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Engineering Notes

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Methodology for Determination of Baseline Specifications of a Nonrigid Airship

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Nomenclature

b = span, m
c = chord, m
C_{DV} = coefficient of volumetric drag
D = drag, N
H = altitude, m
h = height, m
k_a = engine power-lapse factor
k_{drag} = drag factor
k_{se} = envelope surface-area factor
k_{ve} = envelope volume factor
L = Lift, kg
l = length, m
l/d = length-to-diameter ratio
N = number
P = power, hp
P = total pressure, N/m^2
$p_{offtake}$ = ratio of power offtake for accessories
R = range, km
Re = Reynolds number
r = radius, m
S = surface area, m^2
T = temperature
t/c = tip-to-chord ratio
V = volume, m^3
V = velocity, kmph
v = volume ratio
W = weight, kg
Δ_p = internal overpressure, N/m^2
η = efficiency
ρ = density, kg/m^3
σ = density ratio
τ = taper ratio

Subscripts

a = air
air = airlines, inside envelope
b = ballonet
bpc = ballonet pressure control
btr = ballonet trimming
cat = catenaries
con = control system
cr = cruise
crew = crew
ctr = control
duct = propulsive duct
e, env = envelope
e, i = electronics and instruments
empty = empty
eng = engine
f, fin = fin
fte = fin trailing edge
fuel = fuel
gon = gondola
h = helium
inst = installed
lg = landing gear
max = maximum
min = minimum
misc = miscellaneous items
n = nose
pat = patches
pay = payload
prop = propeller
r = root
rig = rigging
sus = suspension
t = tip
tr = transmission system
vec = thrust vectoring system
0 = standard conditions

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I. Introduction

SEVERAL methodologies and procedures for obtaining baseline specifications of fixed-wing aircraft are available, such as that by Loftin [1] for transport aircraft. However, no such methodology is available in open literature for conceptual design studies of airships. To determine the payload capacity of an airship at a particular altitude, one has to either refer to the airship's performance manual or apply some simplistic rules of thumb. This work was driven by a need to fulfill this gap in literature: that is, to develop a methodology for arriving at the baseline specifications of an airship that meets certain operational and performance requirements specified by the user.

II. Description of the Input Parameters

The issues related to performance, aerostatics, weight estimation, and propulsion systems of airships are succinctly explained by Hunt [2], Craig [3], and Cheeseman [4], respectively. Through a study of this literature, the key parameters that constitute the list of inputs to the methodology can broadly be classified under three categories, as listed in Table 1.

Table 1 List of input parameters

Operation related parameters	Performance requirements	Configuration related parameters
Pressure altitude	Range	Fin layout
Atmospheric properties	Cruising altitude	No. of engines
Minimum operating altitude	Cruising speed	Envelope length-to-diameter ratio
Helium purity level	——	Ballonet volume for trim
Power offtake for engine driven accessories	——	Internal overpressure

Table 2 List of design features and options

Design feature	Option 1	Option 2
Engine type	Diesel	Gas
Engine charging	Normally aspirated	Supercharged
Propeller type	Ducted	Unducted
Ballonet type	Separate	Integral
Thrust vectoring	Present	Absent
Fin layout	Cross	Plus
Transmission system	Simple	Complex

The pressure altitude and atmospheric properties have a direct bearing on the volume of the airship envelope and the payload capacity. The difference between the pressure altitude and the minimum operating altitude determines the volume of the ballonets. The lists of design features and options that can be studied in this methodology are listed in Table 2.

The methodology can be applied in either of the two modes: the design mode or the evaluation mode. In the design mode, which is relevant when a new airship is being designed, the envelope volume required to carry a user-specified payload is estimated. In the evaluation mode, which is relevant when the capability of an existing airship is being evaluated, the payload that the airship can carry for a specified envelope volume is estimated.

III. Outline of the Methodology

The flow chart of the methodology in the design mode is shown in Fig. 1. In the design mode, the calculations are initiated with an assumed value of envelope volume. The net lift available at the operating altitude is calculated. The next step is the estimation of geometric parameters of the airship, which include the dimensions of the envelope, ballonets, and fins. This is followed by the estimation of drag coefficient and hence the installed power required and fuel weight. The last step is the estimation of weight breakdown of various components and hence the empty weight, through which the payload capacity is estimated. If this payload does not match the desired value, then envelope volume is adjusted and the calculation is repeated until convergence. In the analysis mode, only the inner loop is executed, because it directly estimates the payload available for a specified envelope volume.

