Propulsion and Power Research 2016;5(1):34–44

http://ppr.buaa.edu.cn/

Propulsion and Power Research

www.sciencedirect.com

ORIGINAL ARTICLE

Assessment of engine's power budget for hydrogen powered hybrid buoyant aircraft

Anwar U. Haque[a], **Waqar Asrar**[a,*], **Ashraf A. Omar**[b], **Erwin Sulaeman**[a], **J.S. Mohamed Ali**[a]

[a]*Department of Mechanical Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia*
[b]*Department of Aeronautical Engineering, University of Tripoli, P.O. Box 81507, Tripoli, Libya*

Received 30 December 2014; accepted 29 May 2015
Available online 23 February 2016

KEYWORDS

Hybrid buoyant aircraft;
Ballonet's inflation;
Operator's constrains;
Engine selection;
Power budget

Abstract It is well known that hydrogen has less undesirable exhaust emissions as compared with other types of liquid fuels. It can be used as an alternative fuel for a hybrid buoyant aircraft in which half of the gross takeoff weight is balanced by the aerostatic lift. In the present study, weight advantage of liquid hydrogen as an ideal fuel has been explored for its further utilization in such aircraft. Existing relationships for the estimation of zero lift drag of airship is discussed with special focus on the utilization of such analytical relationships for the aircraft whose fuselage resembles with the hull of an airship. Taking the analytical relationship of aircraft and airship design as a reference, existing relationships for estimation of power budget are systematically re-derived for defined constraints of rate of climb, maximum velocity and takeoff ground roll. It is perceived that when the propulsion sizing for liquid hydrogen is required, then the presented framework for estimation of its power budget will provide a starting point for the analysis. An example for estimation of the power requirement is also presented as a test case.

1. Introduction

Different modes of transport are available today but due to high fuel prices, transportation cost to reach the destination in minimal time is increasing with additional penalty due to emissions. A century ago, airships were a suitable

*Corresponding author. Tel.: +60 163123192.

E-mail address: waqar@iium.edu.my (Waqar Asrar).

Peer review under responsibility of National Laboratory for Aeronautics and Astronautics, China.

http://dx.doi.org/10.1016/j.jppr.2016.01.008

Nomenclature

B	buoyant
B_R	buoyancy ratio
$C_{L,(L_{aero}/D)_{max}}$	coefficient of lift for maximum lift to drag ratio
$C_{L_{max\_aero}}$	maximum aerodynamic lift coefficient
C_{L_md}	coefficient of lift for minimum drag
$(C_{\_D\_0})_{less\_hull}$	zero-lift drag coefficient, less of the hull
$C_{\_D\_0}$	zero-lift drag coefficient
$C_{\_D\_min}$	coefficient of minimum drag
C_f	skin friction drag
HB	hybrid buoyant
FF	form factor
FR	fineness ratio
hp	horsepower
K	drag due to lift factor
IC	internal combustion
l	characteristics length, (unit: m)
L_{buoy}	aerostatic lift
LTA	lighter than air
$\left(\frac{L_{aero}}{D}\right)_{max}$	maximum lift to drag ratio
LH_2	liquid hydrogen
m_z	gross mass at end of cruise segments
m_y	gross mass at start of cruise segments
m_x	gross mass at start of climb segments
m_w	gross mass at warm-up/takeoff
S_{aero}	characteristic reference area of aerodynamic lift
SFC	specific fuel consumption
NO_x	nitric oxide and nitrogen dioxide
rpm	revolution per minute
$\left(\frac{R}{C}\right)$	rate of climb
$\left(\frac{R}{C}\right)_{max}$	maximum rate of climb
$\left(\frac{R}{C}\right)_{min}$	minimum rate of climb
STOL	short takeoff and landing
V	velocity
V_{max}	maximum velocity
V_{stall}	stall velocity
$V_{(L/D)_{max}}$	velocity for maximum lift to drag ratio
Vol	volume of lifting gas inside the hull
W_{GTM}	weight corresponding to gross takeoff mass
W_{net}	net weight

Subscripts

MC	mid cruise
TO	takeoff
TR	thrust required

source in aviation transportation with less environmental concerns, which were later led by low and high speed aircraft. It is well known that with the passage of time, size and number of aircraft grew bigger and less focus is there on environmental concerns. As per a recent data published online, "*worldwide, flights produced 705 million tons of CO_2 in 2013. Globally, humans produced over 36 billion tons of CO_2*" [1]. One of the triggering elements for air pollution is byproduct of burning of fossil fuels which include CO, CO_2 and unburned hydrocarbons. Recent research on hybrid buoyant (HB) aircraft [2,3] may offer a good solution for the overall reduction in CO_2 and other harmful emission by the aviation industry. In case of aircraft, half of the fuel is used just to keep it aloft [4]. Whereas, the use of aerostatic lift in hybrid buoyant (HB) aircraft has the potential to cancel out such requirement. Such aircraft combine the aerodynamic (similar to aircraft) as well as aerostatic lift (similar to airship) and is considered as "*best of the both worlds*" [5]. Requirement of less infrastructure, shorter runways and less fuel consumption as compared with short takeoff and landing (STOL) aircraft are some of the characteristics of HB aircraft.

Design and development of airships and aircraft took place in almost similar time span. If we look back in the history of aviation, Zeppelin LZ-1 took its first flight on 2nd July, 1900 and Wright brothers had flown the aircraft in 1903 [6]. The first wind tunnel was established for airship but later during world war-II, more interest was shifted towards aircraft and more research was then focused on aircraft. Even to date, much of the latest research work available is more focused on aircraft such as liquid hydrogen as an alternative power source for future aircraft [7] or towards drag reduction and flow control to improve aircraft performance [8].

Airship is found to be competitive with cruises for distances between 200 and 1000 km [9] and HB aircraft which are disguised as airship will be more suitable for sight-seeing and comfortable travel for tourists at low speed. These aircrafts have the characteristics to take off, land and fly as any other aircraft but unlike the others, have a buoyant gas inside the hull. Moreover, the agricultural products such as pepper, palm oil, fresh vegetables and fresh meat do not have a low-priced as well as fast freight mode available as compared with aircraft and ships, respectively [10]. Therefore, by taking advantage of huge volume of hull, export products can also be transported from remote areas having insufficient ground transportation network.

As far as the environmental effects are concerned, liquid hydrogen can be used as an alternative fuel for buoyant aircraft in which voluminous tanks of LH_2 can be accommodated inside the hull. This is the basis for the considerations which led to the volumetric sizing of hull and physical location of the tanks for the LH_2 fueled buoyant aircraft. Usage of liquid hydrogen is ideal for reduction in atmospheric pollution [11] as combustion of hydrogen produces water vapors and it may influence contrail and cirrus cloud formation. Hence no ozone layer depleting chemicals are generated. Moreover, similar to conventional airships [12], water vapors can be collected to compensate the decrease in weight due to burning of fuel to some extent.

