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Simulation of Flexible Flapping Bird Wing in Producing Thrust

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Abstract**—**Birds in flight may flap their wings to produce lift and thrust simultaneously. This may provide inspiration to the engineers to create a flapping-wing based machine. Thrust may be produced in the manner of interactions between fluid motion and flexible wing. Physically, this interaction causes the wing deformation due to static pressure of air flow along the wing surface. Furthermore, the alteration of the wing shape gives significant influence on air flow around. This fluid structure interaction problem is solved computationally using two-way coupling interaction method. In the simulation, the bird wings are modeled as a rectangular flat plate. In addition, the material characteristics of the wing have given Poisson's ratio, Young's modulus and density. The leading edge of the wing in a clamped condition is vertically plunged at a given frequency. Results show that during down stroke the movement of the wing pulls air flow generating rotational flow motion downstream until the end of the down stoke, and after a while as up-stroking, the rear deformed wing pushes it back generating flow acceleration. As a result, maximum thrust are produced which indicated by two peaks of thrust in one cycle. At optimum frequency, the flapping wing generates maximum impulse.

Keywords**—** Fluid structure interaction, thrust generation, flexible flapping wing, computational fluid dynamics.

NOMENCLATURE

F	=	aerodynamic force
I	=	impulse
P	=	static pressure
T	=	thrust
dt	=	time step
F_x	=	X component of the resultant pressure force acting on the vehicle
F_y	=	Y component of the resultant pressure force acting on the vehicle

I. INTRODUCTION

IT is very interesting to study how a bird can fly and climb by flapping its wings. During the flight, birds may flap their wings to interact to the surrounding air flow that may require large energy for producing thrust and lift simultaneously. However, it is observed that a bird only feeds small amount of food. This has become inspiration for the engineers to apply such kind of propulsion system on a Micro Aerial Vehicle for generating thrust with high efficiency.

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Bird wing is composed of skeletons, muscles, and feather. This combination gives high flexibility for bird to morphing its wing shape during flight. Reference [1] shows that the flapping motion of a rigid wing with zero twist produces no thrust. The flexibility of the wing may cause the generation of thrust when the bird flaps.

Research on the generation of thrust of a moving wing has initially been done by Katzmayr in 1922. He conducted experiments using fixed wings placed into an oscillating flow field [2]. His research proved the hypothesis of Knoller-Betz ([3] and [4]). They observed that the vertical motion of the flapping rigid wing generates an effective angle of attack and in turn, produces aerodynamic forces in the form of thrust and lift force simultaneously. In 1999, Lai and Platzer investigated the generation of thrust experimentally with focusing on the effect of flow motion in the wake region due to the wing plunging. The vortex structure resulted by the oscillating wing was captured in the surrounding and the wake region [5]. Two years later, Lai and Platzer found that the generation of thrust is due to arising jet flow as the airfoil plunging motion without the effect of free stream airflow [6].

Based on the researches above, authors are motivated to perform a research on the generation of thrust of flexible wing of bird using computational fluid dynamic approach. The purpose of this study is to examine the characteristics of thrust of flexible flapping wing and the effect of flapping frequency. Flow solution in the computational domain is obtained by solving the Navier-Stokes equations with the k-ω turbulence model. The interaction between fluid motion and wing structures uses a two-way interaction model or a full coupling model. In simulation, the bird wing is modeled as a rectangular flat plate.

II. MECHANISM OF THRUST GENERATION

For flight, most birds flap their wings to maintain its position from the gravity effect. During flapping motion, the outer wing moves faster than the inner wing because the distance to travel for a stroke at the outer wing is larger than the inner wing. Therefore, the local vertical speed due to the wing motion at the outer wing is higher and in turn, the effective angles of attack vary increasingly to the wing tip. Based on the hypothesis by Knoller and Betz, this effective angle of attack generated due to flapping motion relates to the amount of thrust and lift produced.

For a flexible wing in flapping, vortices released continuously from the trailing edge grow larger as they move downstream. It forms a unique pattern of Karman Vortex Street as investigated by Lai and Platzer ([5] and [6]). They showed two different rotations of vortices, namely the clockwise vortices separate from the wing upper surface, and the counter-clockwise vortices released from the lower surface. The vortices in wake region have higher momentum compared to that in front of the wing. This difference produces the wing thrust.

