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Free vertical oscillations in rowing

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1. Introduction

When equally skilled competitors excellent in their techniques are competing the victory can depend on parts of a second that's why all the factors having an influence on the rowing process should be evaluated not just the main of them. One of such factors is vertical oscillation of academic boat.

The facts of mentioning the existence of vertical free oscillations in rowing were not met in literature. These oscillations can hardly be distinguished when visually observing the rowing process due to clearly expressed and effective movements of a rower. Sequentially it is hard to notice the mentioned effect. The phenomenon of vertical oscillations was noticed by the authors [1], when they were analyzing parameters of forced oscillations of keel boats recorded by other authors. The free oscillations are excited by force impulses which act on the seat during each stroke.

When rowing the academic boat human body contacts the boat in three places: by feet, by oars and by seat. At these points interaction forces between human body and the boat appear and they have an effect on the boat's movement. In Fig. 1 impulses of oar force $F_D(t)$ (with the amplitude $F_{D_{max}}$ and duration t_D) periodically acting on the oar handle with the rate frequency SF or period T_Z are presented. During the performance of drawing of an oar rower's body becomes almost completely suspended on the handles and footrests and that's why the force effect $F_S(t)$ on the seat decreases. When the legs are completely stretched and the drawing phase is being terminated by the movement of back and arms the force impact effect $F_S(t)$ on the seat appears with time delay t_v with respect to the drawing phase beginning. Maximum magnitude of the force can significantly exceed the rower's weight D. During the time period t_S the boat is plunged down. After this free vertical damped oscillations of the boat which can be defined by the change of draught $\zeta(t)$ with respect to static draught T_0 proceed. Usually during the stroke period T_Z the oscillations are not fully damped. As the result in steady state rowing the total (summed up) increment $\zeta_\Sigma(t)$ is formed. Due to the effect of damped oscillations with the increase of rowing rate SF the mean draught $\overline{\zeta}$ increases together increasing the wetted surface of the boat S by an increment ΔS. With the increase of the wetted surface the resistance force of the water increases as well in this way decreasing the rowing effectiveness.

In a number of research papers mathematical modeling of academic rowing process, the analysis of bio-

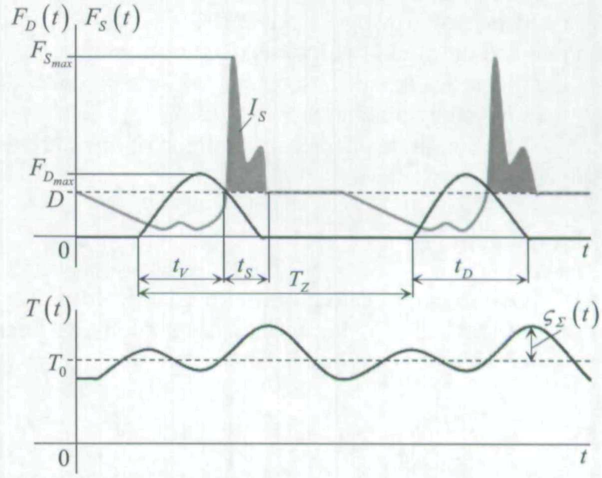

Fig. 1 Interdependencies of oar force $F_D(t)$, vertical force $F_S(t)$ acting on the seat and the boat draught $T(t)$

mechanical, psychological and physical factors are presented [2-4]. Nevertheless their research is limited on the analysis of basic biomechanical and physiological factors, which predefine the rowing performance effectiveness. The examination of the diversity of the boats does not cover all classes of boats examples [5]. It is stated that their influence is negligible. Researchers [4] give an explanation that vertical oscillations do not have substantial influence on the rowing effectiveness, because the forced vertical oscillation related to the rowing rate does not change the mean value of draught. The researcher [6] by processing results of the rowers' test has determined that the rowing effectiveness is decreased with the increase of the rowing rate. According him rowing efficiency (of a boat) is determined by the ratio of oar force and the force of water resistance. Sequentially with increase of the rate water resistance increases as well. Theoretical proof is not provided. A special attention the researcher [7-12] pays to differences in the results of rowers of high excellence, prize winners in high rank competitions and that's why makes analysis of the factors the influence of which equals to units or parts of percents. The decrease in efficiency is explained by the change in wave resistance when the keel boat oscillates with the frequency equal to the rowing rate.