In order to prove this concept, there is a requirement to design and develop HB aircraft such that the performance of hydrogen powered IC engines can be evaluated. Such design work needs the formulation of analytical relationships, especially for the estimation of power budget for the propulsion system. In this regard, a framework of analytical relationships was derived from the existing relationships of airships and aircraft. Limitations of such relationships were also discussed for its further application for HB aircraft. The present research is divided into four sections namely, a review of fuel powered propulsion systems, issues related to the required aerodynamic parameters for propulsion analysis, estimation of power requirement through analytical relationships and at the end, results of a case study for practical implementation of the proposed methodology.

2. Propulsion systems

The engine selection for HB aircraft is an important part of the complete aircraft design process. Like any conventional or unconventional aircraft design, basic engine requirements are largely dictated by the selected mission profile, estimation of required aerodynamic parameters and limitations of gross takeoff mass. Fuel economy, in terms of low specific fuel consumption (SFC) is also important to achieve the desired range. Power requirements for engine always change for different flight segments to achieve the desired values of takeoff, rate of climb and maximum velocity [13]. However, such requirements are different for petrol or diesel engines and perhaps, may also vary with the choice of power plant.

These propulsion requirements decide the final choice of IC engines, which are different in normal and commuter type aircraft e.g. Cessna 152, Cessna 172 and Piper PA-23. Such engines use the combustion of petroleum and air to convert thermodynamic energy to kinematic energy. Diesel engines mix the fuel and air, after the air is compressed and heated. Such a process does not require diesel engines to use spark ignition as the heat of the air ignites the fuel. Moreover, petroleum engines burn fuel faster than the diesel engines. Therefore diesel engines use less fuel and achieve a greater fuel efficiency [14]. Petroleum engines however use pre-mixing in a carburetor or the more modern electronically controlled fuel injector. This allows petroleum engines to have lighter pistons, control rods and crankshafts, due to which such engines run at higher speeds than diesel engines, thus reducing fuel efficiency.

Except for the Hindenburg [15], which was powered by four diesel engines, use of diesel engine is rarely seen in airships. One of the obvious reasons of it might be its heavy weight and availability. In comparison with turbofan engines; diesel engines require low air/fuel ratio [10] and its use in airship which plan to condense the exhaust and reclaim water for ballast would have been beneficial.

Hydrogen gas as an alternative fuel was considered in the past for its potential use in airships [16]. This gas is commonly used in airships for buoyancy and can also be used as a fuel for the engines. In this way, the hydrogen gas can be used to supply additional buoyancy if stored at low pressure in a light container [4]. However, the practicality of this concept had hardly been seen in the literature; one of the potential reasons of which its highly inflammable property.

An alternate option is to use liquid hydrogen (LH_2) as a fuel for internal combustion engine [7]. LH_2 was first tested as a fuel for the aerospace industry on Tupolev Tu-155 aircraft. Unfortunately, at present research on utilizing hydrogen as an alternative fuel is much more focused towards engines for automobile applications. Even the recent development by Boeing of "*Phantom Eye*", a stratospheric aircraft was powered by Ford car engines using liquid hydrogen as a fuel. Therefore, still there is a technological gap for adapting the IC engines of existing fleet of STOL aircraft with hydrogen as a fuel. There are certain pros and cons of hydrogen technology as well, which are discussed briefly in the following section alongwith its historical overview.

2.1. Hydrogen fuel technology

If we look back in the history, gaseous fuels like hydrogen were preferred over liquid fuels like gasoline. It was because of the fact that it was considered safer to work with it, due to the low pressures used for the gaseous fuels and the quick dissipation of the gases in case of leakage [17]. The first IC engine was built by François Isaac de Rivaz in 1806 and it was powered by a mixture of hydrogen and oxygen. This engine was perhaps fueled by "*town gas*" filled with rich hydrogen and not by pure hydrogen. It was perhaps a pre-mixture of gaseous fuel (carbon monoxide and hydrogen); produced by burning coal under very air-deficient conditions. Though liquid hydrogen was also tried by François Isaac de Rivaz but due to explosion during experimentation, use of the same was declared as dangerous. But after a century when carburetor was invented, research was more focused on using gasoline liquid fuel rather than using liquid hydrogen; an environmental friendly fuel.

Indeed, hydrogen burns with a high flame speed, thus making hydrogen engines close to ideal engine cycle [18]. As compared with gasoline, hydrogen has low energy density per unit volume, which produces less energy in the cylinder of the engine [11,16]. It means that an engine operating on hydrogen as a fuel will have less power as compared to that working on gasoline. This is perhaps expected as the inlet manifold is usually supplied with some heat to help vaporize the liquid (gasoline) fuel. Therefore, hydrogen gas expands more than liquid gasoline inside the engine, leading to a drop in the volumetric efficiency of a hydrogen filled engine [11]. At the same time, this physical phenomenon is a function of operating speed of the engine as well. Kahraman [16] conducted experimental study on a 60 hp FIAT engine and he found that in comparison with gasoline powered engine, the power of hydrogen fueled

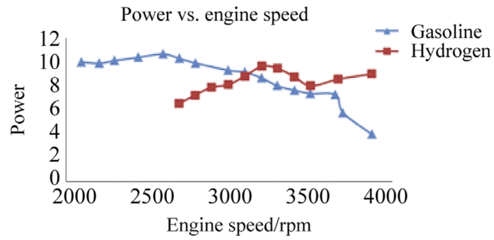

Figure 1 Power vs. engine speed, reproduced from Ref. [16].

Table 1 Requirements for better performance of aircraft.

For	Required
Maximum range	High L/D, high η_p, low SFC, high fuel weight fraction
Maximum endurance	High L/D, high η_p, low SFC, high fuel weight fraction
Steepest climb	High P_A/W_{net}, high L/D, low speed
Fastest climb	High P_A/W_{net}, high L/D

engine was increased by increasing the revolution per minute (rpm) of the engine. This can be explained with the help of Figure 1, reproduced here from Ref. [16].

Another implication of hydrogen gas is its low density property, because of which fuel–air mixture with air will have low energy density. Therefore significant compression or large volume is required to store it in liquid form [18]. Its low density property is more suited for HB aircraft in which the power budget has to be optimized, specially for the constraint of rate of climb $\left(\frac{R}{C}\right)$ due to ballonets inflation with altitude, which is discussed further in Section 4.

In case of the aircraft [13], alongwith other requirements, fuel weight fractions plays a dominant role in overall performance parameters of the aircraft. Such parameters are tabulated in Table 1 for better understanding of the effect of fuel weight fraction.