III. Fluid-Structure Interaction Method

The fluid and structure interaction (FSI) including flapping flexible wing is quite complicated problem in engineering because it involves evaluations in both structural dynamics and fluid dynamics which both influence each other. Change in the structure shape will affect the surrounding fluid and, in turn, the fluid behavior will generate forces that affect the structure shape. For solving the problem based on computational simulation, two different fields including fluid field and solid field must be solved using two separate solvers. Firstly, Computational Fluid Dynamics (CFD) is used for obtaining fluid solution and secondly, Finite Element Analysis (FEA) is used for calculating deformation and stress. Then, the sharing of information of the numerical solutions between the fluid solver and structure solver is carried out at the boundary between fluids and solids (the fluid-structure interface). The information exchange is dependent on the coupling method.

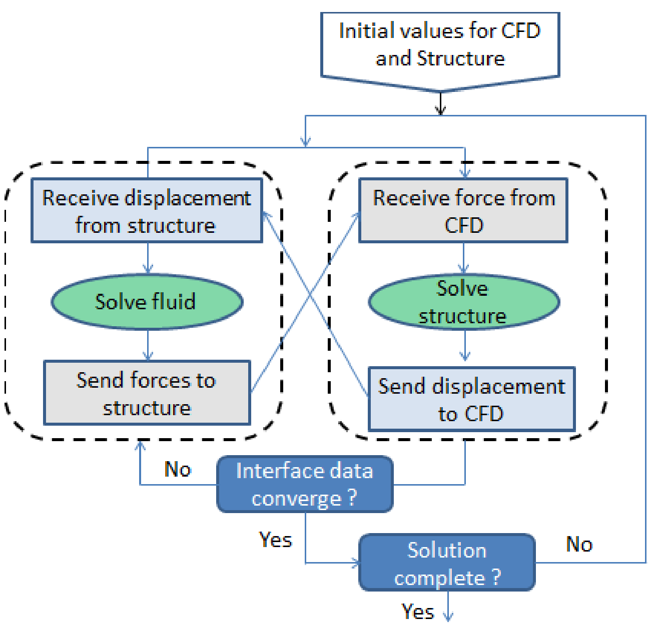


Figure 1 Two-way Coupling interaction between structure and fluid

The solution of fluid-structure interaction can be approached in two ways of coupling evaluation. Firstly, the one-way coupling interaction, that is the computation result of fluid dynamic used as input for the calculation of the structure or vice versa. The second way called two-way coupling interaction is used in this study as shown in a diagram (**Figure 1**). In the latter method, fluid dynamic calculation using CFD outputs result in terms of static pressures or forces that is used as input in structure calculations, and then the structure calculations using FEA outputs result in term of displacement that is used as input in fluid calculation. Coupling process occurs when information from the CFD and FEA solutions is exchanged at each synchronization points at interface. In addition, both solvers have different meshing requirements. The mesh must not be identical at the interface, but must consist of the identical geometrical surface. Within one-time step during the transient simulation as the inner loop, a converged CFD solution based on the fluid mesh is required to provide the forces acting on the wing surface. The forces are then interpolated from the fluid mesh to the surface mesh of the structure. Subsequently, under the effect of the acting forces, a converged solution of the structural dynamics will be attained. The response of the structure to the emerging load represents a displacement of the structural grid nodes. The displacements at the boundary are interpolated to the fluid mesh which leads to its deformation. These steps are repeated until the change in interface data, namely the flow force and the structural displacement fall below a prescribed amount. The outer loop reflects the time step loop. The complete simulation is running until a convergence criterion is reached, e.g. the given real time duration is reached.

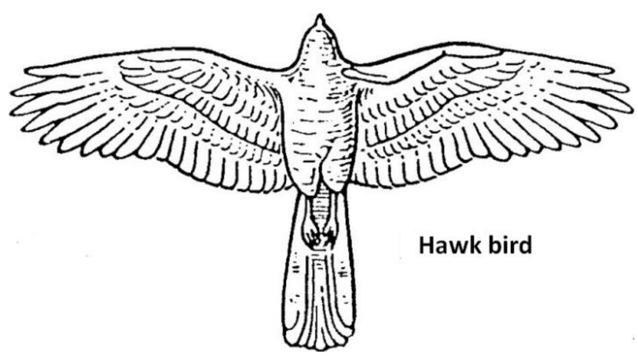


Figure 2 Hawk bird bottom view [7]