Aims of the research – to determine rowing effectiveness parameters for different classes of academic boats conditioned by the factor of vertical free oscillations of the boat complex, to determine the dependence of the effectiveness parameters on characteristics of the boat hull and intensity of the rowers action to the seat, to compare different boats and the possibilities provided by them, to verify theoretical dependence of rowing effectiveness on rowing rate by practical data and elaborate the recommendations to increase rowing effectiveness.

The following problems are solved:

- realistic parameters for different classes of academic boats necessary for the calculation of the influence of vertical oscillation on rowing effectiveness are determined;
- by the method of mathematical modeling according data of boat complexes and the rowers' the draught increment caused due to free vertical oscillations was calculated;
- using the increment of water resistance the dependence of rowing effectiveness change on stroke rate and the strength of vertical action are determined, the theoretical results are compared with practical data obtained by other authors.

The conditions decreasing fatigue of arms are determined.

2. Methodology

Due to complicated form of the vertical force acting on the seat (Fig. 1) for further calculations its linear approximation by broken line is used

$$F_S(t)=\sum_{j=0}^{k} a_j\left(t-\tau_j\right)u\left(t-\tau_j\right) \tag{1}$$

where k is the number of sections of the line, j is the number of a break point, τ_j is time at the j th point of the broken line, a_j is coefficient $a_j=\dfrac{F_{S_{j+1}}-F_{S_j}}{\tau_{j+1}-\tau_j}-\dfrac{F_{S_j}-F_{S_{j-1}}}{\tau_j-\tau_{j-1}}$, F_{S_j} is the values of force $F_S(t)$ at time instants τ_j, $u(t-\tau_j)$ is unit step function (u = 0, when $t<\tau_j$; $u=1$, when $t\geq\tau_j$).

Based on the theory of ships with all assumptions and simplifications made in it the process of vertical oscillations of the boat complex mathematically can be described by second order linear nonhomogenous differential equation

$$\ddot{\varsigma}+2\nu\dot{\varsigma}+\eta^2\varsigma=F_S(t)/2m \tag{2}$$

where m is mass of the boat complex (the boat, the oars and the crew), η is angular frequency of vertical oscillations of the boat [10]

$$\eta=\frac{2\pi}{2.5\sqrt{T}} \tag{3}$$

ν is damping coefficient of vertical oscillations determined from the graphs of Salkajev [13] according dimensions of the boats.

Due to the effect of single force $F_S(t)$ impulse (1) the solution of Eq. (2) giving the change of the draught in time $\zeta(t)$ has the following expression

$$\zeta(t)=\frac{1}{m}\sum_{j=0}^{k}a_j\,u\left(t-\tau_j\right)\left\langle\frac{t-\tau_j}{\eta^2}-\frac{2\nu}{\eta^4}\left\{1-\frac{\eta^2}{2\nu\omega}e^{-\nu(t-\tau_j)}cos\left[\omega\left(t-\tau_j\right)+arctg\frac{\eta^2-2\nu^2}{2\nu\omega}\right]\right\}\right\rangle \tag{4}$$

where ω angular frequency of the oscillations taking into account damping:

$$\omega=\sqrt{\eta^2-\nu^2} \tag{5}$$

The process of vertical oscillations of the boat complex can be considered as steady state as is can be described by the following relationship [1]

$$\zeta_\Sigma(t)=\sum_{i=1}^{5}u(t-(i-1)T_Z)\zeta(t-(i-1)T_Z) \tag{6}$$

where $\zeta_\Sigma(t)$ is total increment of the draught, i is number of the stroke, $u\left(t-(i-1)T_Z\right)$ is unit step function (u=0, when $t<(i-1)T_Z$ and u=1, when $t\geq(i-1)T_Z$, $\zeta\left(t-(i-1)T_Z\right)$ is change of the draught increment under the action of single force $F_S(t)$ impulse I_S starting from the time instant $t<(i-1)T_Z$.

