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Experimental Determination of the Moment of Inertias of USM e-UAV

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Abstract. This paper presents the experimental determination of the moment of inertia of USM e-UAV by using pendulum method. Compound pendulum experiment is used to determine the moment of inertia about x and y axes while the moment of inertia about z-axis is determined using bifilar torsion pendulum method. An experimental setup is developed with appropriate dimension to accommodate USM e-UAV. Experimental data are presented and discussed.

Introduction

School of Aerospace Engineering USM has been developing an aerial observation system that is equipped with high definition camera and 2-axis accelerometer [1]. This system has a platform that is attached to a gyroscope that enables movement in at least two degrees of freedom. Therefore, the camera can remain pointed at a desired target thus eliminating the UAV's attitude motions effect. This system will be mounted on prototype model of USM e-UAV that has been designed and built based on LS-1 slope glider by Carl Maas and Mark Reed that is 10 times bigger than the original design. The structure of this prototype model is made of fiber glass composite and Styrofoam which was fabricated using wet hand lay-up process. In this paper, moment of inertia of this prototype model is determined experimentally by using pendulum method as suggested in [2] and [3]. The moment of inertia of an aircraft is one of the essential parameters in flight dynamic stability analysis where it is used to define the aircraft's stability and control derivatives.

Simple Pendulum Theory

Simple pendulum is a suspension of mass, m from a pivot by inextensible string of length, l where the mass is free to swing side by side. The equation of motion for this simple pendulum under small-angle approximation can be written as follow

$$I\frac{d^2\theta}{dt^2} = -mgl\theta = Wl\theta \tag{1}$$

While the moment of inertia equation for the mass is written as

$$I = \frac{T^2 b}{4\pi^2} \tag{2}$$

where $b = Wl$ and T is the time it takes for the mass to complete one oscillation. This equation shows that the moment of inertia of any rigid body can be determined by using this theory if the value for T is known. Therefore, this simple pendulum theory can be used to determine the moment of inertia for the UAV.

Experimental Set-Up

A pendulum consisting of any rigid body swinging freely about a pivot around horizontal axis is called a compound pendulum. While for a pendulum that consist of any rigid body that rotates freely about vertical axis is called bifilar torsion pendulum. The UAV can be set up based on these two pendulum methods as shown in Fig. 1 and Fig. 2 where the set-up are swing able along x and y axes as well as rotate able about z-axis, respectively. These set-ups are called the assemblage which consists of the aircraft and the swinging gear where the swinging gear consists of base, four cable wires and two hinges. A symmetry mild steel frame was built to suspend total load of 264.9 N.

Fig. 1 Compound pendulum set-up

Fig. 2 Bifilar torsion pendulum set-up

Determination of Moment of Inertia

Center of Gravity. The vertical position of the center of gravity for the assemblage, $\bar{Z}_W^{'}$ and UAV, Z_{UAV} can be determined by using the same experimental set-up shown in Fig. 1. It is required for determination of UAV's moment of inertia about x and y axes.Water level is used to guarantee the assemblage is perfectly horizontal so that the center of gravity of the swinging gear and UAV are vertically aligned. The assemblage is tilted about x and y axes by putting extra weight, w on top of the UAV with some distance, X_{Load} from the cg of the swinging gear as shown in Fig. 3 and Fig. 4, respectively [4].

