft
Power Plant :- Solid Rocket, 80 lb/cu.ft
Liquid Rocket and Turbojet Engine
30 lb/cu.ft
Liquid Rocket Fuel, 70 lb/cu.ft
or 55 lb/cu.ft including tanks, pipes, fittings etc.