ROWING PROPULSIVE MECHANISM BASED ON ROWER BIOMECHANICS AND BLADE HYDRODYNAMICS

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Specially dedicated to:

My beloved father (Mohd Yusof bin Ayob).

My beloved mother (Rahimah binti Abdul Rahman)

My beloved wife (Nurul Hazuwa binti Muhamad Ramli)

For your endless support and encouragement

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ABSTRACT

Rower biomechanics, stroke style, and hydrodynamic of the blade are among the important factors which influence rowing performance. Deeper understanding of these aspects will help the rower and rowing fraternity to decide the best rowing style and blade model in order to perform better. There are three objectives outlined in this study. The first objective was to evaluate the coupling mechanism between rower biomechanics and blade hydrodynamic, using rowing dynamic simulator. The second objective was to assess the fluid flow behaviour around the blade by using Computational Fluid Dynamic method (CFD). The third objective was to compare two different stroke styles which focused on the rower leg and trunk. During the experimental work, the rowers rowed and accelerated the boat. An average handle force of 512 N, and a blade hydrodynamic force of 231 N were obtained by using the strain gauge sensor. From the result, the oar mechanism was in agreement with the first class lever of 45% mechanical advantage. CFD analysis was validated and had good agreement with experimental result with 8.3% error. Blade was identified to work based on drag-induced propulsive and the fluid flow behaviour was dominated by leading edge vortex (LEV). The highest hydrodynamic force was generated by asymmetrical type of Fat blade followed by asymmetrical type of Big blade and symmetrical type of Macon blade with a peak force of 347 N, 307 N and 231 N respectively. Finally, two types of rowing style emphasized on the leg and trunk were compared and evaluated. The leg-typed rowing style was 17% better in increasing the handle force higher as compared to the trunk-typed rowing style. In conclusion, the study explored the connection between rower-oar-boat. Rowing performance showed a 28% enhancement of boat acceleration by the use of leg-type rowing style. Further enhancement of performance was achieved via the asymmetrical type of Fat blade, which increased the hydrodynamic force up to 51%.

ABSTRAK

Biomekanik pendayung, gaya strok, dan hidrodinamik bilah adalah antara faktor-faktor penting yang mempengaruhi prestasi mendayung. Pemahaman yang mendalam tentang aspek-aspek ini membantu pendayung dan komuniti mendayung menentukan gaya mendayung yang terbaik dan model bilah yang sesuai bagi meningkatkan prestasi perlumbaan. Terdapat tiga objektif telah digariskan dalam kajian ini. Objektif pertama, menilai mekanisme gabungan antara biomekanik pendayung dan hidrodinamik bilah menggunakan simulator dinamik mendayung. Objektif kedua, menaksir aliran pergerakan air di sekitar bilah menggunakan pengiraan analisis dinamik bendalir (*CFD)*. Objektif ketiga, membandingkan antara dua gaya strok yang berbeza yang memfokuskan pada kaki dan batang belakang. Semasa eksperimen dijalankan, pendayung mendayung dan memecutkan bot. Purata daya pemegang yang terhasil adalah 512 N, dan daya hidrodinamik purata 231 N diperoleh menggunakan alat pengukur terikan. Daripada keputusan ini, mekanisme dayung didapati mematuhi konsep tuil kelas pertama dengan 45% kelebihan mekanikal. Analisa *CFD* disahkan menyamai kaedah eksperimen dengan peratus ralat sebanyak 8.3%. Bilah didapati bekerja berdasarkan dorongan seretan dan sifat aliran dipengaruhi oleh pusaran pinggir hadapan (*LEV*). Daya hidrodinamik yang paling tinggi dihasilkan oleh bilah jenis tidak simetri *Fat* diikuti dengan bilah jenis tidak simetri *Big* dan bilah jenis simetri *Macon* sebanyak 347 N, 307 N dan 231 N daya puncak yang terhasil. Dua gaya dayungan yang menekankan pada kaki dan belakang badan telah dibandingkan dan dinilai. Gaya dayungan yang memfokuskan pada kaki didapati lebih berkesan dalam meningkatkan daya pemegang sebanyak 17% lebih tinggi berbanding dengan gaya dayungan belakang badan. Kesimpulannya, kajian ini menerokai hubungan antara pendayung-oar-bot. Prestasi mendayung menunjukkan peningkatan 28% pecutan bot menggunakan gaya dayungan kaki. Peningkatan prestasi selanjutnya dicapai mengunakan bilah tidak simetri *Fat*, yang mana meningkatkan daya hidrodinamik sehingga 51%.