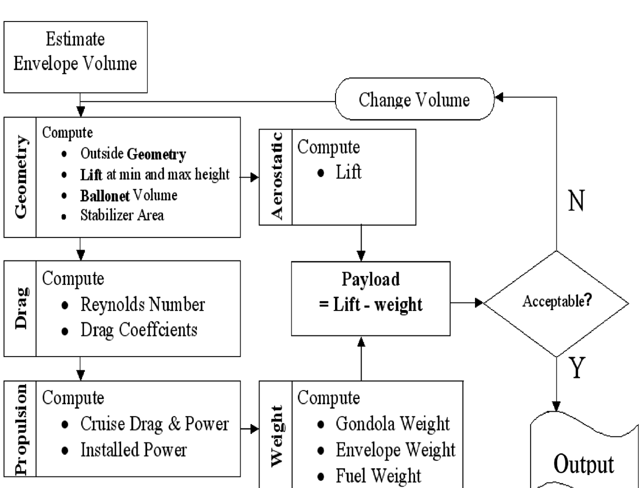

Fig. 1 Flowchart of the methodology.

IV. Details of the Methodology

A description of the various submodules of the methodology is given in the sections that follow.

A. Aerostatics Submodule

The net lift of an airship is directly affected by the variation in the air pressure and temperature in the atmosphere and inside its envelope. The net lift reduces with increase in altitude and is the minimum at pressure altitude. Using the methodology outlined by Craig [3] (pages 212–231), the net lift available at pressure altitude $H_{\max}$ can be calculated as

$$L - V_e(1 - V_{\mathrm{btr}}) \cdot \sigma_{aH\max}(\rho_{a0} - \rho_{h0}(1 + (\Delta_p/P_{H\max}))) \tag{1}$$

B. Geometry Submodule

In this submodule, the length, maximum diameter, and surface area of the envelope and ballonets are estimated. For airship envelopes of conventional shapes, it can be shown that the envelope volume and surface area satisfy the relations

$$\frac{V_e}{l_e^3} = \frac{k_{\mathrm{ve}}}{(l/d)_e^2} \quad \text{and} \quad \frac{S_e}{l_e^2} = \frac{k_{\mathrm{se}}}{(l/d)_e} \tag{2}$$

Young [5] has shown that for envelopes based on the R-101 airship shape, the factors k_{se} and k_{ve} are 2.33 and 0.465, respectively. A study of existing airships with envelopes of double ellipsoid or similar shape was carried out, based on which these factors were estimated to be 2.547 and 0.5212, respectively.

Eq. (2) can be recast to determine envelope length and surface area for the known volume and $(l/d)_e$ ratio as

$$l_e = \sqrt[3]{V_e \cdot (l/d)_e^2/k_{\mathrm{ve}}} \quad \text{and} \quad S_e = k_{\mathrm{se}} l_e^2/(l/d)_e \tag{3}$$

The total ballonet volume is

$$v_b = (v_{\mathrm{bpc}} + v_{\mathrm{btr}}) \times v_e \tag{4}$$

The volume of ballonet required for control purposes can be calculated using

$$v_{\mathrm{bpc}} = 1 - \frac{L_{H\max}}{\sigma_{H\min}(\rho_{a0} - \rho_{h0}[1 + (\Delta_p/P_{H\min})]) \cdot V_e} \tag{5}$$

To fix the appropriate value of v_{btr}, the ratio of total ballonet volume to envelope volume was found for 12 airships and then compared with the ratio necessary for pressure control for operation under International Standard Atmosphere (ISA) and 15 deg higher, as shown in Fig. 2. The effect of increase in v_{btr} on the lift and payload is plotted in Fig. 3, which indicates that this ratio should be kept as small as is practically possible.