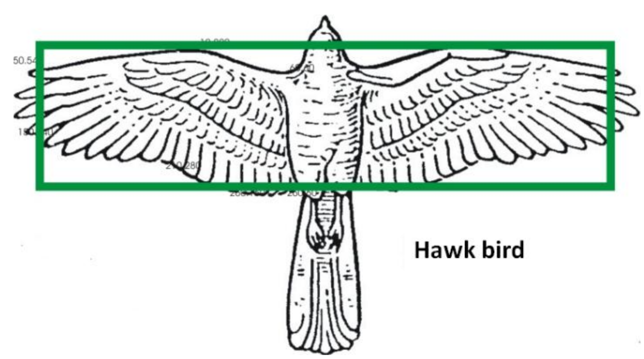


Figure 3 Rectangular flat plate model of wing for simulation

IV. Simulation of Flexible Flapping Wing

A. Geometry and Material Characteristics of Flapping Wing Model

The geometry model of Flapping Wing uses the wing planform of the Hawk bird as shown in **Figure 2**. This bird has the wing area of 0.24 m^2 with its span and chord length of 1.1 m and 0.6 m, respectively. The fundamental material properties of the wing are given as follows: Poisson's ratio of 0.35, Young's modulus of 0.1 GPa and density of 1100 kg/m^3. This material of bird has the Young's modulus that its value between a rubber and a polystyrene material and its Poisson's ratio as same as an aluminum. This indicates that the bird has flexible material. In addition, the bird flies with flapping frequency of 2.87 Hz. There is a computational model simplified from the Hawk bird wing used in this study as shown in **Figure 3**, namely as a rectangular flat plate model its aspect ratio is the same of wing planform of the Hawk bird. The flexible model has only two degrees of freedom, namely heaving and twisting because the leading edge of the wing in a clamped condition. The flexibility matrix method is used to account for structure flexibility and coupling between the different structural nodes. This provides a reasonable approximation for structure flexibility and the way a structure transfers loads between structural nodes.

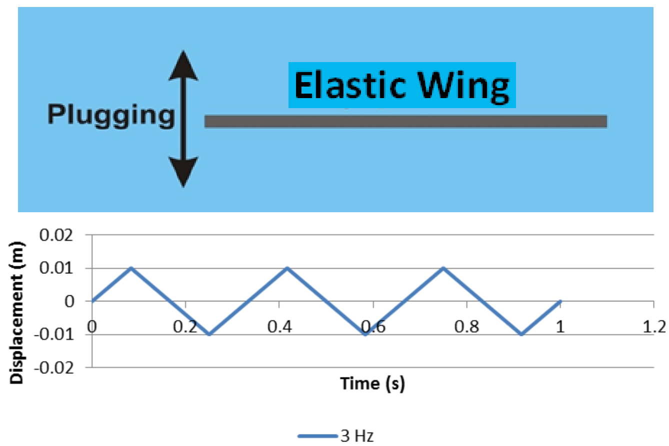


Figure 4 (a) Plugging motion of elastic wing; and (b) Linear function of leading edge motion at 3 Hz

B. Linier Flapping Motion

In order to study the elastic wing effect in generating thrust, the wing is moved in plugging motion by setting the leading edge in a clamped condition. The motion path is performed in a simple way by displacing the wing leading edge vertically with a constant speed, so the wing movement follows a linear function with respect to time as shown in **Figure 4**. As a result, the wing moves down stroke and up-stroke with a given frequency or same speed.

C. Computational Grid and Boundary Conditions

To compute fluid properties in the computational domain the grids are required. The distribution of grids must represent the geometry and physical flow phenomena to be captured. For simulating the flapping wing, the number of grids around eight hundred thousand elements used for the first model as shown in Figure 5. The number of grids is sufficient for capturing the low Reynolds number flow around simple rectangular flat plate.

The setting of boundary conditions is carried out on both structure and fluids. On the fluid domain, it is applied two types of boundary conditions, namely wall and opening (far field) boundary conditions as shown in **Figure 5**. Furthermore, on the structure of the wing, the boundary conditions of a fluid-solid interface and surface displacement are used as shown in **Figure 6**.

