

**The Phase-Averaged Velocity Measurement  
and the Estimation of Pressure Force of a  
Periodically Moving Body**

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## Abstract

Motivated to engineer micro-air vehicles, the relationship of the vorticity distribution with force generated by a flapping rigid plate was investigated with stereo particle image velocimetry. Measurements were conducted under the hovering condition with a flapping rigid plate for the wing model and a sinusoidal function as the flapping motion. The full deformation tensor was obtained by measuring the velocity vectors at three measurement planes offset in the out-of-plane direction. The unsteady state of the flow was resolved by phase averaging. Thus, the governing equations were decomposed into the average and fluctuation terms.

Vortex structures were identified using the second invariant of the deformation tensor and two-dimensional streamlines. Control volume analysis shows the interaction of the vortex structures with the flapping plate as represented by the force acting on the control volume. There is a phase difference between the generated force and flapping motion for all the measured sections of the plate. Maximum force is generated when the plate is at the start of either upstroke or downstroke, ie. the flapping motion is at low velocity. On the leading edge, the unsteady term of the force increases with increasing Reynolds number

The pressure field distribution around the flapping plate was visualized from the velocity field by integrating the Poisson equation using two overlapping meshes. For comparison, the torque of the flapping axis was calculated using the pressure estimation and strain gauge measurement. In this study, qualitative agreement of the two methods is shown for the mid-chord section of the plate. The visualization of the pressure field shows that the vortex flow increases the force generation at low flapping velocity by creating a stagnation pressure from the flow induced by the vortices or *inter-vortex stream*. This mechanism is responsible for the phase difference between the force and the flapping motion. After the initial motion, there are pressure stagnations on the front and rear surface of the plate. Front stagnation is produced by flow stagnation because of the motion of the plate and rear stagnation is generated by the inter-vortex stream.