Assuming a twin spherical ballonet layout, the radius and surface area of each ballonet can be estimated as

$$r_b = \sqrt[3]{(3V_b/8\pi)} \quad \text{and} \quad S_b = 2\pi r_b^2 \tag{6}$$

The size and location of fins are a function of the desired control characteristics of the airship. Geometrical data related to the fins of

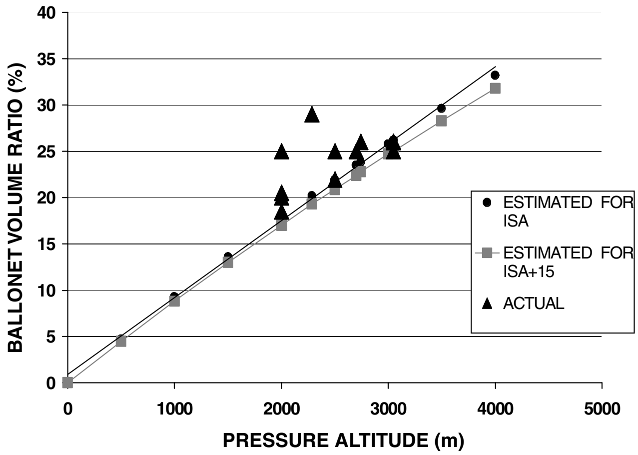

Fig. 2 V_{bpr} **vs** $H_{\max}$ **for 12 airships.**

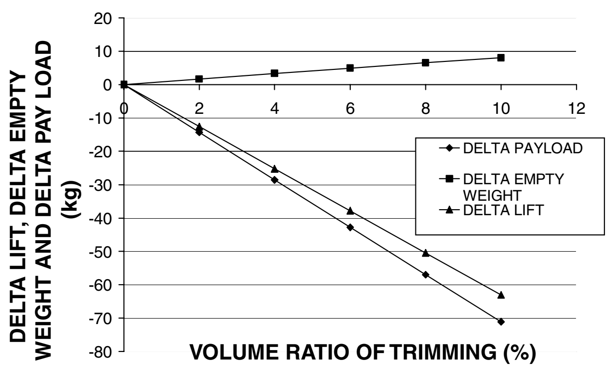

Fig. 3 **Effect of** V_{btr} **on** W_{pay}**,** W_{empty} **and Lift.**

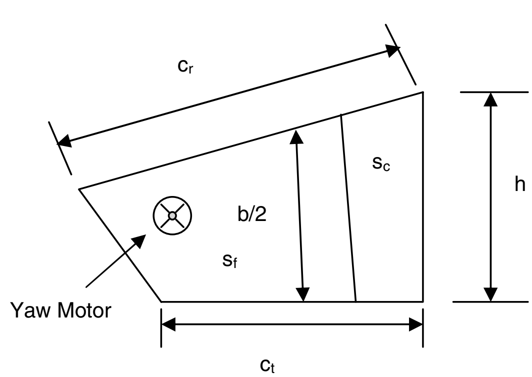

Fig. 4 **Schematic view of a stabilizer.**

Table 3 **Parameters derived from statistical data**

Parameter	Formula	Value
Tail area ratio	$N_f(S_f + S_{\mathrm{ctr}})/S_e$	0.061
Fin location ratio	l_{fte}/l_e	0.907
Fin taper ratio	c_{tf}/c_{rf}	0.596
Fin aspect ratio	$b^2/(S_f + S_{\mathrm{ctr}})$	0.602
Control area ratio	$S_{\mathrm{ctr}}/(S_f + S_{\mathrm{ctr}})$	0.258
Control taper ratio	$c_{t\mathrm{ctr}}/c_{r\mathrm{ctr}}$	0.868

15 airships were collected and analyzed to standardize the fin geometry, as shown in Fig. 4.

Several nondimensional ratios were calculated, and the averages of these ratios were used in the methodology, as listed in Table 3. The fin dimensions and their relative location on the envelope were decided using these ratios. The data indicated that no relationship existed between tail-volume coefficients and L/D ratio; hence, it is assumed that the tail-volume coefficient is independent of L/D, and the average value is taken for all cases.