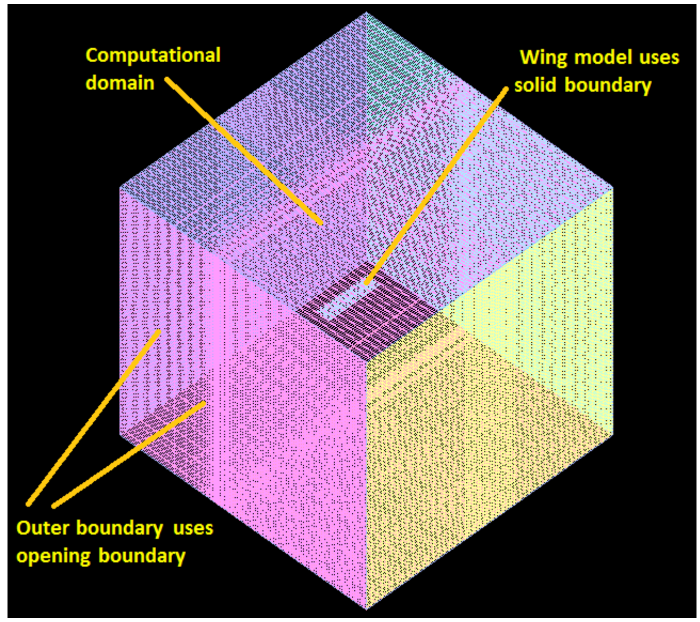


Figure 5 Computational domain and CFD boundaries

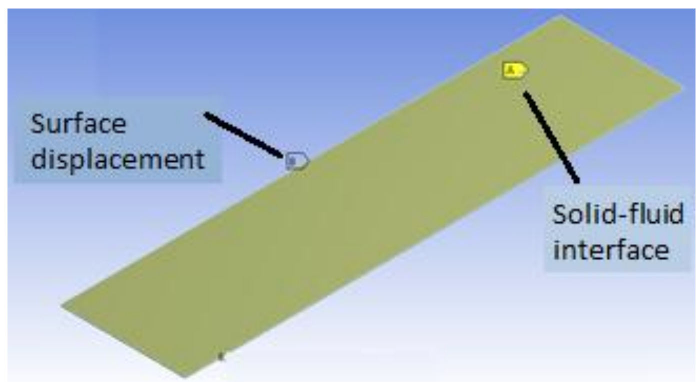


Figure 6 Wing model and structure boundaries

D. Calculation of Thrust and Impulse

Thrust of the flapping wing model is calculated by integrating static pressures along the model surface as follows:

$$F = \int P \cdot dA \tag{1}$$

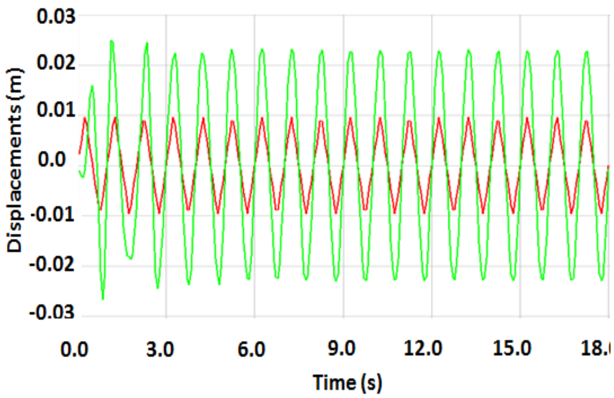
The solution of flow properties such as pressure, velocities and density in the computational domain is obtained by solving Reynolds Averaged Navier-Stokes with k-ω turbulent model. The numerical method is based on Finite Volume discretization approach where the governing equations in the integral form are evaluated at each cell.

The aerodynamic force can be separated into vertical and horizontal components with respect the body axis system. The horizontal component constitutes the wing thrust, and the vertical component is the wing lift. The thrust can be written as negative of the produced aerodynamic forces as follows:

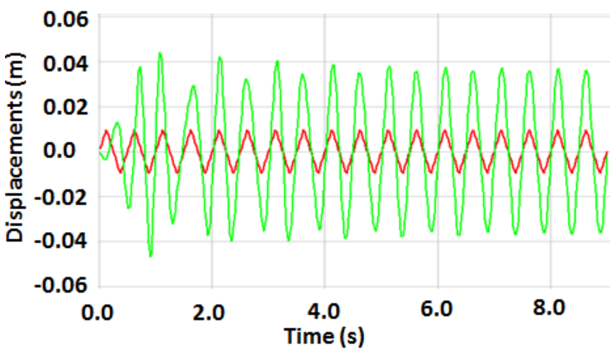
$$T = -F_x \tag{2}$$

Impulse generated by the motion of the flapping wing can be calculated by integrating thrust in one cycle time period as follows:

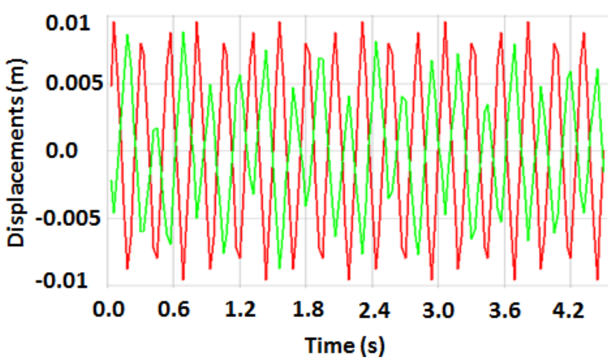
$$I = \int T \cdot dt \quad (3)$$



(a) Flapping frequency of 1 Hz



(b) Flapping frequency of 2 Hz



(c)Flapping frequency of 4 Hz

Figure 7 Structure deformation monitored at leading and trailing edges at various frequencies

