Unmanned Systems, Vol. 5, No. 4 (2017) 237–246
© World Scientific Publishing Company
DOI: 10.1142/S230138501750011X

UNMANNED SYSTEMS
http://www.worldscientific.com/worldscinet/us

Defining Reference Area for Prediction of Aerodynamic Coefficients of a Biologically Inspired Hybrid Buoyant Vehicle

Anwar-Ul-Haque[*,‡], Waqar Asrar[*], Ashraf A. Omar[†], Erwin Sulaeman[*]

[*]*Department of Mechanical Engineering,*
International Islamic University Malaysia (IIUM), Kuala Lumpur 50728, Malaysia

[†]*Department of Aeronautical Engineering,*
University Of Tripoli, P.O. Box 13154, Tripoli, Libya

Geometric and volumetric quantities are usually used to define the reference area for the prediction of aerodynamic coefficients of various aquatic mammals, airships and unmanned vehicle. However, reference area does not have a unique definition, especially for a hybrid buoyant aerial vehicle having hybrid lifting hull which resembles a Steller sea lion. The term square cube root of volume is traditionally used as reference area to nondimensionalize the aerodynamic forces for conventional as well as unconventional airships. Published experimental data are usually available for complete configuration at low speed and in nondimensionalized form. So, a generic model of an aircraft's fuselage was first tested in a wind tunnel as a test case to first determine the lift force and then the influence of different choices of reference area on the lift. A hybrid lifting hull was numerically simulated for the prediction of lift as well as drag coefficients and their ratio. It was found that the volumetric term has undefined correlation with aerodynamic forces in both cases. Changes in aerodynamic coefficients are not prominent when using the wetted area as the reference area. Based on the predicted trends of aerodynamic coefficients and a deep literature survey, the projected planform area is proposed as the best option for reference area of a Steller sea lion as well as for hybrid lifting hull of a hybrid buoyant vehicle.

Keywords: Airship; hybrid airship; marine animals; aerodynamics; reference area; buoyancy.

Nomenclature

C_{L_P}	lift coefficient based on projected planform area
C_{D_A}	drag coefficient based on wetted area
C_{D_F}	drag coefficient based on frontal area
C_{D_P}	drag coefficient based on projected planform area
C_{D_V}	drag coefficient based on $\mathrm{Vol}^{2/3}$
D	aerodynamic drag force, (N)
FF	form factor
HB	hybrid buoyant
HLH	hybrid lifting hull
L	aerodynamic lift force, (N)
LTA	lighter than air
m	mass, kg
Q_{fus}	volume of fuselage, m^3
S_{aero}	aerodynamic reference area, m^2
S_{fus_s}	surface area of fuselage of aircraft, m^2
S_C	projected planform area of canards, m^2
S_{fus_P}	projected planform area of fuselage, m^2
S_H	projected planform area of hull, m^2
S_{plan}	projected planform area, m^2
S_{ref}	reference area, m^2
S_V	volumetric surface area, m^2
S_W	reference area of wing, m^2
S_H	reference area of wing, m^2
V	flying velocity (m/s)
$\mathrm{Vol}^{1/3}$	cube root of volume
$\mathrm{Vol}^{2/3}$	square cube root of volume, m^2
α	angle of attack, (degree)

Received 28 August 2016; Revised 11 September 2017; Accepted 12 September 2017; Published 1 November 2017. This paper was recommended for publication in its revised form by editorial board member, Hongliang Ren.
Email Address: ‡*anwar.haque@live.iium.edu.my*

1. Introduction

The hydrodynamic shapes of aquatic animals like Steller sea lion are regulated by the physical laws of nature. Such animals are perhaps distinct from other marine animals, like fishes and whales due to their high speed, unique body design and different biological adaptations for reducing the drag. Sea animals utilize aerostatic lift to stay uplift to balance the effect of gravity. In 1990, Alexander [1] carried out a study related to the effect of different reference areas for estimation of the drag coefficient of swimming animals. He found that there is a drastic reversal in the drag coefficient data obtained by using the wetted area as the reference area for two species of Idotea: genus of isopod crustaceans. He mentioned that that there is no powerful hydrodynamic basis for the selection of reference area for the estimation of drag coefficient. As per findings of Alexander [1], biologists have no clear convention for choosing reference area and it will be useless to apply the same without justifying it.

In most of the aeronautical applications, frontal area is used where pressure drag has a dominant effect [1,2]. Before World War II, drag coefficients during the deceleration phase of cars were estimated by using the frontal area [3]. The same reference area was used to determine the drag coefficients in sea animals [4] and in some cases of airships [5, 6] as well. Drag of a well-designed contour of an airship is about 2–3% of a sphere with same frontal area [7]. If frontal area is used, then bodies which are shorter in length and blunt in shape will create the lowest drag. But the same is not true for elongated shape bodies, instead wetted area is to be used in order to get the same [8]. This situation becomes more complex when the elongated shape is cambered as well, for example, the cambered shape of the body of insects and the commercial transport aircraft. One is at very low Reynolds numbers where unsteady flapping wings affect mostly the aerodynamic forces. The other one has completely different Reynolds number regime. Cambered airfoil shapes do exist in flies as well: house fly (Fig. 1) and fruit fly (Fig. 2) are two good examples. It can be noted from these figures that if the head, thorax and abdomen are put together, they seem to form a cambered airfoil in lateral view, which is flat on the bottom and more rounded on the top. Unfortunately, the significance of body lift to balance the overall forces in insects has not been systematically investigated [8]. Body lift is basically free of cost lift that balances partial weight of the body in accelerating as well as in glide phase. As per one of the references of flight of honey bee published back in 1953 by Brian Hocking, the resulting body lift was claimed to produce one third of the total lift. Such claims are generally discredited as it is aerodynamically very unlikely that the aspect ratio of the body would be far less than one. Later studies have proven that the contribution of insect's body lift towards overall lift is typically less than 10% [8].

