Dynamic investigation of rowing propulsive mechanism due to rower stroke: Experimental and Computational fluid dynamic

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Abstract: In this paper propulsive mechanics of the rowing was investigated with the aim to determine the relationship between oar angular speed, boat velocity and hydrodynamic of the blade. The experimental test was set up using a single seated rowing simulator that attached to a water tank. While rower rowed the boat, oar angular and boat velocity were recorded. The experiment outcome provided the relationship between oar angular and the boat velocity which then was imported as the input to the computational fluid dynamic (CFD). The hydrodynamic force obtained from the computational study representing force generation that used to accelerate the boat and illustrated fluid flow around the blade during stroke.

Keywords: Rowing, oar, rowing tank, CFD, hydrodynamic force

1. Introduction

Investigation of the rowing propulsive mechanics is challenging because of the complexity of the rower biomechanics and hydrodynamic of the blade. The rower-oar-boat system mostly tested on-water condition with a limited hydrodynamic data recorded as it involved many uncontrolled conditions that may affect the result [1, 2]. Alban Leroyer et al had conducted an experiment using rowing device to replicate real rowing condition in order to investigate the flow around the blade which reported chaos fluid flow forming around the blade [3].

In order to propel the boat, rower pulls the oar's handle. The force profile from the pulling action can be visualized as the increment of the force relative to time or percentage of drive until to the peak before gradually decrease towards the finish [4]. To start the stroke, rower positions the body in a hunched position where the blade is submerged into the water close to surface. The legs then are extended to produce power by sliding the body backwards until to the maximum leg extension followed by bending the hand towards the chest and tilts the trunk backward. Since the oar is attached at the oarlock, causes the blade to rotate and strike the water. The blade motion influenced the boat velocity by providing additional force for the acceleration [5].

During the drive phase, the blade hit the water relative to the flow of the water and generate a hydrodynamic force [6]. The lift and drag force are the hydrodynamic force components that act on the blade which provide thrust to the boat. These forces are varied with the magnitude of relative velocity and angle of attack [7]. When blade is rotated in a large angle, it caused a huge fluid separation happen at the back of the blade. In addition, by introducing curvature to the oar, could modify the flow and thus enhancing force. [7].

The idea of the propulsive mechanism of the rowing sport had attracted many researchers in order to enhance rowing performance through fluid mechanics aspects. There were a few studies carried out to explore hydrodynamic using simplified model of rowing stroke but most of the simplified blade motion without rower stroke. Thus, to explore the real mechanics of the rowing propulsive mechanics experimental test is required and the current study was done to achieve it. Due to that reason, the objective of this study was to investigate the dynamic propulsive mechanism of the rowing boat by considering rower aspect in order to enhance rowing performance.

2. Method

The study was carried out by two stages, experimental test and computational study. In the experimental test, the boat velocity and angular velocity of the oar from rower stroke were collected and imported as the boundary condition for computational fluid dynamics (CFD). The associated values of hydrodynamic force then were obtained.

2.1 Experimental test

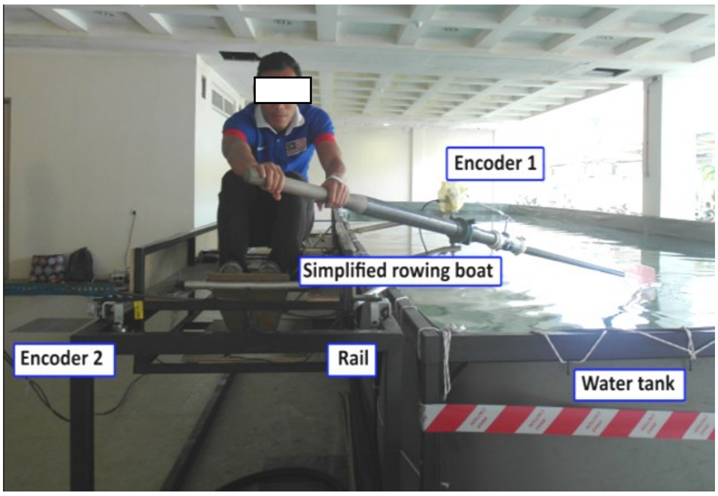

Figure. 1. Rower during measurement test with measurement setup

The test was performed on the fabricated rowing tank specially designed to investigate rowing propulsive mechanics. Rowing tank included the following parts: Water tank, simplified rowing tank and rail. Dimension of water tank are 5m width, 15m length and 1m height, this size was selected as to avoid wall hard effects and the size was enough to study propulsive mechanics of the rowing. During the test, simplified rowing boat was moved in a straight direction along the rail. The oar angular velocity and the boat velocity were measured using two encoders as in Fig.1. The first encoder was located on the oarlock and attached to oar whereas the second encoder was located on the frame of the simplified rowing boat and attached to the roller.

The testing procedure was similar to the common rowing method. Before the test, rower was trained to familiarize with the device in order to obtain a good result. The test was started when the rower pulls the handle. Test was done three times and for each session the data was captured and recorded using Signal express software.

