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Open Jet Testing for Buoyant and Hybrid Buoyant Aerial Vehicles

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***Abstract*—**Open jet testing is a valuable testing technique which provides the desired results with reasonable accuracy. It has been used in past for the airships and now has recently been applied for the hybrid ones, having more non-buoyant force coming from the wings, empennage and the fuselage. In the present review work, an effort has been done to review the challenges involved in open jet testing. In order to shed light on the application of this technique, the experimental results of two different configurations are presented. Although, the aerodynamic results of such vehicles are unique to its own design; however, it will provide a starting point for planning any future testing. Few important testing areas which need more attention are also highlighted. Most of the hybrid buoyant aerial vehicles are unconventional in shape and there experimental data is generated, which is unique to its own design.

***Keywords*—**Open jet testing, aerodynamics, hybrid buoyant aerial vehicles, airships.

I. Introduction

AIRSHIPS were the queen on the sky in early ages; where the major design and development of these flying machines was carried out during the period of first world war. England, France, Germany, Italy, and USA were the countries who contributed in such development programs. Applications for these vehicles include scientific data collection, communications relay, and transportation of goods and for the tourism industry. Wind tunnel testing plays a dominant role for the accurate prediction of aerodynamic and stability characteristics of buoyant vehicles. Open jet as well as wall bounded wind tunnel have been used in the past and are also being utilized presently for different buoyant and hybrid buoyant configuration; the same has resulted in many useful data on the aerodynamic and stability. Hybrid buoyant aerial vehicles *(HBAVs)* have been the focus of research. There is a significant growth potential of the *HBAVs*, the design and development phase of which will be requiring aerodynamic data with flow quality and data uncertainty. The cost spent on the wind tunnel testing of such vehicles is quite significant. Wind tunnels represent a useful tool for aerodynamic and stability study on different airships and hybrid buoyant aircraft. An increase in the number of wind tunnel tests performed on different configurations can be observed from the trend plot line shown in Fig. 1. In this figure, the authors have randomly arranged the decade wise (from 1910 to 2015) wind tunnel testing performed on buoyant and hybrid buoyant vehicles. Data is collected from different sources, hence no reference is provided here. No half model testing has been done as one cannot simulate the yaw angle for the scaled down models as the pitch and yaw axis of the body is asymmetric. Dynamics of *HBAVs* are distinct from those of heavier-than-air craft due to the added mass effects, which can be estimated by using towing tank.

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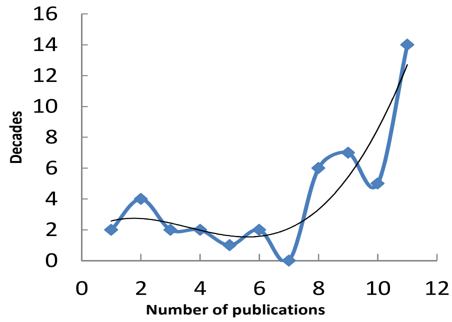


Fig. 1 Trendline plot of the decade wise wind tunnel testings

In the early decades, a limited number of experimental testings were performed on different scaled down models of airships. To the authors' best knowledge, the first model tested in the wind tunnel was of L-33 rigid airship in 1917 [1], followed by the testing of scaled down model of R-29 in 1920, [2]. Late, pressure distribution over the hull of R-101 was experimentally determined along with the estimation of the hinge moments [3]. These calculations, made at the request of the Zeppelin Airship Company of Friederichshafen, Germany, were based on the shape of the ZR III, with the following simplifications: cars, fins, and rudders removed; all cross sections replaced by equivalent circular cross sections. From 1991-2000, about seven different configurations were tested [4]–[10] and this number slightly decreased by two during 2001-2010, [11]–[15]. The highest number of publications were during 2011-2014, [16]–[29]. History of wind tunnel and airships are closely related to one another. Perhaps the first wind tunnel was manufactured but later more efforts were put towards aircraft [30]. Its design and construction was funded by German society for Airship study. It was a closed circuit wind tunnel with rectangular cross section [31].

On the analytical side, fundamental drag equation for aircraft was also derived from airships [32]. Also, Munk-Multhopp's work on pitching moment was also based on the experimental work on airships by Munk [33].

