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Hydrodynamics and vortex structure of undulating fins in stationary water

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ABSTRACT

The fishes swim with high efficiency and low noise, gives us important enlightenment on propulsor design. The Gymnarchus Niloticus Fish (GNF) swimming by a long undulating dorsal-fin generally cruises with high efficiency and extra-ordinal manoeuvrability while keeping its body for the straight line. In the paper the hydrodynamics and vortexes structure of undulating fins in stationary water are calculated by Large Eddy Simulation(LES) and dynamic grid technique with diffusion-based smoothing model. The thrust produced by undulating fins is measured at wave amplitude of 85^0, and the unsteady flow field around undulating fins on the middle cross section and mid-sagittal plane at wave amplitude of 85^0 is measured by phase-locked Particle Image velocimetry(PIV) in the stationary water.

The thrust calculated by numerical simulation is in good agreement with hydrodynamics experiments. The vortex structure and its evolution on cross sections and mid-sagittal plane calculated by LES qualitatively agree well with PIV experiments.

The vortexes structure and mechanism of hydrodynamics generation are analyzed.

1 INTRODUCTION

The Gymnarchus Niloticus fish (GNF) with long undulating fins generally cruises with high efficiency and extra-ordinal maneuverability(figure 1), is able to swim as easily forward as backward and rapidly switch swim direction, while keeping its body for straight line.

According to a large number of observations, the oscillation amplitude of GNF fins is usually between 60 ° and 90 °, and in normal state of tour, the oscillation amplitude is close to 90 °, only in the control of hovering or swimming at very low speed, wave amplitude is small (about 60 °)[1].

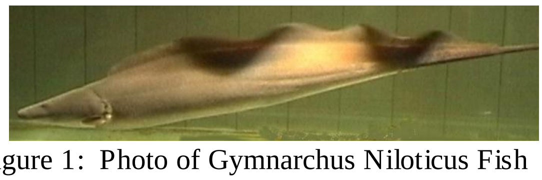


Figure 1: Photo of Gymnarchus Niloticus Fish（GNF）

In 2008, the unsteady flow of undulating ribbon-fin of the weakly electric knife fish was numerical simulated by immersed boundary method to get the horizontal, lateral and vertical forces by Shirgaonkar et al. [2]. They examined the hydrodynamics and the flow fields around a robotic ribbon fin of a non-translating ribbon fin in stationary water using computational fluid dynamics and DPIV.

In 2013, Rahman et al. studied the mechanism of thrust generation by numerical simulation of flow around the double undulating fins [3]. Research indicates that thrust and propulsion were mainly dependent on the aspect ratio and fin angle of undulating fins.

In 2014,Izaak D. Neveln et al. presented the flow structure of an undulating robotic fin model using PIV to measure fluid velocity fields in the wake[4]. They supplemented the experimental robotic work with high fidelity computational fluid dynamics, simulating the hydrodynamics of both a virtual fish, whose fin kinematics and fin plus body morphology were measured from a freely swimming knife fish, and a virtual rendering of the robot.

In the paper the hydrodynamics and vortexes structure of undulating fins in stationary water are calculated by LES and dynamic grid technique. The thrust produced by undulating fins is measured at wave amplitude of 85^0, and the unsteady flow field around undulating fins on middle cross section at wave amplitude of 85^0 is measured by phase-locked PIV in the stationary water[5].

2 NUMERICAL SIMULATION OF FLOW FIELDS OF UNDULATING FINS

In the coordinate system(Figure.2), X axis was along shaft of undulating fins, the mid-saggital plane was set as XOY plane, the Z axis was determined by the right-hand rule. The origin of the coordinate was at left end of the undulating fins, and the wave propagated from the left to the right. The GNF fin surface is expressed as follows

$$\boldsymbol{x} = \boldsymbol{x}(\boldsymbol{r}, \varphi, \boldsymbol{t}) = \frac{\omega \boldsymbol{t}}{\mathrm{k}} + \boldsymbol{r} \cdot \boldsymbol{ctg}\theta - \frac{\mathbf{1}}{\boldsymbol{k}} \sin^{-1}\left(\frac{\varphi}{\varphi_m}\right) \tag{1}$$

where φ_m is wave amplitude, ω is circular frequency, $\mathrm{k} = 2\pi / \lambda$ is wave number, λ is wave length, φ is wave phase of fin ray at x. XOY is mid-sagittal plane.

