VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

ESTABLISHING THE ANALYTICAL RELATIONSHIPS FOR MASS AND VOLUMETRIC MASS FRACTIONS FOR HYBRID BUOYANT AIRCRAFT

Anwar Ul Haque[1], Waqar Asrar[1], Ashraf Ali Omar[2], Erwin Sulaeman[1] and J. S. Mohamed Ali[1]
[1]Department of Mechanical Engineering, International Islamic University Malaysia (IIUM), Kuala Lumpur, Malaysia
[2]Department of Aeronautical Engineering, University of Tripoli, Libya
E-Mail: waqar@iium.edu.my

ABSTRACT

The current data bank of operational empty mass fraction of airships is based on available data obtained from existing and historical airships. For any design related activity, regression analysis on existing data bank of airships will not be able to provide the true picture of mass fractions of hybrid airships. This situation becomes more critical when a wing is attached to the hull of airship and there is no proven algebraic formulation that is able to distinguish between electric and fuel powered propulsion. In the present work, by using theoretical approach; new analytical relationships for mass and volume fraction are derived to estimate the mass and volume fractions of fuel-powered-hybrid buoyant aircraft. Existing formulas for the determination of volumetric weight fractions of fuel powered airship are also discussed. Established relationship of mass and volume fractions will be useful to estimate the masses and dimensions of individual sub-assemblies of hybrid buoyant aircraft.

Keywords: aircraft, empty weight, volume fraction, fuel powered airship, added mass.

INTRODUCTION

The concept of hybrid buoyant (HB) aircraft and its meanings are related with the aerostatic and aerodynamic lift generated by the hull body and/or aerodynamic lift produced by single or multiple wings attached to the hull. Aircraft [1] and airship [2] certification standards and related design books [3-7] refer to 'Weight' in units of kg/lbs but in fact weight is a force (N or lbf). Methods given by Raymer [3], Torenbeek [4] and Roskam [5] are commonly used to define the weights of major components/assembles of aircrafts, either by using analytical relationships or by using their historical trends. For airships, analytical formulas and historical trends do exist [6] but not for HB aircraft in which wings are attached to a voluminous hull. Therefore, there is a need to first define the mass relationships of major assemblies required to define a configuration of a HB aircraft. This gap can only be filled by first defining the gross takeoff mass and operational empty mass followed by defining the volumetric fractions to get first-hand knowledge of volume of hull in terms of useful engineering terms.

ANALYTICAL RELATIONSHIPS

For aircraft [7], gross take-off mass m_{GTM} is expressed as Equation (1). In this relationship, the empty mass m_{empty} is usually estimated through an iterative process after getting some initial value from historical trends or by using empirical relationships of similar type of aircraft. For HB aircraft, no such relationship exits as most of such configurations are unique in its own design. For aircraft, there is no added mass affects. But the same is not true for the case of airship. This is due to the fact that when an airship moves in a fluid [8], the air itself loses some of its kinetic energy and the airship has some mass added to it, which is known as added mass m_{add}. It is important to note that the added mass effect is also there in case of aircraft but is usually neglected as the density of air is small [7]. Analytical relationships for estimation of added mass of different bodies of revolution are mentioned in reference [7]. It is an important factor for calculations related to the estimation of performance parameters of HB aircraft and airships as well. Nonetheless, such affects usually have negligible contribution towards m_{GTM}.

$$m_{GTM} = m_{crew} + m_{fuel} + m_{passengers} + m_{empty} \quad (1)$$

To the best knowledge of authors, except reference [9] which is related to unconventional airships, previous work done on hybrid winged airships [10, 11] have not given any breakdown of the mass/weight and it is not clear that added mass effects were catered to or not as more focus was seen towards the [10, 11] estimation of performance parameters for accelerated and uncelebrated flight segments. Only relationship available for m_{GTM} was for HB aircraft designed to carry only the lifting gas, as shown in Equation (2) [12]. In this equation, the term m_{gases} can further be divided into m_{lift_g}, mass of lifting gas and mass of air, m_{air}. Incase of airship m_{lift_g} only decreases when the lifting gas is expelled out. m_{air} is placed onboard and is used to increase or

