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Engineering Notes

Investigation of Aerodynamic Parameters of a Hybrid Airship

Amelda D. Andan,* Waqar Asrar,† and Ashraf A. Omar‡
International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia

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I. Introduction

HYBRID airships have been acknowledged as a potential means of alternative transportation, and many have come up with promising conceptual designs [1–4]. Hybrid airships have been the subject of research, especially those that can carry huge payloads and those that can operate at high altitudes. It is a concept dated a few decades ago and is now being tried on a significant scale. The flight performance and stability of hybrid airships have been investigated by many researchers [5–9]. However, there are very few studies on aerodynamics or aerodynamic stability. A hybrid airship such as a winged hull airship invites detailed aerodynamic examination since it is unique due to its unconventionality.

Hybrid airships can be developed by attaching wings to a conventional airship. The concept takes in the considerations of the benefits of the aerodynamic lift generated by the wings. Adding wings to the bare hull introduces a considerable amount of aerodynamic lift [10]. The overall lift is generated partially from the aerostatic force of the buoyant body and partially provided by its aerodynamic shape and geometry. Attaching wings to the hull eliminates handling difficulties characteristic in conventional airships. Also, the lifting gas in a winged airship is expected to carry most of the dead weight and the disposable load will be carried by the dynamic lift. Winged airships have yet to be built and are still undergoing intensive study and considerations.

The aerodynamics of any object depend on the shape of its components; so do hybrid airships, and some equipped with advanced integrated designs possess complex aerodynamics. The contribution of the hull to the total aerodynamic drag is usually less; however, the drag is high due to other attached components such as a gondola, a rotor, and cables, which disturb the flow over the hull and contribute their own drag components to it [11]. Also, the placement and orientation of every component on the hybrid airship may affect its aerodynamic performance as well as its aerodynamic stability. The static longitudinal motion is expected to be statically stable. However, lateral motions may be statically unstable due to side gusts against the gondola and wings [12]. The concept and design of a winged airship is always associated with its feasibility, stability, and safety. With modern methods for estimating and measuring aerodynamic properties, the vehicle aerodynamic characteristics can be accurately estimated and calculated. Having said that, care should be taken in designing and integrating the wings on the body of an airship, as it might negatively alter the aerodynamic characteristics of the hybrid airship.

II. Governing Concept

A conventional airship is attached with a pair of wings (Fig. 1). The existing conventional airship is equipped with a gondola for carrying payload. The fins have a diagonal "X" arrangement located at the rear end of the hull for control and stability. The wings are designed using a Clark-*y* airfoil, tapered with no dihedral angle. In an overview, the investigations of aerodynamic characteristics of the hybrid airship models were done in two phases. A computational fluid dynamics (CFD) simulation as well as wind-tunnel testing were performed on scaled models. The physical criteria in the numerical simulation were set to match the Reynolds number in the wind-tunnel test, where $Re = 1.85 \times 10^5$. Aerodynamic parameters were studied over a selected range of pitch and yaw angles of -15 to $+15$ deg at 5 deg intervals.

It is important to clarify the parameter used as reference to determine the aerodynamic performance of both airship configurations. In a typical aircraft, lift is produced almost entirely by the wing, so the wing plan area is usually used to examine its aerodynamic characteristics. Conversely, the lift of a buoyant body is directly associated with its volume, $(V_{\mathrm{hull}})^{2/3}$. The contributions of the wings to the total aerodynamic performance on the winged airship are less compared to the hull. Some authors consider the hull plan area to take into consideration the large friction drag due to the large surface area of an airship. Nonetheless, this Note has adopted $(V_{\mathrm{hull}})^{2/3}$ as the reference parameter in order to examine the total aerodynamic parameters for both a wingless and winged hull airship [6,13,14]. Moreover, this work only focuses on the aerodynamic parameters due to aerodynamic shapes of both bodies; it does not include the forces generated from the buoyant bodies. The volumetric lift coefficient can then be expressed as follows:

$$C_L = \frac{L}{0.5\rho v^2 s} \tag{1}$$

All other aerodynamic parameters will be calculated according to the preceding concept.