Fig. 1. House fly.

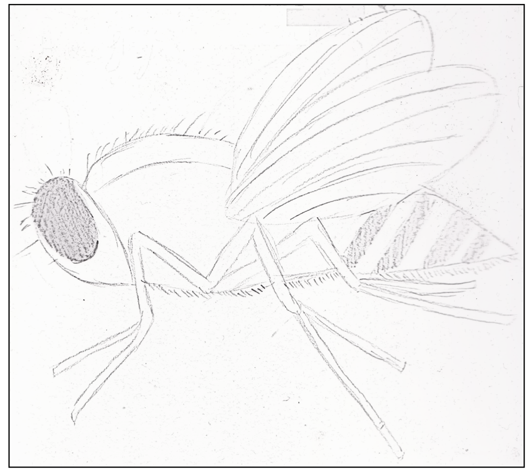


Fig. 2. Fruit fly.

To the authors' best knowledge, studies related to the body lift of marine animals were hardly available. For example, in the case of a Steller sea lion, there is no published study available for the investigation of lift produced by its cambered body shape. This is not a surprise, but perhaps the result of an oversimplification in assuming its geometric resemblance with a symmetric airfoil, which was carried forward in later studies as well [9]. This issue is discussed in detail in the following section. Such inspiration from nature can be utilized for the design and development of hybrid buoyant aerial vehicle with hybrid lifting hull. Cambered profile of a hybrid lifting hull will provide additional lift to meet the requirement of high lift to drag ratio for the cruise, pre-stall and takeoff segment of the flight. Further research on such vehicle needs detailed knowledge of lift force generated by the aerodynamic shape of fuselage.

The cross-section of the fuselage of a commercial transport aircraft is usually circular or oval [10–12]. Such shapes usually provide very small lift at zero angle of attack, where the experimental data of the same were hardly available. In the case of commercial aircraft, lift force is nondimensionalized by the projected planform area of wing. Aerodynamic data, especially the data of lift coefficient of fuselage are hardly available in the literature, except some old wind tunnel tests conducted to investigate the effect of yaw on lateral stability characteristics with NACA 23012 wing [13]. In those cases as well, the coefficient of lift is nondimensionalized by wing's planform area.

To date, no unique definition exists for defining the reference area for a HB vehicle. In the aircraft design, the fuselage is assumed to produce lift from the area of the wing which is buried inside the fuselage, i.e. a fraction of the lift is produced by the fuselage; the major portion of the lift is produced by the wing area outside the fuselage. In the case of a HB vehicle, the fuselage contribution is substantial when compared to the wing. For example, in the case of a hybrid airship, aerodynamic contour of hull can produce up to 40% of the total aerodynamic lift [14], however a true representation of aerodynamic characteristics of a particular shape can be revealed only after obtaining the coefficient of lift; this highlights the need to compare the general trends of coefficient of lift of fuselage with different choices of reference areas: frontal, planform or surface area of fuselage.

During the design and analysis, there is always a requirement for accurate prediction of aerodynamic parameters for the complete mission profile which requires aerodynamic coefficients. At the moment, there is no single definition for the reference area for HB aerial vehicle and hybrid airship. Therefore, for a definition that is valid for all shapes, one may look at sea animals to understand their anatomy to define the reference area for a HB aerial vehicle. To the best of the knowledge of authors, no such studies have been carried out earlier.

In this manuscript, we attempt to find out how lift/drag of the elongated body (similar to the aircraft fuselage) scales with the geometric parameters. The purpose is to give a broader meaning to aerodynamic coefficients for biologically inspired HB aerial vehicle. The applications, which we are interested in, are the flows around the aquatic mammals and other biological systems' inspired HB aerial vehicle.

2. Resemblance Between a HLH and a Steller Sea Lion

The elongated hydrodynamic cambered shape of Steller sea lion allows it to swim faster and helps in delaying flow separation, reducing the overall drag force acting on it. Recently [15], we have used an Eppler 1200 airfoil in the design of a hybrid lifting hull to achieve the required volume and sufficiently flat base to yield the least wasted space and for the ease of attachment of gondola with the hull, as shown in Fig. 3. Eppler 1200 airfoil has laminar flow extended to 50–60% of the airfoil length and has maximum thickness at 36% of chord length. Complete geometric details of the outer contour of the Steller sea lion are not yet available. Only information available is the location of maximum thickness, which is about 34% of body length [16]. It is pertinent to highlight that in this study, selection of Eppler-1200 airfoil for hybrid hull is based on the location of maximum thickness, visual judgment of geometric profile of a Steller sea lion and requirement of takeoff ground roll angle to fulfill future certification requirement [17].

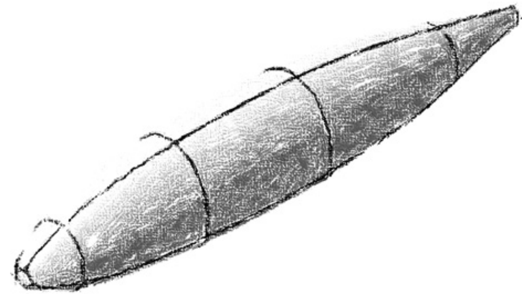


Fig. 3. Hybrid lifting hull.

Fineness ratio (λ), location of maximum width and buoyant independent drag of a Steller sea lion are the three quantities, which are common with this hybrid lifting hull. It is well known that conventional airships usually have fineness ratio value of about 2.3–2.8. However, a fineness ratio between 5 and 6 was found to be optimal for a fixed maximum diameter [18]. Interestingly, as per the findings of Suzuki [16], this range of fineness ratio is found comparable to the Steller sea lion. This marine animal has a fineness ratio of 5.55 and location of maximum thickness of outer profile is at 34% of overall length [4]. This fineness ratio is also common with other marine mammals like dolphins, fishes and whales [19].