2.2 Propulsive modeling

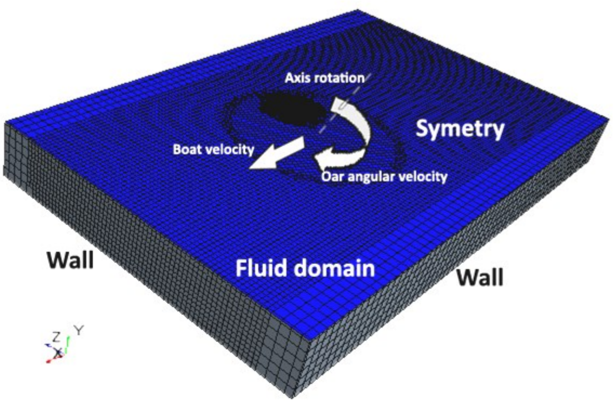

Fig. 2. CFD setup and boundary condition for the simulation study

The data from experimental test were then imported into CFD software to estimate the hydrodynamic force that generated on the blade. CFD model was set as two parts which the first part was the moving frame domain that overset with the water background domain as second part. The equation 1 was used to solve the fluid flow where it leveraged modification of Navier-stoke equation by introducing the rotational rate *ω*, the radial velocity component *Ur* and the distance from the axis of rotation *r*. Moving frame was moved in translation and rotation same as the real blade condition. As illustrated in Fig.2, the sides and the bottom surface of the water domain were assigned as the wall while the top surface was assigned symmetrically to represent open water surface.

$$\rho\frac{\partial U_j}{\partial t} + \rho U_i\frac{\partial U_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \rho[2\omega \, x \, U_r + \omega \, x \, (\omega \, x \, r)] + \mu\frac{\partial^2 U_j}{\partial x_i^2} + \rho g_i \qquad (1)$$

The water domain was meshed with trimmed elements provided by the STAR CCM+ software. Model's mesh elements were arranged with higher concentration around the blade to increase reliability of the CFD. The density of the water was 997.561kgm^{-3} and the dynamic viscosity of the water was 8.8871x10^{-4} Pa-s.

3. Result and discussion

Figure 3 shows the angular velocity profile of the oar during the drive. Based on the result, the rower rowed with the stroke rate of 10 stroke/min. The blade caught the water with initial velocity of 10 degree/s. As stroke progress, angular speed then was increased gradually until it reached 53 degree/s. The speed then maintains around 53-64 degree/s during middle of the drive and it form flat shape profile which mean force is maintenance for certain time on the blade. Towards to the end of the drive, rotation was reduced from 64 to 50 degree/s.

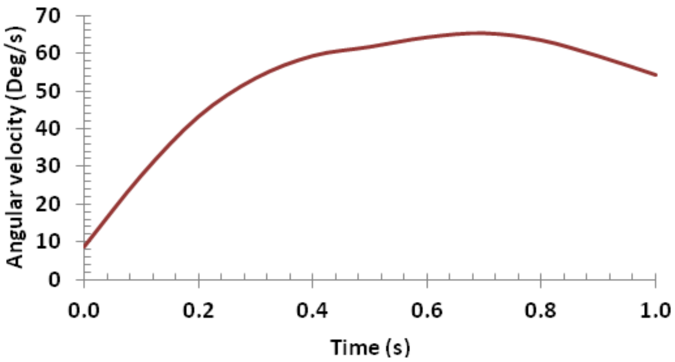

Fig. 3. Angular velocity of the oar during drive phase

Rotation of the oar caused the boat to move. Fig. 4 shows the boat speed profile during the drive. At the beginning, boat already moved with 0.86 m/s because of the momentum from the previous stroke keep it to move. However the boat speed has decreased to 0.79 m/s during the catch as the water hit the blade on the opposite direction of the moving boat. Once drive has begun, speed gradually increased up to 1,86 m/s although the oar speed reduced as explained previously.

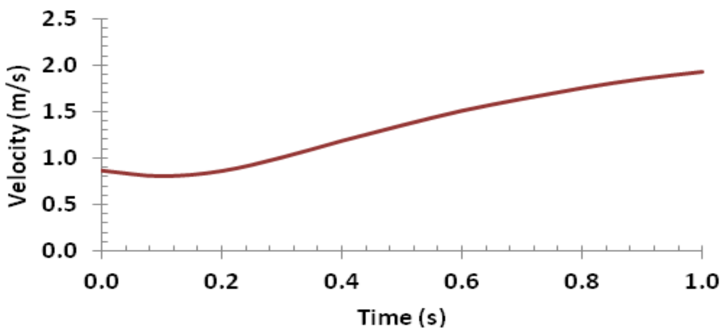

Fig. 4. Boat velocity during the drive phase

Most of the study mentions that stroke rates of the rower are between 28 to 36 stroke/min [8, 9]. However in this study 10stroke/min was applied as the distance for the testing was limited.. The study has a high reliability and consistency in describing the real rowing propulsive mechanics due to the fact that it focused on the effect of the blade rotation to the motion of the boat while investigating the hydrodynamic effect on the blade. According to the result of the oar rotation in Fig. 3, higher angular acceleration happened due to the explosion power that was exerted by the rower's leg. As reported by the Kleshnev, during rowing rower used 46.4 percent of the power from legs, 30.9 percent from hand and 22.7 percent from trunk [10]. Contribution of the hands could be seen from 0.4 s to 0.7 s in which the acceleration was lower than first 0.4 s. Stroke then moved with trunk in which from 0.7 to 1.0 s was negative acceleration since blade moved towards finished phase. During drive, boat's velocity increased exponentially. Movement of the rower during the drive did not only rotate the oar but also increased boat momentum forward. In fact, inertia also played some important roles as even though blade's angular velocity had reduced, the boat was still accelerating and reached velocity of 2 m/s at the end of the drive.