Liquid hydrogen has about four times the volume for the same amount of energy of kerosene based jet-fuel and it is about one-third of the weight of kerosene jet-fuel for the same amount of energy (Figure 2) [19]. Piston engines powered by liquid hydrogen always require less fuel system as compared to that required for hydrogen gas [16]. Considerable advantages in terms of gross takeoff weight of the HB aircraft can be achieved by using hydrogen as an alternative fuel for HB aircraft.

There are two options available for the injection of hydrogen i.e. direct injection (DI) and cryogenic port injection (CPI). The former choice requires pressured hydrogen for the combustion process and for the latter case, the low pressure range of a liquid hydrogen tank is sufficient [20] for the said purpose. CPI concept takes advantage of the formulation of external mixture formation of hydrogen and air by making use of the extremely low temperature. For converting a conventional aircraft to burn LH_2, an additional heat exchanger is needed to heat the liquid hydrogen to a temperature that is suitable for injection into the combustion chamber [21]. Such a heat exchanger can also be utilized to maintain the temperature of lifting gas used in HB aircraft. At the same time, the concept of liquid hydrogen storage and CPI forms a technically straightforward system; supporting the attempt to design an economically hydrogen powered HB aircraft.

The change in energy consumption is small for engines fueled with LH_2. For regional propeller aircraft, it is less than half of that expected in long range aircraft, Figure 3. But HB aircraft powered by LH_2 as a fuel will be beneficial to global society for reduction in CO_2 and NO_x emission

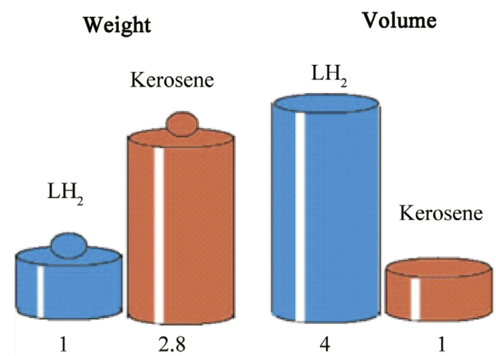

Figure 2 Comparison of LH_2 and kerosene regarding weight and volume [7] (based on data from Ref. [19]).

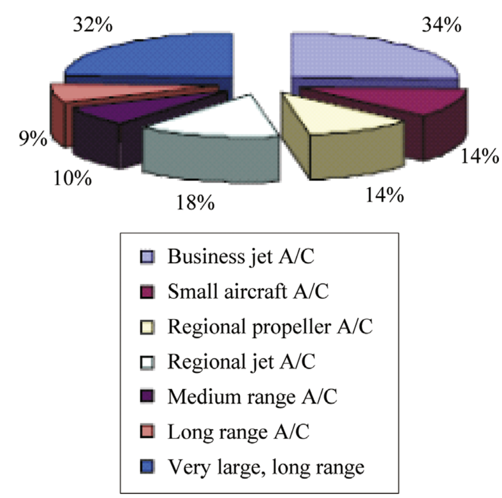

Figure 3 Change of energy consumption for LH_2-fueled aircraft (data from Ref. [19]).

from STOL aircraft of similar weight category. This is due to the fact that some percentage of the gross takeoff weight is supported by "*free of cost lift*", available from the buoyant gas and drag reduction due to the low cruise speed [22]. Moreover, such aircraft will require less fuel as partial W_{GTM} will always be balanced by the aerostatic lift. Therefore, it can be said that lower fuel weight brings considerable advantages to HB aircraft. This effect is more dominant in the takeoff segment of flight in which less demand of power will substantially reduce the wing area and engine size as well. In aviation industry, one by third of operational cost is fuel cost and if the airship's fuel cost is 1/

10th than the reduction in operational cost will be around 70% [23]. For HB aircraft, it is perceived that the operational cost will be more than that for the airships but obviously will be quite less than that for STOL aircraft of similar weight category.

3. Required aerodynamic parameters

Drag force is fundamentally defined "*as the rate of removal of momentum from a moving fluid by an immersed body*", [24]. Accurate estimation of drag is important for thrust calculations and estimation of power requirements for engine. Due to non-availability of historical trends for HB aircraft, which are required to begin with traditional method for aircraft design, it is quite difficult to estimate the values for variables of drag polar equation. In order to fulfill the requirement of aerostatic force, the shape of a HB aircraft is usually in resemblance with that of an airship and drag coefficient of complete configuration is approximated by using Eq. (1) [25]:

$$C_D = C_{DO} + K\left(C_{\_L\_aero} - C_{\_L\_md\_aero}\right)^2 \quad (1)$$

Airships have no or very small chamber, and $C_{\_L\_md\_aero}$ will be equal to zero if the effect of aerodynamic lift is not significant enough [25]. The same relationship also holds good for a HB aircraft with a cambered wing attached with the symmetric shaped hull. However, in the case of hybrid lifting hull [26], the effect of $C_{\_L\_md\_aero}$ is more dominant and hence it cannot be neglected. Zero lift drag coefficient can be expressed as Eq. (2) [25] in which both C_{D_P} and C_{D_F} are accounted. Airship's drag is primarily due to the pure and uncontaminated skin friction, which is shown below in Eq. (3) which is applicable if one uses the component drag buildup method for the complete aircraft. Where FF is analytically expressed by Eq. (4) [25]:

$$C_{D_0} = C_{D_P} + C_{D_F} + C_{D_{int}} + C_{D_{misc}} \quad (2)$$

$$C_{D_F} = \sum C_{f\,comp}(FF)(S_{wet})_{comp}/(Vol)^{\frac{2}{3}} \quad (3)$$

$$FF = 1 + \frac{1.5}{(FR)^{\frac{3}{2}}} + \frac{7}{(FR)^3} \quad (4)$$

Right hand side of Eq. (4) is taken from Hoerner's book of "*Fluid Dynamics Drag*", (Eq. (28), Chapter No. 6 of Ref. [27]); derived to represent effect of thickness ratio on the total drag coefficient of airship. In Eq. (4), the pressure drag term (C_{D_P}); i.e. $\frac{7}{(FR)^3}$ was obtained by interpolating the experimental databank of hulls; shown in Figure 24 of Chapter no. 6 of Ref. [27]) Moreover the fraction $\frac{1.5}{(FR)^{\frac{3}{2}}}$ represents the friction drag coefficient corresponding to the average dynamic pressure for high value of FR i.e. (Eq. (26) and Eq. (27) of Chapter No. 6 of Ref. [27]). Moreover, for the validity of FF (Eq. (3)), C_{D_P} should be equal to zero. This is because of the fact that the FF (Eq. (4)) already contains the term which is representing the contribution of pressure drag.