Mean increment of the draught during one stroke

$$\overline{\zeta}_Z=\frac{1}{T_Z}\int_0^{T_Z}\zeta_\Sigma(t)\,dt \tag{7}$$

Mean increment of the draught during drawing of the oar

$$\overline{\zeta}_D=\frac{1}{t_D}\int_0^{t_D}\zeta_\Sigma(t)\,dt \tag{8}$$

Mean increment of the draught during lift

$$\overline{\zeta}_{DZ}=\frac{1}{T_Z-t_D}\int_{t_D}^{T_Z}\zeta_\Sigma(t)\,dt \tag{9}$$

Increment ΔS of the wetted surface S of the boat caused by the draught increment $\overline{\zeta}_Z$ can be defined as follows

$$\Delta S=B_{ST}\overline{\zeta}_\Sigma \tag{10}$$

where B_{ST} is proportionality coefficient in the dependence of wetted surface S of the boat on draught T.

The force of water resistance is proportional to the wetted surface area. This fact allows expressing the change of the influence of vertical oscillations for different values or stroke rate by the effectiveness coefficient

$$EK_S(SF)=\frac{S}{S+\Delta S(SF)} \tag{11}$$

For practical analysis line drawings of academic boats (single 1x six types, double scull/coxless pair 2x/– eight types, quadruple scull/coxless four 4x/– three types and eight 8+ two types) were used. Majority of the boats were designed and manufactured at the Experimental design centre "Latvijas laivas" (Latvia's ship). Great diversity allowed to cover wide range of the boats from the widest (Type 8303 (1x), Type 7606 (2x/-), Type 8750 (4x/-) and Type 7801 (8+)) to the narrowest (Type 8701 (1x), Type 8906 (2x/-), Type 8650 (4x/-) and Type 8585 (8+)) ones. An average difference of the widths was about 10%.

From line drawings using trapezium method [9] dependences of boat parameters relating load with boat complex mass m (the boat, oars, crew), boat draught T, the wetted surface area S and from Salkajev graphs [10] coefficients of vertical oscillations ν were determined. Boat parameters were calculated inside the mass interval of boat complexes 86-126 kg (1x), 167-247 kg (2x/-), 332-492 kg (4x/-) and 707-1027 kg (8+). The mass m consists of equal masses of all the rowers m_r in the limits from 65 to 105 kg, the coxswain mass of 50 kg for the boat (8+) and the remaining mass of the boat complex – mass of the boat itself and mass of the oars.

Dependences of boat parameters are presented graphically in Figs. 2 - 4.

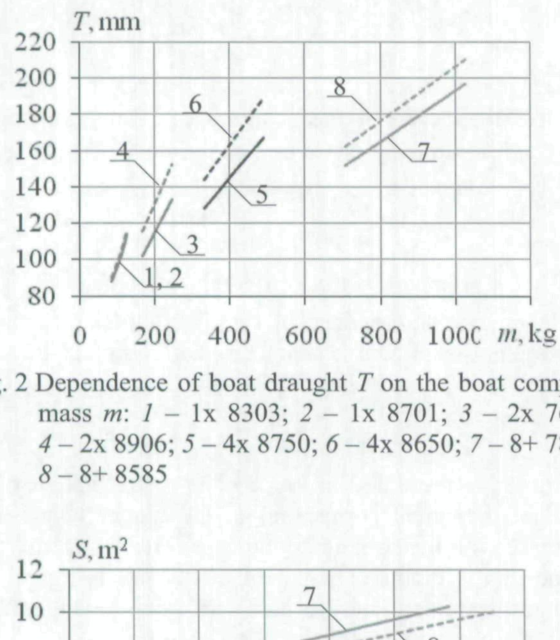

Fig. 2 Dependence of boat draught T on the boat complex mass m: *1* – 1x 8303; *2* – 1x 8701; *3* – 2x 7606; *4* – 2x 8906; *5* – 4x 8750; *6* – 4x 8650; *7* – 8+ 7801; *8* – 8+ 8585