In the case of hybrid airships; the experimental data for aerodynamic are static stability derivatives is quite limited [32]. One thing common in the configurations of *HBAVs* and buoyant vehicles (airships) is the voluminous hull/fuselage which is filled by the lifting gas to provide aerostatic lift. Such configurations were tested in open jet/closed test section in the past, a few of which are shown below in Table I:

TABLE I
FEW WIND TUNNEL TESTINGS

S No.	Name	Reference	Type
1	Goodyear Zeppelin	[34]	Open jet+closed
2	Arkon	[9]	Open jet
3	LZ-120	[35]	Open jet
3	Zhiyuan-1	[11],[18]	Open jet
4	ESTOLAS	[36]	Open jet
5	Dynalifter	[37]	Closed
7	HAV	[38]	Closed
8	*IIUM-HBAV*	[39]	Closed

Most of the experimental data is related to the lifting bodies of hypersonic vehicles, tested inside the test section of the wind tunnel. For example, some experimental data in an old *NACA* report [40] which is based on $W\text{-}F_2$ configuration. As per Ash [41], this was a modified design of $M_2\text{-}F$ with modifications to the after body, the control surfaces, and the canopy location. Others include that on *NASA HL-20* lifting body concept [42]. All such bodies have λ greater than six and have wings blended with the fuselage. Recent interest in the configuration design of hybrid HBAVs with the hull of lifting profile has put a question about the limitations of the wind tunnel testing of such hybrid buoyant vehicles, inside the test section.

Before going into further discussion on the question in research, it is important to first define the nomenclature for the said aerial vehicles, so that a common terminology exists for all; either working in academia or in industry. We are perhaps not the first to highlight that the term hybrid is not fully explored, as the same has recently been pointed out by [43] and [32]. The term hybrid is applicable for hybrid airship but not for the airship which;

> *"refers to any air vehicle which depends on a significant amount of buoyant lift to obtain cruise equilibrium and uses speed to move from one point to another. If there is no speed then the vehicle is a tethered aerostat or an untethered balloon"* [44].

Joner and Schneider [45] have categorized such partially buoyant concepts based on the *STOL* and *VTOL* category. STOL category was further divided into lifting body systems and auxiliary wing systems. Aereon, Dynaairship and Megalifter are few examples of such systems. These systems were probably designed to have higher *L/D* ratio as compared with the multi hull concept. They further divided the *VTOL* category into the lifting body systems and combined/ integrated systems. We are of the view that any aerial vehicle can be hybrid in terms of the propulsion system as well. The aerodynamic lift is basically used by the hybrid buoyant vehicles to meet the additional lift requirement at the takeoff and in the cruise-climb segment, including the steep turns. Moreover, in such configurations, weight of the airship and its payload are supported by the buoyant lift as well as by the aerodynamic lift. It is difficult to keep the gross takeoff weight as constant due to the continuous burning of the fuel during flight. Moreover, similar to a symmetric airfoil, conventional hull of the airship also provides aerodynamic lift, even at a small angle of attack. Therefore, defining the term hybrid in terms of the aerodynamics may be improper and defining it as hybrid buoyant aerial vehicle will avoid the fusion of hybrid propulsion technology with aerodynamic and hydrodynamic technologies. Hence the term "buoyant" is more suitable for aerial vehicles designed on eth Archimedes' Principle. Furthermore, this definition can be extended to cover all types of airships and aircrafts in a broader spectrum.

Wind Tunnel models of Goodyear airship [34] and that of the Akron airship [9] were the two major industrial wind tunnel testing performed for open jet conditions. Such a testing facility is sometimes referred as Eiffel type wind tunnel. It is usually consists of eight parts i.e. inlet, settling chamber, contraction cone, test section, diffuser, drive section and exhaust outlet part. In open jet testing, there is no influence of the wall as it is there for closed circuit tested section. In this way, the boundary layer of the walls also does not affect the results. Moreover, the scaled down models can be manufactured for larger scale factor as compared with those used inside the test section. In this way, the Reynolds number can be increased.