In one of the recent references of general aviation aircraft design and procedures [28], it is recommended that "*if the fuselage resembles the hull of an airship (which, granted, most fuselage do not), then (Eq. (18)) of Ref. [27] should be used*".

$$FF = 3f + \frac{4.5}{\sqrt{f}} + \frac{21}{f^2} \quad (5)$$

Authors are of the view that the Eq. (4) really is not FF by the same definition as used in Eq. (3) as Hoerner had not defined FF for the same. Eq. (5) is actually based on a constant frontal area and it already contains the term S_{wet}/S_{ref} to be equal to $3 \times FR$ [27]; a simple adjustment which allows the use of S_{ref} for the calculation of drag coefficient, Eq. (6). This means that Eq. (5) is Eq. (4) $\times 3 \times FR$ and they return different numbers and thus, are not the same equation. $3FR$ was actually the approximation done by Horner to define S_{wet}/S_{ref}, Eq. (5), where S_{wet} is $0.75 \times l$ and S_{ref} is the maximum cross sectional area.

$$\frac{C_{D_0}}{C_f} = 3FR\left[1 + \frac{1.5}{(FR)^{\frac{3}{2}}} + \frac{7}{(FR)^3}\right] \quad (6)$$

FF for the fuselage of aircraft is represented here as Eq. (7) [29] and Raymer suggests an adjustment factor of 0.85 to be incorporated to include scaling effects for airships [29]. In the present study, the same equation was used with proposed correction factor and for tails and wings, the equations for FF available in Ref. [29] were employed.

$$FF = 1 + \frac{60}{(FR)^3} + \frac{FR}{400} \quad (7)$$

However, due to above mentioned differences in equations of FF, a need was felt to plot Eqs. (4), (5) and (7) taken from Carichner and Nicolai (after correction) [25], Gudmundsson [28] and Raymer [29] respectively, for the ease of readers.

It is quite obvious from quantitative comparison of FF, shown as Figure 4 that for a fuselage which resembles with that of airship, Ref. [28] is perhaps not the true representation of FF. Moreover the values of FF obtained from Refs. [25] and [29] are in good agreement for range of $FR \geq 4$.

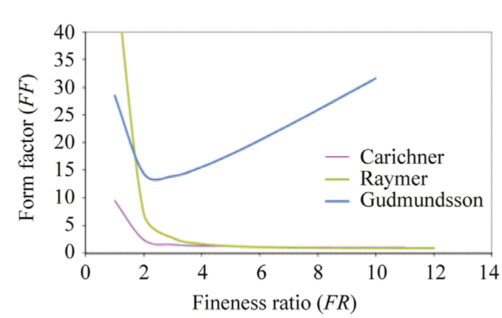

Figure 4 Comparison of FF defined in Refs. [25,28,29].

For streamlined bodies (on the basis of enclosed volume), *FF* is actually a function of *FR* and its value for optimum drag and for Reynolds numbers in the vicinity of 10^7 has been found experimentally in wind tunnels and water channels to be between 5 and 6 [30]. Recently, an analytical study on conventional airships was conducted to find the drag and power requirement for different *FR* [31]. For a known value of maximum diameter, value of *FR* between 5 and 6 was proved to be an optimal value. The authors of Ref. [31] had compared their results with an old reference of airship design citing the optimal value of *FR* to be equal to 2.3 and had revealed that this value is not an optimum from aerodynamic and structure point of view. Interestingly, if we look into the naturally created marine animals then optimum value for Steller sea lion, a hybrid lifting marine animal with voluminous guts and gonads, is about 5.5. The word hybrid lifting is used here to highlight that this marine animal is getting lift from its aerodynamic shape of body [32] as well as due to the effect of buoyancy.

3.1. Redefining the reference area

To date, no unique definition exists for defining the reference area for HB aircraft. In aircraft design, the fuselage is assumed to produce very little lift from the area of the wing, buried inside the fuselage i.e. a fraction of the lift is produced by the fuselage; the rest is produced by the wing area outside the fuselage. For airships, aerodynamic forces are non-dimensionalized either by the frontal area [33], cube root of volume or planform area of hull [25]. Except for blended wing aircraft, planform area of a wing is utilized as reference area to find out the aerodynamic coefficients where the size of the wing is critically so important to the coefficients related to lift. The use of $(Vol)^{\frac{2}{3}}$ parameter as reference area in Eq. (3) is perhaps an attempt to include the effects of *FR* right into the coefficient but it may be handled better by defining the *FF*.

Therefore it is proposed that the reference area S_{ref} for a simple wing-hull configuration can be defined as sum of the planform projected area of hull S_H and wing S_W. Complete discussion on the impact of S_{ref} on the trends of aerodynamic coefficients will be addressed separately. If S_W is the planform area of wing outside the hull, then S_{ref} can be expressed as Eq. (8):

$$S_{ref} = S_W + S_H \tag{8}$$

3.2. Net weight

For HB aircraft, aerostatic lift will always be balancing some % of gross takeoff weight; described as "*dead weight lift*" [15], labeled here as W_{net}. This term is more suitable in comparison with the term "*weight fraction* λ_A" defined for hybrid airship [5] as equal to $1 - \frac{L_{buoy}}{W_T}$, where W_T was defined as total weight. This term is perhaps derived by considering the lifting gas to be inside the ballonets and for altitude $\leq$ the pressure height. However, to the aurthor's best knowledge, if there is no variation in temperature i.e. superheating due to the sun, then aerostatic lift and hence its coefficient C_{Lbuoy} remains consistent until pressure height. Also, since fuel is continuously burning during flight, resultantly overall lift requirement also changes. Therefore, practically speaking it is not possible to keep value of λ constant in any particular flight segment. Hence ΔW [5], i.e. the weight being balanced by the aerostatic lift varies in flight. Similar to "*dead weight lift*" [15], the weight being balanced by the aerostatic lift, W_{net} can be the true representation of dead weight.

Authors are of the view that partial weight of HB aircraft is always balanced by buoyant lift which remains constant till pressure height and the rest of the weight can be represented by W_{net} and its corresponding mass by m_{net}. Therefore it is necessary to rearrange the existing aircraft relationships [13] for W_{net} and m_{net} before applying them for any analysis work.

3.3. Some common relationships of airships and aircraft

For maximum aerodynamic efficiency, there are certain relationships which are common for aircraft [13,28,29] and airships/hybrid [25,34] but differ for hybrid airships mentioned in Ref. [5]. These parameters can be utilized in analytical relationships for estimation of engine's power budget for a HB aircraft. Without any derivation, all such formulas; in terms of W_{net} are tabulated altogether in Table 2 for quick reference. These formulas are also compared with the existing analytical formulas which were derived by Zhang et al. One of the reason is due to the difference in defining the lift.

It is pertinent to highlight that the existing relationships of hybrid airships, mentioned in Ref. [5] were derived such that aerostatic lift was being added to define the total lift. In this way, aerodynamic lift was defined as function of λ_A. But weight fraction λ_A might not have any physical meaning for aerodynamic characteristics of body of any shape. This is because of the fact that aerodynamic coefficients are only function of geometric profile and flow conditions. Comparison study of such parameters is perhaps not possible as the required inputs i.e. C_{DO} and K are missing in Ref. [5].