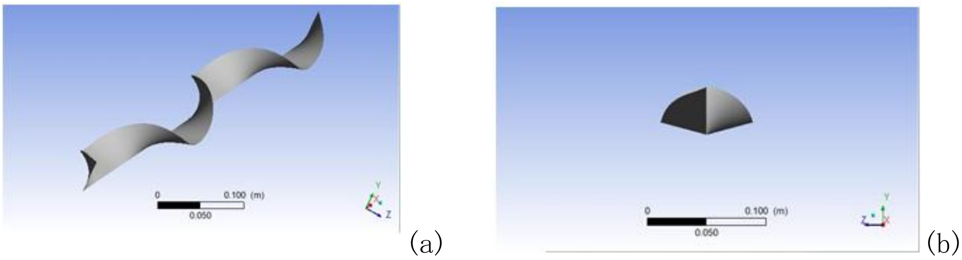


Figure 2: 3D configuration of undulating fin surface

Here simplification is made, we only investigate the flow field and hydrodynamics for an isolated undulating fins not connecting with any walls alike fish body.

The hydrodynamics and vortexes structure of undulating fins in stationary water are calculated by unsteady LES and dynamic grid technique[5].

3 EXPERIMENTS ON HYDRODYNAMICS AND FLOW FIELD

The test model of undulating fins is made of flexible rubber, and is 800mm long and 50mm high, respectively (Figure 3) [5]. The experiment is carried out at a small towing tank(25m×3m×1.5m). In the experiment, the kinematic parameters of undulating fins are set as follows: $\lambda/L= 0.5$, $\Phi max=85°$, f=2.0Hz, $h/L= 0.065$, where h is fin height.

Figure 3: Test model of undulating fins

The ratio of rotation frequency of motor shaft to sway frequency of rigid fins is designed as 1:3, and the rotary Encoder E80H30-1024 with resolution of 0.35^0 is installed on the motor shaft to get the wave phase of undulating fins, and transmit to the synchronous controller to trigger the laser to illuminate the flow field and the CCD camera to capture particle images.

The flow field on the middle cross section(x/L=0.5) and mid-sagittal plane of undulating fins is measured at different wave phase, respectively. 100 pairs of particle images are sampled at each phase.

4 COMPARISONS BETWEEN NUMERICAL SIMULATION AND EXPERIMENTS

For comparison with the hydrodynamics experiments, in the numerical simulation of hydrodynamics, the main geometry and kinematics parameters of undulating fins are set as the same as hydrodynamics experiments, i.e. L=800mm,L/λ=2,f=2.0Hz, h/L=0.065, φ_m =85^0. The results indicates both the thrust of numerical simulation and experiments are linear to square of frequency. The numerical results agree well with the experiments[5].

Although the thrust by numerical simulation agrees well with the experiments at wave amplitude 85^0, but the vortex structure extracted from the flow field by numerical simulation is not obvious. Perhaps the grids deformation is too large at wave amplitude 85^0, and the number of computational grids cannot meet the requirements for capture of vortex structure. So we reduce the wave amplitude of undulating fins in numerical simulation, here only the numerical results at wave amplitude of 30^0 is shown, and it cannot be compared quantitatively with the experimental results at wave amplitude 85^0. Figure 4 presents the comparison of contour of in-plane velocity and streamlines map on cross section x/L=0.5. Subgraph a1~a4 and b1~b4 corresponds to PIV and CFD results at equally distributed wave phases at wave amplitude 85^0 and 30^0,respectively[5]. Figure 5 and figure 6 show streamlines and contour of in-plane velocity on the mid-sagittal plane by PIV and CFD, respectively. In the numerical simulation, the geometry and kinematics parameters of undulating fins are set as follows: L=800mm,L/λ=2,f=2.0Hz, h/L= 0.065, φ_m =30^0. A global structured grid of 3.3×10^6 is used to model the computational domain with time space Δt=0.001s. Generally speaking, shown as figure 4～6, it is obvious that the characteristics of flow structure of numerical results qualitatively agree well with the experiments. There is a strong jet flow near the mid-sagittal plane both in measurement results and simulation results. The series of anti-Karman vortexes(streamwise vortexes) locate alternatively with different sign of vorticity on both side of the jet flow. Compared with experiments at wave amplitude of 85^0 ,because of the wave amplitude is smaller(30^0) in the numerical simulation, the numerical simulated anti-Karman vortexes are more concentrated near the mid-sagittal plane.