3. Available Choices of Reference Area

There are different choices available for defining the reference area for different airships and aircraft to nondimensionalize the aerodynamic forces and moments, (Table 1). All these options are reviewed and discussed below along with the justifications provided in the available references: [14], [20] and [21] have defined $\mathrm{Vol}^{2/3}$ as the reference area for obtaining the drag force coefficient of airship. Full justification of its utilization could not be seen in these references and its usage is referred to as 'it is traditionally used' or 'it is a matter of convenience'. As per Carichner and Nicolai [14], decision on the use of volume $\mathrm{Vol}^{2/3}$ was taken in one of the conferences on the subject of LTA. Authors of this reference are of the view that nondimensionalizing by square cube root of volume is basically a matter of convenience as the volume can easily be

Table 1. Comparison of definitions of reference area used for different airships and aircraft.

Reference area	Hybrid airship with hybrid lift hull	Winged hybrid airship	Aircraft	Hybrid wing body aircraft
S_{plan} of hull/(Vol$^{2/3}$)	S_{plan} of hull/(Vol$^{2/3}$)	S_{plan} of wing/(Vol$^{2/3}$)	S_{plan} of wing	total S_{plan}

determined by using Archimedes law. In fact, volume isn't so important for a regular aircraft except aircraft like Pregnant Guppy [22] and use of Vol$^{2/3}$ parameter for airships was perhaps an attempt to include the effects of fineness ratio right into the coefficient, but it may be better handled by *FF*. Furthermore, it might be inappropriate to use the term "Pregnant Guppy," but it is perhaps the correct aircraft name.

Airship drag is primarily due to skin friction and it will be more appropriate to use planform area of hull as the reference area [14]. This approach is similar to the approach used for defining the reference area for the aircraft. For airships, the pitching moment is nondimensionalized by the length of the hull body [14]. But for aircraft, it is the mean aerodynamic chord of wing [23]. In the case of a winged hybrid airship, aerodynamic lift and drag are nondimensionlized by the term S_{aero} [24], which corresponds to the reference area of wing.

For a hybrid airship with lifting hull, S_{aero} corresponds either to the planform area of the hull [14] or Vol$^{2/3}$ [25]. In the latter case, Vol$^{2/3}$ as the reference area has been justified due to the linear relationship between the planform area of aerodynamic hybrid lifting surfaces and envelope area of the hull with Vol$^{2/3}$ [25]. For blended wing aircraft, it is the total planform area which is usually taken as reference area and used in design and analysis [26, 27].

In the case of a winged hybrid airship (WHA), getting aerodynamic lift from the wing and aerostatic lift from the hull, emphasis is given to the independent computation of the drag force of the hull and of the wing [25]. In light of above-mentioned discussion on buoyancy and drag, authors are of the point of view that there is no need of separate term to account the effect of volume in drag term. Moreover, such a definition will also limit any experimental work related to the aerodynamics of the complete configuration of a winged hybrid airship. This is because of the fact that the component build-up method can be used in the experimental work by individually testing the full/half model of wing and full/half model of hull of a winged hybrid airship. But the drag contribution due to wing–hull interaction will still be unknown for any future design and analysis work. Reference 25, justifies the use of Vol$^{2/3}$ as the reference area due to the existence of a linear relationship between the planform area of aerodynamic hybrid lifting surfaces and envelope area of the hull with Vol$^{2/3}$ for a specific hull in which the shape is invariant. But such reasoning may not be valid for different shapes where the planform area is held constant and the height is varied. Multiple shapes of such hulls of the same projected area but of different surface areas can be generated.

4. Results and Discussion

HB aerial vehicle can be scaled allometrically for constant aerostatic lift and isometrically for variable aerodynamic lift. Such scaling is also common in hybrid airship whose aerodynamic lift is generated from the outer contour of hybrid lifting hull and aerostatic lift due to lifting gas [28]. The critical geometric parameter for allometric scaling is volume of gas bags and surface area. For isometric scaling of aerodynamic lift, the surface wetted area is used which preserves the dimensional properties of hybrid lift. In the case of airship, it is difficult to predict the wetted area of a hull in the early design phases. For subsonic commercial aircraft, analytical relationships are available for the estimation of volume and surface area. Such relationships for the estimation of frontal and surface area of conventional aircraft are discussed below with special focus on the utilization of the same relationships for defining the surface area of HB aircraft.

4.1. *Analytical relationships*

Fuselage of a passenger aircraft is approximated as a slender body of revolution with a cylindrical mid-section and streamlined nose and tail section [29]. In such as an aircraft, $S_{fus_{surf}}$ and Q_{fus} are interrelated and can be estimated by using Eqs. (1) and (2) by Torenbeek [29]:

$$Q_{fus} = (S_{fus})_{front}\, \bar{d}_{fus}(l_{fus} - 2/\lambda_{fus}), \tag{1}$$

where λ_{fus} is the fineness ratio, $S_{fus_{front}}$ is the frontal area of fuselage and $\bar{d}_{fus}$ is equal to the effective diameter of fuselage. The $S_{fus_{surf}}$ is given as follows:

$$(S_{fus})_{surf} = 2(2\pi\lambda_{fus})^{1/3} Q_{fus}^{2/3}(1 + 1/\lambda_{fus}^2). \tag{2}$$

Although Eqs. (1) and (2) are applicable for conventional aircraft, they can also be used to calculate the volume and surface area of a hybrid lifting hull of hybrid buoyant aircraft. However, a correction factor due to aerodynamic lofting of the airfoil shaped hull is required. For example, by using the volume of hybrid lifting hull [15], the surface area calculated by using Eq. (2) is 32 m^3 less than that of the

Table 2. Comparison of geometric parameters.