C. Drag Submodule

For most airships, the flow over the hull is turbulent and the volumetric drag coefficient C_{DVe} for these conditions is calculated using the following formula by Hoerner [6] and reported by Cheeseman [4] [Eq. 3.7]:

$$C_{\mathrm{DVe}} = \left(\left[0.172 \sqrt[3]{\left(\frac{l}{d}\right)_e} + \left(\frac{0.252}{(l/d)_e^{1.2}} \right) + \left(\frac{1.032}{(l/d)_e^{2.7}} \right) \right] \right) \Big/ Re^{1/6} \tag{7}$$

Assuming that the hull drag comprises a fixed percentage of the total drag, the drag coefficient for the airship is estimated as

$$C_{\mathrm{DV}} = C_{\mathrm{DVe}}/k_D \tag{8}$$

Table 5 **Comparison of weight breakdown for Sentinel-1000 with values quoted by Netherclift [9]**

Component	Estimated	Quoted	% difference
W_e	2098.4	2061	2
W_{fin}	762.7	960	−21
$W_{\mathrm{gon}} + W_{\mathrm{lg}}$	748.2 + 82.4	910	−9
$W_{\mathrm{eng}} + W_{\mathrm{fuel}} + W_{\mathrm{tr}} + W_{\mathrm{vec}}$	635.8	622.7	2
$W_{\mathrm{prop}} + W_{\mathrm{duct}}$	220.8	356	−9
W_{con}	236.4	249.6	−5
$W_{e\&i}$	418.9	438	−4
W_{misc}	124.6	128.7	−3
W_{empty}	5328.2	5726	−7

Table 4 **Component weight breakdown formulas**

Sub-System	Component	Factor	Reference parameter
	W_b	0.2	S_b
	W_{air}	0.025	W_e
	W_{cat}	0.115	W_e
	W_{pat}	0.035	W_e
	W_{sus}	0.012	V_e
Envelope	W_n	0.021	V_e
	W_{fin}	2.05	S_{fin}
Tail	W_{rig}	0.0475	W_{fin}
	W_{lg}	0.008	V_e
	W_{con}	0.46	$(V_e)^{2/3}$
	$W_{e,i}$	0.037	V_e
	W_{gon}	10.75	V_{gon}
	W_{crew}	77	N_p
Equipped gondola and subsystems	W_{misc}	0.011	V_e

Table 6 Weight breakdown of Ulita's UM-10 and US-LTA 185M airship

Airship	Ulita's UM 10			US LTA 185 M		
Component	Estimated	Quoted	% difference	Estimated	Quoted	% difference
W_e	136.3	135.6	0.5	1194	1369	−13
W_{fin}	34.5	29.8	16	473	420	13
W_{gon}	121.8	120.0	1.5	1125	1039	4
W_{empty}	292.6	291.0	0.6	2792	2870	−3

Based on the drag breakdown of three airships reported by Cheeseman [4], an average value of k_D was taken as 0.5243. The total drag at cruise is calculated as

$$D = \tfrac{1}{2}\rho_a V_{\mathrm{cr}}^2 C_{\mathrm{DV}} V_e^{2/3} \tag{9}$$

D. Propulsion Submodule

Power required to overcome drag during cruise is calculated by

$$P_{\mathrm{cr}} = (D V_{\mathrm{cr}})/\eta_{\mathrm{prop}} \tag{10}$$

The total installed power at sea-level static conditions is then estimated as

$$P_{\mathrm{inst}} = P_{\mathrm{cr}}(1 + p_{\mathrm{offtake}})/k_{\mathrm{alt}} \tag{11}$$

The fuel weight can then be estimated using

$$W_{\mathrm{fuel}} = (R/V_{\mathrm{cr}}) \cdot \mathrm{sfc} \cdot P_{\mathrm{cr}}(1 + p_{\mathrm{offtake}}) \tag{12}$$

E. Weight-Estimation Submodule

This submodule estimates the weight of each major system and subsystem of an airship (viz., envelope, tail, equipped gondola and other subsystems), thus leading to the estimation of the empty weight. The volume of the gondola is required to estimate its weight. It is reasoned that gondola volume will be proportional to the payload, which itself will be proportional to the envelope volume. The gondola volume ratio [i.e., the ratio of the apparent volume of the gondola (length times breadth times height) to the envelope volume] was obtained for 21 airships, and the average value was found to be 0.007. Because most airship gondolas are rounded at the front and back for improved aerodynamic characteristics, the gondola volume is assumed to be less than the apparent volume by a factor of 1.4. Hence, the ratio of gondola volume to envelope volume is taken to be 0.005.

