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Analysis of Airship Lateral Maneuverability

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Abstract

EQUATIONS of motion have been derived and used to investigate analytically lateral and directional maneuverability characteristics of an advanced airship configuration consisting of auxiliary aerodynamic and powered yaw control augmentation. Theoretical expressions for turning radius, sideslip angle, roll angle, and the corresponding rudder deflection or auxiliary control needed in a steady turn have been obtained in terms of vehicle geometry, stability, control, and flight parameters. These theoretical results are also analyzed and shown to agree with experimental observations of the past. Potential for improving vehicle maneuverability either by relaxing its inherent static stability or by use of auxiliary yaw controls is discussed and illustrated with an example 2.8-million ft³ airship.

Contents

Maneuverability characteristics of an airship have been determined in the past on the basis of empirical, experimental, or flight test[1,2] data and, more recently, using nonlinear flight dynamics simulations.[3] However, in the present case a convenient set of equations of motion has been derived and used to obtain theoretical results which provide better insight into the vehicle maneuverability and its dependence on various geometric, stability, and control parameters. These results are expected to be beneficial during design and configuration development.

The equations of motion have been derived here by considering an advanced V/STOL airship configuration (Fig. 1) consisting of synchronously vectorable cruise/lift thrusters, symmetrically located on either side of the airship's car. Thrust vectoring is assumed to be limited to the pitch plane. Auxiliary yaw controls in the form of an aerodynamic canard or a powered lateral thruster at the bow and differential cruise/lift thrust are assumed to be available for augmenting conventional rudder control, in this formuation. Forward and sideward motion of the vehicle are described here by corresponding force equations in a wind axes system whose origin is at the hull volumetric center. Roll-and-yaw motions of the airship are described by corresponding moment equations in a body axes system whose origin is also at the hull volumetric center. These equations of motion [Eqs. (1–4)] include the effects of gravity, buoyancy, static, and acceleration-induced aerodynamics and control inputs. Eq. (5) represents the corresponding kinematics set:

$$\begin{aligned} m\dot V &= (T_1 + T_2)\cos(\theta_t + \alpha)\cos\beta - C_D\tfrac{1}{2}\rho V^2 \forall^{2/3} \\ &\quad - (W - B)\sin\gamma - mVr(K_x - K_y)\sin\beta\cos\beta\cos\alpha \\ &\quad - m\dot V(K_x\cos^2\alpha\cos^2\beta + K_y\sin^2\beta) \\ &\quad + mV\dot\beta\cos\beta\sin\beta\,(K_x\cos^2\alpha - K_y) + F_c\sin\beta \end{aligned} \tag{1}$$

$$\begin{aligned} MVr_w &= (-T_1 - T_2)\cos(\theta_t + \alpha)\sin\beta \\ &\quad + (C_{y_\beta}\beta + C_{y_r}r + C_{y_{\delta_r}}\delta_r)\,\tfrac{1}{2}\rho V^2\forall^{2/3}\cos\beta \\ &\quad + (W - B)\sin\phi_w\cos\gamma - mVr\cos\alpha\,(K_x\cos^2\beta \\ &\quad + K_y\sin^2\beta) + m\dot V\sin\beta\cos\beta\,(K_x\cos^2\alpha - K_y) \\ &\quad - mV\dot\beta\,(K_x\cos^2\alpha\sin^2\beta + K_y\cos^2\beta) + F_c\cos\beta \end{aligned} \tag{2}$$

$$\begin{aligned} I_x\dot p - I_{xz}(\dot r + pq) - (I_y - I_z)qr &= -\sin\theta_t(T_1 y_{t1} \\ &\quad + T_2 y_{t2}) + (Wy_m - By_b)\cos\phi\cos\theta \\ &\quad - (Wz_m - Bz_b)\sin\phi\cos\theta \\ &\quad + (C_{l_\beta}\beta + C_{l_p}p + C_{l_r}r)\,\tfrac{1}{2}\rho V^2\forall \\ &\quad - \mathscr{L}_{\dot p}\dot p - F_c z_c \end{aligned} \tag{3}$$

$$\begin{aligned} I_z\dot r - I_{xz}(\dot p - qr) - (I_x - I_y)pq &= -\cos\theta_t(T_1 y_{t1} \\ &\quad + T_2 y_{t2}) + (Wx_m - Bx_b)\sin\phi\cos\theta \\ &\quad + (Wy_m - By_b)\sin\theta \\ &\quad + (C_{n_\beta}\beta + C_{n_r}r + C_{n_{\delta_r}}\delta_r)\,\tfrac{1}{2}\rho V^2\forall - N_{\dot r}\dot r \\ &\quad + F_c x_c + N_t \end{aligned} \tag{4}$$

$$\begin{aligned} \dot\phi_w &= p_w + q_w\sin\phi_w\tan\gamma + r_w\cos\phi_w\tan\gamma \\ \dot\gamma &= q_w\cos\phi_w - r_w\sin\phi_w \\ \dot\beta &= r_w + p\sin\alpha - r\cos\alpha \\ p_w &= p\cos\alpha\cos\beta + (q - \alpha)\sin\beta + r\sin\alpha\cos\beta \\ \dot\phi &= p + q\sin\phi\tan\theta + r\cos\phi\tan\theta \\ \dot\theta &= q\cos\phi - r\sin\phi \end{aligned} \tag{5}$$

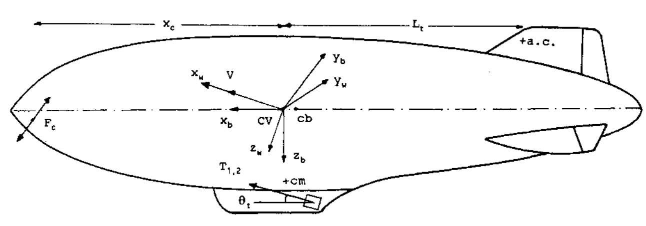

Fig. 1 Airship configuration and geometry.