The practice of estimating the flying qualities of a model from a wind-tunnel test of a scaled model makes it essential that the scaled model test results be corrected to freestream conditions. Wind-tunnel model data have undergone tare drag correction and flowfield correction for result reduction. Evaluation of tare drag is a difficult task, and many have come up with various methods in determining this type of drag [15–17]. Each method has its own advantage and disadvantage, yet it has to be included for data reduction in order to have further accurate results. A conservative method in determining the tare drag was applied in the experimental work instead of measuring it in the wind tunnel. Since the mounting system consists of a simple cylinder strut, the drag of the exposed parts is easily calculated using the relationship of the cylinder drag coefficient with the Reynolds number. The cylinder drag coefficient at $Re = 1.84 \times 10^5$ is approximately $C_{D,\mathrm{cyl}} = 1.2$ [18]. Thus, the drag produced by the mounting system is calculated by

$$D_{\mathrm{cyl}} = q_x S C_{D,\mathrm{cyl}} \tag{2}$$

Two most basic flowfield corrections applied in this wind-tunnel testing are solid blockage and wake blockage. The flowfield corrections were done to consider the limitation of stream boundaries in a wind-tunnel test. Solid blockage $\varepsilon_{\mathrm{sb}}$ is the effect of placing a model in the test section, resulting in a smaller area through which air can flow. This will cause the velocity of airflow over the model to

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*Academic Trainee, Department of Mechanical Engineering, P.O. Box 10.
†Professor, Department of Mechanical Engineering, P.O. Box 10.
‡Professor, Department of Mechanical Engineering, P.O. Box 10. Member AIAA.

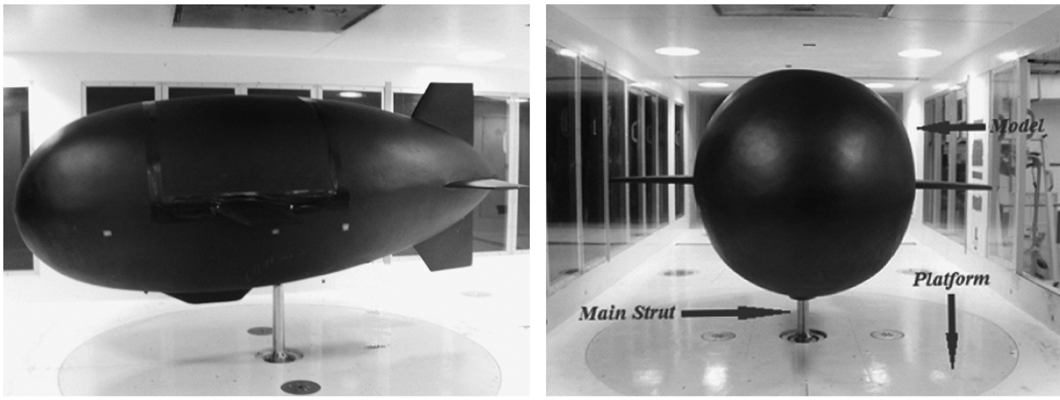

Fig. 1 Schematic of the model setup.

increase, eventually increasing aerodynamic forces and moments. It is a function of model size and the wind-tunnel cross section. Nonetheless, solid blockage can be corrected by increasing the effective wind-tunnel air speed. This study has adopted Thom's short-form equation in estimating solid blockage [19]. The solid blockage is defined as

$$\varepsilon_{\mathrm{sb}} = \frac{K(\text{model volume})}{C^{\frac{3}{2}}} \tag{3}$$

For a wing–body combination, the solid blockage is taken to be the sum of each component, as determined by Eq. (3). The volume of the blimp is 0.756 m^3 and the wing volume is 0.009 m^3. The solid blockage for the winged hull airship is calculated as the sum of the blimp and wing components $\varepsilon_{\mathrm{sb}} = 0.96(0.756)/(2.25 \times 1.5)^{1.5} + 0.90(0.009)/(2.25 \times 1.5)^{1.5} = 0.1184$.