Table 2 List of parameters for max aerodynamic efficiency.

Parameters	Aircraft and airship [13,25]	Hybrid airship [5]
$V_{(L/D)_{max}}$	$\sqrt{\frac{2}{\rho}\cdot\sqrt{\frac{K}{C_{DO}}}\cdot\frac{W_{net}}{S_{aero}}}$	$\sqrt{\frac{2}{\rho}\cdot\sqrt{\frac{K}{C_{DO}}}\cdot\frac{\Delta W}{S_{aero}}}$
$C_{L,(L/D)}$	$\sqrt{\frac{C_{DO}}{K}}$	$\frac{1}{\lambda_A}\sqrt{\frac{C_{DO}}{K}}$
$(L/D)_{max}$	$\sqrt{\frac{1}{4KC_{DO}}}$	$\frac{1}{\lambda_A}\sqrt{\frac{1}{4KC_{DO}}}$
V_{stall}	$\sqrt{\frac{2}{\rho}\cdot\frac{W_{net}}{S_{aero}}\cdot\frac{1}{C_{Lmax}}}$	$\sqrt{\frac{2}{\rho}\cdot\sqrt{\frac{K}{C_{DO}}}\cdot\frac{\Delta W}{S_{aero}}}$

In order to select a suitable power plant, it is required to first estimate the thrust and hence the power required for steering the HB aircraft in different flight conditions, which is discussed in the following section.

4. Estimation of propulsion requirements

Estimation of thrust to weight ratio ($\frac{T}{W_{net}}$) is a prerequisite in a propulsion system requirement. For steady level flight, thrust to weight ratio (Eq. (9)) is simply the reciprocal of the lift to drag ratio [35]:

$$\frac{T}{W_{net}} = \frac{1}{\left(\frac{L_{aero}}{D}\right)} \tag{9}$$

However, thrust needs to be converted into power by using Eq. (10) [36].

$$P = \frac{1}{\eta_{pr}} \times T \times V \tag{10}$$

Before we discuss the relationships to be defined for above mentioned constraints, few analytical relationships are highlighted here for reference: in steady level unaccelerated and level flight of aircraft, thrust is equal to drag and lift is equal to weight. Conditions of minimum thrust and minimum power are different [27]. Minimum thrust to weight ratio $(\frac{T}{W_{net}})_{min}$, Eq. (11) [5] and its corresponding velocity are given as follows, Eq. (12) [5] , which are expressed in terms of W_{net}.

$$\left(\frac{T}{W_{net}}\right)_{min} = \sqrt{4KC_{DO}} \tag{11}$$

$$V_{(TR)min} = \left(\frac{2}{\rho}\sqrt{\frac{K}{C_{DO}}}.\frac{m_{net}}{S_{ref}}\right)^{1/2} \tag{12}$$

Power required by a HB aircraft for steady level flight is estimated by using Eq. (13), which is obtained by using Eq. (10) and Eq. (1) for steady level cruise flight condition for which $T = D$. Coefficient of lift and velocity corresponding to minimum power condition can be obtained by using Eq. (14), [13] and Eq. (15), [13] expressed in terms of W_{net} and the same can be plugged back in Eq. (13) for estimation of $P_{R_{min}}$.

$$P\_R\_min = \frac{V \times q\left[C_{DO} + K\left(C\_L\_aero - C\_L\_md\_aero\right)^2\right]}{\eta_p} \tag{13}$$

where,

$$C\_L_{\_min\_P\_R} = \sqrt{\frac{K}{3C_{DO}}} \tag{14}$$

$$V_{min_{P_R}} = \sqrt{\frac{2W_{net}}{\rho S}\sqrt{\frac{K}{3C_{DO}}}} \tag{15}$$

Design constraints considered in the present study are as follows:

(1) Takeoff distance, specially the ground roll segment which is limited due to the operator's constraint of runway length.
(2) $\left(\frac{R}{C}\right)_{max}$ due to effects of ballonet's inflation.
(3) V_{max}, defined by the structural limitations.

Analytical relationships for estimation of power for all these constraints are derived in annexure ‘A’, (Eqs. (A-7), (A-8) and (A-11)). These derived formulas are also applicable for calculations involved for estimation of the same for the scenario when there is no lifting gas inside the hull i.e. without considering the weight being balanced by aerostatic lift [35]. Mass of payload and of lifting gas is incorporated while calculating m_{net}. Hence, these design parameters are not considered as the design constraints for required purpose.

4.1. Takeoff flight

The ground roll is the distance that an airplane covers along runway before it lifts into the air. In the case of aircraft, maximum power required in ground roll for takeoff flight segment can be estimated by using Eq. (16) [25], which is perhaps more practical to be used in buoyant vehicles powered by reciprocating or internal combustion engines. As other formula for winged hybrid airship is derived for jet engines [5] and is of no practical importance for HB aircraft in which similar to airships, flying speed is limited due to structural constraints.

$$S_{g_{TO}} = \frac{\left(\frac{W_{net}}{g} + m_{gas}\right)V_{TO}^2}{2[T - D - \mu(W_{net} - L_{aero})]_{@0.707V_{LO}}} \tag{16}$$

Some of the references of aircraft and hybrid airship design do include the rotation distance S_R as well in $S_{g_{TO}}$. Eq. (16) can be rewritten as Eq. (17) to include it:

$$S_{g_{TO}} = \frac{\left(\frac{W_{net}}{g} + m_{gas}\right)V_{TO}^2}{2[T - D - \mu(W_{net} - L_{aero})]_{@0.707V_{LO}}} + NV_{TO} \tag{17}$$

where N is rotation time and V_{TO} is the takeoff speed. As per FAR-23 [36], liftoff velocity i.e. $V_{LO} = 1.1 \times V_{stall}$. This relationship has been utilized further to develop the analytical relationships for the estimation of thrust and power for takeoff condition, (Eq. (A-6) to Eq. (A-7)).