	$(S_{\text{fus}})_{\text{front}}$	Q_{fus}	$(S_{\text{fus}})_{\text{surf}}$	$(S_{\text{fus}})_{\text{surf}}/(Q_{\text{fus}})^{2/3}$	$(S_{\text{fus}})^{1/2}_{\text{surf}}/(Q_{\text{fus}})^{1/3}$
Analytical relationship	27.32	525	408	6.53	0.32
Reference hull [4]	26.65	535	440	7.04	0.39

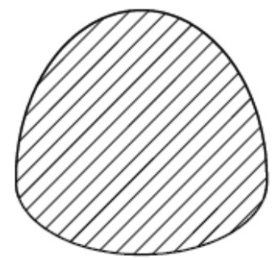
actual profile of hull which is obtained by using standard Eppler-1200 laminar airfoil, Fig. 2. Moreover, in Eq. (2) [29], $Q_{\text{fus}}^{2/3}$ used is related to the surface area, but the results are different for a conventional-shaped hull/fuselage and a hybrid lifting hull for a known value of fineness ratio λ_{fus} and volume of fuselage Q_{fus}. Moreover, as the surface area increases with the increase in volume, there will be change in the lift and drag coefficients. A detailed comparison of geometric parameters obtained by using Eqs. (1) and (2) for λ_{fus} equal to 5.2 and $\overline{d}_{\text{fus}}$ equal to 5.9 is shown in Table 2.

In the field of biology, [30] introduced a volumetric surface area term S_V (Eq. (3)) for comparing bluegill and trout of nearly the same mass.

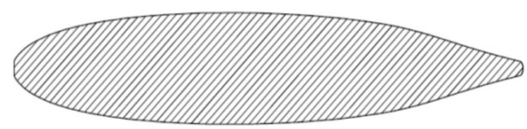
$$S_V = \frac{\text{wetted surface area}}{(\text{volume})^{2/3}}, \tag{3}$$

where S_V accounts for the effect of size as well as the shape. S_V for bluegill and trout of almost similar $\text{Vol}^{2/3}$ was 10.1 and 9.7, respectively. Moreover, slight difference in $\text{Vol}^{2/3}$ was due to the difference in mass of a particular bluegill and trout. Equation (3) was further applied in the present study in the case of fuselage and hybrid lifting hull. Similar results can be obtained for fuselage of conventional aircraft and hull of a HB aerial vehicle with hybrid lifting hull. The difference in volume of the two is about 10 m^3, but values of S_V are quite close (see the third column in Table 2). The difference between the values of surface areas values is quite high and a slight difference in the values of S_{fus_f} is observed. Therefore, for the shape under discussion, Eq. (2) perhaps needs to be revised to account for the effect of lofting required for an airfoil-shaped hull.

Webb [30] mentioned S_V is a nondimensional parameter, which is shape as well as size-dependent. Another solution to cater to the effect of size and shape is to divide the square root of surface area by the cube root of volume. However, the effect of shape of hybrid lifting hull is not prominent compared with that obtained by using $S_{\text{fus}_s}/Q_{\text{fus}}^{2/3}$. An aircraft's fuselage is sized as per the payload requirement and its wetted area is different from that of a hybrid lift producing hull, which is the cause of the obvious difference in it. S_{ref} is referred to here as the total wetted area and may not be confused with name S_H, whose value is 142 m^2 for a hybrid lifting hull [15]. For the purpose of clarification, pictorial views of frontal area and projected planform area of a hybrid lifting hull used in a conceptual design study in Ref. 15 are shown in Fig. 4.



(a) Frontal view



(b) Projected planform view

Fig. 4. Schematic views of hybrid lifting hull of a HB aerial vehicle.

4.2. *Proposed reference area*

Defining the reference area is important to standardize engineering values. Moreover, an adequate and meaningful definition of the reference area is required by the researcher to non-dimensionalize the aerodynamic forces. Recently Vogel [8] highlighted highlighted the complication in the selection of a suitable reference area for the estimation of drag force for sea animals. For streamlined bodies, wetted area (less than any fractal character of the surface) is a suitable selection of the reference area with two-third power of the volume of sea animals which have voluminous guts and gonads. However, in a comparative study of the estimation of drag in deceleration glide phase of sea-lions [31], it was found that the drag coefficient obtained by using the frontal area as reference area is significantly high when compared with that obtained by using the wetted area and $\text{Vol}^{2/3}$. Moreover, drag coefficient obtained by using $\text{Vol}^{2/3}$ and frontal area does not account for any boundary layer effects and hence gives no information about the skin friction and induced drag. Drag is purely an aerodynamic or hydrodynamic term as there is no term known as aerostatic or buoyancy drag. Recently, this has been proven by Suzuki [16] in which he experimentally determined that drag is independent of the buoyancy and dive depth (Fig. 1). In this way, there is no contribution of drag due to buoyancy whether it is a case of HB aerial vehicle [15] or a marine animal like stellar sea lion [16] and perhaps no term can be defined to account for the effect of the same. Drag coefficient of streamlined symmetric body of revolution of hull is correlated with friction coefficient of flat plate [6].