On the other hand, the wake leaving a body in a closed wind tunnel will have a higher velocity and lower pressure compared to the freestream velocity. As the boundary layer grows on the model, the wake puts the model in a pressure gradient, eventually increasing the air velocity on the model. This effect is known as wake blockage $\varepsilon_{\mathrm{wb}}$, and it is a function of the model shape and the ratio of the wake area to the tunnel area. Maskell's correction method was applied to calculate the wake blockage [19]. The total wake blockage is obtained as the following:

$$\varepsilon_{\mathrm{wb}} = \frac{S}{4C} C_{D0} + \frac{5S}{4C}(C_{Du} - C_{Di} - C_{D0}) \tag{4}$$

If separation occurs,$C_{Du} > C_{Di} + C_{D0}$ and, for unseparated flow, $C_{Du} = C_{Di} + C_{D0}$. Nevertheless, if $C_{Du} - C_{Di} - C_{D0}$ equals a negative value, the term is set as zero. Examining Eq. (4), all data are straightforward except for C_{Di} and C_{D0}; extra steps are needed to determine both drag coefficients. One way is to plot C_{Lu}^2 versus C_{Du}; C_{D0} corresponds to the minimum value of C_{Du}, whereas the slope of the linear portion of the curve is taken as C_{Di}. The wake blockage correction for the winged airship is shown in Table 1.

The total blockage effect was found by summing the solid blockage and the wake blockage as follows:

$$\varepsilon_t = \varepsilon_{\mathrm{sb}} + \varepsilon_{\mathrm{wb}} \tag{5}$$

The freestream velocity and dynamic pressure are then corrected, as expressed in Eqs. (6) and (7). The freestream dynamic pressure has to be corrected before applying any modification on the aerodynamic coefficients:

$$V_c = V_u(1 + \varepsilon_t) \tag{6}$$

$$q_c = q_u(1 + \varepsilon_t)^2 \tag{7}$$

Other corrections such as weight tares, moment transfer correction, as well as wind axes corrections were done automatically by the six-component balance software during the wind-tunnel testing.

III. Results and Discussion

The volumetric aerodynamic parameters of both the winged and wingless airships are presented in Fig. 2. Results of the CFD simulation for volumetric lift coefficients are within a decent range of comparison with the experimental results, as shown in Fig. 2a. Results show that lift exhibits linear behavior in the selected range of the angle of attack, where $\alpha = 0$ deg acts as the axis symmetry. Moreover, results show lift increases almost linearly up to a maximum pitch angle of 15 deg. Wings are expected to contribute generous lift to the existing wingless airship. The hull is found to be contributing the highest lift; also, the wings offer lift forces equals to half of the hull lift forces. On average, it is observed that the winged airship has triple the amount of lift forces compared to that of a wingless airship at positive pitch angle. Tremendous increase in lift occurs at $\alpha = 5$ and 15 deg. For the winged airship configuration, both numerical and experimental results show no significant reduction in lift, which indicates no sign of stalling. The linear behavior proves that no major flow separation occurs on either model.

In comparison with lift prediction, the agreement of the drag prediction between CFD results and wind-tunnel data tends to be less (Fig. 2b). The volumetric drag coefficient curves illustrate parabolic behavior with the angle of attack. The graph clearly shows that drag gradually increases as it moves to the extreme left and right of the pitch angle. Although experimental results differ slightly from CFD results, there is no significant divergence between both. Minimum drag and axis of symmetry occur at $\alpha = 0$ deg; this is explainable through the symmetrical shape of the bodies. Numerical and experimental results show 20 to 40% more drag for the winged hull compared to the wingless airship. As in the case of lift, the hull is found to be contributing the highest drag compared to other

Table 1 Wake blockage correction

α, deg	C_{Du}	C_{Lu}	C_{Lu}^2	$(S/4C)(C_{D0})$	$(5S/4C)(C_{Du}$-C_{Di}-$C_{D0})$	ε_{wb}
−15	0.2359	−0.4947	0.2447	0.0008	0	0.0008
−10	0.1631	−0.4044	0.1636	0.0008	0	0.0008
−5	0.0863	−0.1523	0.0232	0.0008	0	0.0008
0	0.0662	0.0948	0.0090	0.0008	0	0.0008
5	0.0718	0.3239	0.1049	0.0008	0	0.0008
10	0.1047	0.6597	0.4352	0.0008	0	0.0008
15	0.1690	0.8988	0.8080	0.0008	0	0.0008