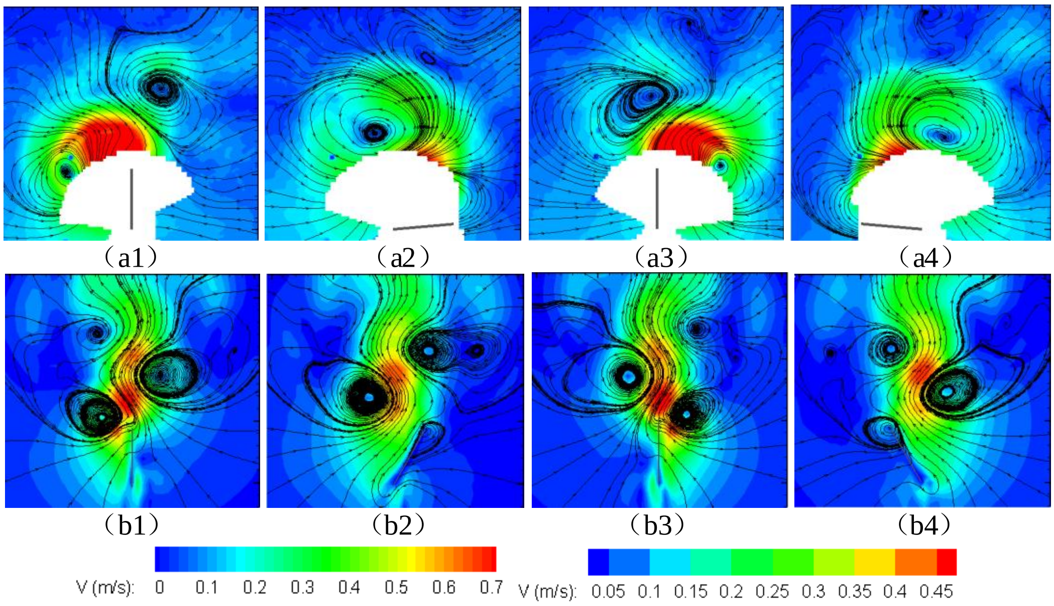


Figure 4: The comparison of contours of in-plane velocity and streamlines map on cross section x/L=0.5

In figure 5～6,it can be observed, there is an obviously fluid jet on the mid-sagittal plane generated by the travelling wave of the undulating fin. The jet effuses from the fin tip and flows downwards and backwards. However, the crescent vortexes in numerical results(figure 6) is not so clear as shown in the experiments(figure5). The angle between the main direction of the jet and X axis is much smaller in the experiments at wave amplitude 85^0 than that in the numerical simulation at wave amplitude 30^0.

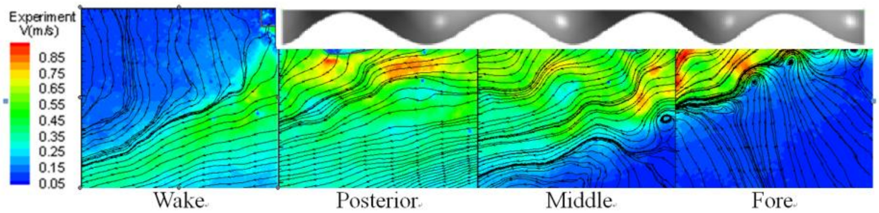


Figure 5: Streamlines and contour of in-plane velocity on the mid-sagittal plane(PIV)

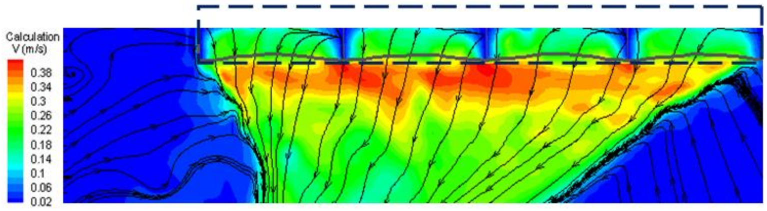
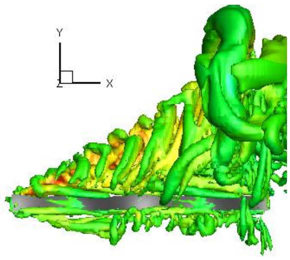