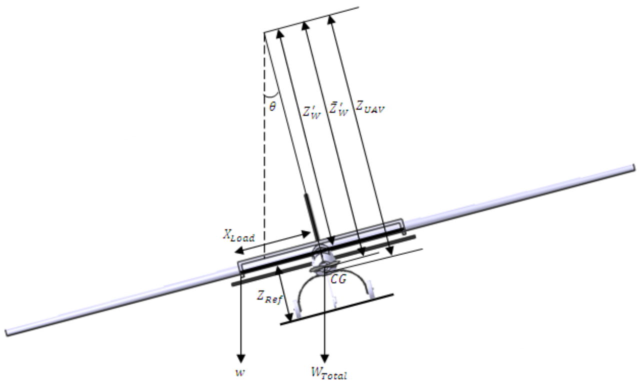

Fig. 3 UAV and swinging gear tilted about ***x***-axis

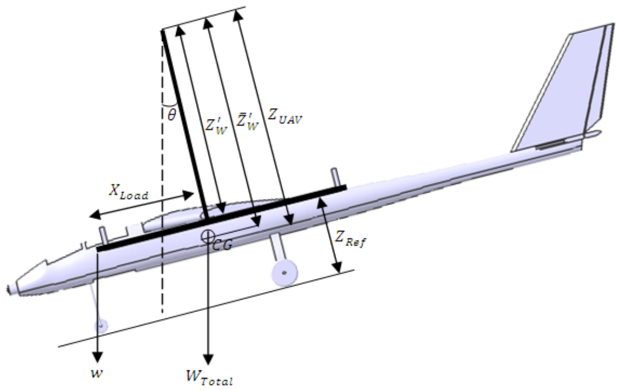

Fig. 4 UAV and swinging gear tilted about ***y***-axis

Based on the moment equilibrium, the vertical position of the cg of the assemblage based on Fig. 3 and Fig. 4 is defined as

$$\bar{Z}_W^{'} = \frac{w}{W_{Total}} \left(\frac{X_{Load}}{\tan\theta} - Z_W^{'} \right) \tag{3}$$

where W_{Total} is the total weight of the assemblage, θ is the tilt angle and $Z_W^{'}$ is the vertical distance from the pivot to the cg of the swinging gear.

Note that the tilt angle, θ is determined based on the schematic diagram shown in Fig. 5 where

$$\theta = tan\,\frac{(H_2 - H_1)}{D} \tag{4}$$

Further, the center of gravity of the UAV can be calculated by

$$Z_{UAV} = \frac{\bar{Z}'W - Z_W^{'} W_{SG}}{W_{UAV}} \tag{5}$$

where W_{SG} is the weight of swinging gear and W_{UAV} is the weight of the UAV.

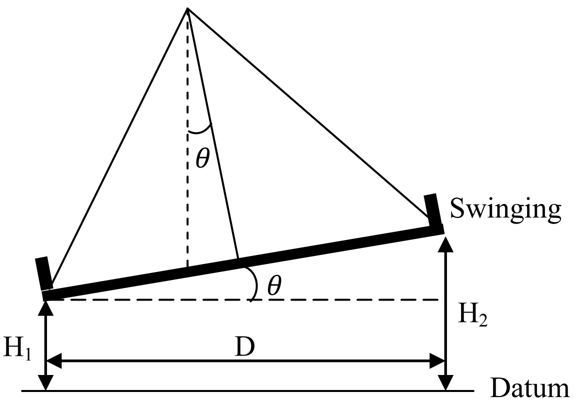

Fig. 5 Schematic diagram of tilt angle determination.

Compound pendulum Method. This method is used to determine the moment of inertia of the UAV about x and y axes [5]. The moment of inertia of the assemblage for this set-up is determined as follow

$$I_{assemblage_x}, I_{assemblage_y} = \frac{T^2 W \bar{Z}_W'}{4\pi^2} \quad (6)$$

The moment of inertia of the UAV is determined by subtracting the moment of inertia of the swinging gear and the extra moment of inertia of the UAV due to displacement of its center of gravity from the moment of inertia of the assemblage. This can be expressed as

$$I_x, I_y = \frac{T^2 W \bar{Z}_W'}{4\pi^2} - \frac{T_{SG}^2 W_{SG} Z_W'}{4\pi^2} - mZ_{UAV}^2 \quad (7)$$

Note that for the compound pendulum experiment, the period required is determined through 50 oscillations of pendulum

Bifilar torsion pendulum. This method is used to determine the moment of inertia of the UAV about z axis. The moment of inertia of the assemblage for this set-up is determined as follow

$$I_{assemblage_z} = \frac{T^2 W a^2}{16\pi^2 L} \quad (8)$$

The moment of inertia of the UAV about this axis can be determined by subtracting only the moment of inertia of the swinging gear from the moment of inertia of the assemblage which expressed as

$$I_z = \frac{T^2 W a^2}{16\pi^2 L} - \frac{T_{SG}^2 W_{SG} a^2}{16\pi^2 L} \quad (9)$$