decrease the aerostatic force by increasing or decreasing the volume of lifting gas, respectively. On the other hand, for HB aircraft have good ground handling qualities and the ratio of aerodynamic to total lift is about 49:51, [12]. Therefore, under all flying conditions some part of m_{GTW} will always be balanced by the aerostatic force. This lift force due to buoyancy is termed 'dead lift' [13] and its corresponding mass is introduced here as 'dead mass', m_{dead}. m_{GTM} is defined above and this term accounts for the mass of air and lifting gas as well [3]. For the purpose of all derivations and further calculations related to accelerated segments of flight of HB aircraft, added mass effects needs to be considered and can be incorporated for this segment of flight. Therefore, for HB aircraft it will be an important condition for which design take-off mass can be defined and it depends whether the flight segment is accelerated or un- accelerated. For un-accelerated flight segment, term m_{add} will not be considered as there will be no added mass effects on HB aircraft. To incorporate this effect, Equation (3) was rewritten as rewritten as Equation (4). For unconventional airships [9], m_{net} is expressed in terms of weight (W_{full}) and is shown below as Equation (5) in which term m_{add} cannot be added as this term represent the apparent mass not the weight. Equation (5) shown above was taken from reference [9] in which W_{full} is defined only for the cruise condition and based on the assumption that the weight of the airship does not change if fuel is burned [3]. It is important to highlight that the lifting gases are always weightless, but has mass and hence cannot be represented by W_{gas}. Moreover, Equation (5) is derived such that the unconventional airship can move towards ground, in a situation of any failure, mass of fuel consumed will be balanced by water ballast obtained by exploiting the humidity of air [14]. Apart from this practice, there are two other buoyancy compensation approaches namely, by compressing the lifting gas with the help of outside air brought inside the ballonet or by keeping aerogen gas in ballonets followed by heating it for reduction in volume of lifting gas [7]. But HB aircraft will avoid the jettisoning of lifting gas due to burning of fuel, by deflecting the control surfaces to fly the aircraft at or below the pressure height. This phenomenon resemble with that of an aircraft in which pilot has more control due to the availability of more pitching force with the help of elevators.

$m_{GTM} = m_{crew} + m_{fuel} + m_{passengers} + m_{empty} + m_{gases}$	(2)
$m_{net} = m_{GTM} - m_{dead}$	(3)
$m_{net} = m_{GTM} - m_{dead} + m_{add}$	(4)
$W_{full} = W_{env} + W_{fuel} + W_{engines} + W_{cabin} + W_{struct} + W_{batteries} + W_{gas} - W_{air} + W_{payl} + W_{crew} - L$	(5)

Operational empty mass

Operational empty mass is a frequently used term for estimation of empty mass of airship [15] and it will be more suitable to derive the relationship based on existing terms used in airship design. Definition of empty mass for aircraft is almost similar to that for airships. The basic difference between them is of masses of ballonets (with air), lifting gas and, buoyancy management system, m_{bms_inst}, which includes ballonet trimming and pressure controlling values [15] and its related control system. For winged hybrid airship, there will also be an additional mass of wing, m_w. The outer skin of aircrafts is usually made of some aluminum alloy and for airships it is some high strength fabric like Vectran, Spectra and Zylon etc. [7] and its mass is represented as m_{fab}. HB aircraft will also have a fabric skin to cover the metallic/non-metallic skeleton. All other terms, including mass of wing, are defined on the basis of the breakdown of empty mass relationships of general aviation aircrafts. Contribution of major assemblies and components towards estimation of operational empty mass (m_{opr_empty}) of a HB aircraft can be expressed by Eq. 6. In this equation, $m_{eng}, m_w, m_{emp}, m_{hull}, m_{ldg}, m_{ldg}, m_{f\tan k}, m_{avionics}$, $m_{fab}, m_{eng\_acces}, m_{air\_con}, m_{fshg}, m_{lift\_g}, m_{b\ln t}$ m_{bms_inst} and m_{trap_fuel} are mass of engine, wing, empennages, landing gears, gondola, fuel tanks, avionics, fabric, accessories of engine, air conditioning unit, ballonets, gas bags and trapped fuel respectively. Basic contribution for estimating the m_{opr_empty} is the mass of structure which needs detailed structural analysis for airships [3] and it basically includes m_w, m_{emp}, m_{hull} and m_{gond}. It will provide a first-hand knowledge about the response of the vehicle under any static or dynamic load. Mass of air has been incorporated in $m_{b\ln t}$ and mass of lifting gas in m_{g_bag}. It is important to note that it mendatory for a HB aircraft to have the ballonets as part of the system's anatomy.