There is no specific reference available for the estimation of hydrodynamic lift generated by the shape of sea lions or other pinnipeds such as seals. However, there are some old data on penguins [32] and most of the work has been on flippers of cetaceans — whales, dolphins, and porpoises [33]. These sophisticated aquatic mammals are capable of achieving fast swimming speed and have better controllability with the help of flippers. Lift coefficients of such flippers have nonlinear behavior with an increase in the angle of attack and the corresponding drag coefficients are less dependent on planform shape [34]. For a HB aerial vehicle, S_{ref} can be defined as the sum of the projected area of hull (S_H), wing (S_W), the area of symmetric/cambered wing outside the hull and (S_C) for canards, if used.

$$S_{\text{ref}} = S_H + S_W + S_C. \tag{4}$$

4.3. *Effect of reference area on aerodynamic lift coefficient*

The hull of conventional airship does not provide aerodynamic lift and hence there is no requirement to estimate the induced drag. In the case of hybrid airship with hybrid lift hull, drag due to lift can be expressed in terms of planform area and aspect ratio of hull [14]. In the case of lift, only the planform area of wing is used as the reference area. In the absence of a wing in studies of lift due to fuselage alone, reference area selection is an open question. This revealed the need to see the general trends of coefficient of lift of fuselage with different choices of reference areas like frontal area, planform area, surface area of fuselage alone. In order to find the influence of different available choices of reference area on the lift coefficient of a conventional fuselage, there is a need to first revisit the trends of lift coefficients by either opting for varying the free stream velocity or varying the angle of attack. Earlier option is computationally cheap but experimentally expensive. However, later option is an experimentally cheap one as a single blow down is required to get an overall trend. Therefore, it was planned to first opt for option one for lifting hull and option two for a generic model of a transport aircraft.

4.3.1. *Generic model of a transport aircraft*

In order to get a quantitative trend of aerodynamic lift coefficient generated by a fuselage of aircraft, a generic model of 1 m length of fuselage having maximum diameter equal to 0.13 m was recently tested at 30 m/s in the IIUM-LSWT,

Fig. 5. Generic model of a transport aircraft.

Fig. 5. The total pressure variation in the test section has been found to be within $0.999 \leq C_{pt} \leq 1.003$ and the dynamic pressure variation from −0.5% to 0.4% from the plane mean value. Sign convention used in the experimental studies is such that positive axial force is along the positive x-axis (forward from tail to nose) and positive normal force is along the positive y-axis (upwards). Variation in lift force with angle of attack is obtained in wind axis and is shown in Fig. 6. Since there was no wing attached to the fuselage, till vs. α equal to 20°, no stall characteristics were observed from the general trend of C_L vs. α. No correction in values of C_L was applied as body lift is usually ignored for the case of wind tunnel testing on scale down models of aircraft. Aircraft Digital DATCOM was also run to get the general trend of the lift generated by the fuselage of a commercial aircraft. The results (Fig. 6) show that change in lift force at low

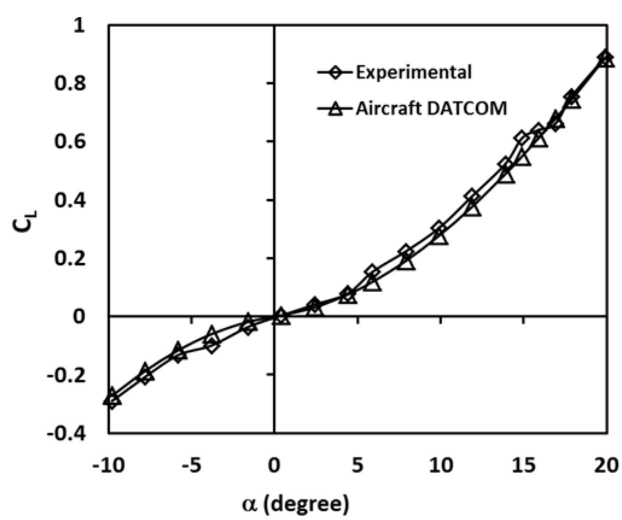


Fig. 6. Variation in C_L with α.

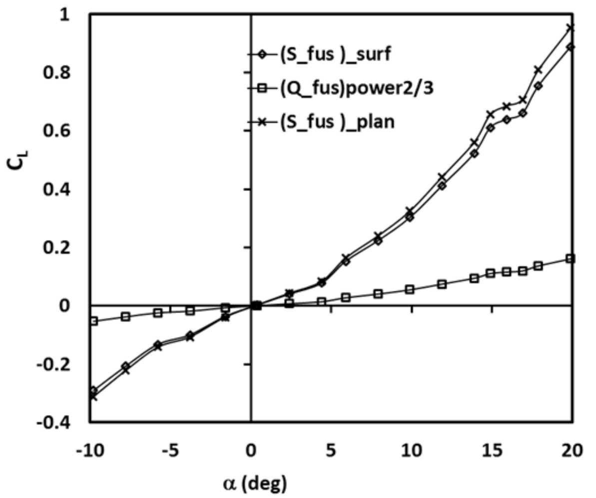


Fig. 7. Variation in C_L with α for different choices of reference areas.

angles ($\pm 50^\circ$) of attack is quite small. Such shapes perhaps cannot generate sufficient lift to hold partial weight of aircraft at low speed.

As the scope of present work is limited to the lift force, trends of drag force are not reported here. Lift force was nondimensionalized by $S_{\mathrm{fus}_{\mathrm{surf}}}$, Q_{fus}, S_{fus_s} and their corresponding values were $0.012\,\mathrm{m}^2$, $0.01\,\mathrm{m}^3$ and $0.11\,\mathrm{m}^2$, respectively. Comparison of values of C_{L_P}, C_{L_V} and C_{L_A} is shown in Fig. 7, which shows that variation in C_{D_V} with α is quite small and at low α, values of C_{L_P} and C_{L_V} are the same. One of the obvious reasons is the small value of lift force generated by the fuselage. At higher values of α, values of C_{L_P} are more than C_{L_A}, obtained by using S_{fus_s} as S_{ref}. In this way, use of S_{fus_p} as S_{ref} has preserved the change in lift coefficient obtained by increasing the value of α. Based on this finding, S_{fus_p} was used further for the estimation of C_L for the case of hybrid lifting hull.

