Development of UTHM's Airship Virtual Simulator

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Abstract

Airship virtual simulator was developed by programming the solution of the airship equations of motion to *Matlab* GUI. This paper shows a case study done by applying the physical data of a designed airship called 'UTHM's Airship' in the airship equations of motion for development of airship virtual simulator. In this study, the approximate and calculated stability modes of the designed airship were compared for validation purposes. The virtual simulator operates by selecting the desired control angle of elevator, rudder or vectored thrust as input and the response outputs are shown in motion of pitch, yaw or roll angle through a moving airship figure in the simulator. At the end of this paper, the virtual simulator had successfully helped interprets the response of the designed airship into an interesting and easy to understand visualization.

Keywords: airship, virtual simulator, airship response, stability modes.

1. 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 dynamic stability. Dynamic stability describes the transient motion involved in the process of recovering the equilibrium whenever slightly disturbed. To determine the dynamic stability and response to control of the designed airship, a mathematical model of airship dynamic was developed. Derivation of the airship equations of motion follows the same principle as aircraft. Assumption had been made in which that the motion of airship is constrained to small perturbation conditions about the trimmed equilibrium flight. The mathematical model of airship dynamic was derived based on works done by Mueller [3] and Gomes [4]. Then the program was developed with the aid of *Matlab* software in order to predict the stability and response of the designed airship.

Time step response owing to rudder, elevator and vectored thrust deflection angle input during trimmed flight are successfully computed through the mathematical model program. However, a new challenge persists as the response outputs graphs are difficult to understand by user that do not have the basic knowledge in vibration and dynamics field. To overcome this problem, mathematical model of airship dynamic is programmed into a graphical user interface (GUI) to become a virtual simulator. By doing this, user can select the angle of the airship's control input and the response are interpreted into an interesting and easy to understand airship visualization. Thus, the moving airship figure in the virtual simulator gives a better understanding regarding the response of the designed airship.

2. METHODOLOGY

2.1 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 were obtained from the non linear equations of motion during the initial condition of trimmed equilibrium flight. These non linear equations of motion was 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 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. The linearised longitudinal and lateral decoupled equations of motion describing small perturbations about the trim state follow when the trim terms, which sum to zero, are removed [1]-[4], [7]. It may be written in state space form as shown in Appendix 2. Nomenclatures used can be referred to Appendix 1.

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 easily be achieved with the aid of *Matlab* software.

2.1 Case Study: UTHM Airship

UTHM's Airship is a remotely control 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	6 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 [5]-[6]. The preliminary dimensions of the designed airship are shown in Figure 1.

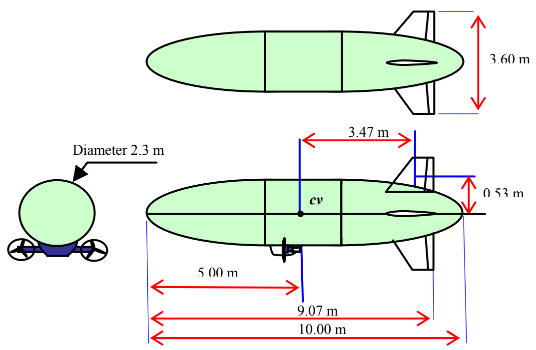

Figure 1: Preliminary dimension of UTHM's Airship

3. VALIDATION

Cook [9] has carried out an analysis of the numerical behavior of the state matrix using data for a typical modern airship, which provides considerable insight into the stability modes characteristic. The conclusion of this study has subsequently been shown by Gomes (1990) to be in good agreement with observed airship stability characteristic.

According to Goineau [10], for all flight speeds the longitudinal state matrix can be approximated by

$$\mathbf{A} = \begin{bmatrix} x_u & x_w & x_q & x_\theta \\ 0 & z_w & z_q & 0 \\ 0 & m_w & m_q & m_\theta \\ 0 & 0 & 1 & 0 \end{bmatrix} \qquad (1)$$

and the lateral state matrix can be approximated by

$$\mathbf{A} = \begin{bmatrix} y_v & y_p & y_r & y_\phi \\ l_v & l_p & l_r & l_\phi \\ 0 & 0 & n_r & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad (2)$$

Without seriously disturbing the zeros of the characteristic equation,

$$\Delta s = \det(s\mathbf{I} - \mathbf{A}) = 0 \qquad (3)$$

Where s is the Laplace operator, **I** is the identity matrix and the **A** is the state matrix. The approximate longitudinal and lateral stability modes are as outline in Appendix 3.