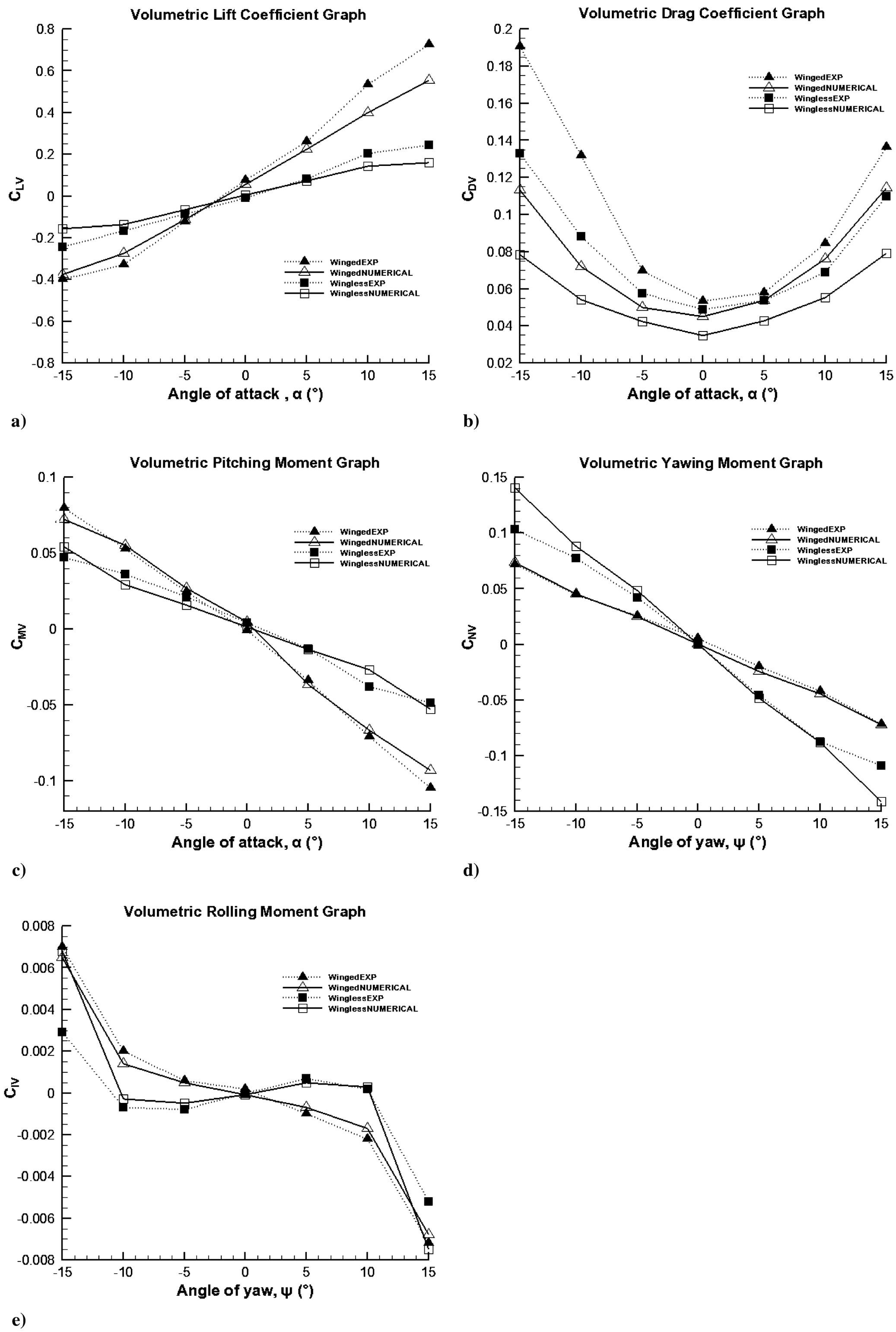

Fig. 2 Volumetric force and moment coefficients at $Re = 1.85 \times 10^5$.

components. Although the wings contributed a favorable increase in lift, however, undesirable increase in drag is inevitable.