4.2. Rate of climb

In conceptual cycle of aircraft design [27], the rate of climb can be estimated by using the relationship between power available ($T \times V$) and power required ($D \times V$) [36]. Generally, to fulfill the certification requirements for FAR-23/CS-23, the aircraft are designed such that they fulfill the requirement of $\left(\frac{R}{C}\right)$, laid down in these certification standards [36]. Interestingly, minimum rate of climb requirement is the same for LTA aircraft i.e. airships [37] and small utility aircraft [38] i.e. 1.5 m/s. At the same time, for an airship, $\left(\frac{R}{C}\right)$ will also affect the change in volume of ballonets filled with air and can be estimated by using the Eq. (18) [39]:

$$\Delta Vol_{blnt} = \frac{RdVol_{env}}{60 \times 1000} \tag{18}$$

where R is climb rate (ft/min), d is change in density, ΔVol_b is volume change in ft^3/sec and Vol_{env} is volume of envelope in ft^3. This is an important factor in the acceleration segment of an airship because; if the climb rate is high, ballonets inflate and deflate at higher rate. R has the same meaning as that of $\left(\frac{R}{C}\right)$ used in the present work. In comparison with aircraft [35], the acceleration segment of airship is quite small [25] including the climb segment for takeoff and the $\left(\frac{R}{C}\right)$ which can be estimated by using Eq. (19) [25]. Rearranging this equation will take the form of Eq. (20):

$$\frac{dh}{dt} = V \sin\gamma = \frac{V(T\cos(\alpha + i_T) - D)}{m_{net}} \tag{19}$$

$$ROC = \frac{T\ \cos(\alpha + i_T)V - qVK\left(C_{L_{aero}} - C_{L_{md_{aero}}}\right)^2}{m_{net}} \tag{20}$$

In this expression, i_T is the incidence angle of power plant, V is forward velocity and q is dynamic pressure. For steady flight of a propeller driven HB aircraft with $(\alpha + i_T) = 0$, relationship of $\left(\frac{R}{C}\right)_{max}$ given in Ref. [13] can be rearranged to account for the effect of brake shaft horsepower for reciprocating IC engines and by replacing the gross takeoff mass with m_{net}, shown below as Eq. (19):

$$\left(\frac{R}{C}\right)_{max} = \frac{\eta_{pr}P}{m_{net}} - \left[\frac{2}{\rho}\sqrt{\frac{K}{3C_{DO}}}\left[\frac{m_{net}}{s}\right]\right]^{\frac{1}{2}} \frac{1.155}{\left(\frac{L_{aero}}{D}\right)_{max}} \tag{21}$$

4.3. *Maximum velocity*

For the calculation of $W_{net_{MC}}$, there will be requirement to select the pair of cruise segments, such that $V_{\max}$ is at mid cruise condition. In the case of aircraft, "*In steady, level flight, the maximum velocity is determined by the high speed interaction of the thrust required and thrust available curves*". Thrust is directly the function of velocity and its corresponding drag. Aircraft usually cruises at constant speed by deflecting the aerodynamic surfaces. But airships vary the velocity to keep the pressure altitude as constant. For hybrid airships [25], three cruise strategies are provided: keep aerodynamic lift constant for $\left(\frac{L_{aero}}{D}\right)_{max}$ condition, keep speed constant and start the cruise segment with the option of constant aerodynamic lift to reduce the cruise duration and then maintain a constant speed. In this way; the cruise segment will be split into a number of segments. In a recent reference of hybrid airship, for shorter flight durations, condition of $\left(\frac{L_{aero}}{D}\right)_{max}$ was more emphasized. Similar to aircraft, for HB aircraft, there can be another option i.e. to fly at Carson's speed; "*the least wasteful way of wasting fuel*", which is equal to $1.32V_{(L/D)_{max}}$ [13]. Unfortunately, in any of the cases discussed above, altitude corresponding to the minimum fuel consumption for HB aircraft cannot be met. This is because of the fact that the requirement of thinner atmosphere for less fuel consumption during the cruise segment is quite high due to the limitation of pressure height.

Analytically, value of m_{net_MC} can be expressed by using Eq. (23); derived for a simple mission profile by using Eq. (22), in which $\frac{m_y}{m_x}$ and $\frac{m_z}{m_y}$ are the mass fractions for the takeoff and climb segment respectively. There is always a certain amount of fuel which is usually trapped in fuel pipes or in the fuel tank, known as trapped fuel. Before the start of mission analysis, we subtract the trapped fuel, usually about 6% of the overall fuel mass. Moreover from the historical trends of aircraft [13,29], mass fractions for warm-up/takeoff and climb segments are 0.97–0.99 and 0.985 respectively.

$$\frac{m_z}{m_x} = \frac{m_z}{m_y} \times \frac{m_y}{m_x} \tag{22}$$

If the half fuel condition is assumed for mid cruise segment [13], then m_{net_MC} can be expressed as Eq. (23) which can be further rearranged to take the form of Eq. (24):

$$m_{net\_MC} = m_w - \frac{1}{2}(m_z - m_w) \tag{23}$$

$$m_{net\_MC} = \frac{1}{2}m_z\left(1 + \frac{m_w}{m_z}\right) \tag{24}$$

5. Case study

A case study is presented here to evaluate the proposed analytical methodology for HB aircraft, Figure 5. This is perhaps an extension of the previous design exercise [26] in which 49% of gross takeoff mass is balanced by the aerostatic lift and Rotax 912 engines were used to power the aircraft. Wing span of conceptual HB aircraft model is about 20 m and length of the hull is about 33 m. C_{D_0} was estimated by using component buildup method [29] and by using S_{ref} to be equal to the total planform area, obtained from the CAD software. It is well known that cruising altitude of general aviation small aircraft is usually 3–5 km, due to the requirement of thinner atmosphere for less fuel consumption during the cruise segment. But in the present case study, due to the limitation of pressure height, the

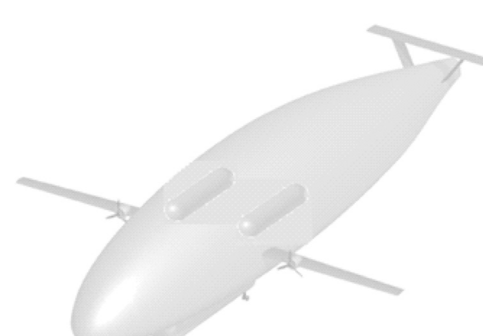

Figure 5 Pictorial view of a HB aircraft.

Table 3 Input parameters of case study.

Input parameters		Value
Conditions and constraints	S	150 m^2
	W_{net}	4900 N
	m_{gas}	100 kg
	$m_{net_{MC}}$	450 kg
	$V_{\max}$	100 km/hr
	$\left(\frac{R}{C}\right)_{max}$	8 m/s
Aerodynamics	C_{DO}	0.018
	$C_{L_{max}}$	2.0
	K	0.03

Table 4 Estimated power (hp) at different η_{pr} for defined constraints.

Condition	P_{TO}	$P_{\left(\frac{R}{C}\right)_{max}}$	$P_{V\,max}$
Full load	62	70	96

cruise altitude is assumed to be limited to only 1.5 km. Since the effect of hydrogen fuel on specific fuel consumption of engine is not known at this stage. Therefore, it is assumed to be same as that for existing fuel for the selected engine. $\left(\frac{R}{C}\right)_{max}$ is assumed to be equal to 8 m/s and all the required inputs for revised analytical formulation of power budget are tabulated below altogether in Table 3. Efficiency of propeller for defined constraints of TO, V_{max} and $(R/C)_{max}$ is 0.85, 0.8 and 0.75 respectively.