In recent years, Zhiyuan-1 a demonstration stratospheric airship and ESTOLAS (Extremely Short Take Off and Landing on Any Surface) aircraft model [46] were tested in open jet condition, shown in Figs. 2 and 3 respectively. ESTOLAS is a novel aircraft design which combines the best features of an airship, a plane, a helicopter and a hovercraft. Zhiyuan-1 is a demonstration, stratospheric airship by Shanghai Jiaotong University [18]. The total length of airship is 25m and that of its scaled down model is 1.8 m. Full scale model can occupy a volume of 750 m^3. The range of flight's Reynolds number is 1.8 to 9.3×10^6 and its model is tested at Reynolds number equal to 3.2×10^6 [18].

Fig. 2 Zhiyuan-1 airship model [18]

In subsonic wind tunnels with large test sections, scaled down models are attached to the balance with the help of model support system. Such a system mainly includes a main strut and an auxiliary strut, also known as pitch rod, Fig. 4. Such arrangement is different from that used in the case of open jet testing, shown in Figs. 2 and 3.

Fig. 3 ESTOLAS model for tube test, courtesy of A. Gamaleyev

The configuration shown in Fig. 4 is of a scaled down model of a HB aircraft to be tested in a closed-loop wind tunnel with a test section of dimensions 1.5m × 2.3m × 6m and maximum speed of 50 m/s [18]. In this tunnel, the balance section is placed on the floor to have some height for the external balance. Both the struts (main as well as auxiliary i.e. pitch rod for alpha mechanism) are attached with the balance. Whereas, the balance is usually housed in the strut in the case of internal balance attached with the model at its end. The configuration shown in Fig. 4 has fuselage structures made in machined aluminum. The model is supported by the strut at its central fuselage. It will then have an interface allowing pitch angle setting. The shape of the profile will be guided using ribs in machined aluminum, placed at a regular distance to ensure the exact contour. The wings and the canards are made in a composite, reinforced by structure in aluminum.

For *HBAVs*; the position of the gondola is subject to the requirement of the position of center of gravity to fulfill the desired static longitudinal stability criteria. For wall bounded testing, the position of the gondola may interact with the position of the strut. Hence, its contribution towards the overall aerodynamic and the stability response of the vehicle can be considered separately. Perhaps its position is also dependent on the stability results of clean configuration obtained from wind tunnel experimental. In case of the landing gears attached to the gondola, landing gears may not be modeled for the sub-scaled models, tested in subsonic wind tunnel of conventional test section size. One of the prospective reasons is that it is not possible to reproduce such small parts by using the same scale factor used for scaling hull, wings, horizontal and vertical tail.

Defining the scaling criteria for the manufacturing of the wind tunnel models for open jet testing is quite challenging. The term “scaling” is usually defined for a wind tunnel model to determine a scale down factor, without washing out the minute geometric details of the actual configuration. *HBAVs* need to be scaled as per the volume of hull and span of the wings and empennage. For such vehicles the thickness of the wing and empennage and overall weight of the model are the limiting factors for scaling the wind tunnel models. The scale down factor for *HBAV’s* open jet testing models is more than those tested inside the test section of the wind tunnels.

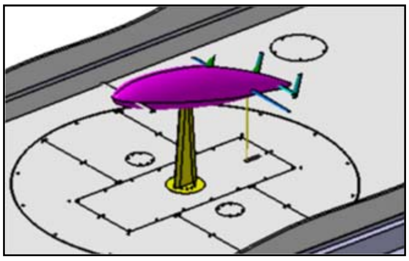


Fig. 4 Isometric view of HB aircraft installed in test section

II. Model Manufacturing

Manufacturing of the subscaled models should be ditto copy of full scale model. However, there is always requirement of additional screws for the mating parts. For example, long screws are required for the attachment of the wing and empennage with the main hull body. In such models, the empennage will act as a cantilever beam as one of its end is housed within the fuselage. This requires complete fluid structure analysis to first check the deflection of the aerodynamic surface under severe flow conditions during testing.