Using this method, an analysis of the eigenvalues of the simplified state matrix, **A** for both longitudinal and lateral enables an approximate description of the stability modes to be made. This approximate description of the stability modes can be compared to the calculated stability modes from the dynamic modeling for validation purposes.

4. AIRSHIP VIRTUAL SIMULATOR

The mathematical model of airship dynamic is programmed in to a GUI to become an airship simulator. GUI layout is consisting of 2 main panels of inputs and outputs. The input panel has three sliders to set the desired input angle for elevator, rudder and vectored thrust. The simulator also have two pushbutton for 'Simulate' and 'Reset' as shown in Figure 2 below.

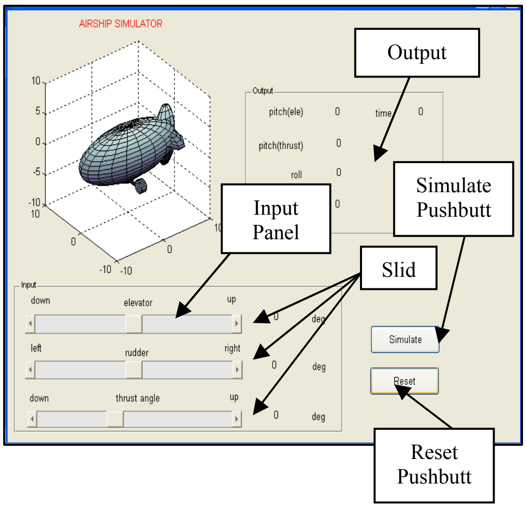

Figure 2: Airship simulator layout

In the input panel, user can move the slider to the left or right to the desired value of angle. For elevator and rudder the typical control is from -30 to +30 degree, but for the vectored thrust the typical control is from -45 to 70 degree as designed. Direction of the deflection is as shown on both end side of the sliders, where '-' value for elevator and vectored thrust indicated deflection downward and '+' value indicate deflection upward. As for rudder '-' value indicate deflection to the right and '+' value indicate deflection to left as if the user are the pilot of the airship. User can use the reset button to reset the input value to zero (default). After setting the input variables, users can now push the simulate button to execute the mathematical model of airship dynamic.

5. RESULT AND DISCUSSION

Validation of the result is done by comparing the calculated solution of the mathematical model done with approximate solution which was calculated from the state matrix. Table 3 below shows the comparison between these both solutions.

From Table 2, the approximate stability modes were calculated during hover and speed. The exact solution should be the value revolves around the approximate stability for hover mode since the exact solution of the designed airship was during a very low speed of 20km/h. The exact solution was in range within the approximate solution and compared well. Hence the computer simulation output is valid for this analysis.

Table 2: Comparison between calculated and approximate solution

Speed: 20km/h –Sea level				
Longitudinal Stability Mode	Calculated Solution (20km/h)		Approximate Solution	
	Roots	Characteristic	Roots	Characteristic
Surge	$(s+0.2693)$	Stable T_s=3.71 sec	$(s+0.2693)$	Stable T_s=3.71sec
Heave/Pitch Subsidence	$(s+0.07872)$	Stable T_h=12.70sec	$(s+0.1190)$	Stable T_h=8.40sec
Pendulum	$(s^2+0.0628s+0.1445)$	Stable ω_p=0.38 rad/s ζ_p=0.08	$(s^2+0.022437s+0.1468)$	Stable ω_p=0.38rad/s ζ_p=0.03
Speed: 20km/h –Sea level				
Lateral Stability Mode	Calculated Solution (20km/h)		Approximate Solution	
	Roots	Characteristic	Roots	Characteristic
Yaw Subsidence	$(s+0.1204)$	Stable T_y=8.31sec	$(s+0.0984)$	Stable T_y=9.09sec
Sideslip Subsidence	$(s+1.2930)$	Stable T_d=0.77sec	$(s+1.2029)$	Stable T_d=0.87sec
Roll Oscillation	$(s^2+5.7020+96.7300)$	Stable ω_p=9.84rad/s ζ_p=0.29	$(s^2+1.2030+103.9400)$	Stable ω_p=10.20rad/s ζ_p=0.06

From the *Matlab* programming conducted, the longitudinal response to elevator is shown on Figure 3 which the input is a 1 degree elevator step.