Additionally, the reference point for computation of moments is at the center of volume. The center of gravity is designed in such a way that it lies at the same point as the center of volume. Both airships need to have the ability to develop restoring moments that exceed the upsetting moments to exhibit static stability. The slope of C_{MV} versus the α curve must be negative for the models to be statically stable. The volumetric pitching moment graph shows both airships satisfy the condition for longitudinal static stability (Fig. 2c). The hull is observed to be the major contributor for pitching stability in both airship configurations. Equally, the proposed wings are also found to have static pitching moment stability. The gondola and the horizontal tail are unstable about their longitudinal axis. The vertical tail in the wingless airship configuration has a stable pitching moment. In contrast, the contribution of vertical tails to pitching moment on the winged airship is destabilizing. The experimental result shows that the winged airship is more stable in its longitudinal axis compared to the wingless airship. In addition, it can be clearly observed that the trim angles for both airship configurations are at $\alpha = 0$ deg, which

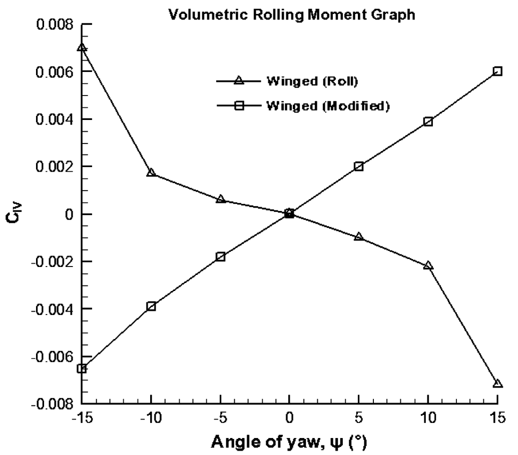

Fig. 3 Improved rolling moment stability at $Re = 1.85 \times 10^5$.

usually is a desirable trim angle. In a nutshell, both experimental and numerical results present good prediction for static pitching moment stability for both models.

The static directional stability is taken to be the airships' yawing moment developed due to yaw. The negative slopes of volumetric yawing moment curves confirmed that both models are statically stable (Fig. 2d). The fuselage contribution to directional stability is highly influenced by wing geometry and placement; even so, the hull is found to be the major contributor to static directional stability. The vertical tail's contribution to directional motion is destabilizing, and this may be caused by the hull sidewash. The contribution of the horizontal tail to directional stability can safely be disregarded since it is observed to be really small. The wings almost have no influence on the total yawing moments of the winged airship. Nevertheless, results show the winged airship attains better directional stability compared to the wingless airship.

Lastly, the volumetric rolling moment static stability curve needs to satisfy $C_{lV} > 0$ to achieve rolling stability. CFD and experimental results demonstrate a relatively good range of comparison for both models (Fig. 2e). Yet, results reveal that the wingless airship model only possesses static rolling stability in a range of yaw angles of -5 to $+5$ deg. Numerical simulations show that the gondola and the lower part of the vertical tail contribute most of the rolling instability for the wingless airship model. In contrast, adding wings to the aforementioned model increases the rolling moment instability; results show the winged airship model does not have static rolling stability at all (Fig. 2e). The wings are found to be contributing a considerable amount of rolling moment instability. It is known that rolling stability is highly influenced by the wing placement and the wing dihedral angle. A possible explanation for the rolling instability may be caused by the wing placement; the wing was designed to be placed slightly below the center of gravity and this causes rolling motion to be unstable. In addition, the dihedral angle helps to assist rolling stability; however, the wing was designed with no dihedral angle. Therefore, modifying the wing placement and increasing the dihedral angle will help solve this problem. The wings were then placed in a midwing configuration with a dihedral angle of 5 deg. Redesigning the wings improved the rolling moment stability with no significant change in other aerodynamic parameters, as shown in Fig. 3.

IV. Conclusions

The present Note discusses the results from aerodynamic studies on a preliminary design of a winged hybrid airship. The proposed design was successfully simulated by using a commercial CFD solver as well as wind-tunnel testing. The CFD simulation and wind-tunnel testing data agree well with each other. Investigation shows promising positive feasibility of real flight tests. Results show lift force tripled at a positive angle of attack for the winged airship. Moreover, parabolic increase of drag with lift is observed in the volumetric drag coefficient graph. With wings, drag increases in the range of 20 to 40%. Both airships possess static longitudinal and directional stability, as seen by the behavior of the volumetric pitching moment and volumetric yawing moment parameters. However, both airship configurations were found to have static rolling moment instability. Modifying the wing dihedral and wing placement makes the static rolling motion stable with negligible changes to other aerodynamic characteristics. The lower part of the vertical tail may be made smaller than the upper vertical tail to improve the lateral static instability. The design may be improved by carrying drag reduction and shape optimization on each component of the hybrid airship. The placement of individual components attached to the hull may be further investigated in detail to improve the aerodynamic interactions and stability of the model. Further study on the dynamic stability will fully determine the stability behavior of the hybrid airship.

