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DOI
10.1016/j.proeng.2016.06.299

Publication date
2016

Document Version
Final published version

Published in
Proceedings of 11th Conference of the International Sports Engineering Association, ISEA 2016

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 317 – 323

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

Drag and power-loss in rowing due to velocity fluctuations

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Abstract

The flow motions in the turbulent boundary layer between water and a rowing boat initiate a turbulent skin friction. Reducing this skin friction results in better rowing performances. A Taylor-Couette (TC) facility was used to verify the power losses due to velocity fluctuations $P_{V'}$ in relation to the total power $\bar{P}_d$, as a function of the velocity amplitude A. It was demonstrated that an increase of the velocity fluctuations results in a tremendous decrease of the velocity efficiency e_V. The velocity efficiency e_V for a typical rowing velocity amplitude A of $20 - 25\%$ was about $0.92 - 0.95\%$. Suppressing boat velocity fluctuations with 60% will increase boat speed with 1.6%. Riblet surfaces were applied on the inner *and* outer cylinder wall to indicate the drag reducing ability of such surfaces. The results of the measurements at constant velocity are identical as the results reported earlier, while the experimental configuration was different. This confirms once more the consistency of the TC-system for drag studies. The maximum drag reduction *DR* was 3.4% at a Reynolds number $Re_s = 4.7 \times 10^4$, which corresponds to a shear velocity in this TC-system with water of $V = 4.7$ m/s. For typical rowing velocity fluctuations, the riblets maintain to reduce the drag with 2.8% and corresponds to a averaged velocity increase of 0.9%. The drag reducing ability of riblets is partly lost due to velocity fluctuations with high amplitudes ($A > 20\%$). From these results, it is concluded that the friction coefficient C_f will vary within one cycle. Higher acceleration/deceleration leads to a additional level of turbulent kinetic energy.

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: drag reduction, rowing, oscillation, efficiency

1. Introduction

Benefits of research in sport engineering are often considered as ”free seconds” in the world of sport athletes and coaches. The holy grail for many sport scientists is to develop a sport-dependent innovation or knowledge that may help the athlete to go faster, higher or stronger (”Citius, Altius, Fortius” [1]).

Many improvements and developments were accomplished in rowing over the last decades to achieve better performances. New generation materials (e.g. carbon fibers) and near-optimal boat design are nowadays common practice. Another interesting research topic is the interaction between boat surface and water, as $\pm$80-90% of the total hydrodynamic drag in rowing is caused by the turbulent skin friction [2,3]. Reducing this energy dissipation will result in a higher average velocity when maintaining the delivered mechanical power by the rower and consequently results in

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doi:10.1016/j.proeng.2016.06.299

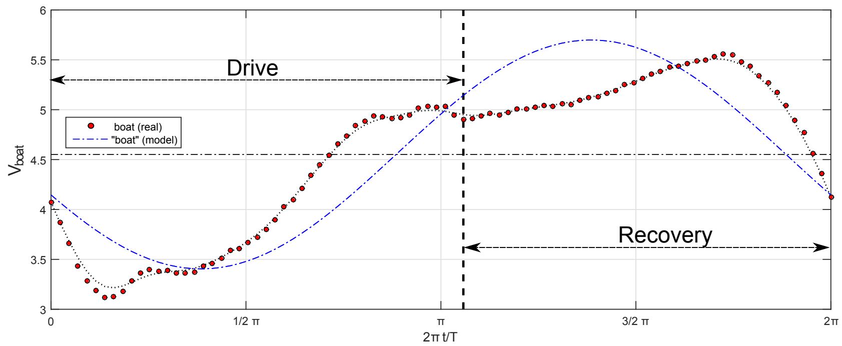

Fig. 1: Boat velocity of international lightweight single sculler[a]. Velocity amplitude A = 20-25% of the averaged boat speed $\bar{V}_{boat}$=4.6 m/s.

[a]www.worldrowing.com/athletes/athlete/42157/kuyt-conno

better performances of rowing athletes.
One solution to suppress the turbulent friction are drag reducing surfaces, which are frequently inspired by nature [4]. Superhydrophobic surfaces ("Lotus leaf" [5]) and riblets ("shark skin" [6]) are most applied subjects in these drag studies, while compliant coatings ("dolphin skin" [7]) are often overlooked.
General turbulent drag research are usually performed under constant bulk velocity in time. However, a rowing boat experiences velocity fluctuations during one rowing cycle (Fig.1), which may diminish the effect of the drag reducing surface. The boat velocity fluctuates because (1) the rowing cycle is devided in two phases (propulsion/drive and recovery phase) and (2) the rower moves relative to the boat and induce an acceleration of the boat in opposite direction of the acceleration of the rower [8–10].