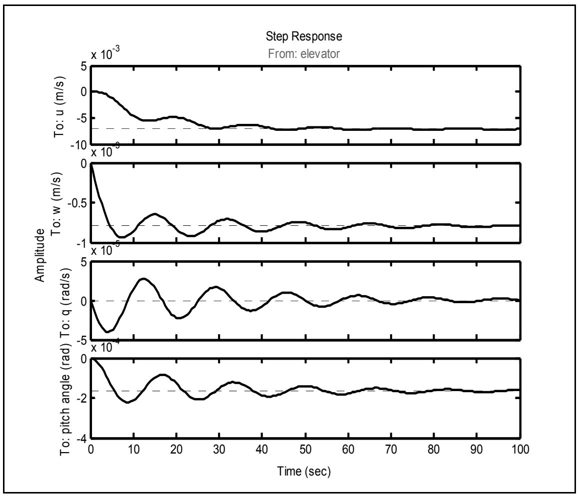

Figure 3: Longitudinal response owing to 1 degree elevator input

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 4.

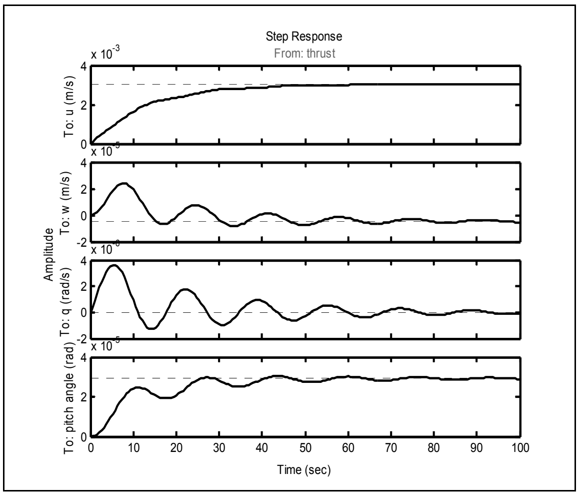

Figure 4: Longitudinal response owing to 1 degree thrust input

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 5.

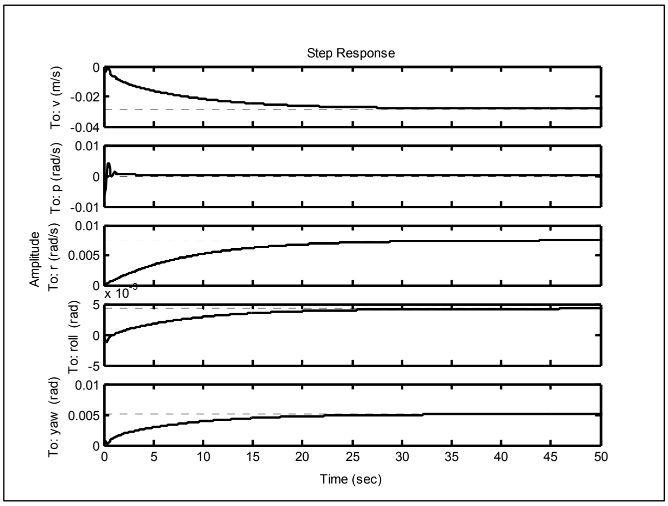

Figure 5: Lateral response owing to 1 degree rudder input

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.

Figure 6 below shows the examples movement of the airship figure due to response of control by setting the control angle to different values.

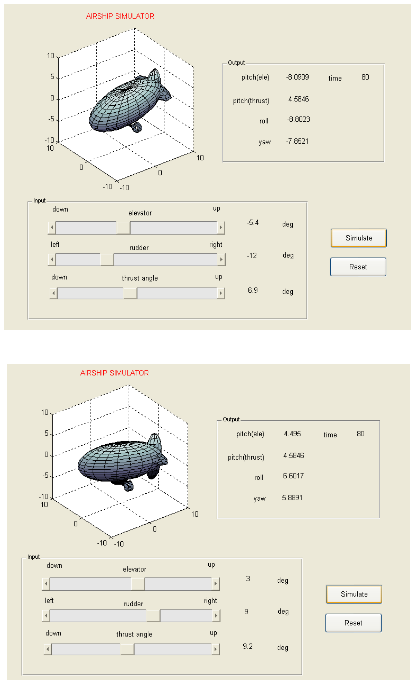

Figure 6: Airship response owing to various control input

6. CONCLUSION

UTHM's Airship is dynamically stable during cruising speed 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. Virtual simulator of airship has successfully interprets the response output into an easy to understand and interesting visualization.