V. RESULTS AND ANALYSIS

A. Displacement of structure of flexible wing

To investigate characteristics of thrust, a rectangular flat plate model is used. This model is moved a plugging at three different frequencies, namely 1 Hz, 2 Hz, and 4 Hz. Due to the structure flexibility of the model, structure can have various displacement along the model surface and changes with respect to time. The displacement is monitored at two points, namely at leading edge and trailing edge. The leading edge is moved vertically with constant speed with maximum displacement of 0.10 m. **Figure 7** shows the structure motion at the trailing edge at frequencies of 1 Hz, 2 Hz, and 4 Hz respectively. At the flapping frequency of 1 Hz, the resulted displacement of trailing edge is about twice the displacement of the leading edge. The displacement of the trailing edge becomes larger as flapping frequency increases. It is almost four times the displacement of the leading edge. However, further increase of flapping frequency (4 Hz) provides no more increase in the trailing edge displacement. In addition, the displacement of the trailing edge is less than that of the leading edge with the different phase about 180 degree between the leading edge and trailing edge motion as shown in **Figure 7c**.

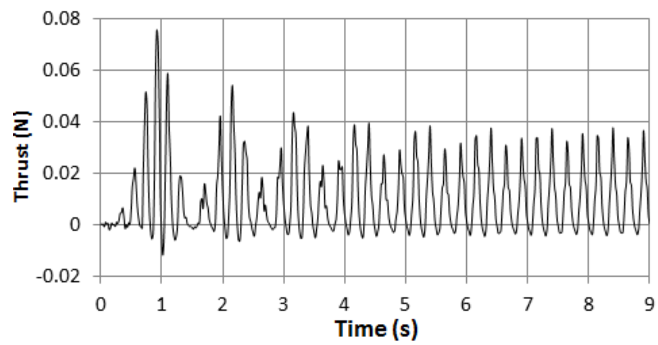


Figure 8 Generated thrust of the flapping wing at frequency of 2 Hz

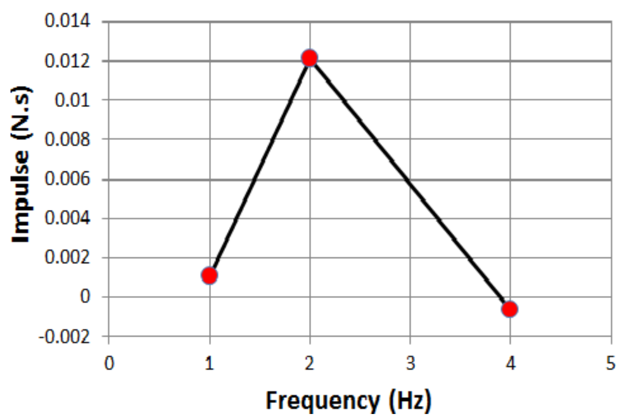


Figure 9 Impulse generated at various frequencies

B. Characteristics of thrust and impulse

The interaction between the structure motion of the model and the surrounding fluid generates thrust and lift. There is a relation between the displacements of the trailing edge of the model with the generated thrust. The larger displacement of the model trailing edge the bigger amount of flapping thrust can be generated. **Figure 8** shows the generated thrust for 9 seconds of the stroke at the flapping frequency of 2 Hz. In the first 5 seconds, generated thrust is still in a transition condition in which the maximum and minimum thrust changes with respect to time. Above 5 seconds, stroke maximum and minimum of generated thrust becomes steady condition. By integrating the generated thrust with respect to time in a cycle in steady condition the impulse of the flapping motion can be obtained. The comparison of impulse for three different frequencies is shown in **Figure 9**. The higher the frequency of the flapping wing, the larger the impulse becomes. However, further increase in frequency may decrease the impulse and result in a negative value.

