Wing Tip Kinematics of Ornithopters

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Abstract—**Ornithopters are the miniature flapping wing aircrafts that imitate the bird flight. The major source of lift and thrust generation in these aircrafts is the to and fro motion of wings. In order to understand a complete dynamics of an ornithopter, one must possess the knowledge of the kinematics of flapping wing. In this study a model is generated in SolidWorks for analysing the kinematics of flapping wing of the ornithopters. These analyses are presented on a costumed designed Ornithopter. The kinematic analysis of SolidWorks is then verified through analytical model developed in the past using the Euler angle transformations and vector kinematics. A good agreement between the two results is obtained.**

***Keywords* — Ornithopter, kinematics, flapping, SolidWorks, transformation.**

I. Introduction

Ornithopters are biologically inspired aircrafts with enormous potential for different applications such as aerial reconnaissance, remote areas survey and inspection missions. Advances in materials and analytical methods have enabled the production of effective small-sized aircrafts. In the early days the flapping flight research was focused on the human transport but due to some accidents the human transport via flapping wing was discarded. Today the flapping wing flight research has been shifted to micro-aerial vehicles. Many aerospace engineers and biologists have studied the animal flight to develop accurate theories for flapping wing bird-sized vehicles. Environments such as forests, caves, tunnels and urban structures make reconnaissance, surveillance and search missions difficult and dangerous to accomplish. Therefore, these micro-aerial vehicles are considered ideal for these missions due to their high manoeuvrability [1]. The growing interest in unmanned small-sized aircrafts especially for surveillance in constrained areas triggered the authors to explore this field. Such small-sized aircraft can easily navigate in tight corners at low speeds and blend in with the surroundings so that nobody could identify or detect.

There has been substantial interest in the flapping wing flight over the past few years. Several scientists and biologists have performed multiple experiments on natural birds to understand the kinematics of flapping wing. Ristroph *et al.* [2] performed experiments using motion tracking technique on free-flying *Drosophila* to obtain three-dimensional wing trajectories. Similarly, Walker *et al.* [3] measured complete wing trajectories of locusts and hoverflies in a wind tunnel. Graetzel [4] also performed experiments on *Drosophila* using high speed camera in order to obtain the flapping motion of wing. Zhang *et al.* [5] used planar single-crank double-Rocker mechanism developed in *ADAMS* a modelling software to define the wing motion. The experiments conducted by Ellington [6] and Ennos [7] showed that the wing motion varies as a simple harmonic function. Jackson and Bhattacharya [8] derived the equations of motion of flapping using Eulerian Method. The central body was considered to be a point mass. Two frame of references were used, one for each wing. This assumption eliminated the rotational motion of the central body.

In order to understand the flight of ornithopter, its mechanics needs to be studied. Using the vector kinematics and Euler angle transformation proposed in [9], the transformation matrices are obtained between Global, Body and Wing coordinates to define the linear and angular motion of wing w.r.t Global frame of reference. To support the kinematics, a 3D model is developed in SolidWorks which is capable to undergo the flapping motion of wing. The flapping wing motion trajectory is obtained which conforms the analytical model.

II. Design Specifications

Ornithopter conceptual design is developed for the initial design parameters using empirical relations proposed by Wei Shyy [10]. Apart from geometric parameters other important parameters such as wing span, mass, wing surface area, root chord and flapping frequency are obtained based on the scale down model and are tabulated in Table I.

TABLE I: Important Parameters

Parameters	**Formulae**	**Values**
Span	Approx.	1 m
Mass	$(0.88 \times b)^{[illegible]}$	0.66 kg
Wing Area	$0.16 \times m^{[illegible]}$	0.1186 sq.m
Root Chord	$(8 \times S)/(b \times \pi)$	0.305 m
Flapping Frequency	$3.87 \times m^{-[illegible]}$	4.42 Hz

Flapping Angle	Approx.	30 deg

On the basis of geometric parameters AutoCAD design is made and is shown in Fig. 1.

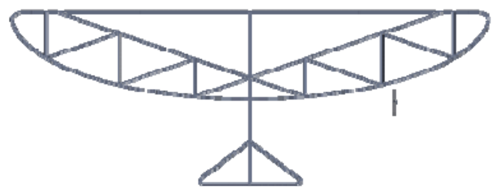

Fig.1 AutoCAD Design

Detailed measurements of wing and tail are given in Table II.