The boat velocity V_{boat} can be decomposed into $V_{boat} = \bar{V} + V'$. The velocity fluctuations V' around the mean velocity $\bar{V}$ increases the total dissipated energy E_d of hydrodynamic drag on the boat in one rowing cycle (Eq.1 [8]). De Brouwer et al. [10] divide the total averaged power dissipated to drag $\bar{P}_d$ into useful power related to the mean velocity $P_{\bar{V}}$ and wasted power related to the velocity fluctuation $P_{V'}$. Minimizing velocity fluctuations V' results in a decrease of total dissipated energy E_d.

$$E_d = \bar{P}_d \Delta t = \int P_d \, dt = \int \frac{1}{2} \rho C_d S_b V^3 dt \tag{1}$$

In Equation 1, P_d is the needed power to exceed hydrodynamic drag (W), ρ is the water density (kg/m^3), C_d is the drag coefficient, S_b is the wetted boat surface (m^2) and V is the boat velocity relative to the water (m/s). The drag coefficient C_d is often improperly been considered as a constant value within one rowing cycle and based on the mean velocity $\bar{V}$. However, the periodic acceleration and deceleration of the fluid modifies the flow conditions in the boundary layer, resulting in a change of the turbulent kinetic energy and so the drag coefficient C_d within one rowing cycle.

In this paper we only focus on frictional drag, as it contributes the most to the total hydrodynamic drag on a rowing boat. The aim was to verify experimentally the relative power loss to velocity fluctuations $P_{V'}$ in relation to the power used $\bar{P}_d$, as a function of the velocity amplitude A. Hence, we have used a Taylor-Couette (TC) system that previously has shown to be a very accurate and compact facility to measure the frictional drag of surfaces [11]. Furthermore, we have investigated the influence of the velocity fluctuations on the drag reducing ability of riblet surfaces.

2. Experiments

The TC facility consists of two coaxial acrylic glass cylinders that both can rotate independently. The inner cylinder radius is $r_i = 110$ mm and total length is $L_i = 216$ mm. The outer cylinder has a radius $r_o = 120$ mm and a length $L_o = 220$ mm (Fig. 2). The radial gap between the cylinders is $d = r_o - r_i = 10.0$ mm, which makes the gap ratio $\eta = r_i/r_o = 0.917$. The TC-system was filled with water at room temperature ($19.5 \pm 0.2\ ^o$C).
The experiments were performed under exact counter-rotation of the two cylinders ($\omega_i r_i = -\omega_o r_o$). The fluid motions between the rotating cylinders generated a shear stress on the surfaces that was recorded with a co-rotating torque meter (HBM T20WN/2Nm, abs. precision ± 0.01 Nm) that is assembled in the shaft between the driving motor (Maxon, 250W) and inner cylinder. The outer cylinder was driven by an identical external motor via a driving belt. Experiment control and data acquisition were computer-executed. The total torque M_{tot} and rotation rate signal of the inner cylinder was recorded at a sampling rate of 2 kHz.

The rowing velocity V during one rowing cycle was modeled in the experiment as a sinusoidal function around the mean velocity, $V = \bar{V} - A\bar{V}sin(2\pi t/T)$ (e.g. Fig.1). For all experiments, the mean shear velocity $\bar{V}$ between the two cylinders was set to be around 5.2 m/s. The relative velocity amplitude A was 0-35% of the mean velocity $\bar{V}$ and the velocity period T of one cycle was 3 s. Each amplitude-step is measured for 180 sec.
The riblet surface was a commercial foil (3M) with the grooves aligned in the azumithal direction and with a triangular cross-section geometry (riblet spacing $s = 120\ \mu$m, height $h = 110 \pm 8\ \mu$m (Fig.3)). The foil is adhered to the surface of the inner *and* outer cylinder, to prevent a rotation effect of the flow [11].