In more detail, the thrust in steady condition for a cycle at various flapping frequencies is depicted in **Figure 10**. For the rectangular flap plate wing model, from lower to moderate flapping frequency, namely 1 Hz to 2 Hz, the motions of the leading edge and trailing edge have same phase. In the beginning of down stroke, the thrust increases until it reaches a maximum value. It then decreases with further down stroking and reaches the minimum value when the position of the wing is lower at about 75% of the length of the down stroking. During the continuing of the down stroke to the lowest position, the thrust increases again. Thrust increase continues to the beginning of the up stroking. Continuing the up stroking the thrust decreases after reaching another maximum value. The decrease in thrust takes place afterwards until reaching a minimum value when the position of the wing is higher at about 75% of the length of the up stroking. Then, the thrust increases until the up stroke is finished. However, at higher flapping frequency, namely 4 Hz, due to the trailing edge motion provides 180 deg. phase difference compared to the leading edge, the thrust decreases and becomes negative in the beginning of the down stroke. It then increases until the end of down stroking. The same pattern of the thrust is produced during up stroking.

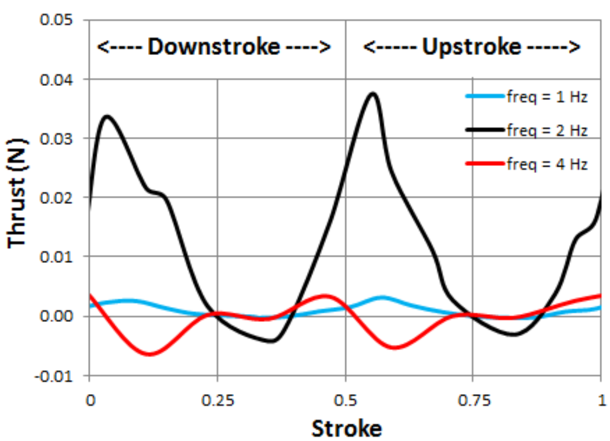


Figure 10 Thrust for a cycle at various frequencies

C. Flow behavior in Steady Condition

The reason why the thrust can be generated by the flexible wing can be explained by flow behavior that occurs around the wing in motion as shown in **Figure 11** for the flapping frequency of 2 Hz in steady condition. In the beginning of the down stroke, the position of the leading edge is lower than that of the trailing edge, so flow around the trailing edge is pushed downstream. As a result, an additional momentum is resulted in downstream, which in turn, higher thrust is obtained. Further down stroking, a curl flow occurs on the upper surface close to the trailing edge. This curl flow develops with further down stroking until reaching the lower position at about 75% of the length of the down stroke. This curl flow has the direction of rotation as a counter clock wise that reduces the flow momentum downstream. The continuation of down stroking causes the curl flow moving far upward that induces and accelerates the flow on upper surface to downstream. This causes the momentum of flow in downstream increases.

For the motion of the wing in upstroke as shown in **Figure 11**, the additional thrust generated in the beginning of up stroking causes a compression on flow due to the motion of trailing edge upward. This compression gives the effect of a jet flow so that the momentum of flow downstream increases. Further up stroking, the trailing edge motion generates a curl flow in clock wise direction. This reduces the momentum downstream so that the thrust decreases.

D. Flow Behavior in Transient Condition

Thrust generated by flapping motion is produced by the difference of flow momentum between downstream and upstream. The generation of momentum from the starting to the time of 9 seconds in downstream presented with velocity contours is shown in **Figure 12**. The high speed flow region continuously grows with as the number of cycles increases until reaching maximum speed. This flow then diffuses downstream affecting larger region. In order to observe downstream velocity in the transient condition, velocity distributions are computed along several lines as shown in **Figure 13**. The averaged velocities can then be computed with the results as depicted in **Figure 14**. In the first position, flow velocity in the transition condition occurs in the first two seconds. Velocity fluctuation in this position comes from two opposite vortices generated by the trailing edge motion. At the succeeding positions, the transition occurs in longer time with the velocity decreases. The flow velocity becomes smoother due to process of diffusion.

