Identification of the Bending Moment on the Paddle of a Kayaker

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Abstract: This contribution deals with the experimental identification of the loading acting on the paddle of a kayaker. To identify loading, strain gauges were installed at three positions of the paddle shaft, always in two directions. The paddle was then loaded with known force in the laboratory to identify the relation between the bending moment and the bending strain. Operational loading followed to identify the level of bending strain during use. With knowledge of the relation between the bending moment and the bending strain, the bending moment during operational use was identified in each measured position and direction and also the global bending moments were identified for each position combining both directions in position.

Keywords: Paddle; Shaft; Composite; Kayak; Loading identification

1 Introduction

The aim of the work is to identify the loading that acts on the paddle of the kayaker during sprint kayaking. Knowledge of loading is important for the development of an optimised design and will be used as one of the entries for multicriteria optimisation. In general, sports equipment has been manufactured and improved for decades. Our long-term aim is to propose a design that will help improve the performance of an athlete. Thus, the first step in this long-term objective is to identify the loading. Usually, the experimental identification of the loading is done using one measurement position on each side of the paddle as in [1,2]. Based on [3], the loading during stroke is quite complex, as the paddler moves with the paddle at a specific angle from the boat to the side. Also, the paddle blade is not just a flat plane shape, but it has curvature using the same idea as the aeroplane wing profile to help the athlete move forward.

2 Method

Positions of interest on the paddle are shown in Fig. 1 and described in Table 1. An approach of identification of the bending moment over the bending strain was chosen. Three positions were chosen at the paddle shaft for the strain measurement and, at each of these positions, strain gauges (SGs) were installed. Linear SGs were used, half-bridge connected for bending strain measurement. At the positions on the left and right sides of the paddle, the SGs were orientated in the expected maximum strain position and a perpendicular position close to the blades to be able to identify the global bending of the shaft. The last measured place was between the hands to obtain two measurement places for each (left and right) stroke. As the measured paddle was feathered, the SGs between the hands were rotated against the SGs close to the blades by ± half the feathering angle. With coefficient k we can get the relation between bending strain and bending moment as the formula:

$$M_o = k \cdot \varepsilon_o. \tag{1}$$

The SGs were wired to the small amplifier that was attached to the paddle shaft together with a small battery and controlled remotely via Bluetooth. Data were recorded in the memory card inside the amplifier.

Fig. 1 Positions of interest of the paddle.

Table 1. Description of positions of interest.

Position	Description
PI_1	Position of the left blade
PI_2	Position of the measurement, left close to the throat
PI_3	Left hand grip position
PI_4	Position of the measurement, between hands
PI_5	Right hand grip position
PI_6	Position of the measurement, right close to the throat
PI_7	Position of the right blade

3 Laboratory loading

To identify the relation k between bending moment M_o and bending strain ε_o, it was necessary to load the paddle with known force. This was done separately for the left and right sides of the paddle to have the maximal bending moment close to the measured place. The paddle was loaded at first only in the expected maximal orientation as the perpendicular one is unstable. In both cases, the paddle was placed inside the loading machine and loaded over the strap as shown in Fig. 2. The loading scheme with PI_2, PI_4, and PI_6 representing the places with SGs is shown in Fig. 3. The position of SGs between the hands was not loaded separately as it was loaded during the loading of the left blade.

Fig. 2 Paddle during the laboratory loading.

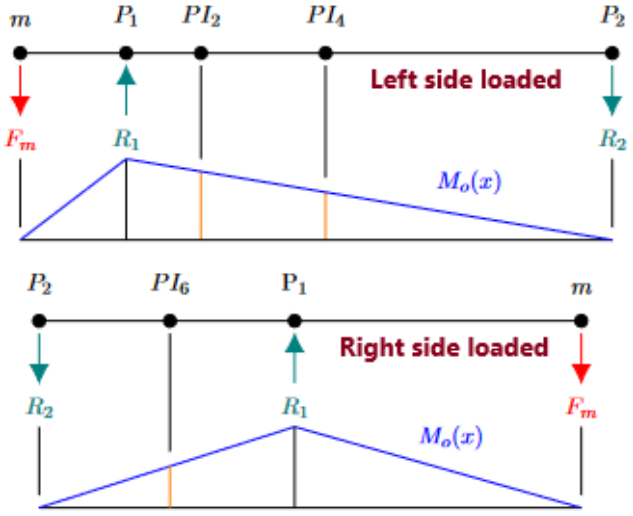

Fig. 3 Scheme of the laboratory loading with the bending moment.

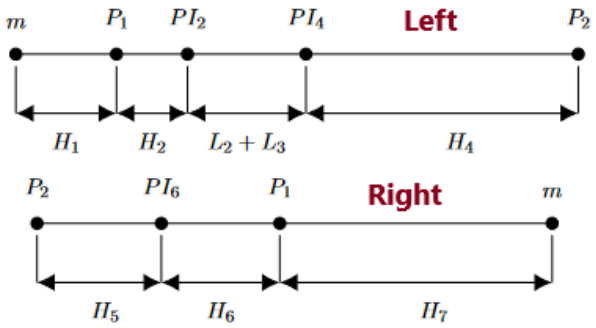

Fig. 4 Distances between positions during the laboratory loading.

