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Response Analysis of UTHM's Airship

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Abstract:

Response of airship owing to deflection angle of elevator, rudder and vectored thrust during trimmed equilibrium flight can be computed by solving the airship equations of motion. In this study, the linearised decoupled airship equations of motion were used and the solution was computed with the aid of *Matlab* software. This paper shows a case study done by applying the physical data of a designed airship called 'UTHM's Airship' in the equations of motion and solved it in order to understand and analyze the response of the designed airship. For 'UTHM's Airship', the longitudinal response of elevator and thrust vectorization has relatively low longitudinal control power and a rather sluggish response characteristic. Meanwhile the lateral response of rudder demonstrates a relatively high rudder control power and quicker lateral response compared to longitudinal response. The results had successfully given an initial insight of the 'UTHM's Airship' response and dynamic stability.

1. Nomencleature

a	-	State matrix
a	-	Coordinate centre of gravity
b	-	Input matrix
B	-	Buoyancy force
g	-	Gravitational constant
J	-	Moment of inertia
L	-	Rolling moment
M	-	Pitching moment
m	-	Mass matrix
m	-	Airship mass
N	-	Yawing moment
p	-	Roll rate perturbation
q	-	Pitch rate perturbation
r	-	Yaw rate perturbation
U	-	Axial velocity
u	-	Input or control vector
u	-	Axial velocity perturbation
v	-	Lateral velocity perturbation
W	-	Normal velocity
w	-	Normal velocity perturbation
X	-	Axial force

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x	-	State vector
Y	-	Lateral force
Z	-	Normal force

Greek Letter

β	-	Sideslip angle
δ	-	Control angle
θ	-	Pitch attitude
ϕ	-	Roll attitude
ψ	-	Yaw attitude

Subscripts

a	-	Aerodynamic
e	-	Trim equilibrium
ele	-	Elevator
p	-	Roll rate
q	-	Pitch rate
r	-	Yaw rate
rud	-	Rudder
δ	-	Control angle
u	-	Axial velocity
V_0	-	Total velocity
v	-	Lateral velocity
w	-	Normal velocity
x	-	Body axis reference
y	-	Body axis reference
z	-	Body axis reference

Examples of Notation

Dimensional derivatives denoted thus

$$\overset{o}{M}_q = \frac{\partial M}{\partial q} \quad \text{etc.}$$

2. Introduction

An airship is a lighter than air vehicle which produces the significant lift due to aerostatic effect or buoyancy force. It is basically an aircraft that derives its lift from a lifting gas usually helium while it is propelled forward by an engine. It differs from the conventional aircraft in terms of lift producing mechanism. The potential of the airship can be realized in terms of less fuel consumption, high endurance, and ability to hover.

One of the crucial subjects of airship is stability. An airship is considered stable if the response approaches zero as time approaches infinity. Thus, through response output, the stability of the airship can also be determined. The response of airship can be computed by solving the airship equations of motion.

Although the airship equations of motion had been discussed by previous researchers [1-4], the true challenge is actually to develop the overall programming code from scratch since none of the programming codes were reveals in any literatures. This paper shows a case study done by applying the physical data of a designed airship called 'UTHM's Airship' in the equations of motion and solved it in order to understand and analyze the response of the designed airship.

3. Airship Equations of Motion

Equations of motion are equations that describe the behavior of system. Equations of motion of airship was based on Newton's second law of motion which simply states that mass times acceleration equal to disturbing force. For the rotary degree of freedom, moment of inertia times angular acceleration equal to disturbing moment. The disturbing force and moment of the designed airship were due to the aerodynamic effects, thrust effects, gravitational effects, buoyancy effects, coriolis effects and centrifugal effects when disturbed from its equilibrium state [1-4].

The responses owing to control inputs are obtained from the non linear equations of motion during the initial condition of trimmed equilibrium flight. These non linear equations of motion is linearised by constraining about small perturbation condition and restricted to the chosen designed cruising speed. Since only small perturbation is consider, it is convenient to simplify the equations by

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assuming that longitudinal and lateral motion is decoupled [1-4]. The linearised decoupled equations were then converted to state space form for the convenience of computing the transfer function and response of the designed airship.