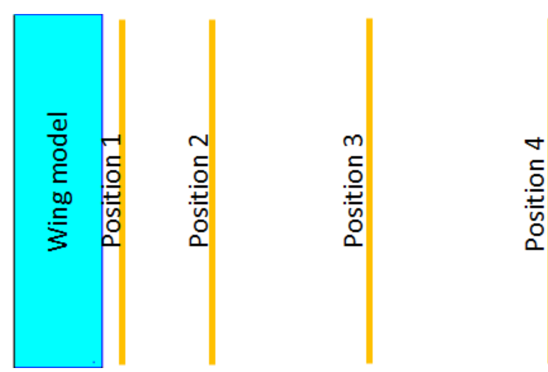


Figure 13 Position for computing velocity distribution

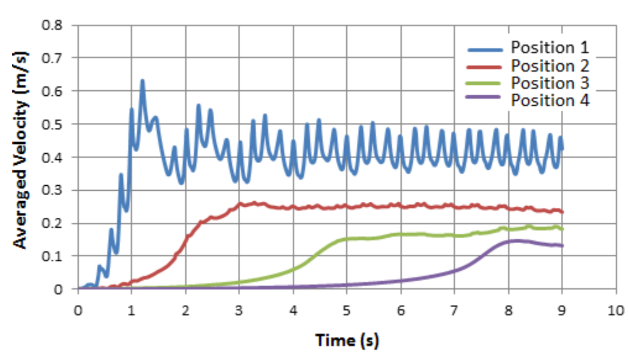
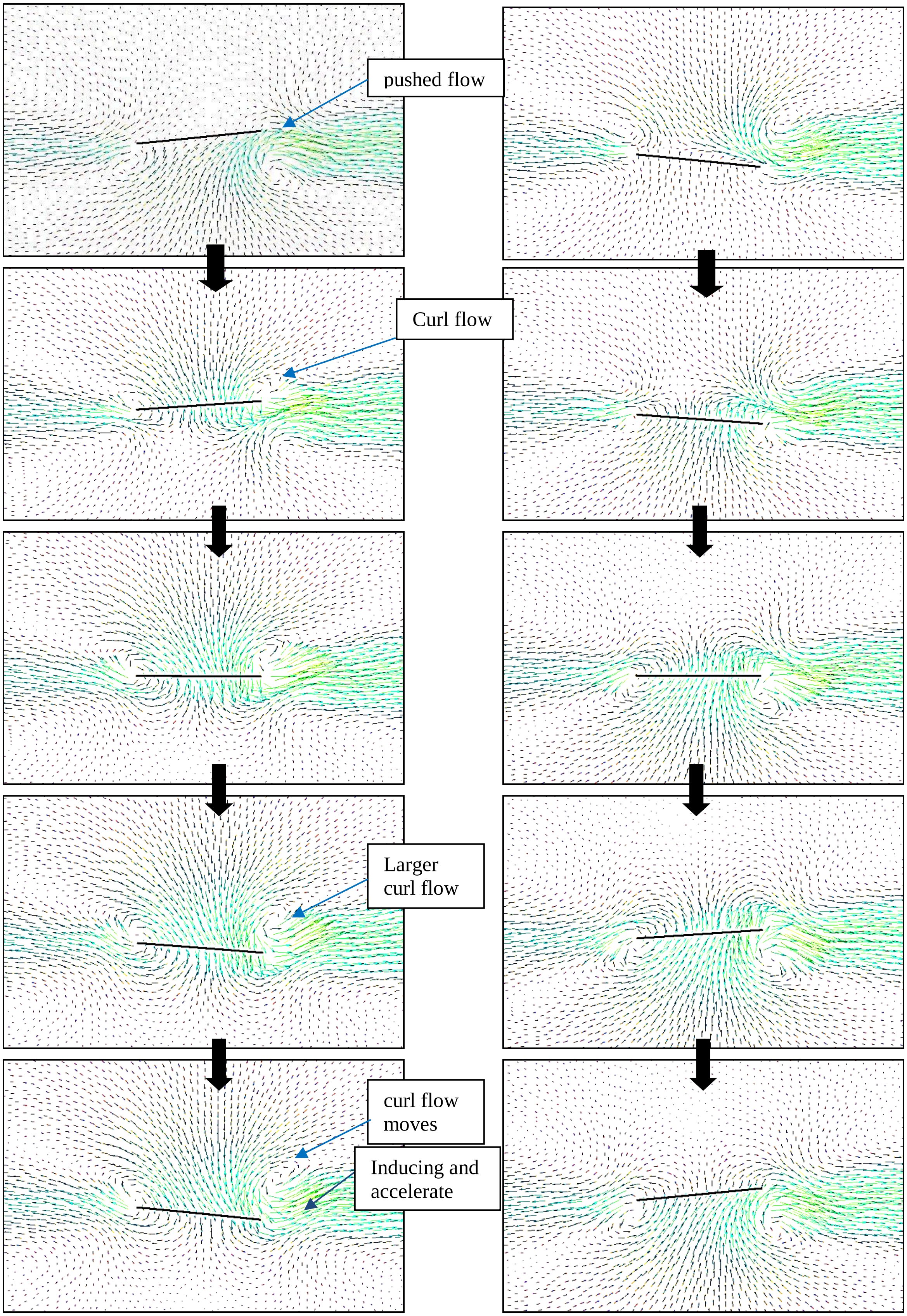


Figure 14 Averaged velocity at several positions downstream



(a) Down stroke **(b) Upstroke**

Figure 11 Instantaneous velocity vector during down stroke and upstroke at frequency of 2 Hz