4.3.2. *Hybrid lifting hull*

In a recent design exercise of HB aerial vehicle with hybrid lifting hull, drag coefficient was estimated by using computational fluid dynamics (CFD) and drag force was nondimensionalized by exposed planform area of wing [15]. But it is perhaps not the true representation as there can be a design case without a wing attached to the hybrid lifting hull. In the present work, a comparative study of drag coefficient estimated by using different reference areas for a hybrid lifting hull [15] was carried out. First, L and D forces are computed using CFD and the results are shown in Table 3. The C–O type grid was used and numerical simulations were carried out by using fully structured grid so that the flow should be aligned with the grid. Contours of pressure coefficient over hybrid lifting hull surface and its surface grid are shown in Figs. 8 and 9, respectively. It can be observed that pressure is decreasing from the leading edge to trailing edge with a gradual increase in the thickness of body.

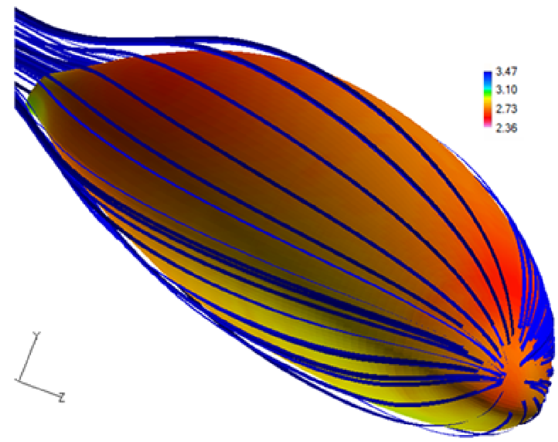


Fig. 8. Contours of coefficient of pressures on hybrid lifting hull with streamlines plot.

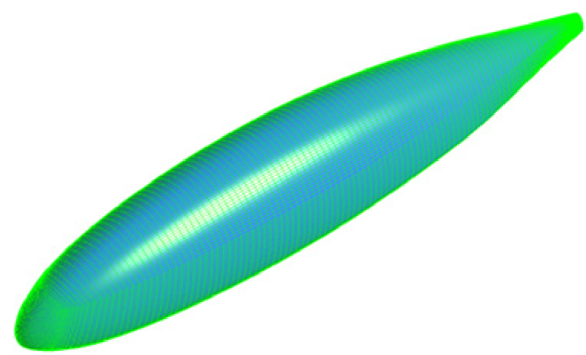


Fig. 9. Surface Grid on hybrid lifting hull.

The drag force D is nondimensionalized by all available choices of S_{ref} as proof. Based on the findings of the above section, L is nondimensionlized only by S_{fus_P}, i.e. S_H to find C_{L_P}, which is further used to find aerodynamic efficiency after calculating the values of ratio C_{L_P}/C_{D_A} and C_{L_P}/C_{D_P} (Table 2).

Table 3. Comparison of aerodynamic data obtained by using different reference areas.

V (m/s)	$(C_D)_F$	$(C_D)_V$	$(C_D)_A$	$(C_D)_P$	$(C_L)_P$	$L(N)$	$D(N)$	L/D	$(C_L)_P/(C_D)_A$	$(C_L)_P/(C_D)_P$
25.72	0.041	0.002	0.002	0.007	0.013	1085	445	2.43	6.5	1.85
20.57	0.039	0.002	0.002	0.006	0.011	946	364	2.59	5.5	1.83

It can be easily perceived from this table that although there is no change in the drag area, comparison with coefficients obtained by using the values of reference area, Q_{fus} and S_{fus_s} coefficient of drag does vary promptly if the speed changes. Similar variation was also observed in the case of steller sea lion [31]. Linear relationship of $\mathrm{Vol}^{2/3}$ with S_{fus_s} and S_{fus_p} was not able to capture the effect on drag coefficient. In the case of a hybrid lifting hull, one can also say that $\mathrm{Vol}^{2/3}$ is only related with buoyancy and drag force is independent of it.

Variation in aerodynamic coefficients predicted by using S_{fus_p} is quite obvious, but the change in their ratio is not so noticeable. If we nondimensionalized the lift force by S_{fus_p} and drag force by S_{fus_f}, then change in their ratio C_{L_P}/C_{D_A} with free stream velocity is remarkable. If one uses planform area for lift coefficients and wetted area for drag coefficients, then the loss would be in describing the real meaning for their ratio. However, lift-to-drag ratios are still meaningful in terms of its general trend with change in free stream velocity. Also, no analytical relationship is available to estimate the planform area of hull and therefore, C_{L_P}/C_{D_A} would be hard to use to compare hulls that differed in shape. Only solution available is to use the CAD software. Similar to the results obtained for a conventional fuselage of transport aircraft (Fig. 7), value of C_{L_p} increases from 0.011 to 0.013 against change in L from 946 N to 1085 N by just an increment of 5 m/s in free stream velocity.

Though Fish [35] emphasized on the usage of computational tools for better understanding of biological systems and their further adaptation for engineering applications, it is well known that CFD usually overpredicts the drag force, especially the zero lift drag [36]. Any further comparative study on shapes similar to Steller sea lion needs accurate estimation of hydrodynamic as well as aerodynamic force. Moreover, whether steller sea lion's body or other secondarily aquatic mammals take advantage of a cambered profile of body is another question and wind/water tunnel testing is one of the prospective solutions for the estimation of the same at different flight conditions.