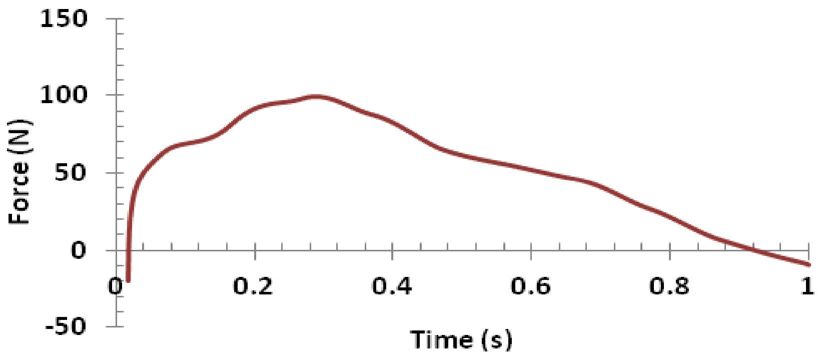

Fig 5. Hydrodynamic force acting on the blade during drive

The thrust force was generated on the blade during the drive. When the blade moved and hit the water, hydrodynamic force was generated as in Fig.5. In a very short time, which was at 0.008s, hydrodynamic force boost up from 0 to 38 N. Since hydrodynamic force associated with rotation of the oar then force was gradually increased until 100N at 0.25. After passing the maximum point, hydrodynamic force then decreased slowly until the oar angular speed was lower than boat velocity at 0.84s and caused negative force to happen.

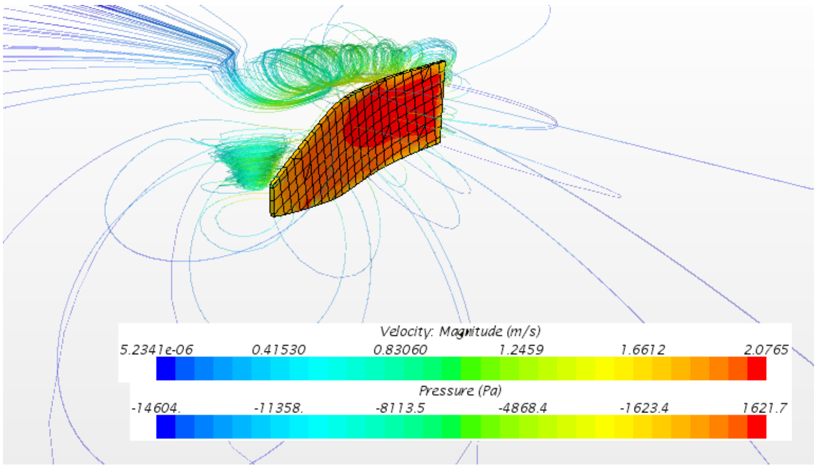

Figure. 6. Blade stream line and hydrodynamic force acting on the blade at 0.3 s

Generation of the hydrodynamic force is related with fluid velocity and pressure as illustrated in Fig. 6. From the picture, it was found that positive pressure appeared on the front surface of the blade and the maximum force appeared at the middle of the blade. The negative pressure then appeared at the back surface of the blade as fluid flowed through and form negative air pocket pressure. The fluid flow that was created by the water streamline was complicated. When the blade hit the water, it caused the water to flow to the back of the blade and produces a chaos turbulence which can be shown by the circular pattern near to the edges of the blade.

It is important to relate oar rotation to hydrodynamic of the blade and the boat velocity as they work as a propulsive system to move the whole rowing boat. Fluid flow around the oar blade as shown in Fig. 6 is experiencing turbulence which can be characterized as a chaotic condition. Fluid flow showed irregular behavior and pressure varied rapidly resulting flow velocity. Increasing in hydrodynamic force acting of the blade related to increasing oar angular acceleration and relative velocity between blade angular velocity and boat translation velocity. The blade acceleration is defined as changing of angular velocity graph per time. However, when angular acceleration is reduced and boat move even faster due to the mass inertial that acts on the rowing system.

4. Conclusion

This study successfully relates the propulsive mechanics of the rowing in dynamic condition which is focused on the moving boat while blade is rotated by the rower. Considering the biomechanics aspect of the rower in term of the blade motion simultaneously with boat velocity, the study has provided the hydrodynamic force value and its force profile.

Acknowledgement

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