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LIST OF ABBREVIATIONS

3D	-	Three dimensional
CFD	-	Computational fluid dynamic
FEA	-	Finite Element Analysis
FISA	-	International Rowing Federation
FSI	-	Fluid structure interaction
ISAK	-	International standards for anthropometric assessment
LEV	-	Leading edge vortex
NI	-	National Instruments
RANS	-	Reynold average Navier-Stoke
SD	-	Standard deviation
SST	-	Menter's Shear Stress Transport

LIST OF SYMBOLS

∇	-	Nable operator
Ao	-	Projection area
C_d	-	Drag coefficient
C_l	-	Lift coefficient
C_p	-	Hydrodynamic coefficient
d	-	Outboard length
dr	-	Degree of freedom
f	-	External force
F_d	-	Drag Force
F_D	-	Skin drag force
F_l	-	Lift force
F_n	-	Normal force
F_P	-	Hydrodynamic force
F_r	-	Handle force
F_T	-	Boat thrust force
F_t	-	Shear force
F_x	-	Force in x direction
F_y	-	Force in y direction
F_x	-	Force in x direction
F_y	-	Force in y direction
g	-	Gravity
h	-	Depth of fluid
h	-	Parallel axis to blade surface
I	-	Identity matrix
K	-	Number of pulse

k-ω	-	k-omega turbulence model
l	-	Inboard length
l_b	-	Travelling boat distance
m_{boat}	-	Mass boat
m_{crew}	-	Mass crew
$\dot{m}_{fs}$	-	Mass flow rate of water
n	-	Normal axis to blade surface
n_r	-	Number of rower
p	-	Fluid pressure
P	-	Significant level
$P_{dynamic}$	-	Dynamic pressure
P_{static}	-	Static pressure
P_{total}	-	Total pressure
q	-	The distance of the vector to the axis of blade rotation
r	-	Correlation coefficient
R	-	Electrical Resistance
t	-	Time
T	-	Transpose for matrix calculation
t_t	-	t-value of t-test
$\acute{u}_i\acute{u}_j$	-	Reynold stress tensor
v	-	Fluid velocity $v = (v_1,v_2,v_3)$
v	-	Kinematic viscosity
$\acute{v}$	-	Turbulence velocity fluctuating.
$\bar{v}$	-	Average fluid velocity
$\bar{v}_i$	-	Mean velocity component in xi direction
V_{boat}	-	Velocity boat
V_{crew}	-	Velocity crew
V_{Ext}	-	External voltage
v_f	-	Normal component of water velocity
v_{fs}	-	Normal component of free surface velocity
v_j	-	Mean velocity component in xj direction
v_r	-	Relative speed

X_{boat}	-	X boat axis
x_i	-	x_i direction
x_j	-	x_j direction
Y_{boat}	-	Y boat axis
η_o	-	Oar efficiency
θ_t	-	Oar accuracy test angle
θ	-	Oar swing angle for calibration
θ_p	-	Angle between Fp to boat direction
$\dot{\theta}_c$	-	Oar angular speed
$\dot{\theta}_f$	-	Oar angular rotate the fulcrum
θc	-	Catch angle
θ_s	-	Submerge angle
μ	-	Fluid dynamic viscosity
ρ	-	Fluid density
σ_n	-	Strain of blade shaft
σ_r	-	Strain of handle shaft
τij	-	Fluid shear stress
ω	-	Rotational rate

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Rowing is one of the oldest Olympic sports. The first rowing event is held in 1900 Olympic games [1, 2]. Basically, the rowing boat is propelled by using the oar where the blade is submerged, and the handle is pulled to generate the hydrodynamic force. The performance is depending on the use of the human's ability and sport equipment. Both of aspects should match properly to successfully competing for the highest level such as World competition or Olympic Games.

A clear understanding of the rower biomechanics is very well related to kinetic, kinematic, physiological, and anthropometrics of the rower and it brings major attention to the sport community. By altering the function and utilization of the body segment, it enables the responsible party to cope with demand of the sport performance.

The stroke of the rowing involves the coordination of legs, trunk and arms segments at certain sequences which are categorized as a cyclic type of sport [3, 4]. The stroke is divided into four phases which are catch, drive, finish and recovery phase [4, 5].

Rowing style involving body position of the catch, timing and body segment emphasis [6]. Rowing style and boat performance can be evaluated using the handle force profile generated during the stroke. Currently, researchers begin to explore the definition of the ideal force profile to enhance the performance and maximise the utilization of rower biomechanics [5]. Normally the highest work generate by the rower produces the fastest boat speeds. However as there is a limitation on the physiological of the rower's body, thus the most suitable rowing style needs in depth exploration.