The estimated power required is listed in Table 4. Among these values, one may chose the maximum value. This is also to stay on the safe side, specially for the worst case scenarios. This is because of the fact that a lesser value might turn out to be giving very less horse power than required. However, taking a higher value means we have taken a value, which gives the maximum possible horsepower and hence thrust.

Furthermore, advantages of liquid hydrogen technology for hybrid buoyant aircraft can only be further explored if we have a realistic data set of required propulsion parameters.

Since the quantity of air in ballonets may vary to fulfill the requirement of change in volume. Therefore, the present case study can be extended in future to evaluate the effect of inflation and deflation of ballonets on power requirement for IC engine selection.

6. Conclusions

Framework of methodology for estimation of power budget for IC engine was established in this work, with emphasis on the utilization of existing analytical relationships of aircraft, airships and hybrid airship. Some anomalies in the existing analytical relationships for the estimation of drag for thrust requirement and condition are also highlighted. Revised analytical relationships were derived for estimation of power budget for HB aircraft and each proposed formula is expressed in the simplest form, which was further utilized in a case study for the ease of implanting the analytical formulation. It is perceived that the analytical effort done in the present work will help in future for filling the technological gap for estimation of power budget for engines of HB aircraft for greener solution.

Acknowledgments

The support of the Ministry of Science, Technology and Innovation (MOSTI), Malaysia, under the Grant 06-01-08-SF0189 is gratefully acknowledged. Authors are thankful to Dr. Daniel P. Raymer and Professor. S. Gudmundsson for useful discussions on the equation for form factor.

Appendix

Based on the thrust estimation relationships derived by Anderson [13], revised analytical formulas of power requirement P_R for three major design constraints; discussed earlier in Section 4 are given below:

1. *Takeoff distance*

Takeoff distance of an aircraft can be estimated by using Eq. (A-1), [13]:

$$S_{TO} = s_g + S_a \qquad (A-1)$$

Where, ground roll for takeoff flight segment $S_{g_{TO}}$ can be estimated by using Eq. (A-6) [25] and airborne distance s_a by using Eq. (A-2) [13]:

$$S_a = R\sin\theta_{OB} \qquad (A-2)$$

In this formula, R is flight path radius and $\theta_{OB}\theta_{OB}$ is the included flight path angle. Both these variables can be obtained by using Eqs. (A-3) and (A-4) respectively [13].

$$R = \frac{6.96(V_{stall})^2}{g} \qquad (A-3)$$

$$\theta_{OB} = \cos^{-1}\left(1 - \frac{h_{OB}}{R}\right) \qquad (A-4)$$

Where h_{OB} is the obstacle height and its value is equal to 50 ft for FAR-23 certification. Substituting back Eq. (A-2) in Eq. (A-1) with value of S_g known from Eq. (17) after substituting the value of R from Eq. (3) and rearranging the expression will take form of Eq. (A-6) for required thrust.

$$R = \frac{6.96(V_{stall})^2}{g} \qquad (A-5)$$

$$T = \frac{\left(W_{net}/g + m_{gas}\right)V_{TO}^2/2}{S_{g_{TO}} - S_a} + [D + \mu(W_{net} - L_{aero})]_{@0.707\,V_{LO}} + NV_{TO} \qquad (A-6)$$

Power required will simply be the product of thrust T, (Eq. (A-6)) and forward takeoff velocity $V_{TO} = 0.707\ V_{LO}$.

$$P_{TO} = \frac{1}{\eta_{pr}}\left[\frac{\left(\frac{W_{net}}{g} + m_{gas}\right)\frac{V_{TO}^2}{2}}{s_{TO} - s_a} + [D + \mu(W_{net} - L_{aero})]_{@0.707V_{LO}} + NV_{TO}\right]V_{TO} \quad (A-7)$$

2. Maximum rate of climb

For a known value of $\left(\frac{R}{C}\right)_{max}$, Eq. (20) can be rearranged to find the value of required power for this constraint to form Eq. (A-8):

$$P_{\left(\frac{R}{C}\right)_{max}} = \frac{m_{net}}{\eta_{pr}}\left[\left(\frac{R}{C}\right)_{max} + \left(\frac{2}{\rho}\sqrt{\frac{K}{3C_{DO}}}\left(\frac{m_{net}}{S}\right)\right)^{\frac{1}{2}}\frac{1.155}{\left(\frac{L_{aero}}{D}\right)_{max}}\right] \quad (A-8)$$

3. Maximum velocity

An airship can have a mixed cruise strategy [25], which is discussed in Section 4.3. If the same holds good for a HB aircraft than for V_{max} corresponding to mid cruise condition, the required power ($P_{V_{max}}$) can be estimated by using Eq. (A-9) [13]:

$$P_{V_{max}} = \frac{1}{\eta_{pr}} \times T \times V_{max} \quad (A-9)$$

For a HB aircraft, if the altitude for the specified V_{max} is the pressure altitude due to inflation of ballonets and natural expansion of lifting gas; then for a steady level flight condition, $T = D$ and required $L_{aero} = W_{net} - \Delta W_{fuel}$. This means that to account for the change in m_{net} due to burning of fuel, L_{aero} should be equal to net mass (defined here as $m_{net_{MC}}) \times g$, minus the fuel consumed till mid cruise segment. Drag force is simply the product of reference area, dynamic pressure and coefficient of drag (Eq. (1)), which can be rearranged to take the form of Eq. (A-10) for V_{max} at mid cruise condition:

$$T = D = \frac{1}{2}\rho_\infty V_{max}^2 S_{ref} C_{DO} + \frac{2KS_{ref}}{\rho_\infty V_{max}^2}\left(\frac{m_{net_{MC}}}{S_{ref}}\right)^2 \quad (A-10)$$

Substituting the value of thrust from Eq. (A-10) to Eq. (A-9) will give the power required for V_{max} constraint due to inherent structural limitations to withstand the maximum load, Eq. (A-11):

$$P_{V_{max}} = \frac{1}{\eta_{pr}}\left[\frac{1}{2}\rho_\infty V_{max}^2 S_{ref} C_{DO} + \frac{2KS_{ref}}{\rho_\infty V_{max}^2}\left(\frac{m_{net_{MC}}}{S_{ref}}\right)^2\right]V_{max} \quad (A-11)$$