VOL. 11, NO. 1, JANUARY 2016 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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$$m_{opr\_empty} = m_{eng} + m_w + m_{emp} + m_{hull} + m_{ldg} + m_{gond} + m_{ftank} + m_{avionics} + m_{fab} + m_{eng\_acce} + m_{fshg} + m_{air\_con} + m_{blnt} + m_{gbag} + m_{lift\_g} + m_{air} + m_{bms\_inst} + m_{trap\_fuel} \quad (6)$$

Volumetric fractions of mass

Volume fraction is an important design parameter for sizing as well as for the estimation of required space and dimensions of major components/assemblies. In a recent research article [14], the expression for estimation of full weight of a fuel powered airship as given in equation (7) was proposed. This expression was basically derived for a battery powered airship by replacing the weight of solar panels by the fuel weight. It also considered the weight of the vehicle as constant, through the flight.

Traditionally, the total weight of airships is categorized into two groups [3, 16-17]: one its propulsion weight and second its structural weight. Weight of the structure is further fractionalized by volume of hull (Vol) such that the volumetric fractions can describe the contribution of weight of the structure. In the present work, mass contribution of individual components and assemblies towards gross take-off buoyant mass is defined by first defining them into seven groups. This is perhaps meaningful since the suggested categorization covers all major and minor systems including power system as well as lifting mechanism. The nomenclature used to define these categories is not to coin new terms, rather these are defined such that individual subgroups can be differentiated from application point of view. Also, the subgroups which have negligible contribution towards the volume of hull can be neglected. For example, volumetric fractions of propulsion group (m_{prop_gp}) landing gears (m_{ldg}) and buoyancy management system (m_{bms_inst}) are not given as it gives no physical meaning for its utilization in any engineering work. This is because of the fact that the engine is always outside the body and attached with wing/hull or separately to the gondola. Due to the weight imitations, landing gears will always be non-retractable as retractable one requires additional retracting mechanism and which is perhaps not suitable for HB aircraft. For the ease of reader, complete description of each mass subgroup and their corresponding surface and volume fractions are tabulated below in Table-1.

Table- 1. Breakdown of mass subgroup.

Components/ Group	Description	Surface and volumetric fraction
m_{pers_gp}	Passengers, crew, payload and furnishings	$\left(\frac{m_{pers\_gp}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol$
m_{fuel_gp}	Total fuel (including the reserve and trapped fuel) and fuel tank	$\left(\frac{m_{fuel\_gp}}{S_{fuel\_tank}}\right)\left(\frac{S_{fuel\_tank}}{Vol}\right)Vol$
m_{str_gp}	Total airframe (including internal structure of hull, empennages and wing)	$\left(\frac{m_{int\_str\_afr}}{S_{hull+emp+w}}\right)\left(\frac{S_{hull+emp+w}}{Vol}\right)Vol$
$m_{avns\_inst\_gp}$	Avionics and instrumentation	$\left(\frac{m_{iavns\_inst\_gp}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol$
m_{env_gp}	Total fabric/material used for hull, empennages and cabin or gondola	$\left(\frac{m_{env\_gp}}{S_{env\_gp}}\right)\left(\frac{S_{env\_gp}}{Vol}\right)Vol$
m_{bag_gp}	Gasbags of lifting gas + air filled ballonets	$\left(\frac{m_{bag\_gp}}{S_{bag\_gp}}\right)\left(\frac{S_{bag\_gp}}{Vol}\right)Vol$

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Total mass of values [15] and necessary instruments for measuring and controlling the buoyancy are quite small. Therefore, volumetric or surface fraction for m_{bms_inst} will be quite small as compared with the volume and surface of hull, respectively. m_{bag_gp} Includes mass of material used for lifting gas bags as well as the material used for ballonets. Usually, lifting gas is filled in hull of non-rigid airships and air is filled in ballonets [15], but rigid airships can have individual gasbags floating inside the hull with no ballonets or gasbags and ballonets are constructed as integral part [18-19]. The same is applicable for the HB aircraft as well, in which there can be no ballonets inside the fuselage and the lifting gas is free to expand due to change of temperature.