TABLE II: ORNITHOPTER MODEL SPECIFICATION

Parameter		Values in cm
Full Length		61.25
Wing	Span	100
	Chord	30.5
	Primary Spar	50
	Sec. Spar	46.14
	Area	1198
	Aspect Ratio	8.348
Tail	Span	23.59
	Chord	15.25
	Area	359.8

III. KINEMATICS OF ORNITHOPTER

Three frames of reference are used to understand kinematics of ornithopter includes Global, Body and Wing frame denoted by G, B and W respectively.

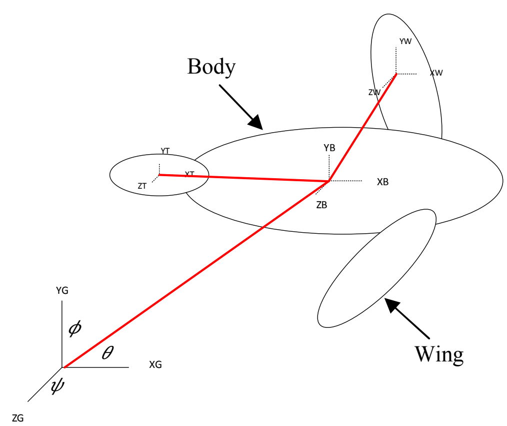

Fig. 2 Cross section

The rotational and translational kinematic equations are given by [8]:

$$\{\omega\} = [E]x\{\dot{\phi}\}$$
$$\{V\} = [R]x\{\dot{r}\}$$

Where, ω and V are the rotational and translational velocity respectively in one reference frame, $\dot{\phi}$ is the rate of change of Euler angles, $\dot{r}$ is the rate of rate of change of linear displacement in other reference frame, E is the Euler rate transformation matrix and R is the Euler transformation matrix between the two frame of references.

Now, the transformation matrices between the three frames that are Global, Body and Wing are defined next. In Euler transformation of wing to body, there is only one rotation about the *x*-axis.

$$R_W^B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_W) & -\sin(\theta_W) \\ 0 & \sin(\theta_W) & \cos(\theta_W) \end{bmatrix}$$

where, θ_W defines the flapping angle that changes sinusoidally.

$$\theta_W = \theta_{max}\sin(\omega t)$$

where, $\omega = 2\pi f$, f is the frequency in hertz.

Similarly for the transformation between body and global frames, the Euler sequence of 1-2-3 is considered. The sequence of rotation angles is θ-φ-Ψ.

$$R_B^G = \begin{bmatrix} c_1 b_1 & c_1 a_2 b_2 - c_2 a_1 & c_1 a_1 b_2 + c_2 a_2 \\ c_2 b_1 & c_2 a_2 b_2 + c_1 a_1 & c_2 a_1 b_2 - c_1 a_2 \\ -b_2 & a_2 b_1 & a_1 b_1 \end{bmatrix}$$

where:

$a_1 = \cos(\theta_B)$
$a_2 = \sin(\theta_B)$
$b_1 = \cos(\varphi_B)$
$b_2 = \sin(\varphi_B)$
$c_1 = \cos(\Psi_B)$
$c_2 = \sin(\Psi_B)$

In a similar manner, Euler rate transformation matrices are obtained [11]. The wing motion is given as an identity matrix since the rotation is in one axis.

$$E_W^B = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Likewise, for the body motion, we get:

$$E_B^G = \begin{bmatrix} c_1 b_1 & -c_2 & 0 \\ c_2 b_1 & c_1 & 0 \\ -b_2 & 0 & 1 \end{bmatrix}$$

Now, the linear and angular motion of wing w.r.t Global frame of reference can be written as:

$$V_W^G = V_B^G + V_W^B$$

$$\omega_W^G = \omega_B^G + \omega_W^B$$

IV. MODEL OF ORNITHOPTER IN SOLIDWORKS

In the initial design, flapping frequency is estimated to be 4.42 Hz and to achieve this frequency a gear mechanism is design using design approach mentioned in ref. [12]. Based on the design developed analytically a model of Ornithopter is generated in SolidWorks.

The model is capable to have inner body rotation including the flapping of wings at the desired flapping frequency and amplitude.