3. Results & Discussion

In fluid mechanics, the Reynolds number Re_s is a dimensionless number that indicates the ratio between momentum forces to viscous forces (Eq.2), with V the shear velocity (m/s) and ν the kinematic viscosity of water (m^2/s). The Reynolds number is the primary parameter to indicate similarity in flow conditions. The water temperature increase slightly ($\pm 0.2\ ^o$C) during the measurements, but can be neglected as it has a marginal effect on the viscosity.

$$Re_s = \frac{Vd}{\nu} \qquad \text{with} \qquad V = |\omega_i r_i - \omega_o r_o| = 2\,|\omega_i r_i| \tag{2}$$

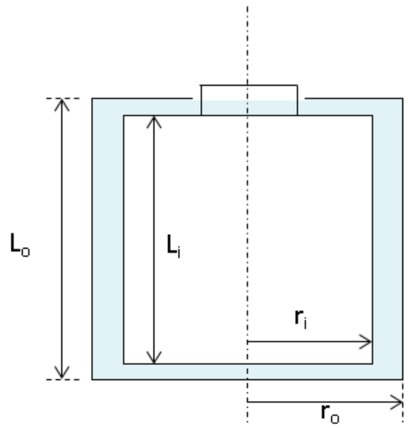

Fig. 2: Sketch of the Taylor-Couette facility.

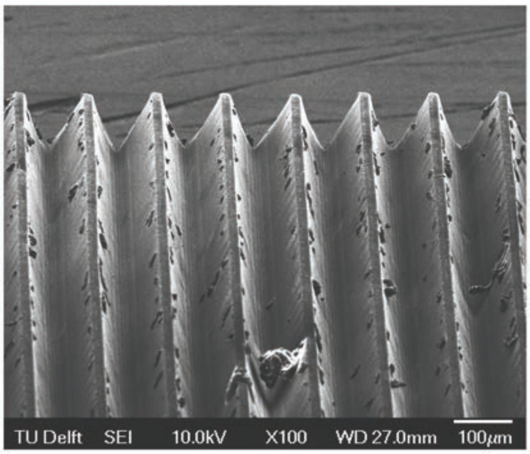

Fig. 3: SEM image of sawtooth riblet surface.

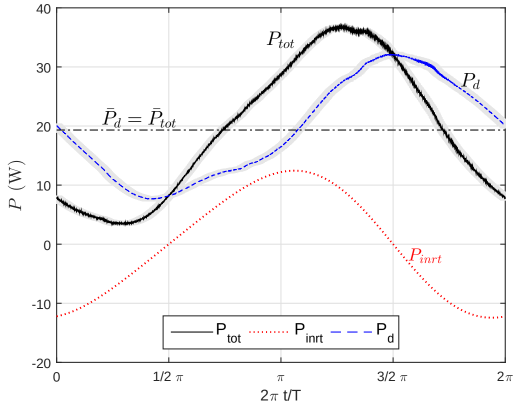

Fig. 4: Power P_{tot}, P_{inrt} and P_d, corresponding to averaged velocity $\bar{V} = 5.2$ m/s and velocity amplitude $A = 20\%$. Gray areas indicate the 95% confidence interval.

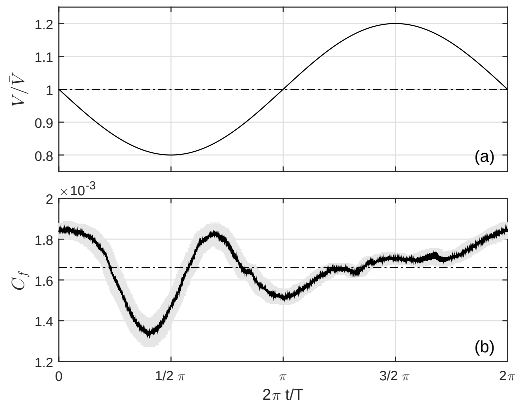

Fig. 5: (a) Relative velocity $V/\bar{V}$ with velocity amplitude $A = 20\%$, (b) Related friction coefficient C_f. Gray areas indicate the 95% confidence interval.