In summary, there is no analytical correlation of the term as defining the planform area traditionally used in airships. Planform area as reference area is found to be best suited to nondimensionalize the aerodynamic forces acting on the surface of the hybrid lifting hull. Comparative studies on the trends of aerodynamic data to be obtained from wind tunnel testing on scaled down models of hybrid lifting hull for different flight regimes will further reveal the usage of proposed reference area.

5. Conclusion

This paper adequately put forward a case for choosing the correct reference area for hybrid lifting hull. The methodology consists in the examination of different possibilities of the scaling (related to the dimensions of the body) and investigation whether the aerodynamic coefficient (the forces are obtained by numerical experiment) then becomes more or less universal. Based on the literature survey, it is concluded that the surface area of a hybrid lifting hull is related to the weight due to square cube law and it is related to volume for defining the buoyancy ratio. There is similarity of volumetric variable in defining the reference area between few under water animals and airship, but its further utilization for hybrid buoyant aerial vehicle is not suitable due to the volume independency of lift as well as drag force. Size of the wing beneath inside the voluminous fuselage is of importance to coefficients related to lift generated by the exposure to air. Both wings and fuselage projected planform areas can be added together to define the reference area of a HB aerial vehicle without canards.

Acknowledgments

The support of the Ministry of Science, Technology and Innovation (MOSTI), Malaysia, under the grant 06-01-08-SF0189 is gratefully acknowledged. Thanks to Professor Steven Vogel for the useful discussions during the course of this review work. Special thanks to Dr Fadhil and Mr. Surya for providing assistance in generating the experimental data of fuselage and its model manufacturing.

References

[1] D. E. Alexander, Drag coefficients of swimming animals: Effects of using different reference areas, *Biol Bull.* **179** (1990) 186. doi: 10.2307/1541768.
[2] G. K. Batchelor and A. D. Young, An introduction to fluid mechanics, *J. Appl. Mech.* **35** (1968) 624. doi: 10.1115/1.3601282.
[3] B. Y. D. Bilo and W. Nachtigall, A simple method to determine the drag coeficient of aquatic animals, *Exp. Biol.* **87** (1980) 357–359.
[4] O. Cheneval, Biomechanics of turning manoeuvers in steller sea loins. 2005; (May). Available at: https://circle.ubc.ca/bitstream/id/54541/ubc_2005-0397.pdf. [accessed on 15 September 2014].
[5] W. E. Pinebrook, Drag minimization on a body of revolution, *Computer Methods in Applied Mechanics and Engineering* **39**(2) (1983) 179–197.
[6] L.Thorsten and S. Wagner, Drag reduction and shape optimization of airship bodies, *Journal of Aircraft* **35**(3) (1998) 345–351.
[7] S. Vogel, *Life in Moving Fluids: The Physical Biology of Flow* (Princeton University Press, 1987).
[8] S. Vogel, *Comparative Biomechanics: Life's Physical World* (Princeton University Press, 2013).
[9] A. U. Haque, W. Asrar, A. A. Omar, E. Sulaeman and J. S. M. Ali, Cambered profile of a california sea lion's body, *J. Exp. Biol.* **1**(c) (2014) 2–3. doi: 10.1242/bio.20146130.
[10] M. Nita and D. Scholz, From peliminary aircraft cabin design to cabin design to cabin optimisation-part I, *Sci. Bull.* **75**. Available at: http://www.scientificbulletin.upb.ro/rev_docs_arhiva/fulld22_936656.pdf. Accessed March 10, 2014.

[11] R. Vos and J. van Dommelen, A conceptual design and optimization method for blended-wing-body aircraft, In *53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conf. 20th AIAA/ASME/AHS Adaptive Structures Conf. 14th AIAA* (Reston, Virigina, 2012), American Institute of Aeronautics and Astronautics, pp. 1–14. doi: 10.2514/6.2012-1756.

[12] A. Abbas, J. de Vicente and E. Valero, Aerodynamic technologies to improve aircraft performance, *Aerosp. Sci. Technol.* **28**(1) (2013) 100–132. doi: 10.1016/j.ast.2012.10.008.

[13] M. J. Bamber and R. O. House, Wind tunnel investigation of effect of yaw on lateral-stability characteristics. II: Rectangular N.A.C.A. 33012 Wing with a Circular fuselage and a Fin; (1939). NACA Technical Note 703, National Advisory Committee for Aeronautics. Langley Aeronautical Lab.; Langley Field, VA, United States.

[14] G. E. Carichner and L. M. Nicolai, *Fundamentals of Aircraft and Airship Design, Vol. 2, Airship Design* (ed. J. A. Schetz). (American Institute of Aeronautics and Astronautics, AIAA, 2013).

[15] A. U. Haque, W. Asrar, A. A. Omar, E. Sulaeman and J. M. Ali, Conceptual design of a winged hybrid airship, in *21st AIAA Lighter-Than-Air Systems Technology Conf.* Reston Virgiana, 2010. American Institute of Aeronautics and Astronautics, AIAA–2014–2710. doi: 10.2514/6.2014-2710.

[16] I. Suzuki, K. Sato, A. Fahlman, Y. Naito, N. Miyazaki and A. W. Trites, Drag, but not buoyancy, affects swim speed in captive Steller sea lions, *Biol. Open.* **3** (2014) 379–386. doi: 10.1242/bio.20146130.

[17] A. U. Haque, W. Asrar, A. A. Omar, E. Sulaeman and J. S. M. Ali, Stability and takeoff ground roll issues of hybrid buoyant aircraft, *Appl. Mech. Mater.* **660** (2014) 503–507. doi: 10.4028/www.scientific.net/AMM.660.503.

[18] G. Ilieva, J. Páscoa, A. Dumas and M. Trancossi, MAAT – Promising innovative design and green propulsive concept for future airship's transport, *Aerosp. Sci. Technol.* **35** (2014) 1–14. doi: 10.1016/j.ast.2014.01.014.