For bifilar torsional pendulum experiment, the period required is determined through 20 oscillations of pendulum

Result and Discussion

Table 1 shows the geometric data used for $\bar{Z}_W'$ and Z_{UAV} determination while Table 2 and Table 3 show $\bar{Z}_W'$ and Z_{UAV} values when the UAV is tilted about x and y axes, respectively, for 6 different weights. The mean values for $\bar{Z}_W'$ and Z_{UAV} for both conditions are used for the moment of inertia determination. The swinging gear is highly expected to experience secondary oscillation where the system is not perfectly oscillate about its axis and performing double oscillation that will lead to twisting motion to occur at the same time. The effect of secondary oscillation is considered an uncontrolled error for both experiments. Table 4 and Table 5 summarize the moment of inertia for the swinging gear and the UAV based on the compound pendulum method and bifilar torsional pendulum method, respectively.

Table 1: Parameters for $\bar{\boldsymbol{Z}}'_{\boldsymbol{W}}$ and $\boldsymbol{Z}_{\boldsymbol{UAV}}$ determination.

Geometry	Unit	Tilting about x-axis	Tilting about y-axis
W_{UAV}	N	209.0	209.0
W_{SG}	N	55.9	55.9
W_{Total}	N	264.9	264.9
Z_{ref}	m	0.480	0.480
Z_W'	m	0.805	0.785
x_{load}	m	2.547	1.755

Table 2: $\bar{\boldsymbol{Z}}'_{\boldsymbol{W}}$ and $\boldsymbol{Z}_{\boldsymbol{UAV}}$ when the UAV is tilted about $\boldsymbol{x}$-axis.

	$w(N)$	$\theta(deg)$	$\bar{Z}'_W(m)$	$Z_{UAV}(m)$
1	2.61	1.547	0.928	0.961
2	4.19	2.473	0.920	0.951
3	5.23	3.094	0.916	0.945
4	6.07	3.566	0.918	0.948
5	7.23	4.183	0.922	0.954
6	8.14	4.746	0.919	0.950
		Mean value	0.921	0.951

Table 3: $\bar{\boldsymbol{Z}}'_{\boldsymbol{W}}$ and $\boldsymbol{Z}_{\boldsymbol{UAV}}$ when the UAV is tilted about $\boldsymbol{y}$-axis.

	$w(N)$	$\theta(deg)$	$\bar{Z}'_W(m)$	$Z_{UAV}(m)$
1	2.61	1.060	0.927	0.965
2	4.19	1.700	0.923	0.959
3	5.23	2.120	0.920	0.956
4	6.07	2.464	0.913	0.947
5	7.23	2.941	0.911	0.945
6	8.14	3.336	0.901	0.932
		Mean value	0.916	0.952

Table 4: Determination of moment of inertia for compound pendulum method.

Parameter	x-axis		y-axis	
	SG	UAV	SG	UAV
Elapse time for 50 oscillations (s)	106.4	132.4	106.2	127.0
Period (s)	2.128	2.648	2.125	2.538
Moment of inertia (kgm^2)	1.4682	18.854	1.5086	15.294

Table 5: Determination of moment for bifilar torsional method.

$L = 0.4m, d = 0.47m, a = 1.27m$		
Parameter	SG	UAV
Elapse time for 20 oscillations (s)	27.6	44.8
Period (s)	1.38	2.24
Moment of inertia (kgm^2)	2.7184	27.783

Conclusion

An experimental set-up to perform compound pendulum and bifilar torsional pendulum experiments for the moment of inertia determination of USM e-UAV has been developed where the moment of inertia along x and y axes are determined from the compound pendulum experiment while the moment of inertia along the z-axis is determined from the bifilar torsional experiment. The set-up is made of assemblage that consists of the swinging gear and the UAV. Result from experiments show that the moment of inertia of the swinging gear, $\mathbf{I}_{SG} = [1.4682 \quad 1.5086 \quad 2.7184]^T$ and the moment of inertia of the UAV, $\mathbf{I}_{UAV} = [18.854 \quad 15.294 \quad 27.783]^T$. The moment of inertia value for the UAV is essential for flight dynamic stability analysis where it is used to define the aircraft's stability and control derivatives.

Acknowledgment

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