3.1. Velocity fluctuations

The velocity development during one cycle is shown in Figure 5a. The torque M_{tot} on the inner cylinder surface has been measured and is converted to the total power P_{tot} needed to rotate the cylinder (Eq.3). The velocity fluctuations initiate an inertia-resistance I_{inrt} that acts on the cylinder. The power associated with inertia P_{inrt} is determined via Equation 4. Straightforward, the power needed to overcome the hydrodynamic drag P_d is equal to $P_d = P_{tot} - P_{inrt}$. The combined plot with P_{tot}, P_{inrt}, and P_d is shown in Figure 4. The mean power $\bar{P}_d$ is equal to $\bar{P}_{tot}$, as $\bar{P}_{inrt} = 0$.

$$P_{tot} = M_{tot} \cdot \frac{V}{r_i} \tag{3}$$

$$P_{inrt} = I_{inrt} \cdot \alpha \cdot \frac{V}{r_i}, \qquad \text{with} \qquad I_{inrt} = \frac{1}{2} \cdot \sum m_i (R^2 + r^2)_i \qquad \text{and} \qquad \alpha = -\omega \cdot \frac{1}{2} \frac{\bar{V}}{r_i} \cdot A \cdot cos(\omega t) \tag{4}$$

$$C_f = \frac{P_d}{\rho \pi r_i L_i V^3} \tag{5}$$

The friction coefficient C_f (Eq.5) is displayed in Figure 5b. There is a strong unexplained up-and-down motion visible between $\pi/3$ and π, which is attributed to the small wobble in the P_d-curve at that location. Nevertheless, the C_f-curve suggests a fluctuating C_f-value within one cycle.
The power loss $P_{V'}$ as a function of the velocity amplitude A is determined by the mean power for drag $\bar{P}_d$ minus useful power $P_{\bar{V}}$. The results are presented in Table 1 and Figure 6. The velocity efficiency e_V is specified by $1 - (P_{V'}/\bar{P}_d)$, and reduces significant with increasing velocity amplitude A. As reported [8,10], the velocity efficiency is 0.92-0.95 for a typical rowing velocity amplitude of 20-25%. Reducing the velocity fluctuations will enhance the performance of the rowing athletes. Likely, out-of-phase rowing achieves this required result [3,12,13].

3.2. Velocity fluctuations & Riblets

The influence of the velocity fluctuations on the drag reducing ability of riblet surfaces is determined via two steps; (1) measurements at several constant velocities, and (2) measurements at one mean velocity $\bar{V}$ with several velocity amplitudes A. The Reynolds numbers of the measurements with smooth and riblet surfaces need to be similar to make a suitable comparison. Figure 7 represents a classical drag reduction curve of a riblet surface [14], as a function of

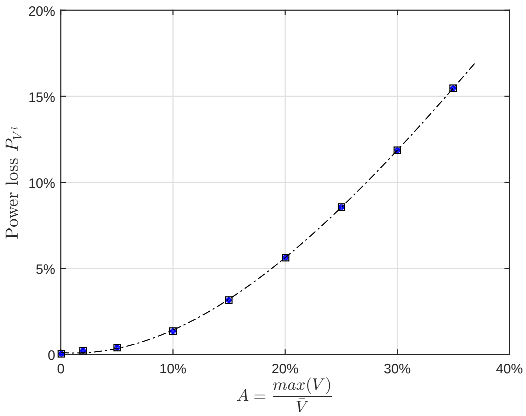

Fig. 6: Power loss $P_{V'}$ vs velocity amplitude A

A	$\bar{P}_d$ (W)	$P_{V'}$ (W)	e_V
0	$18.29 = P_{\bar{V}}$	0	1.000
2	18.33	0.04	0.9979
5	18.36	0.07	0.9963
10	18.55	0.25	0.9864
15	18.89	0.60	0.9682
20	19.38	1.09	0.9438
25	20.00	1.71	0.9145
30	20.76	2.47	0.8812
35	21.64	3.35	0.8454

Table 1: Power used $\bar{P}_d$, Power loss $\bar{P}_{V'}$ and velocity efficiency e_V.

Reynolds number Re_s. The drag reduction in this study is determined by $DR = (1 - C_{f,rib}/C_{f,0})/2$ (*remark*: 2 surfaces with riblets). The errorbars are significant larger for the results at low Reynolds numbers, where the torque-meter is less precise with relative much noise. The current results are nearly identical to the previous results (inner cylinder, rotation effect correction [11]); a maximum drag reduction of $DR = 3.4\%$ at $Re_s = 4.7 \times 10^4$, and a drag saving regime between $Re_s = 1.0 \times 10^4 - 8.5 \times 10^4$. Figure 8 displays the drag reducing ability of the riblet surface, as a function of the velocity amplitude A, with corresponding Reynolds number $Re_s = 5.2 \times 10^4$. When we presume that the flow is not disturbed by the acceleration/deceleration of the boundary layer, the DR will slightly decline (”steady” oscillation). However, the drag reduction is decreasing significantly in relation to the maximum drag reduction $DR_{max} = 3.4\%$ when the velocity amplitude A is increased (”real” oscillation). So, the acceleration/deceleration of the boundary layer affects the drag reducing ability of riblet surfaces. Excessive periodic acceleration/deceleration ($A > 20\%$) will amplify the level of turbulent kinetic energy, which is related to the friction coefficient C_f.