The far most important thing in wind tunnel model manufacturing is the selection of suitable scaling factor, which should be optimized as per the wind tunnel capabilities. Not only large, even minute details have to be exactly copied/shown in the scaled down wind tunnel model for the accuracy of results e.g. flushing of thin wings and voluminous fuselage body. For such models, not only different parts are required to be manufactured separately, some individual parts also have to be divided in sub parts. This has to be carried out sense fully and tactfully so that the integration of the parts of the model may be easily carried out without any problem and errors. For example, the wind tunnel model of *YEZ-2A* airship [47] is carried out using different combination of angles of these control surfaces . It can be observed from this testing and few previous testing of aerostats and airship that the model was rotated to 90 degree, such that the yaw axis becomes the pitch axis and vice versa. The basic reason behind this rotation is to avoid the interference of external strut. However, such a rotation will not be possible of *HBAVs* in which a wing is attached to the voluminous hull. Weight of the mode is an important consideration to cater the threshold values of the balance. In fact, using the full cross-section of the wind tunnel and keeping the weight up to a certain limit is quite a difficult job due to the voluminous fuselage. However, this issue becomes more critical for models to be tested in open jet testing due to comparatively higher scaling factor than those tested inside the test section.

For composites manufacturing, specially of the hull, the Vacuum Assisted Resin Infusion *(VARI)* or Light Resin Transfer Molding *(LRTM)* are the two most commonly methods used in the model manufacturing. In case of *VARI* it is an open molding process thus requiring only one contact surface but results in lesser structural strength and rigidity as compared to *LRTM* that is a closed molding process and requires upper and lower molds. For commercial and industrial applications, once the prototype is successfully qualified, filament wound composite structure can also be considered as it gives the maximum structural strength and rigidity to such structures of revolution. Regardless of the composite manufacturing technique, the mold making itself is the most critical and challenging task. Careful design and analysis is required to determine the optimum thickness of the composite structure and orientation of fiber angles. Typically for such structures, an intermittent sequence of glass fiber matte and unidirectional composite fabric is used for the manufacturing purposes. This also requires a detailed stress and strength analysis of composites structures using some finite element code for design and evaluation purposes. Finally the composite layup needs to be cured as per requirements of the used epoxy. It can either open to air curing or in controlled conditions depending on the size of mold and available curing facility.

Different approaches were available for integration of the control surfaces with the model. One of the prospective approaches is that the control surfaces be installed on the wings and tail with the help of different angle plates. A major problem is that the thickness of the control surfaces after scaling down was very small. Another problem was that these control surfaces had to be adjusted for different angle plates repeatedly and many times. The control surfaces and the plates are usually made of aluminum to reduce weight, but it is not possible to use steel screws because of repeated mounting and dismounting. This is because repeated use of steel screws in aluminum would wear out the threads in aluminum very soon. Thus the angle plates and control surfaces needs to be manufactured from steel. An alternative option is to use servos for controlling the deflection of control surfaces. Open jet testing serve this purpose efficiently and testing done for ESTOLAS model [46] is one of the example of it.

Surface finish of the wind tunnel models is very important for data quality. Lapping is one of the prospective option for metal parts. However, thee lapping process do not remove the burrs, and is ineffective in the round and the sharp edges. An alternative option is to make parts in composite, reinforced by structure in aluminum.

III. Static Testing

Talking of limitations related to open-jet wind tunnels, a major point of concern is the static pressure fluctuations in the test chamber. These static pressure fluctuations can not only affect the simulation quality, but can also limit the free stream velocity in the test section. It is well known that in open jet testing facilities, fluctuations in the static pressure is the limiting factor of the speed envelope and it also affects the flow quality. Large scale vortex structures are shed from the edges of the nozzle and jet length needs to be adjusted before conducting any experiment [48]. Moreover, similar to the standard wind tunnel testing, the open jet data is also subject to the correction and is affected by the model-nozzle and model collector interference [49]. These corrections depend upon the particular tunnel in which the model is tested, and are made necessary chiefly by the effects of sale, turbulence, and jet. Furthermore, add-on devices can perhaps help in decreasing the pressure at the exit plane of the nozzle [50].

Open jet testing has been traditionally known as open throat testing. The results of obtained by such testing are always quite in good agreement with the closed throat testing. An example of the same has been shown in Fig. 5 in which results of these two types of testing were compared for the Goodyear Zeppelin airship's hull model and were found to be within 8 percent. However, deviation in the results is observed at low Reynolds number cases and air stream turbulence is perhaps the basic reason for such deviation. Fig. 5 has been taken from [34] and used with permission of NASA. Furthermore, Increasing the turbulence appeared to increase the value of the minimum drag and maximum lift to drag ratio [51].