7. APPENDIX

7.1 Appendix 1

NOMENCLEATURE

a/A	-	State matrix
a	-	Coordinate centre of gravity
b	-	Input matrix
B	-	Buoyancy force
g	-	Gravitational constant
I	-	Identity matrix
J	-	Moment of inertia
L	-	Rolling moment
l	-	Normalised rolling moment
M	-	Pitching moment
m	-	Mass matrix
m	-	Normalised pitching moment
m	-	Airship mass
N	-	Yawing moment
n	-	Normalised yawing moment
p	-	Roll rate perturbation
q	-	Pitch rate perturbation
r	-	Yaw rate perturbation
s	-	Laplace operator
T	-	Time constant
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
x	-	Normalised axial force
x	-	State vector
Y	-	Lateral force
y	-	Normalised lateral force
Z	-	Normal force
z	-	Normalised normal force

Greek Letter

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

Subscripts

a	-	Aerodynamic
d	-	Sideslip mode
e	-	Trim equilibrium
ele	-	Elevator
h	-	Heave/ Pitch subsidence mode
p	-	Roll rate
q	-	Pitch rate
r	-	Yaw rate
rud	-	Rudder
s	-	Surge mode
u	-	Axial velocity
V_0	-	Total velocity
v	-	Lateral velocity
w	-	Normal velocity
x	-	Body axis reference
y	-	Body axis reference
y	-	Yaw subsidence mode
z	-	Body axis reference

Examples of Notation

Dimensional derivatives denoted thus

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

Normalised derivatives denoted thus

$$y_v = \frac{\partial y}{\partial v} \quad \text{etc.}$$

7.2 Appendix 2

The linearised longitudinal and lateral 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 follows;

The linearised longitudinal equations of motion

$$\mathbf{x}^T = [u \; w \; q \; \theta]$$

$$\mathbf{u}^T = [\delta_e \; \delta_t]$$

$$\mathbf{m}=\begin{bmatrix} \mathrm{m}_x & 0 & \left(\mathrm{ma}_z-\overset{o}{X}_q\right) & 0 \\ 0 & \mathrm{m}_z & -\left(\mathrm{ma}_x+\overset{o}{Z}_q\right) & 0 \\ \left(\mathrm{ma}_z-\overset{o}{M}_u\right) & -\left(\mathrm{ma}_x+\overset{o}{M}_w\right) & J_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{b}=\begin{bmatrix} 0 & \overset{o}{X}_t \\ \overset{o}{Z}_\delta & 0 \\ \overset{o}{M}_\delta & \overset{o}{M}_t \\ 0 & 0 \end{bmatrix}$$

$$\mathbf{a}=\begin{bmatrix} \overset{o}{X}_u & 0 & -\mathrm{m}_z W_e & -(\mathrm{mg}-B)\cos\theta_e \\ 0 & \overset{o}{Z}_w & \mathrm{m}_x U_e & (\mathrm{mg}-B)\sin\theta_e \\ 0 & 0 & \overset{o}{M}_q-\mathrm{ma}_x U_e-\mathrm{ma}_z W_e & -\{(\mathrm{mga}_z)\cos\theta_e-(\mathrm{mga}_x)\sin\theta_e\} \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