F. Component Weight Breakdown

Craig [3] (pages 235–271) has provided a list of factors that, when multiplied with a specific reference parameter of the airship (such as envelope surface area or volume), estimate the weight of various components. The formulas for weight breakdown that are used in the methodology are listed in Table 4.

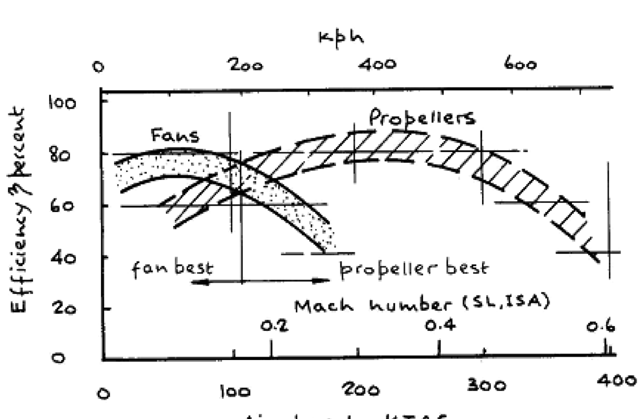

Fig. 5 Variation of propulsive efficiency with forward speed [8].

Table 7 Comparison of estimated and quoted empty weight for four airships

Airship	Estimated	Quoted	% difference
PD 300	1664	1500	11
MD 900	5193	4680	11
Skyship 600	3601	3331	8
A 150/S 42	2524	2863	−12

G. Modeling the Effect of Design Features and Options

The selection of a particular design feature or option has a direct effect on some of the formulas and parameter values. The choice of engine type (diesel or gas) affects the engine-specific fuel consumption and weight per unit power. These parameters were taken as 0.46 lb/(hp · h) and 0.85 kg/hp for gas engines and 0.37 lb/(hp · h) and 1.025 kg/hp for diesel engines, respectively, which are the average of the values suggested by Cheeseman [4].

The choice of normally aspirated vs supercharged engine affects the value of the power-lapse factor with altitude (k_{alt}), which, for normally aspirated piston-prop engines, was estimated using the following formula suggested by Raymer [7] (for supercharged engines, k_{alt} is assumed to be unity):

$$k_{\mathrm{alt}} = \sigma_{\mathrm{cr}H} - \left(\frac{(1 - \sigma_{\mathrm{cr}H})}{7.55}\right) \tag{13}$$

The use of a ducted propeller leads to improved η_p, lower noise levels, and higher operational safety near the ground, at the cost of increase in weight and complexity. Stinton [8] has plotted the variation of η_p of propellers and ducted fans with airspeed. For the estimation of propulsive efficiency, the graph shown in Fig. 5 is used.

During flight, the front part of the airship flattens due to the dynamic pressure of ambient wind. To avoid the front portion of the airship from sinking in, a hard-capped nose along with long strengthening members (i.e., nose battens) are provided. The choice of fin layout affects the number of fins, the total surface area, and hence the weight of the fin structure. All airships generally have a four-fin arrangement, for simplicity in the design of control system.

Provision of thrust vectoring leads to an additional weight penalty, which is estimated as 14% of the weight of the vectored mass. This value is the mean of the range suggested by Craig [3].

V. Validation of Mass Estimation

A comparison of estimated and actual weights for Sentinel 1000, for which a detailed weight breakdown was listed by Netherclift [9], is shown in Table 5. Some details of component weights were also made available for Ulita's UM-10 airship by Berger [10] and in the performance manual of a US-LTA 185M airship.[†] A comparison of the estimated values with the quoted values is listed in Table 6. Here again, the estimated weights compare well with the quoted values, except for the fin weight.

The values of empty weight of four other airships were obtained from various sources: for PD 300, from its performance manual[‡]; for

[†]Private communication with Ray Olma, 14 July 2001.

[‡]Private communication with Gennady Oparin, 4 August 2001.