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Table 1 Airship maneuverability characteristics

								R/L = 2.5, V = 10 Knots			
								$F_c = 0$		F_c = 500 lb	
Design case	$C_{y\beta}$	$C_{y\delta_r}$	$C_{n\beta}$	$C_{n\delta_r}$	$C_{y_r}V$	$C_{n_r}V$	δ_r/β	β (deg)	δ_r (deg)	β (deg)	δ_r (deg)
I	−0.773	0.256	−0.886	−0.306	163	−266	1.105	−10.8	−12.0	−6.0	−9.5
II	−0.837	0.297	−0.708	−0.384	211	−353	1.228	−16.8	−13.6	—	—
III	−0.645	0.198	−0.959	−0.233	128	−206	0.896	− 9.1	−10.2	—	—

Note: All angles are in radians except when specified otherwise.

The nomenclature used here is typical of describing[4] dynamics of aircraft. However, note that K_x, K_y are the additional mass coefficients along x and y body axes. $\forall$ represents volume of airship's hull and B represents the force due to buoyancy. T_1, T_2 are the thrust magnitudes of cruise/lift propulsors while N_t is the yaw control torque due to differential thrust on these devices. Also, (x_m, y_m, z_m) are the coordinates of the vehicle center of mass, (x_b, y_b, z_b) are the coordinates of its center of buoyancy, and (x_c, z_c) are the coordinates of the auxiliary lateral thurst F_c.

Instead of a numerical solution, a theoretical solution to the above was obtained here, albeit for the simple case of steady turning in a horizontal plane. The prevailing side-slip angle and pitch angle were assumed to be small in such a case. The corresponding solution is given below in terms of maneuverability and control parameters: turning radius in ship lengths (R/L), side-slip angle (β), rudder deflection (δ_r), and roll angle (ϕ).

$$\frac{R}{L} = \frac{-C_{n_r}V/L}{\dfrac{N_t + F_c x_c}{1/2\,\rho V^2 \forall} + C_{n\beta}\beta + C_{n\delta_r}\delta_r} \tag{6}$$

$$\beta = \frac{\dfrac{2m(1+K_x)}{\rho \forall^{2/3} R} C_{n\delta_r} - C_{n\delta_r} C_{y_r}(V/R) + C_{y\delta_r} C_{n_r}(V/R) + \dfrac{N_t + F_c(C_{y\delta_r} x_c - C_{n\delta_r}\forall^{1/3})}{1/2\,\rho V^2 \forall}}{(C_{y\beta} C_{n\delta_r} - C_{n\beta} C_{y\delta_r})} \tag{7}$$

$$\delta_r = \frac{C_{n\beta} C_{y_r}(V/R) - C_{n\beta}\dfrac{2m(1+K_x)}{\rho \forall^{2/3} R} - C_{y\beta} C_{n_r}(V/R) + \dfrac{N_t + F_c(C_{n\beta}\forall^{1/3} - C_{y\beta} x_c)}{1/2\,\rho V^2 \forall}}{(C_{y\beta} C_{n\delta_r} - C_{n\beta} C_{y\delta_r})} \tag{8}$$

$$\phi = \sin^{-1}\left[\frac{mVr_w(1+K_x)z_a - F_c z_c}{W(z_m + z_a) - B(z_b + z_a)}\right] \tag{9}$$

In the absence of any auxiliary control, and hence for a conventional airship, turn sensitivity may be conveniently defined by the parameter δ_r/β which indicates rudder deflection needed to generate unit side-slip in the maneuver. This parameter happens to be independent of turning radius. Also, in this case the turning radius would be independent of turning speed since $(c_{nr} \cdot V)$ is a constant for a given airship configuration. It is clear that for a given rudder deflection the product $(R/L \cdot \beta)$ is also a constant. Similar observations have been made previously on the basis of experimental and flight test data. The corresponding roll angle of the vehicle in the turn [Eq. (9)] is basically a statement of equilibrium between the metacentric roll moment and that due to the aerodynamic sideforce acting through a point z_a below the volumetric center.

Table 1 shows the maneuverability characteristics for an airship ($\forall = 2.8 \times 10^6$ ft^3; W = 147,560 lb; L = 460 ft) having an inverted-Y tail configuration, predicted by using the above theoretical results. Typical effects of relaxing inherent yaw stiffness ($C_{n\beta}$) of the vehicle (case II vs. case III) and incorporating an auxiliary lateral thruster (case I) are shown here by corresponding increase in its turn sensitivity (δ_r/β) and decrease in rudder control requirement. It should be noted that this type of theoretical analysis during the conceptual and preliminary design of an advanced airship would help in sizing and configuring its controls to meet maneuverability requirements and also in conducting trade studies. It is in this light that the theoretical results presented here should be viewed and used in developing future airship configurations and also in augmenting flight control and maneuverability of conventional airships.

References

[1]"Patrol Airship Concept Evaluation," NADC Rept. 85019069, March 1985.

[2]"Dynamic Flight Tests of Skyship-500 Airship," STI TR 1151-4, March 1986.

[3]Jex, H. R., Magdaleno, R. E., and Johnson, W. A., "LTASIM A Desktop Nonlinear Airship Simulation," AIAA Paper 91-1275, April 1991.

[4]Etkin, B., "Dynamics of Atmospheric Flight," John Wiley, New York, 1972.