3.1 Linearised Decoupled Equations of Motion

The linearised longitudinal decoupled equations of motion describing small perturbations about the trim state follow when the trim terms, which sum to zero, are removed. It may be written in state space form as below [1-4, 7].

$$\mathbf{x}^T = [u\ w\ q\ \theta]$$
$$\mathbf{u}^T = [\delta_{ele}\ \delta_t]$$
$$\mathbf{m} = \begin{bmatrix} \mathrm{m}_x & 0 & \left(\mathrm{ma}_z - \overset{o}{X}_{\dot{q}}\right) & 0 \\ 0 & \mathrm{m}_z & -\left(\mathrm{ma}_x + \overset{o}{Z}_{\dot{q}}\right) & 0 \\ \left(\mathrm{ma}_z - \overset{o}{M}_{\dot{u}}\right) & -\left(\mathrm{ma}_x + \overset{o}{M}_{\dot{w}}\right) & J_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\mathbf{b} = \begin{bmatrix} \overset{0}{X}_\delta & \overset{0}{X}_t \\ \overset{0}{Z}_\delta & 0 \\ \overset{0}{M}_\delta & \overset{0}{M}_t \\ 0 & 0 \end{bmatrix} \tag{1}$$
$$\mathbf{a} = \begin{bmatrix} X_a & 0 & -\mathrm{m}_z W_e & -(\mathrm{mg} - B)\cos\theta_e \\ 0 & Z_a & \mathrm{m}_x U_e & (\mathrm{mg} - B)\sin\theta_e \\ 0 & 0 & M_a - \mathrm{ma}_x U_e - \mathrm{ma}_z W_e & -\{(\mathrm{mga}_z)\cos\theta_e - (\mathrm{mga}_x)\sin\theta_e\} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

The linearised lateral equations of motion may be developed similarly as below [1-4, 7].

$$\mathbf{x}^T = [v\ p\ r\ \phi]$$
$$\mathbf{u}^T = [\delta_{rud}]$$
$$\mathbf{m} = \begin{bmatrix} m_y & -\left(\mathrm{ma}_z + \overset{o}{Y}_{\dot{p}}\right) & \left(\mathrm{ma}_x - \overset{o}{Y}_{\dot{r}}\right) & 0 \\ -\left(\mathrm{ma}_z + \overset{o}{L}_{\dot{v}}\right) & J_x & -J_{xz} & 0 \\ \left(\mathrm{ma}_x - \overset{o}{N}_{\dot{v}}\right) & -J_{xz} & J_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\mathbf{b} = \begin{bmatrix} \overset{0}{Y}_\delta \\ 0 \\ \overset{0}{N}_\delta \\ 0 \end{bmatrix} \tag{2}$$
$$\mathbf{a} = \begin{bmatrix} Y_a & \mathrm{m}_z W_e & -\mathrm{m}_x U_e & (\mathrm{mg} - B)\cos\theta_e \\ 0 & L_a - \mathrm{ma}_z W_e & \mathrm{ma}_z U_e & -(\mathrm{mga}_z)\cos\theta_e \\ 0 & \mathrm{ma}_x W_e & N_a - \mathrm{ma}_x U_e & (\mathrm{mga}_x)\cos\theta_e \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

In lateral perturbation, the sideslip angle β is given by [2]

$$\beta \cong \tan\beta = \frac{v}{V_0} \tag{3}$$

Since $\beta = -\psi$, yaw angle is given by

$$\psi = -\beta = -\frac{v}{V_0} \tag{4}$$

In order to incorporate yaw angles, in the output equations, the lateral perturbation equations can be modified as follows [2].

$$\mathbf{x}^T = [v\ p\ r\ \phi\ \psi]$$
$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{1}{V_0} & 0 & 0 & 0 \end{bmatrix} \tag{5}$$
$$\mathbf{D} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

4. Solution of the Equations of Motion

The process of solution requires the numerical values for the derivatives and other parameters are substituted and then the whole model is input to a suitable computer program. The output, which obtained instantaneously, is most conveniently arranged in terms of response transfer functions. Time step for the airship response to control can be obtained by finding the inverse Laplace transform of the appropriate transfer function expression. The solution of equations of motion can painlessly be achieved with the aid of *Matlab* software.

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Due to limited pages in this paper, the programming codes are not shown here.

5. Case Study: UTHM's Airship

UTHM's Airship is a remotely control non-rigid airship for aerial monitoring purposes. The basic specifications of the designed airship are as outlined in Table 1 below.

Table 1: Basic specifications of UTHM's Airship

Specifications	
Flight performance	
Min. Payload	8 kg
Max. speed	40 km/h
Cruising speed	20 km/h
Operating altitude	120 meter
Envelope	
Shape	Ellipsoid + cylinder
Length	10m
Max. diameter	2.3m
Volume	Approx. 30 m^3

The airship envelope consists of ellipsoidal shape for nose and tail section, and cylinder for the middle section. The designed airship was equipped with vectored thrust system moving in vertical direction from -45 to 70 degree measured positive angle of thrust line up from the horizontal. For elevators and rudders, the control is from -30 to 30 degree measured positive of elevator deflection upward and rudder deflection to left as if the pilot of the airship. The preliminary dimensions of the designed airship are shown in Figure 1 below [5-6].