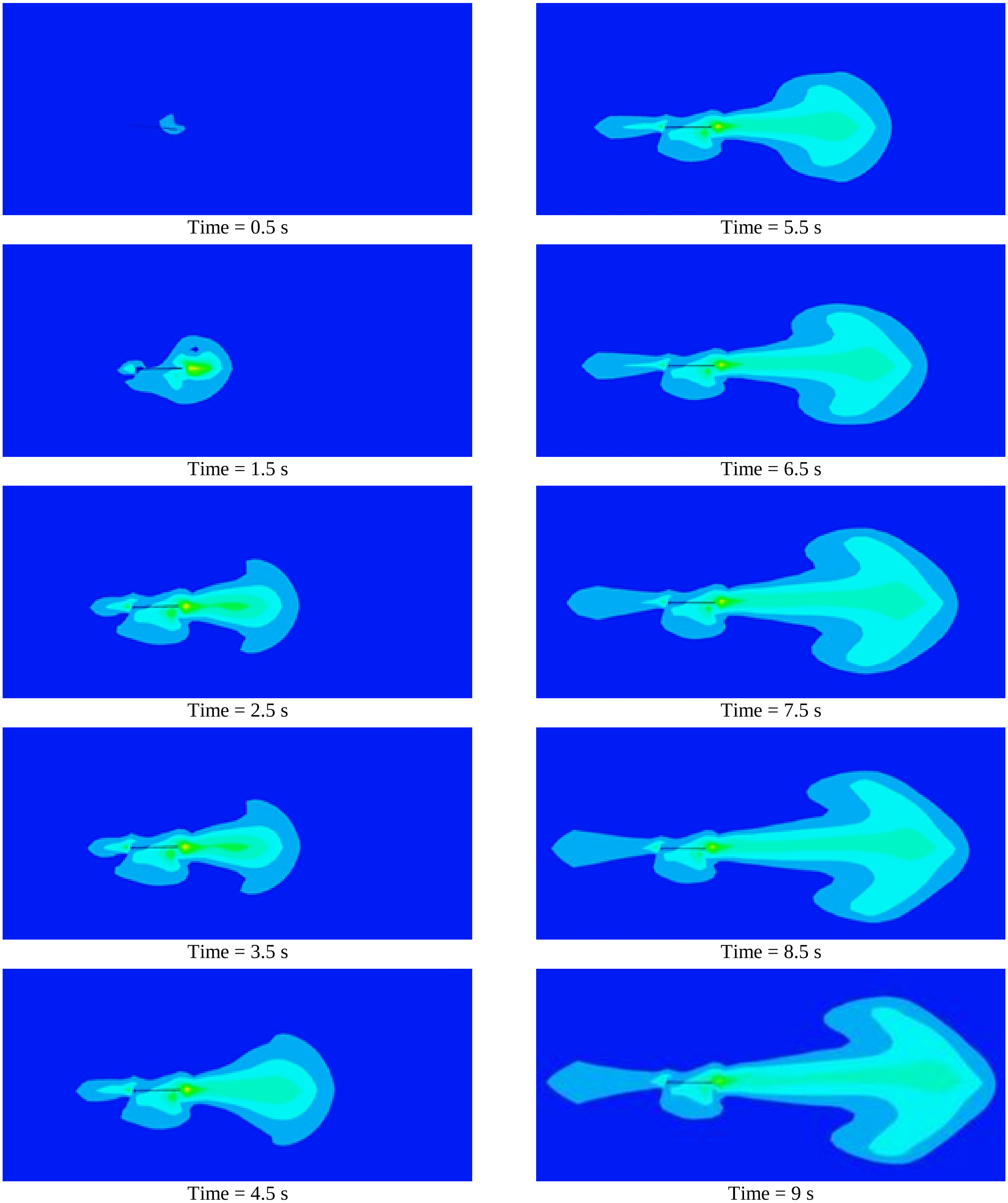


Figure 12 Instantaneous velocity during down stroke and upstroke at frequency of 2 Hz

VI. Conclusion

The flapping motion of flexible wing excites the surrounding fluid producing aerodynamic loads including lift and thrust. The generated thrust is affected by the deformation of the wing trailing edge. Flapping frequency is one of factors influencing the deformation. The maximum thrust may be obtained in moments at the beginning of down stroke and upstroke. During down stroking, the flapping generates a curl flow in counter clock wise on the upper surface close to the trailing edge. Jet flow occurs behind the trailing edge contributing much of the overall thrust generation. Optimum thrust for the rectangular flat plate model is generated at the flapping frequency of 2 Hz to 3 Hz.

Acknowledgment

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