Volume fractions shown in Eq. 8 are useful for the estimation of m_{GTM} of HB aircraft. In this way, m_{GTM} so obtained from Equation (8) can be substituted back in Equation (4) to get the final expression for m_{net}, Equation (9). It can be observed that the term m_{add} can be added in Equation (9) to account the added mass affects for any calculations related to accelerated flight segment. Surface to volume fraction and mass to surface volume are two important terms used for engineering and scientific applications. For example, $\left(\frac{m_w}{S_w}\right)$ is wing loading and it is one of the key parameters used for designing of any type of aircraft and HB aircraft as well. The term $\left(\frac{m_{air\_con}}{S_{cabin}}\right)$ gives vital information for the requirement of size of air-conditioning unit. $\left(\frac{Vol_{lift\_g}}{Vol}\right)$ can tell exactly about the volume occupied by the lifting gas in total volume of hull. $\frac{S_{bag}}{Vol}$ caters for the change in volume due to change in surface area of gas bags during ascent (compression) and descent (expansion) of HB aircraft.

$W_{full} = SW_{fabric}\left(\frac{S_{env}}{Vol}\right)Vol + \left(\frac{W_{fuel}}{Vol}\right)Vol + SW_{eng}\left(\frac{1}{\eta}\right)\left(\frac{P_{ow}}{Vol}\right)Vol + SW_{st\_emp}\left(\frac{S_{st\_emp}}{S_{env}}\right)\left(\frac{S_{env}}{Vol}\right)Vol + \alpha SW_{batt}\left(\frac{1}{\eta}\right)\left(\frac{P_{ow}}{Vol}\right)Vol + \left(\frac{W_{cabin}}{W_{payload}}\right)W_{payload} + \left(\frac{W_{str}}{Vol}\right)Vol + g\left(\rho_{gas} - \rho_{air}\right)Vol + W_{pass/goods} + W_{crew} - \left(\frac{L}{Vol}\right)Vol$	(7)
$m_{GTM} = \left(\frac{m_{bag\_gp}}{S_{bag\_gp}}\right)\left(\frac{S_{bag\_gp}}{Vol}\right)Vol + \rho_{lift\_g}\left(\frac{Vol_{lift\_g}}{Vol}\right) + \left(\frac{m_{air\_con}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol + m_{bms\_inst} + \left(\frac{m_{avionics}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol + \left(\frac{m_{int\_str\_afr}}{S_{hull+emp}}\right)\left(\frac{S_{hull+emp}}{Vol}\right)Vol + \left(\frac{m_w}{S_w}\right)\left(\frac{S_w}{Vol}\right)Vol + m_{bms\_inst} + \left(\frac{m_{env\_gp}}{S_{env\_gp}}\right)\left(\frac{S_{env\_gp}}{Vol}\right)Vol + \left(\frac{m_{pers\_gp}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol$	(8)
$m_{GTM} = \left(\frac{m_{bag\_gp}}{S_{bag\_gp}}\right)\left(\frac{S_{bag\_gp}}{Vol}\right)Vol + \rho_{lift\_g}\left(\frac{Vol_{lift\_g}}{Vol}\right) + \left(\frac{m_{air\_con}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol + m_{bms\_inst} + \left(\frac{m_{avionics}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol + \left(\frac{m_{int\_str\_afr}}{S_{hull+emp}}\right)\left(\frac{S_{hull+emp}}{Vol}\right)Vol + \left(\frac{m_w}{S_w}\right)\left(\frac{S_w}{Vol}\right)Vol + m_{bms\_inst} + \left(\frac{m_{env\_gp}}{S_{env\_gp}}\right)\left(\frac{S_{env\_gp}}{Vol}\right)Vol + \left(\frac{m_{pers\_gp}}{S_{cabin}}\right)\left(\frac{S_{cabin}}{Vol}\right)Vol - m_{dead}$	(9)

Volume of hull

In order to find the volume of fuel powered HB aircraft, we started from the existing relationship for volume (Vol) of hull (Equation (10)) for unconventional airship. This equation was obtained by rearranging Equation (7) for full fuel condition [14]. We started from this relationship as it is the only reference available to develop the fundamental relationship for finding the volume of fuel powered HB aircraft. From airship's anatomy point of view, only difference is due to the wing which is absent in an unconventional airship and its affect can be considered in mass of structure and fabric. Where, SW_{fabric} is the envelope fabric weight per unit area,