It is clarified that the reduction in velocity fluctuations will increase the velocity efficiency e_V. Out-of-phase rowing results in a significant reduction of 60% in velocity fluctuations of the boat [10,13]. For example, velocity amplitude goes from 20% to 8%, leads to an averaged boat velocity increase of roughly 1.6%; combined with riblets at $A = 8\%$

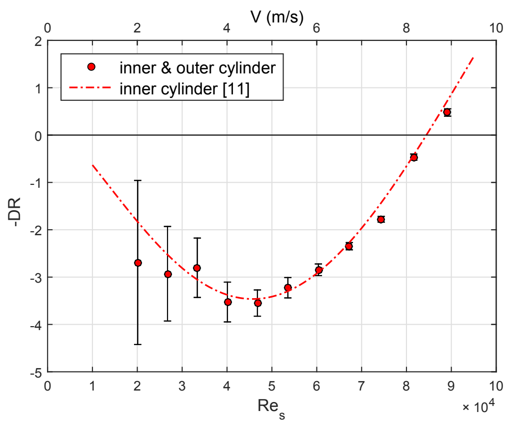

Fig. 7: Drag reduction of riblets at several constant velocities, corresponding to $Re_s = 1 \times 10^4$ to 9×10^4.

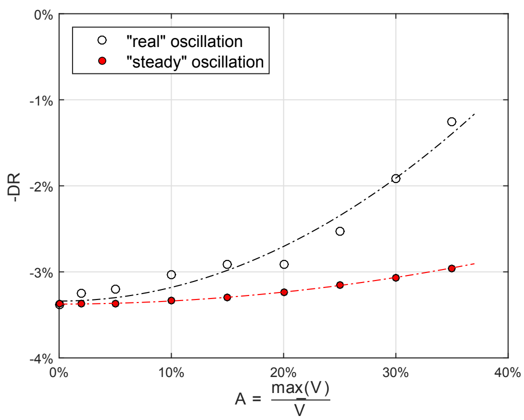

Fig. 8: Drag reduction of riblets at several amplitudes around averaged velocity $\bar{V} = 5.2$ m/s.

results overall in 2.7%. If we assume that the "normal" mean velocity is $\bar{V} = 5.2$ m/s, than the combination results in a new mean velocity $\bar{V}_{new} = 5.34$ m/s, which gives a substantial 10 s advantages over a race of 2000 m.

4. Conclusion

The turbulent kinetic energy in the boundary layer between water and a rowing boat can be suppressed by two options:

- A reduction in velocity fluctuations.
- The application of drag reducing material, e.g. riblets.

A TC-facility was used to verify the power losses due to velocity fluctuations $P_{V'}$, as a function of the velocity amplitude A:

- Velocity fluctuations increase results in a tremendous decrease of velocity efficiency e_V.
- For a typical rowing fluctuation amplitude $A = 20 - 25\%$, the velocity efficiency e_V is about $92 - 95\%$.
- Suppressing boat velocity fluctuations with 60% will increase boat speed with 1.6%.

Riblet surfaces were applied on the inner *and* outer cylinder wall:

- Maximum $DR = 3.4$ % at $Re_s = 4.7 \times 10^4$ ($\sim V = 4.7$ m/s).
- For $\bar{V} = 5.2$ m/s, excessive periodic acceleration/deceleration ($A > 20\%$) affects the drag reducing ability of riblet surfaces.
- At this mean velocity with an amplitude $A = 20\%$, the riblets maintain DR of 2.8%.
- Maintaining the power output of the rower, this corresponds to an averaged velocity increase of 0.9%.

Compliant surfaces are currently tested on their ability to suppress the near-wall shear stress and pressure fluctuations due to the deformability of the surface under unsteady/turbulent loads.

Acknowledgements

The author (AG) would like to thank Ernst Jan Grift for his contribution in the fruitful discussions.
This project has been financed by InnoSportNL.

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