References

[1] Calkin, D. E., "Feasibility Study of a Hybrid Airship Operating in Ground Effect," *Journal of Aircraft*, Vol. 14, No 8, Aug. 1977, pp. 809–815.
doi:10.2514/3.58857

[2] Ardema, M. D., "Feasibility of Modern Airships: Preliminary Assessment," *Journal of Aircraft*, Vol. 14, No. 11, Nov. 1977, pp. 1140–1148.
doi:10.2514/3.58902

[3] Mackrodt, P. A., "Further Studies in the Concept of Delta-Winged Hybrid Airships," *Journal of Aircraft*, Vol. 17, No. 10, 1980, pp. 734–740.
doi:10.2514/3.57960

[4] Mowforth, E., *An Introduction to the Airship*, 2nd ed., Airship Association, London, 1991.

[5] Ke, S. Z., Zhong, H. H., and Bi, F. S., "Flight Performance Analysis of Hybrid Airship," 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, AIAA Paper 2009-901, Orlando, FL, Jan. 2009.

[6] Liu, T., Liou, W. W., and Schulte, M., "Aeroship: A Hybrid Flight Platform," *Journal of Aircraft*, Vol. 46, No. 2, March–April 2009, pp. 667–674.
doi:10.2514/1.39950

[7] Kang, S., Lee, W., Nam, M., Tsubouchi, T., and Yuta, S., "Wheeled Blimp: Hybrid Structured Airship with Passive Wheel Mechanism for Tele-Guidance Applications," *Proceedings of the 2003 IEEE/RSJ*, Las Vegas, 2003, pp. 3552–3557.

[8] Nagabhushan, B. L., "Dynamic Stability of a Buoyant Quad-Rotor Aircraft," *Journal of Aircraft*, Vol. 20, No. 3, March 1983, pp. 243–249.
doi:10.2514/3.44859

[9] Tischler, M. B., Ringland, R. F., and Jex, H. R., "Heavy-Lift Airship Dynamics," *Journal of Aircraft*, Vol. 20, No. 5, May 1983, pp. 425–433.
doi:10.2514/3.44888

[10] Fink, D., "Hybrid Heavy Lift Vehicle Under Study," *Aviation Week*, 24 July 1974, pp. 49–51.

[11] Mowforth, E., Basic Principles, *Airship Technology*, edited by G. A. Khoury, and J. D. Gillet, Cambridge Univ. Press, Cambridge, England, 1999, p. 17.

[12] U.S. War Department, *Airship Aerodynamics: Technical Manual*, Univ. Press of the Pacific, Honolulu, 2003, p. 46.

[13] Jones, S. P., and DeLaurier, J. D., "Aerodynamic Estimation Technique for Aerostats and Airships," *Journal of Aircraft*, Vol. 20, No. 2, Feb. 1983, pp. 120–126.
doi:10.2514/3.44840

[14] Lutz, T., Wagner, S., "Drag Reduction and Shape Optimization of Airship Bodies," AIAA Paper 1997-1438, 1997.

[15] Bray, R. M., "A Wind Tunnel Study of the Pioneer Remotely Piloted Vehicle," Master's Thesis, Naval Postgraduate School, Monterey, CA, June 1991.

[16] Swanson, R. S., and Gillis, C. L., "Wind-Tunnel Calibration and Correction Procedures for Three-Dimensional Models," Langley Memorial Aeronautical Lab., NACA ARR Rept. No. L4E31, Langley Field, VA, Oct. 1944.

[17] Brown, C. E., and Chuan, F. C., "An Analysis of Performance Estimation Methods for Aircraft," Langley Research Center, NASA CR-921, Washington, D.C., Nov. 1967.

[18] Anderson, J. D., *Fundamentals of Aerodynamics*, 3rd ed., McGraw–Hill, Singapore, 2001.

[19] Barlow, J. B., Rae, W. H., and Pope, A., *Low Speed Wind Tunnel Testing*, Wiley-Interscience, New York, 1999.