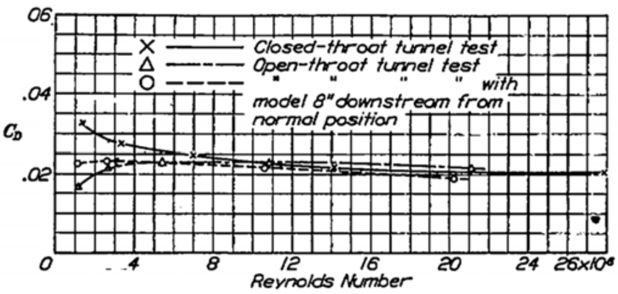
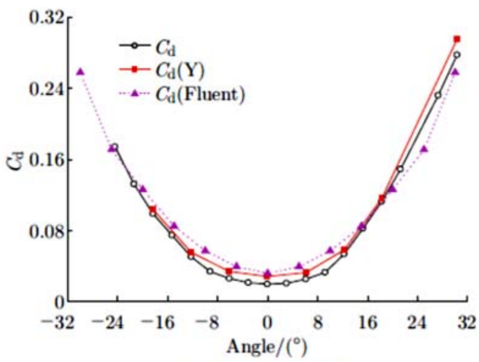
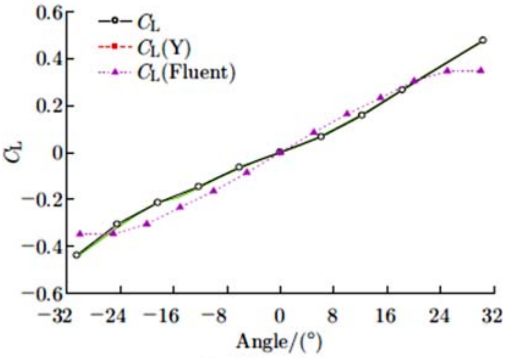


Fig. 5 Drag coefficient of Goodyear Zeppelin airship model. Fineness Ratio, 4.8; zero pitch; bare hull [34]

Open jet testing has been performed to study the effects of the surface roughness of the complete geometry of airship, Fig. 6 [18]. Surface roughness was introduced by employing the turbulence strips at three different locations. In this figure, hollow circles and solid squares represent the aerodynamic data with and without strip respectively. Whereas, the solid triangles symbolise the computational data obtained by using Fluent ®, a commercial Computational Fluid Dynamics analysis software.



(a) Drag coefficient



(b) Lift coefficient

Fig. 6 Aerodynamic coefficients of Zhiyuan-1 airship model [18]

It can be observed that the turbulence strips had affected the drag till α equal to 15° and no obvious difference in results was observed for angles greater than this. The lift coefficient curves increased "*monotonously*" with increase in the pitch angle and no stall characteristics were captured for the defined range of pitch angle. Moreover the computational results were found to be in good agreement with those obtained from the wind tunnel testing.

Similar to airship models in which empennage are arranged at different angles on the hull, for hybrid buoyant aerial vehicles different empennage positions can be marked on the aft position of hull; thus providing a range of angle settings for moment and force measurement tests related to the study of the stability response along different axis. *ESTOLAS* model is one of the examples in which aerodynamic effects of the different settings of the flap deflection were experimentally studied, Fig. 7. Relative to the aircraft centerline, the stall angle is limited to 7° due to the use of high lift airfoil and incidence angle of 5°. The value of the lift coefficient and the corresponding stall angle were found to increase with increment in the deflection angle of the flaps. A shift in the drag polar at the positive deflection angle of the flaps was also observed due increase in the coefficient of drag.