S_{env} is total airship envelope surface, SW_{eng} is weight to power ratio of the propulsion system, P_{ow} is power density, SW_{st_emp} is weight of internal structural frame per unit area, α is Night/day, η is electric/fuel operations coefficient, SW_{batt} is ratio of battery weight to energy stored, S_{st_emp} is internal structural frame weight per unit area, SW_{batt} is ratio of battery weight to energy stored and L is aerodynamic lift at zero angle of attack. In Equation (10), W_{cabin} was considered to be outside the hull but cargo cabin can be inside the hull body as well. It is not clear from this expression that weight of avionics, buoyancy management/control system, reserved fuel and additional weight due landing gears (if there) is accommodated or not. Also the usage of batteries in a fuel powered airship can be there in any airship but its volume is usually quite small as compared with the volume of hull. In comparison with Equation (10), related term for defining the mass of battery was catered in the mass group of avionics and instrumentation $m_{avn\_inst\_gp}$. Based on all these facts, Eq. 8 was rearranged to formulate new relationships for fuel powered HB aircraft, which is shown below as Eq. 11. Based on the engineering and scientific knowledge of airships and aircraft, a new relationship was derived in which some additional terms m_{air_con}, $m_{avionics}$, m_w, $m_{bms_{inst}}$, m_{dead} m_{fuel_gp} were introduced for the exact representation of masses of different components of fuel powered hybrid buoyant aircraft.

$$Vol = \frac{W_{full} - \left(\frac{W_{cabin}}{W_{payload}}\right) W_{payload} - \left(W_{pass/goods} + W_{crew}\right)}{\left\{\begin{array}{l}\left[SW_{fab} + SW_{st_{emp}}\left(\frac{S_{st_{emp}}}{S_{env}}\right)\right]\left(\frac{S_{env}}{Vol}\right) + \left(SW_{eng} + \alpha SW_{batt}\right)\left(\frac{1}{\eta}\right)\left(\frac{P_{ow}}{Vol}\right) + \left(\frac{W_{str}}{Vol}\right) + \left(\frac{W_{fuel}}{Vol}\right) + \\ g\left(\rho_{gas} - \rho_{air}\right) - \left(\frac{L}{Vol}\right)\end{array}\right\}} \quad (10)$$

$$Vol = \frac{m_{net} - m_{bms_{inst}} - m_{ldg} + m_{dead}}{\left\{\begin{array}{l}\left(\frac{S_{cabin}}{Vol}\right)\left[\left(\frac{m_{air\_con}}{S_{cabin}}\right) + \left(\frac{m_{avionics}}{S_{cabin}}\right) + \left(\frac{m_{pers\_gp}}{S_{cabin}}\right)\right] + \left(\frac{m_{bag_{gp}}}{S_{bag_{gp}}}\right)\left(\frac{S_{bag_{gp}}}{Vol}\right) + \rho_{lift\_g}\left(\frac{Vol_{lift\_g}}{Vol}\right) + \\ \left(\frac{m_{int\_str\_afr}}{S_{hull+emp}}\right)\left(\frac{S_{hull+emp}}{Vol}\right) + \left(\frac{m_w}{S_w}\right)\left(\frac{S_w}{Vol}\right) + \left(\frac{m_{fuel\_gp}}{S_{fuel\_tank}}\right)\left(\frac{S_{uel\_tank}}{Vol}\right) + \left(\frac{m_{env\_gp}}{S_{enc\_gp}}\right)\left(\frac{S_{env\_gp}}{Vol}\right)\end{array}\right\}} \quad (11)$$

CONCLUSIONS

This work addresses an important issue for the preliminary design of modern hybrid airships and an effort was done to re-arrange the equations used in the weight fractions method. Relationships derived for mass and volumetric fractions can be useful for any design related activity for fuel powered HB aircraft. By clarifying the categories of subgroups, it can help many related researchers to communicate with each other without ambiguity. More advanced lightweight materials are now available and it is perceived that through an iterative process, a data bank of these fractions can be generated in future. Moreover, it will give an attempt to validate the presented procedure through the application to any existing or new design

ACKNOWLEDGMENTS

The support of the Ministry of Science, Technology and Innovation (MOSTI), Malaysia, under the grant 06-01-08-SF0189 and the Ministry of Education, Malaysia under the grant FRGS 13-020-0261 are gratefully acknowledged.

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