The hydrodynamics force is used to overcome the boat drag and thereby accelerate the boat. Skillful rowing technique enhances the hydrodynamic force and improves the boat speed. In addition, the use of advance technology in producing better equipment accelerates the enhancement process. In the competition, there are three types of commonly used blade: Macon, Big blade and Fat blade [7-9]. Thus, a proper understanding of the fluid flow around the blade is necessary to improve the blade performance. Meanwhile, the blade slips problem and the inefficiency in blade propulsive are among the main problem which affects the rowing performance [10, 11]. Further assessment of each blade's features towards the hydrodynamic force deepens the understanding of the fluid mechanics of the blade propulsive.

Selection of the best rowing style and the blade design are the important factor that contribute to the increase of rowing performance. Varieties of blade design and rowing styles used by the rower contribute to variety of rower kinematic and hydrodynamic performance of the blade. Rower kinematic can be assessed by using video analysis where interested body segments are emphasised. Meanwhile, the hydrodynamic force of the blade associated fluid flows around the blade of the different rowing styles can be extracted by using computational study due to the limitations of the experimental study.

1.2 Problem statement

Rower forces profile, physiological and anthropometry of the rower, fluid dynamic around the blade and optimization of blade design have been explored by the previous researchers [5, 9, 12-16]. However, coupling mechanism between biomechanics of the rower and hydrodynamic of the blade during the stroke received less attention. Biomechanics is interested in figuring out how the rower converts his physiological capacity in order to propel the boat by using hydrodynamic force. Even so, most of these studies that focus on the blade have simplified the rowing stroke mechanism which causes the analysis to be regarded as not optimum. The deficiency is happening due to the complexity of the rowing system that leads the analysis of biomechanics and hydrodynamics as undefined. Moreover, most of the researchers tend to analyse the biomechanics' aspect directly with the boat speed by neglecting the hydrodynamics effect on the oar blade or the other way around.

To date, there is limited research related to the fluid flow around the oar blade that considering the factor human power [7, 9, 17-19]. A study of this topic would elucidate the unsteady fluid mechanics around the oar blade of the drive phases. In the competition, there are three types of commonly used blades. However, the issue has been raised and the question needs to be answered is how the blade really works. It is lift-induce or drag-induced mechanism and how the force is generated [4, 9, 20, 21]. This issue deserves to be questioned since there are several studies focused on the blade but the conclusions gained are different. Besides that, this study also allows further investigation into areas for optimization and improvement. The blade designs have been changed several times, however its performance has not been tested for a detailed qualitative assessment of what would constitute as an effective design and utilization.

Besides that, the biomechanics evaluation of the rower stroke is limited and the related studies do not cover the effect of the stroke styles to the rowing performance. Usually on-the-water evaluation, a method known as 'seat racing' is used [22-24]. It is done by using a boat of four where the boats are lined up to race against each other. After the established and fixed distance, the coach would measure the disparity between the two boats based on the racing time. Through the method, technique assessment applied is not precise because the evaluation depends on the coach‘s experience and judgment is made based on the visual consideration. Previously V. Kleshnev (2006), reported the four rowing styles are classified according to the body position, timing and body emphasis [6]. This is a good approach to enhance the rowing biomechanics. However, the advantages of each style towards the performance are not reported which leaves a big question.

1.3 Objectives of the study

The objectives of the study are outline as follow:

1. To evaluate the coupling mechanism between rower biomechanics and the blade hydrodynamics
2. To assess the fluid flow around the blade and the hydrodynamic force generated on existing blade designs by using Computational Fluid Dynamic analysis.
3. To compare between two different stroke styles which focusing on the rower leg and trunk.

1.4 Scope of the study

In investigating the biomechanics and the hydrodynamics of the rowing, a dynamic rowing simulator is used to replicate the actual rowing mechanics under control condition. The study is carried out using two main methods, experimental and computational study. The experimental study is used to obtain the rower handle and blade force, kinematics, angular speed of the oar and the boat translation speed.

The oar angular speed and the boat translation speed are then assigned as the input into the computational study. The scope of the study is simplified as the following list:

a) Boat motion is controlled using rail and allowed to move in one degree of freedom
b) Biomechanics of rowing is focused on the single rower for the sweep type oar and boat.
c) Rower kinematics is captured using video and analysed using motion software
d) Biomechanics of the rower is fixed to the handle force profile and rower kinematic for each rowing style.
e) Blade designs and features are only focused on commercial blade model: Macon blade, Big blade and Fat blade.
f) Computational fluid dynamic (CFD) and experimental study are used in order to assess the effect of the rowing styles to hydrodynamic of the blade.
g) The study is focused on the start of the race which the data of the first three strokes are captured.