3.1 Left side

For the left side, weight m = 10 946 g was used during laboratory loading. Distances according to the schemes in Fig. 3 and Fig. 4 are in Table 2. We can construct the equilibrium equations and identify the bending moments at the PI_2 and PI_4 positions:

$$M_{o(PI_2)} = R_2 \cdot (L_3 + L_4 + H_4), \tag{2}$$

$$M_{o(PI_4)} = R_2 \cdot H_4. \tag{3}$$

By expressing the k in formula (1), we can obtain the coefficient for the left position directly using the measured strain at this position $\varepsilon_{o(PI_2)}$ = 568 μm/m. The coefficient is:

$$k_{(PI_2)} = \frac{M_{o(PI_2)}}{\varepsilon_{o(PI_2)}} = \frac{36\,370}{568} = 64.03\ \frac{\text{Nmm}}{\mu\text{m/m}}. \tag{4}$$

For the central section, the loading is not orientated directly on any of the SGs. Considering the approach of finding the resultant of generally acting moment, in case of perpendicular positions, it is:

$$M_o = \sqrt{M_{o(M)}^2 + M_{o(R)}^2}, \tag{5}$$

where $M_{o(M)}$ and $M_{o(R)}$ are representing two perpendicularly oriented moments. Using formula (1) in (5), we get:

$$M_{o(PI_4)} = \sqrt{\left(k_{(PI_4)} \cdot \varepsilon_{o(PI_4-M)}\right)^2 + \left(k_{(PI_4)} \cdot \varepsilon_{o(PI_4-R)}\right)^2} =$$

$$= k_{(PI_4)} \cdot \sqrt{\varepsilon_{o(PI_4-M)}^2 + \varepsilon_{o(PI_4-R)}^2}, \tag{6}$$

and thus, we can find the global strain for the PI_4 position as:

$$\varepsilon_{o(PI_4)} = \sqrt{\varepsilon_{o(PI_4-M)}^2 + \varepsilon_{o(PI_4-R)}^2}. \tag{7}$$

The coefficient for the PI_4 position is then:

$$k_{(PI_4)} = \frac{M_{o(PI_4)}}{\varepsilon_{o(PI_4)}} = \frac{15\,008}{253} = 59.32\ \frac{\text{Nmm}}{\mu\text{m/m}}. \tag{8}$$

Table 2. Distances during laboratory loading of the left side of the paddle.

Position	Distance [mm]
H_1	368
H_2	45
$L_2 + L_3$	306
H_4	215

3.2 Right side

For the right side, weight m = 14 891 g was used during laboratory loading. Distances according to the schemes in Fig. 3 and Fig. 4 are in Table 3. Again, we can construct the equilibrium equations and identify the bending moments at the PI_6 position:

$$M_{o(PI_6)} = R_2 \cdot H_5, \tag{9}$$

Again, by expressing the k in formula (1), we can obtain the coefficient for the right position directly using the measured strain at this position $\varepsilon_{o(PI_6)}$ = 1014 μm/m. The coefficient is:

$$k_{(PI_6)} = \frac{M_{o(PI_6)}}{\varepsilon_{o(PI_6)}} = \frac{65\,155}{1014} = 64.2\ \frac{\text{Nmm}}{\mu\text{m/m}}. \tag{10}$$

Table 3. Distances during laboratory loading of the right side of the paddle.

Position	Distance [mm]
H_5	530
H_6	32
H_7	473

3.3 Result

As the $k_{(PI_2)}$ value is almost the same as the $k_{(PI_6)}$, average of these two values was used for both, and for the perpendicular positions on the left and right. The $k_{(PI_4)}$ value is slightly different from them as it is affected by the joint between the hands.

4 Operational loading

The paddle was loaded on a short track by a kayaker simulating sprint kayaking. The strains were meassured, section of recorded signals is shown in Fig. 5. With the use of (1), we can identify the bending moments from them as shown in Fig. 6. With the use of formula (5) we obtained the global bending moments at PI_2, PI_4, and PI_6 positions, which is shown in Fig. 7. Maximal values of the bending moments during measurement were identified as $PI_{2\text{-}max}$ = 101 011 Nmm, $PI_{4\text{-}max}$ = 89 352 Nmm and $PI_{6\text{-}max}$ = 99 575 Nmm. Unfortunately, during this first measurement, the PI_6 – R channel did not measure any signal, which means that the absolute value for the right side is affected and the real value will probably be slightly higher.