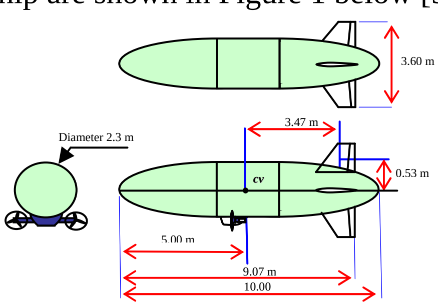

Figure 1: Preliminary dimension of UTHM's Airship

6. Results and Discussion

From the *Matlab* programming conducted, the longitudinal response to elevator is shown on Figure 2 which the input is a 1 degree elevator step.

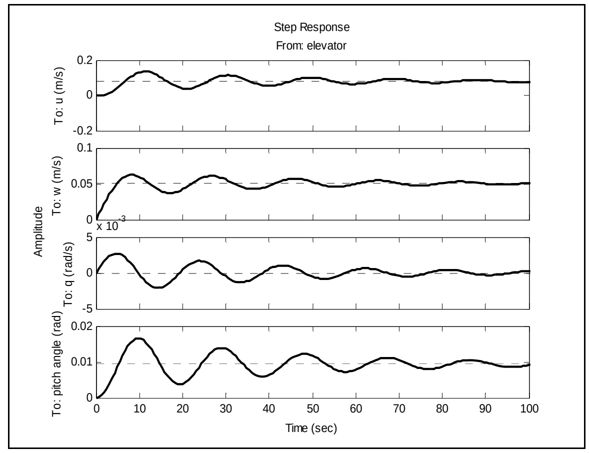

Figure 2: Longitudinal response owing to 1 degree elevator input

The magnitudes of the response variables are very small and the time taken for the transient to settle down is in order of approximately 80 seconds. Although it is longitudinally stable, it also clearly demonstrates a relatively low longitudinal control power and a rather sluggish response characteristic.

The longitudinal response to a 1 degree step in thrust is shown on Figure 3.

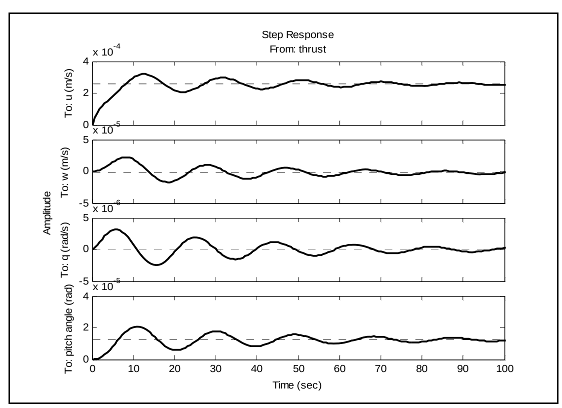

Figure 3: Longitudinal response owing to 1 degree thrust input

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It is clear that, although the engines are mounted below the centre of gravity, the pitch response to a thrust change is very small. The only significant response is in axial velocity perturbation, *u* as might be expected. Again the general magnitude is small and time scale of response is approximately 80 seconds. This confirms although it is longitudinally stable, the longitudinal control power is low and response is sluggish.

The lateral response to a 1 degree step command input to rudder is shown on Figure 4.

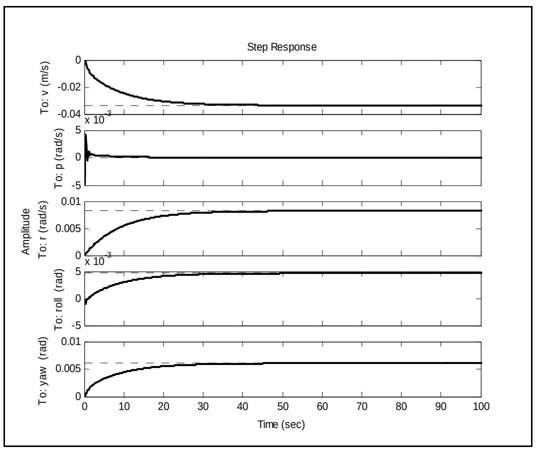

Figure 4: Lateral response owing to 1 degree rudder input

The significant response magnitudes are for lateral velocity perturbation, *v*. It is clear that rudder control power is low. However, the transient settle in approximately 50 seconds, indicating a quicker lateral response than longitudinal response and a stable lateral motion.

7. Conclusion

UTHM's Airship is dynamically stable during designed cruising speed of 20km/h with time taken for the transient to settle down is in order of 80 seconds for longitudinal and 50 second for lateral response. Although the response shows a stable airship, the open loop responses of the airship are sluggish with very low control power. Thus this indicated the need of designing a control system to enhance the response of the airship.

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