Table 8 Input parameters and baseline specifications of the Demo and PaxCargo airships

Parameter	Demo airship	PaxCargo airship
	Key input parameters	
Payload weight	To be calculated	1500 kg
Envelope volume	1000 m^3	To be calculated
Temperature deviation from ISA	$+15°C$	$+15°C$
Minimum altitude	2000 m	2000 m
Cruising altitude	3500 m	3500 m
Pressure altitude	4000 m	4000 m
Cruising speed	78 kmph	92 kmph
Range	100 km	500 km
Envelope l/d ratio	3.0	4.0
Engine type	Gas	Diesel
Engine charging	Normally aspirated	Supercharged
	Key output parameters	
Payload weight	73.2 kg	Known
Envelope volume	Known	11,177 m^3
Ballonet volume	226 m^3	2531 m^3
Maximum speed	86 kmph	102 kmph
Installed power	80 hp	300 hp
Fuel weight	9.96 kg	218.4 kg
Empty weight	535 kg	5036.7 kg
Lift at pressure altitude	618.1 kg	6908 kg

MD 900 and A150/S 42, from [11]; and for Skyship 600, from [12]. The comparison between these quoted and calculated values of empty weight is shown in Table 7. It is seen that the methodology predicts the empty weight within $\pm 12\%$.

VI. Results

The methodology was applied to obtain the baseline specifications of two airships (viz., Demo and PaxCargo) for operation over hot and high conditions. For the PaxCargo airship, the methodology was applied in the *design* mode to obtain the envelope volume required for a specified payload capacity of 1500 kg. For the Demo airship, the payload capacity was determined by applying the methodology in the *analysis* mode for a specified envelope volume of 1000 m^3. The key input parameters and the baseline specifications obtained through the methodology are listed in Table 8. The general layouts of the Demo and PaxCargo airships are shown in Figs. 6 and 7.

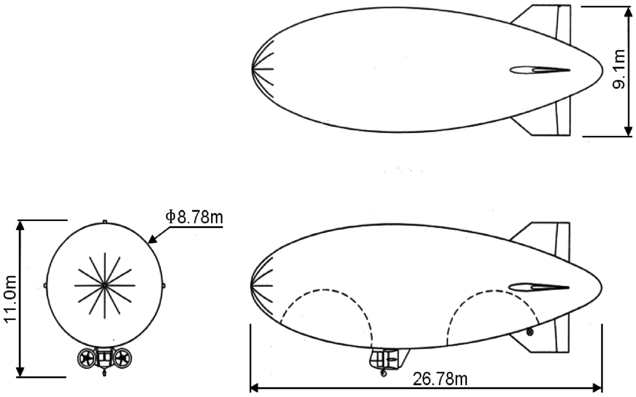

Fig. 6 General layout of the Demo airship.

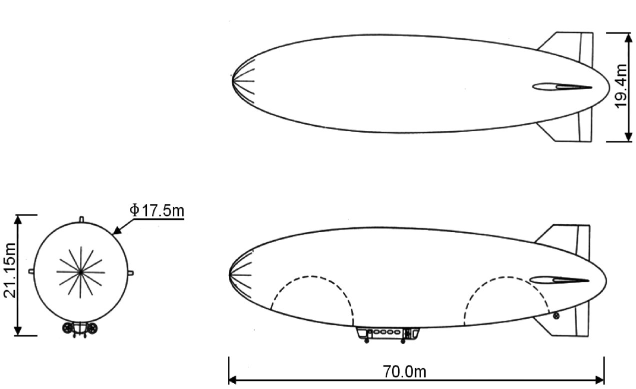

Fig. 7 General layout of the PaxCargo airship.

VII. Conclusions

The methodology presented in this paper is a useful tool during the conceptual design studies of a nonrigid airship. It can be used to arrive at the baseline specifications of an airship to be designed to meet specific operational requirements. It can also be used to evaluate the capability of an existing airship to meet these requirements.

Though several empirical formulas and statistical data of existing airships have been used in the methodology, the component weights and empty weight are within 15% of quoted values, which is quite reasonable in the conceptual design phase. The formulation of the methodology is open-ended, and so it can be continuously upgraded and fine-tuned as more accurate information becomes available. It can also be adopted for carrying out multidisciplinary design optimization of an airship system: for instance, to determine the optimum combination of design parameters and options that corresponds to highest payload available.

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