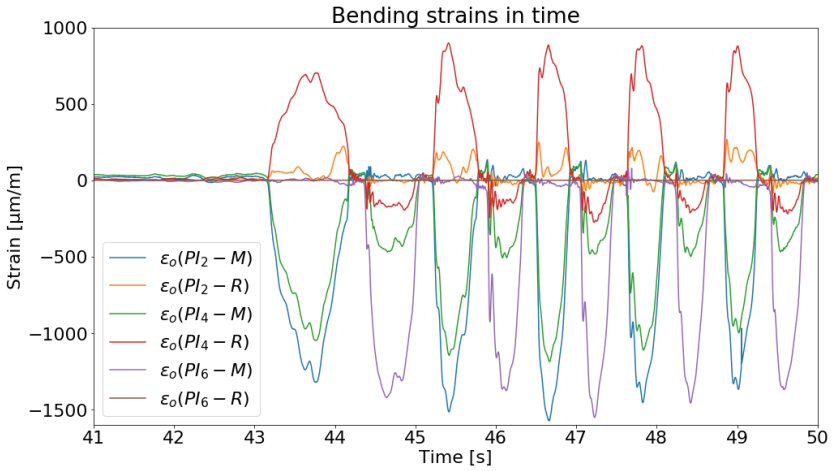

Fig. 5 Section of measured bending strains during the operational loading.

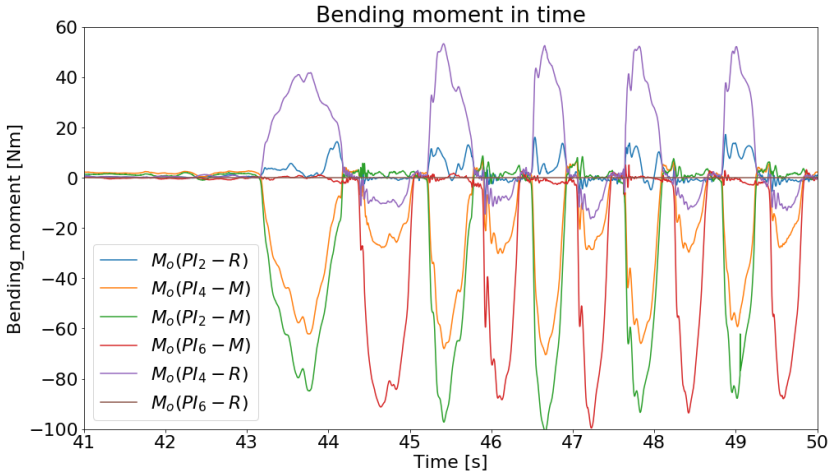

Fig. 6 Section of calculated bending moments during the operational loading.

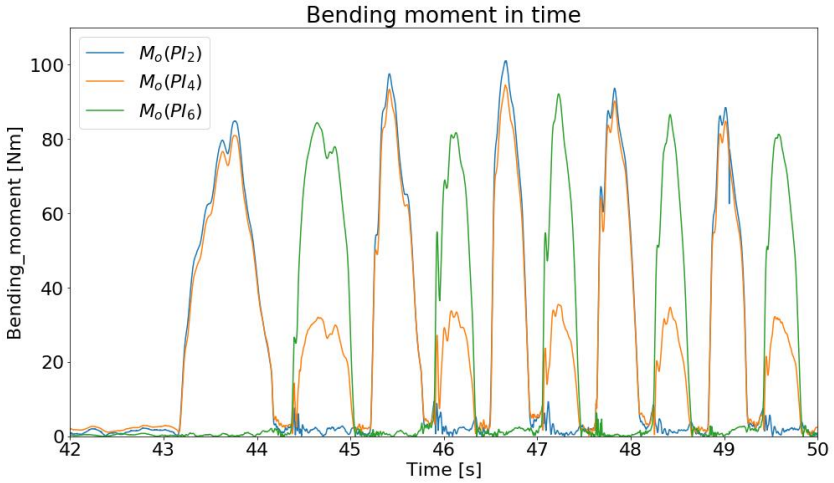

Fig. 7 Section of global bending moments during the operational loading.

Conclusion/Summary

The bending moment identification approach proved to be useful. The choice of two perpendicular positions of SGs in each *PI* position helped to improve the precision of the identified values. It was possible to identify the relation between the bending moment and the bending strain and use it for identification of bending strains/moments during operational loading. With a malfunction of the $PI_6 - R$ channel during operational loading, we probably got slightly underestimated values of global bending moment at PI_6 position which we can estimate from the behaviour of PI_2 position. During each stroke, two places were actively measuring, which is important for further identification of forces acting on the paddle shaft. Thus, this setup will be used for future measurements to identify the forces acting on the paddle, which will serve as input for the optimisation of the paddle shaft.

Acknowledgements

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References

[1] Prétot C., et al., "On the Physics of Kayaking," *Available from* https://doi.org/10.3390/app12188925 *Accessed:* 2023-11-30.

[2] Gomez B., et al., "Analysis of the on-water paddling force profile of an elite kayaker," *Available from* https://ojs.ub.uni-konstanz.de/cpa/article/view/4822 *Accessed:* 2023-11-29.

[3] Social Nature Movement, "How does a kayak wing paddle blade work?" *Available from* https://socialnaturemovement.nz/wing-blades-explained/ *Accessed:* 2023-06-05.