[19] F. Fish, Influence of hydrodynamic-design and propulsive mode on mammalian swimming energetics, *Aust. J. Zool.* **42** (1994) 79. doi: 10.1071/ZO9940079.

[20] G. A. Khoury, *Airship Technology*, Vol. 10 (Cambridge University Press, 2012).

[21] G. A. Khoury and J. D. Gillett, *Airship Technology* (Cambridge Univ. Press, 1999).

[22] Aero Spacelines, 377 PG Pregnant Guppy: Available at: http://www.allaboutguppys.com/pg/377pgf.htm. Accessed September 7 (2014).

[23] D. Raymer, *Aircraft Design: A Conceptual Approach*, 5th ed. (Schetz JA, ed.). (American Institute of Aeronautics and Astronautics, Inc., Washington, DC, 2004), doi: 10.2514/4.869112.

[24] K.-S. Zhang, Z.-H. Han and B.-F. Song, Flight performance analysis of hybrid airship: Revised analytical formulation, *J. Aircr.* **47**(4) (2014) 1318–1330. doi: 10.2514/1.47294.

[25] A. R. Verma, K. K. Sagar and P. Priyadarshi, Optimum buoyant and aerodynamic lift for a lifting-body hybrid airship, *J. Aircr.* (2014) 1–6. doi: 10.2514/1.C032038.

[26] A. Filippone, Data and performances of selected aircraft and rotorcraft, *Prog. Aerosp. Sci.* **36**(8) (2000) 629–654. doi: 10.1016/S0376-0421(00)00011-7.

[27] N. Qin, A. Vavalle, A. Le Moigne, M. Laban, K. Hackett and P. Weinerfelt, Aerodynamic considerations of blended wing body aircraft, *Prog. Aerosp. Sci.* **40** (2004) 321–343. doi: 10.1016/j.paerosci.2004.08.001.

[28] B. T. Buerge, Scalability of heaviness fraction for large airships, in *Aerodynamic Decelerator Systems Technology Conferences*. AIAA Lighter-ThamAir Systems Technology (LTA) Conference. Reston: AIAA (2013).

[29] E. Torenbeek, *Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes* (Oxford, UK: John Wiley & Sons, Ltd, 2013). doi: 10.1002/9781118568101.app1.

[30] B. Y. P. W. Webb, Is the high cost of body/caudal fin undulatory swiming due to increased friction drag or internal recoil? *J. Exp. Biol.* **162** (1992) 157–166.

[31] L. L. Stelle, R. W. B. Lake and A. W. Trites, Hydrodynamic drag in steller sea lions (Eumetopias jubatus), *J. Exp. Biol.* **203**(12) (2000) 1915–1923.

[32] J. Ward, Animal locomotion, *Nature* **9** (12 February 1874) 281–282. doi: 10.1038/009281a0.

[33] L. N. Cooper and S. N. Johansson, Hydrodynamic performance of the minke whale (Balaenoptera acutorostrata) flipper, *J. Exp. Biol.* **211** (12) (2008) 1859–1867. doi: 10.1242/jeb.014134.

[34] P. W. Weber, L. E. Howle, M. M. Murray and F. E. Fish, Lift and drag performance of odontocete cetacean flippers, *J. Exp. Biol.* **212** (2009) (Pt 14):2149–2158. doi: 10.1242/jeb.029868.

[35] F. Fish, Imaginative solutions by marine organisms for drag reduction, *Proc. Int. Symp. Seawater. Drag. Reduct.* **1** (1998) 443–450.

[36] D. W. Levy, T. Zickuhr and J. Vassberg, Data summary from the first AIAA computational fluid dynamics drag prediction workshop, *J. Aircr.* **40** (2003) 875–882. doi: 10.2514/2.6877.

Anwar-Ul-Haque was born in Pakistan in 1977. In 1998, he completed his bachelor's degree in Aerospace from National University of Sciences and Technology, Pakistan. In 2003, he got master's degree in Aerospace with distinction from University of Sheffield, Sheffield, England. He worked as Research Associate for Hybrid Buoyant Vehicle Project of MOSTI (*Malaysia*) in International Islamic University of Malaysia (IIUM), Kuala Lumpur, *Malaysia*. The major field of his study is related to the Configuration Design and Experimental Aerodynamics. He has published about 70 research papers in peer reviewed International journals and conferences.

Waqar Asrar is a professor in the Department of Mechanical Engineering, Faculty of Engineering, at International Islamic University Malaysia (IIUM). He graduated with a PhD in engineering science and mechanics from Virginia Polytechnic Institute and State University, USA, in 1983. His research interests are in aerodynamics and computational fluid dynamics. He is currently in charge of the IIUM Low Speed Wind Tunnel.

Ashraf A. Omar is a professor in the Department of Aeronautical Engineering at the University of Tripoli (UOT), Libya, where he has been a faculty member since 2014. Before joining UOT, he was an assistant professor (2003), associate professor (2003–2007), and professor (2008–2014) at International Islamic University Malaysia (IIUM). He completed his PhD at Seoul National University, South Korea. His research interests are in the area of computational fluid dynamics and aerodynamics.

Erwin Sulaeman has been an associate professor in the Department of Mechanical Engineering, Faculty of Engineering, at International Islamic University Malaysia (IIUM), since 2010. Previously, he worked as a specialist engineer at PTDI, Indonesian Aircraft Industry in Bandung, Indonesia for over 20 years. He completed his PhD in aerospace engineering at Virginia Polytechnic Institute and State University, USA, in 2002. His research interests are in the fields of structure, structural dynamics, unsteady aerodynamic, aeroelasticity, and heat transfer.