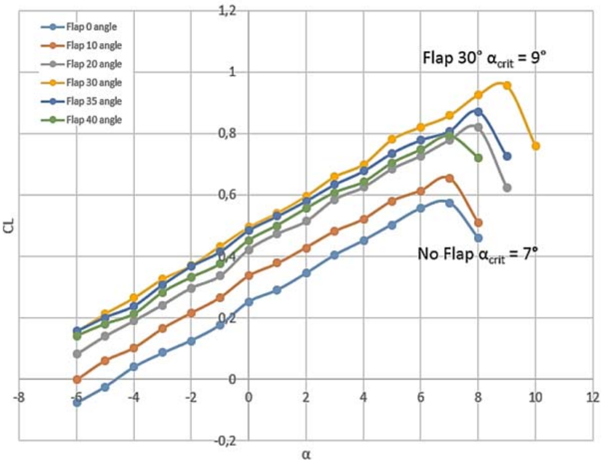


Fig. 7 C_L vs α plot of ESTOLAS Model with flap deflection [46]

IV. Discussion on Future Testing

One of the things common in the history of wind tunnel and airship is the time when design and development work was started. The first wind tunnel which was designed and developed was for the use of airship models [16]. However, unfortunately in past, more efforts were diverted towards aircraft technology and wind tunnels were design mainly to meet the requirements of the scaled down models of aircraft during world war–II [17]. The repurcation of this shortfall was badly felt in the last decade in which different buoyant and hybrid buoyant vehicles could not be tested inside the test section and open jet testing facilities were used for the said purpose [18]-[21]. For such vehicles, the drawback is that there might be the pressure loss due to the interaction of the flow with atmosphere [22]. If such models are tested inside the test section, then experiments can be performed under well controlled flow conditions [23]. However, the geometric scaling issues are quite difficult to handle, especially when a thin wing is attached to the voluminous fuselage.

Trim analysis (including hover and steady state), gust analysis (high frequency disturbances introduced by atmospheric turbulence), dynamic stability response (natural as well as forced), effect on aerodynamic parameters due to motion and inflation/deflation of the ballonets with shift in center of gravity and aeroelastic effects needs to be cater in wind tunnel testing. Especially, the aerodynamic results of flexible body of unconventional shaped *HBAVs* can be employed for the design & development of control system. It is due to the fact that the structural deformations (shear and torsional) will influence the aerodynamic forces. Another important problem of steady-state aeroelasticity is reversal, where the aeroelastic effects tend to decrease the lift of a lifting surface under certain circumstances. The typical example is an airfoil with a control surface attached to it. If the control surface is rotated in order to increase the lift, it is possible that the lift in the control surface itself will tend to twist the nose of the main airfoil down, causing a net decrease in the total lift. An essential area of research for experimental testing of *HBAVs* is also of *Dynamic Aeroelastic Instability* in which the flutter of the overall structures is there due to small disturbances induces more or less violent oscillations. Consider, for example, a thin wing attached to a voluminous fuselage of *HBAVs* and is tested in a wind tunnel. Usually, it is observed for the case of the wing that for low speeds of the flow, a perturbation of the wing sets an oscillatory motion, which is gradually damped. However, the same is not true at high subsonic speed. In this case, the wing is oscillatory unstable and is said to flutter. Hence, there is a need to conduct experiments to show that the oscillation is self-sustained, i.e., no external driving force is necessary, indicating that energy is being extracted from the flow. Closely related to the *Aeroelastic Stability Problems* for *HBAVs* are the response problems, in which the response of an aeroelastic system to an externally applied load is to he found. The external load may be caused by deformations of the elastic body or by disturbances in the fluid flow. The quantity of interest may be the displacement, the motion, or the stress state of the elastic body. In the case of the flutters, the response to a finite disturbance becomes indefinite. The major distinction between the response and stability problems is in the linearization used in the mathematical equations describing the physical problem. For stability analysis, the disturbances are usually regarded as small, thus the small deformation theory of elasticity and the linearization of the governing equations is justified. However, for response problems, it is necessary to consider finite deformations, since in this case we are interested not only in the modes of deformation but also in the absolute magnitude of the deformation and stress.