1.5 Significant of the study

There are several studies reported in force profile, biomechanics influenced factor, rower kinematic, flow around the blade, and blade design towards the performance [7, 12, 13, 22, 25, 26]. However, the studies of those aspects are done separately although the real rowing system combined all of them together as one system. Thus there are missing information especially in the study coupling mechanism between rower and oar blade need to be taken into account, thus a new comprehensive study is necessary to deepen our knowledge about rowing.

The existing blade designs used in competition indicates the improvement in performance especially for Macon blade and Big blade. However, there is no paper reported on Fat blade. In previous study, it is stated that under the quasi-static condition, Big blade is assessed to improve the performance about 2% higher compared to Macon blade [7]. Unfortunately, there are only a few studies comparing the performance of each blade design specifically under the dynamic condition in which hydrodynamic force is generated due to the relative speed between the oar and boat. Therefore the computational simulation applied in the study improvises the previous study by providing the hydrodynamic force of the blade which moving dynamically due to rower stroke of the drives phase.

The rowing style can influence the rowing performance through the optimization of the rower biomechanics [6, 13]. The study explores the differences in rowing style and contributes to deepen the knowledge to enhance the performance by helping the rower to maximise the power produced and minimise the energy lose [27, 28].

Finally, the development of the method and analysis bring the rowing to great progress in the biomechanics as well as hydrodynamic aspect. The coach does not need to solely rely on his or her eyes only as has been applied on the training session [24]. Besides that, the introduction of the proposed study would help to bring this sport technology to the new levels in sport engineering. Through further research, a definition of the ideal force profile, as well as other parameters, may transpire. The efforts of the rowing crew could be reviewed after the assessment session. The method could also provide the rower and coach with important technical information. Besides, monitoring stroke timing and force generated. Optimization of force application also could be analysed and the rower could inspect his or her performance for each of the stroke.

1.6 Thesis organization

This thesis consists of seven chapters (Figure 1.1). Chapter 1 is an introduction which consists of the background study, problem statement, the objective of the study, the scope of the study, significant of the study and thesis organization. Chapter 2 contains literature review which reviews all papers related to the study and place the research work in the right boarder. Chapter 3 elaborates the method used in the study and it is organised into three main subtopics. The first subtopic is experimental study used to evaluate the coupling mechanism between biomechanics and hydrodynamics of the rowing. The second subtopic is followed by a computational study which replicated the real mechanics of blade propulsive and investigates the blade features based on quasi-static condition. The third subtopic elaborates the method used to asses rowing styles. An elaborated assessment of the coupling mechanism analysis is delivered on Chapter 4. Meanwhile, in chapter 5, it elucidates the topic about blade propulsive mechanics. Chapter 6 then focuses more on the rowing styles which expands the previous two chapters in detail. Chapter 7 is the final chapter which describes the conclusion of the study other than discussing some limitation and recommendations for further improvement the future work.

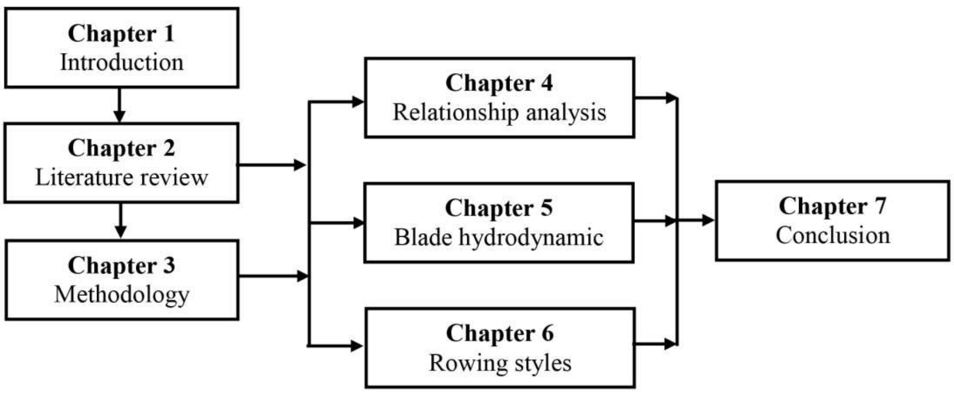

Figure 1.1: Thesis organization chart.

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