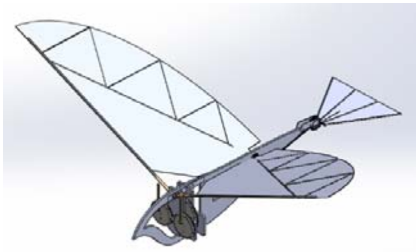

Fig. 3 Model Generated in SolidWorks

V. Body Motion

The kinematics of wings are studied next by defining the body motion parameters and assumed the motion is linear.

The displacement along *x* direction is linearly proportional to the time. However, along *y* and *z* no linear displacement and velocity is considered. The body is assumed to move in straight path with zero acceleration. The same body motions are introduced in SolidWorks model for clarity.

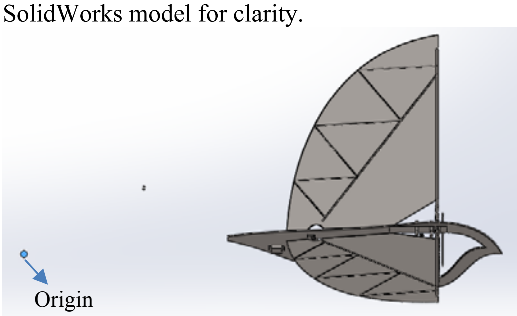

Fig. 3 Model in SolidWorks

The center of gravity position is considered to be aligned initially with the Global origin and the path of the wing tip is traced as the body moves in straight line.

Fig. 4 Sinusoidal Behaviour of Wing Tips

Simulation is carried out for 10 sec and it is observed that the motion of the wing tips is sinusoidal which resembles the motion defined in the analytical model. Here, for the kinematic analysis flapping frequency of 0.475 Hz is used to visualize the periodicity of the system.

VI. Results and Discussions

Results are plotted against different parameters to validate the analytical model.

Angular Motion vs Time

Angular displacement, velocity and acceleration of wing tip are plotted against time in Fig. 4.

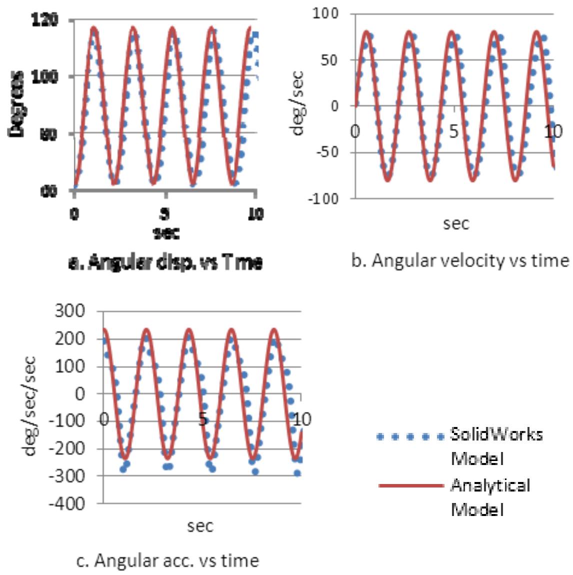

Fig. 4 Angular Motion of wing tip

It is observed in Fig. 4a. that the total flapping angle is 60 deg in both cases, which confirms the design requirement. Initially the wing is at lower extreme position and as the body moves, the wing starts to oscillate with the applied frequency. Similarly, the angular velocity of wing tip is obtained and is shown in Fig. 4b. which shows that initially the wing tip velocity is zero, but as the wing starts to flap, the velocity increases and it becomes maximum at zero flapping angle. Same reasoning is applicable for the angular acceleration of wing tip and can be seen in Fig. 4c.

The results show that the kinematic analytical model resembles significantly with the model generated in SolidWorks.

Linear Motion vs Time

Now the Linear motion of the wing is studied separately.