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

$$\mathbf{x}^T=[v\ p\ r\ \phi]$$

$$\mathbf{u}^T=[\delta_r]$$

$$\mathbf{m}=\begin{bmatrix} m_y & -\left(\mathrm{ma}_z+\overset{o}{Y}_p\right) & \left(\mathrm{ma}_x-\overset{o}{Y}_r\right) & 0 \\ -\left(\mathrm{ma}_z+\overset{o}{L}_v\right) & J_x & -J_{xz} & 0 \\ \left(\mathrm{ma}_x-\overset{o}{N}_v\right) & -J_{xz} & J_z & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{b}=\begin{bmatrix} \overset{o}{Y}_\delta \\ 0 \\ \overset{o}{N}_\delta \\ 0 \end{bmatrix}$$

$$\mathbf{a}=\begin{bmatrix} \overset{o}{Y}_v & \mathrm{m}_z W_e & -\mathrm{m}_x U_e & (\mathrm{mg}-B)\cos\theta_e \\ 0 & \overset{o}{L}_p-\mathrm{ma}_z W_e & \mathrm{ma}_z U_e & -(\mathrm{mga}_z)\cos\theta_e \\ 0 & \mathrm{ma}_x W_e & \overset{o}{N}_r-\mathrm{ma}_x U_e & (\mathrm{mga}_x)\cos\theta_e \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

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

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

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

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

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

$$\mathbf{x}^T=[v\ p\ r\ \phi\ \psi]$$

$$\mathbf{C}=\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{1}{V_0} & 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{D}=\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

7.3 Appendix 3

The approximate longitudinal and lateral stability modes are as follows;

Longitudinal	
Mode	Low Speed
Surge Mode	$(s - x_u)$ $T_s = -\frac{1}{x_u}$
Described by real root of $\Delta(s)$. The surge mode effects the final steady state axial velocity perturbation, *u* to become a finite value that can be reached in approximately exponential fashion. Generally this mode is described by the larger of the two real roots in $\Delta(s)$.	
Pitch Subsidence Mode	$(s - z_w)$ $T_h = -\frac{1}{z_w}$
Described by real root of $\Delta(s)$. In pitch subsidence mode, longitudinal disturbance results in a vertical displacement of normal velocity perturbation, *w* of the airship. Both the new steady state of normal velocity perturbation, *w* becomes finite values that can be reached in approximately exponential fashion.	
Longitudinal Pendulum Mode	$(s^2 - m_q s - m_\theta)$
Described by the complex pair root of $\Delta(s)$. In longitudinal pendulum mode, the resulting motion composed mainly of oscillations in the axial velocity perturbation, *u* accompanied by oscillations in pitch rate perturbation, *q* and pitch angle, *θ*. Predicted motion is an oscillation in pitch with negligible height changes.	

Lateral	
Mode	All Speed
Yaw Subsidence Mode	$(s - n_r)$ $T_y = \frac{-1}{n_r}$
Described by real root of $\Delta(s)$. Yaw subsidence mode associated with lateral velocity perturbation, *v* and yaw rate perturbation, *r*. A small banking motion of roll angle, ϕ about the ox body axis is also developed in the usual approximate exponential fashion. The yaw rate perturbation, *r*, contribute to a new sideslip angle which is reached in approximately exponential fashion. Generally this mode is described by the smaller of the two real roots in $\Delta(s)$.	
Sideslip Subsidence Mode	$(s + y_v - \frac{y_\phi l_v}{l_\phi})$ $T_d = -\left(\frac{l_\phi}{y_v l_\phi + y_\phi l_v}\right)$
Described by real root of $\Delta(s)$. Sideslip subsidence mode associated with lateral velocity perturbation, *v* and a very small yaw rate perturbation, *r*. A very small yaw rate perturbation, *r*, contribute to a new sideslip angle which is reached in approximately exponential fashion. A small banking motion of roll angle, ϕ about the ox body axis is also developed in the usual approximate exponential fashion	
Oscillatory Roll Mode	$(s^2 - \left(l_p + y_v - \frac{y_\phi l_v}{l_\phi}\right)s - l_\phi)$
Described by the complex pair root of $\Delta(s)$. Associates with roll rate perturbation, *p* and roll angle, ϕ. Roll rate perturbation, *p* is in phase with lateral velocity perturbation, *v*. Following a small lateral perturbation, the airship developed an oscillatory motion about the ox body axis.	

ACKNOWLEDGMENT

We are grateful to UTHM for funding this research under short term grant (vot: 0160). Grateful appreciation also is extended to Profesor Ir. Mohammad Zainal bin Md Yusof, Capt. Al-Amin Said (Blimp Inc. Sdn. Bhd) and all the members of the grant for their advices, ideas, and technical support to this project.

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