References

[1] Air Transport Action Group, Facts and figures. URL: ⟨http://www.atag.org/facts-and-figures.html/⟩, 2015 (accessed 06.03.15).
[2] A. Gamaleyev, ESTOLAS Project Description. URL: ⟨http://www.estolas.eu/⟩, 2012 (accessed 06.03.14).
[3] R. Rist, World's First Practical Airship. URL: ⟨http://www.dynalifter.com/⟩, 2012 (Cited 10.03.13).
[4] B. Prentice, R. Knotts, Cargo airships: international competition, Journal of Transportation Technologies (4) (2014) 187-195. URL: http://dx.doi.org/10.4236/jtts.2014.43019 (Cited in July 2014).
[5] K.S. Zhang, Z.H. Han, B.F. Song, Flight performance analysis of hybrid airship: revised analytical formulation, J. Aircr. 47 (4) (2010) 1318–1330.
[6] R. Hills, A review of measurements on AGARD calibration models, 1961.
[7] B. Khandelwal, A. Karakurt, P.R. Sekaran, V. Sethi, R. Singh, Hydrogen powered aircraft : the future of air transport, Prog. Aerosp. Sci. 60 (2013) 45–59.
[8] A. Abbas, J. De Vicente, E. Valero, Aerodynamic technologies to improve aircraft performance, J. Aerosp. Sci. Technol. 28 (1) (2013) 100–132.
[9] A. Colozza, J. Dolce, High-altitude, long-endurance airships for coastal surveillance, NASA Tech. Report NASA/TM-2005-213427, 2005.
[10] B.E. Prentice, R.P. Beilock, A.J. Phillips, The rebirth of airships, J. Transp. Res. Forum 44 (1) (2005) 173–190.
[11] J.A. Yamin, The performance of hydrogen-powered 4-stroke SI engine using locally designed fuel regulator, J. Braz. Soc. Mech. Sci. Eng. 32 (3) (2010) 195–199.
[12] A. Ceruti, P. Marzocca, A conceptual approach to unconventional airship design and synthesis, J. Aerosp. Eng. 27 (6) (2013), http://dx.doi.org/10.1061/(ASCE)AS.1943-5525.0000344.
[13] J.D. Anderson, Aircraft Performance and Design, McGraw-Hill, Boston, 1999.
[14] H. Hiroyasu, Diesel engine combustion and its modeling, in: Proceedings of 1st International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines, Tokyo, Japan, pp. 53–75.
[15] J.T. Prentice, E. Barry, R.E. Beilock, A.J. Phillips, The 5th International Airship Convention and Exhibition, 2014.
[16] E. Kahraman, Analysis of a Hydrogen Fueled Internal Combustion Engine (Doctoral Dissertation), Izmir Institute Of Technology, Izmir, 2005.
[17] X. Bevenot, A. Trouillet, C. Veillas, H. Gagnaire, M. Clement, Hydrogen leak detection using an optical fibre sensor for aerospace applications, Sensors Actuators B: Chem. 67 (1) (2000) 57–67.
[18] K. Gillingham, Hydrogen internal combustion engine vehicles : a prudent intermediate step or a step in the wrong direction? Global Climate and Energy Project Report, January 2007.
[19] H. Nojoumi, I. Dincer, G.F. Naterer, Greenhouse gas emissions assessment of hydrogen and kerosene-fueled aircraft, Int. J. Hydrogen Energy 34 (3) (2009) 1363–1369.
[20] D. Verstraete, P. Hendrick, P. Pilidis, K. Ramsden, Hydrogen fuel tanks for subsonic transport aircraft, Int. J. Hydrogen Energy 35 (2010) 11085–11098.
[21] G.D. Brewer, The prospects for liquid hydrogen fueled aircraft, Int. J. Hydrogen Energy 7 (1) (1982) 21–41.

[22] A.U. Haque, W. Asrar, A.A. Omar, E. Sulaeman, J.S.M. Ali, Stability and takeoff ground roll issues of hybrid buoyant aircraft, Appl. Mech. Mater. 660 (2014) 503–507.

[23] H. Watanabe, Future possibility of world airship transportation as new business, In: Airships to the Arctic V, Calgary, Alberta. URL: ⟨http:// www.isopolar.com/wpcontent/uploads/2013/03/Hiroyuki-Watanabe-presentation-Future-Possibility-of-World-Airship-Transportation-as-New-Business.pdf⟩, October 2009 (accessed: 06.05.15).

[24] S. Vogel, Comparative Biomechanics: Life's Physical World, Princeton University Press, USA, 2013.

[25] G.E. Carichner, L.M. Nicolai, Fundamentals of Aircraft and Airship Design: Volume II, Airship Design, American Institute of Aeronautics and Astronautics, Washington DC, 2013.

[26] A.U. Haque, W. Asrar, A.A. Omar, E. Sulaeman, J.S.M. Ali, Conceptual design of a winged hybrid airship, in: Proceedings the 21st AIAA Lighter-Than-Air Systems Technology Conference, Paper No. AIAA-2014-2710, Atlanta, GA, 16–20 June 2014.

[27] S.F. Hoerner, Fluid Dynamic Drag, Bakerfield, CA, published by the author Hoerner Fluid Dynamics, 1965.

[28] S. Gudmundsson, General Aviation Aircraft Design: Applied Methods and Procedures, Butterworth-Heinemann, United Kingdom, 2013.

[29] D. Raymer, Aircraft Design: A Conceptual Approach, Fifth Edition, American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 2012.

[30] F.R. Goldschmied, Aerodynamic hull design for HASPA LTA optimization, Journal of Aircraft 15 (9) (1978) 634–638.

[31] G. Ilieva, J. Páscoa, J.C. Páscoa, A. Dumas, Numerical research on efficiency performance of the propulsion system for an innovative airship, in: Proceedings of the ASME 2012 International, Design Engineering Technical Conferences & Computers andInformation in Engineering Conference IDETC/CIE 2012, DETC2012-70927, Chicago, IL, USA, August 12–15, 2012, .

[32] A.U. Haque, W. Asrar, A. Omar, E. Sulaeman, J.S.M. Ali, Cambered profile of a california sea lion's body, J. Exp. Biol. 218 (2015) 1270–1272.

[33] T. Michele, R. Emilia, S.M.I. Di, D. Antonio, Constructal design for efficiency: the case of airship design, in: Proceedings of IMECE2013 ASME International Mechanical Engineering Congress and Exposition, Paper No. IMECE2013-63448, San Diego, California, USA, November 15–21, 2013.

[34] T. Liu, W.W. Liou, M. Schulte, Aeroship: a hybrid flight platform, J. Aircr. 46 (2) (2009) 667–674.

[35] L.M. Nicolai, G.E. Carichner, Fundamentals of Aircraft and Airship Design: Volume I, Aircraft Design, American Institute of Aeronautics and Astronautics, Washington DC, 2013.

[36] J. Roskam, Airplane Aerodynamics and Performance, Kansas, Design, Analysis and Research Corporation, 1997.

[37] FAA Regulations, Regulations on Airship Design Criteria, FAA P-8110-2, 2001.

[38] EASA Standard, Certification Specifications for Normal, Utility, Aerobatic and Commuter Category Aero Planes CS-23, Amendment 3, Available online: ⟨http://www.easa.europa.eu/agency-measures/certification-specifications⟩ (Cited 09.01.13).

[39] J.D. Khoury, G.A. Gillett, Airship Technology, Cambridge University Press, New York, NY, 1999.