In past, wind tunnel testing on scaled models of airships has provided useful data on the aerodynamics and stability characteristics of hulls of different fineness ratio and its interaction with different empennage arrangement to check the control surface effectiveness. However, such tests are unique in nature as the Reynolds number (based on the cube root of the volume as reference area) is quite high. But, similar to any aircraft, if the Reynolds number is based on mean geometric cord, than it will be limited greatly due to the fact that the Reynolds numbers during the wind tunnel tests is small as compared with real flight one. For a fixed dimension of test section size of a subsonic wind-tunnel, Reynolds number is increased by increasing the flow velocity, which is limited by maximum achievable velocity by the fan of the wind tunnel. Like conventional aircraft, aerodynamic data obtained from wind tunnel for hybrid buoyant vehicles needs to be extrapolated to cater for the high Reynolds number effects. Moreover, it should be corrected from flight test data as well. Hence, all the necessary corrections may be catered far before using the wind tunnel data for engineering design purposes.

Force and measurement data of *HBAVs* at low speed is quite limited. Operational preparedness for its commercial application and its utilization to explore flow physics will remain incomplete till the time one has the complete matrix of data comparison as per the operational envelope of the wind tunnel. Moreover, as per general practice, low speed wind tunnel results may not be declared successful without discussing the margin of error on the measured values of aerodynamic forces and without justifying the reason for tunnel to tunnel variations in the aerodynamic and the stability data. In this regard, an effort can be done to test a standard *HBAVs* model at different testing facilities. It is perhaps not a new practice and LZ-120 airship's model was among the first, tested in two different wind tunnels [35]. Hence, the wind tunnel testing on similar model of *HBAVs* in different wind tunnels can birth to standard calibration models for wind tunnels.

During the flight test, a series of sensors are placed at the point where the *HBAVs* are firstly affected by the incoming air i.e. at the nose of the voluminous fuselage. The readings of these sensors are required to be correlated with the experimental pressure testing, which is perhaps quite limited for *HBAVs* in the open literature. But the same is not true of the case of airships as limited number of references are available [18], [22], [52]. Pressure distributions over the aerodynamic profile of the configuration are useful for the study of the aeroelastic behavior of the hull as well. It is perhaps an input for the central problem in steady-state aeroelasticity for which one has to estimate the effect of elastic deformation on the lift distribution over lifting surfaces such as wings of *HBAVs* at low speeds. Additionally, the estimation of the total drag and zero lift drag coefficient through wind tunnel testing of fuselage alone testing will be quite interesting, especially when such shapes can also generate some percentage of the overall aerodynamic lift. These data's can be utilized to estimate the contribution of the body towards the induced drag as well. In the case of the commercial aircraft, this type of drag is a matter of concern for environment and fuel saving. Worldwide, winglets are used in more than 5,000 individual airplanes and in 20 different types of aircrafts to reduce the induced drag [24]. By using blended winglets in jet aircrafts, about three billion gallons of jet fuel is jet fuel which in return reduced the CO_2 emission by more than 32.2 million tones [25]. Furthermore, to the author's best knowledge, the estimation of damping derivatives is perhaps missing and use of Damping Pitch Rate *(DPR)* apparatus [16] is one of the prospective methods for the estimation of the same.

Authors will not be wrong in mentioning that the airships are back in the form of *HBAVs* and it is the time to further explore the different testing techniques for unconventional configurations of *HBAVs*. In order to generate the real experimental data; the continuing trends in the provision of test facilities in experimental aerodynamics require innovative testing of *HBAVs* with data reliability for cost effective and safe design and development of such vehicles. Wind tunnel testing did so far on different configurations have shown the importance of the precise model manufacturing, which absolutely relies on precise machining of the components of scaled model of *HBAVs*. In some models, the empennage will act as a cantilever beam as one of it end is housed within the fuselage. This requires complete fluid structure analysis to first check the deflection under severe flow conditions which may the model with encounter during testing.

VI. Conclusion

In the light of future demand of economical hybrid airships for transportation of agricultural product and for tourism industry, it is anticipated that once the design of *HBAVs* get matured then, there will be a need to do the wind tunnel testing of its scaled down models at subsonic speed. Based on the initial literature survey, it is concluded that there still a gap in open jet testing of *HBAVs*. For example, the flow diagnostics testing to capture the vortical flow over aerodynamic contour of *HBAVs*. Nonetheless, the continued discovery of new knowledge in wind tunnel testing of *HBAVs* is critical for its future design and development.

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