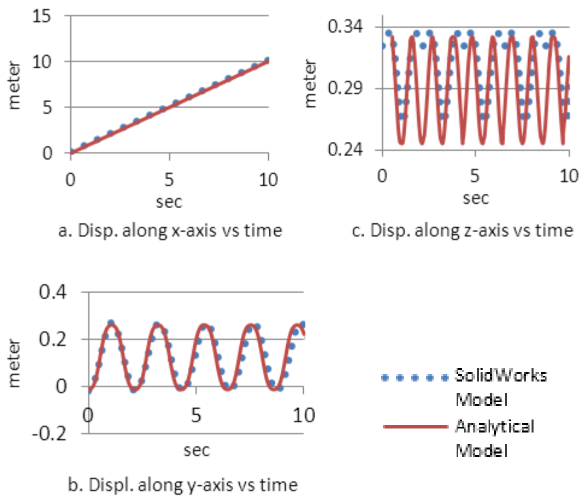

Fig. 5 Linear Displacements of wing tip

The linear displacement in *x*-axis is along the motion of the body which remains the same as that of body motion as shown in Fig. 5a. Similarly, along *y*-axis in Fig. 5b, vertical movement of the wing tip as the body moves horizontally is studied. It is observed that the tip vertical displacement is proportional to the flapping angle of the wing that changes its shape sinusoidally. In *z*-axis the body motion is zero, however, due to wing flapping, *z* position of the wing tip oscillates abruptly with small amplitude which is shown in Fig. 5c.

Next, linear velocities along *x*, *y* and *z* are studied.

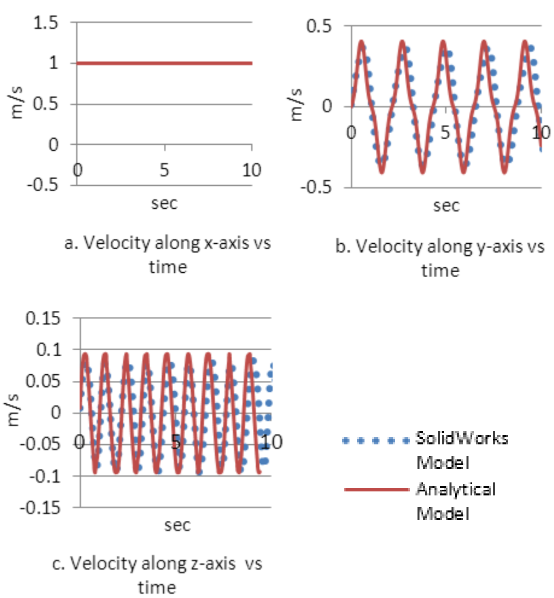

Fig. 6 Linear Velocities of wing tip

Finally, the linear accelerations in three axes are plotted with time in Fig. 7 which conforms with the results of angular motion verses time and linear motion verses time.

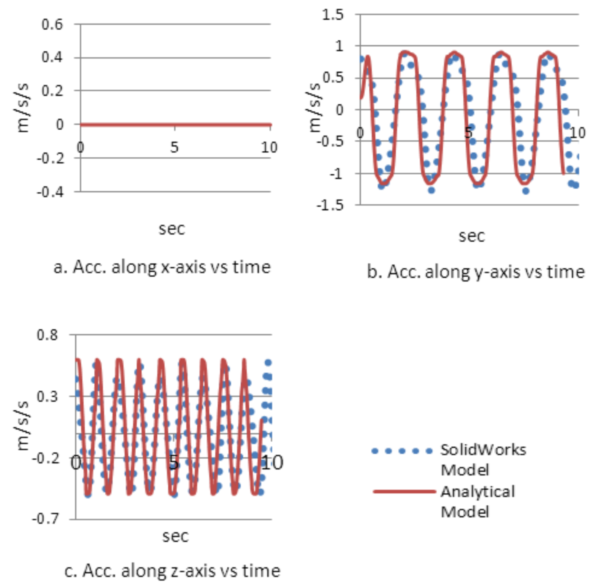

Fig. 7 Linear Accelerations of wing tip

VII. CONCLUSIONS

This study focuses the motion of wing while flapping during the flight of Ornithopter. Two methods are studied separately in order to understand the wing kinematics. In the analytical method, conventional Euler Angle and Euler rate transformations are used in order to define the external as well as the internal movements of Ornithopter. The Euler Angle sequence of 1-2-3 is used to define the rotation of body w.r.t global coordinate system. SolidWorks is then used to verify the theoretical prediction. The simulation is performed for 10 seconds. The results obtained from both techniques conform to each other. The resemblance of the results shows that kinematic model can be used for further dynamical study of Ornithopter.

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