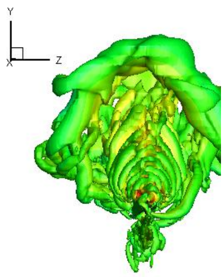
Figure 6: Streamlines and contour of in-plane velocity on the mid-sagittal plane(CFD)

5 SPACIAL VORTEX STRUCTURE OF UNDULATING FINS

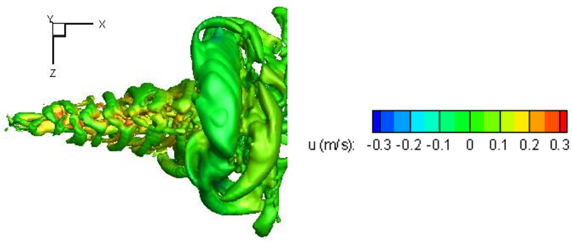
The spatial vortex structure is extracted from the flow field of undulating fins at wave amplitude 30°. Figure 7 shows iso-surface of vorticity magnitude $Q=1s^{-2}$ and contour of the streamwise velocity. In the case the parameters are set as: L= 800mm, f =2.0Hz, L/λ=2, $\Phi_{max}=30^0$, *h*/*L*= 0.065[5]. The results indicate that there are mainly two kinds of vortexes, i.e. streamwise vortexes and crescent vortexes.



（a）Side view



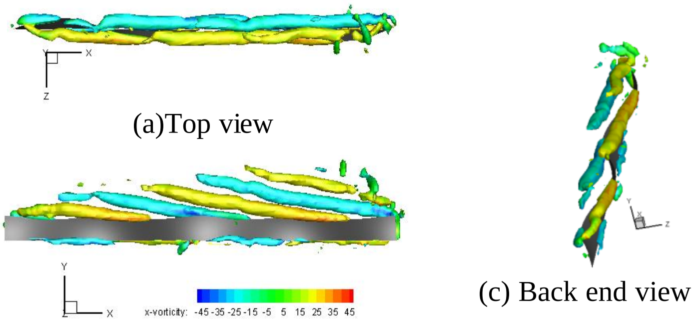
（c）Front end view



（b）Top view

Figure 7: Vortex structure and contour of *x*-velocity around the fin surface

Figure 8 shows the streamwise vortex structure of iso-surface of $Q=200s^{-2}$[5]. The colour represents rotation direction of streamwise vortexes. Comparing figure 7 with figure 8, it is obvious that vorticity intensity of streamwise vortex is the strongest among three kinds of vortexes. Figure 8 also shows streamwise vortexes alternately distribute on each side of fin surface.



(a)Top view

(b) Side view

(c) Back end view

Figure 8: Streamwise vortexes from different views($Q=200s^{-2}$)

It can be seen the crescent vortexes mainly package in the periphery of the streamwise vortexes. Figure 8 also indicates that the crescent vortexes induce high speed jet, which produces the main thrust.

6 CONCLUSION

The flow field and hydrodynamics of undulating fins in stationary water are investigated by numerical simulation of LES and hydrodynamics measurements and PIV experiments.

The phase-locked PIV experiments is carried out to measure in-plane velocity field on middle cross section and mid-sagittal plane at wave amplitude 85^0. Generally speaking, the numerical results such as the vortexes structure and its evolution with phase angle at wave amplitude of 30^0 qualitatively agree well with the experiments results at wave amplitude 85^0. Compared with experiments at wave amplitude of 85^0 ,because of the wave amplitude is smaller(30^0) in the numerical simulation, the streamwise vortexes are more concentrated near the mid-sagittal plane.

The numerical results at wave amplitude 30^0 indicates that there are mainly two kinds of vortexes, i.e. streamwise vortexes and crescent vortexes. The results indicate the intensity of streamwise vortex is the strongest among all kinds of vortexes. There is a strong jet flow on the cross section near the mid-sagittal plane. The streamwise vortexes locate alternatively with different sign of vorticity on both side of the jet flow. The streamwise vortexes mainly induce the vertical jet, which generates the main heave force.

The crescent vortexes alternately distribute on the two sides of mid-sagittal plane in the front of undulating fins, and mainly induce high speed axial jet, which produces the main thrust.

ACKNOWLEDGEMENTS

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