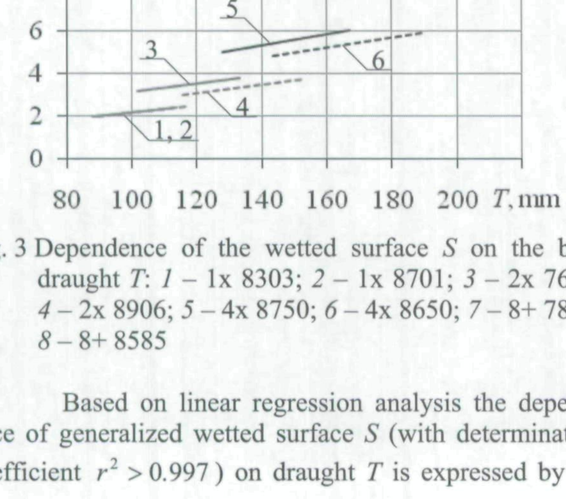

Fig. 3 Dependence of the wetted surface S on the boat draught T: *1* – 1x 8303; *2* – 1x 8701; *3* – 2x 7606; *4* – 2x 8906; *5* – 4x 8750; *6* – 4x 8650; *7* – 8+ 7801; *8* – 8+ 8585

Based on linear regression analysis the dependence of generalized wetted surface S (with determination coefficient $r^2 > 0.997$) on draught T is expressed by regression Eq. (12) the coefficient values of which are presented in Table.

$$S = A_{ST} + B_{ST}T \tag{12}$$

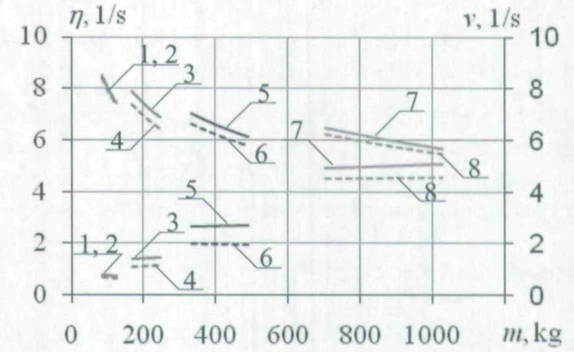

Fig. 4 Dependence on natural frequency of vertical oscillations η and attenuation coefficient ν of boats on boat complex mass m.: *1* – 1x 8303; *2* – 1x 8701; *3* – 2x 7606; *4* – 2x 8906; *5* – 4x 8750; *6* – 4x 8650; *7* – 8+ 7801; *8* – 8+ 8585

Table

The values of regression coefficient for Eq.(12)

Boat class	Coefficient	Value
1×	A_{ST}	0.5877
	B_{ST}	0.0159
2×/-	A_{ST}	0.9912
	B_{ST}	0.0194
4×/-	A_{ST}	1.6035
	B_{ST}	0.0245
8+	A_{ST}	3.0851
	B_{ST}	0.0348

When calculating the draught increments during a stroke (T_Z), oar drawing (t_D) and lift (t_{DZ}) phases at different rowing rates the values of oar drawing time t_D, impulse I_S, delay t_V, and maximum value $F_{S_{max}}$ of vertical force $F_S(t)$ were evaluated and the dependence of the force action time on stroke rate was taken into account. Based on them the dependences of force and time parameters on stroke rate were obtained in the form of regression equations as follows

$$t_D = -0.0083SF + 1.0173 \quad \text{with } r^2 = 0.2762 \tag{13}$$

$$t_V = -0.0055SF + 0.7196 \quad \text{with } r^2 = 0.2016 \tag{14}$$

$$t_V = -0.008SF + 0.7766 \quad \text{with } r^2 = 0.2074 \tag{15}$$

$$F_{S_{max}} = 19.79SF + 257 \quad \text{with } r^2 = 0.1443 \tag{16}$$

The impulse of oar force $F_D(t)$ is presented by a positive half period of sinusoid: the amplitude $F_{D_{max}}$ corresponds time instant $0.5t_D$. Oar angle during drawing phase changes from 30 to 120 degrees independently on the stroke rate.

When calculating real draught increments according formula (4) the form of the force $F_S(t)$ similar to the one presented in Fig. 1 is used. That's why in formula (1) it is used $k = 6$. Time and amplitude parameters of separate points on broken line are represented in the form of the ratio of time and amplitudes [14]. The parameter values are obtained from the data of force $F_S(t)$ measurement and result averaging. The ratios of time and amplitude are kept constant when values of the parameters t_s and $F_{S_{max}}$ themselves change according formulas (15) and (16) in dependence on the stroke rate. Increasing or decreasing amplitude of the vertical force effect the draught increment changes proportionally as expressed by formula (4).

3. Results and discussion

As it is presented in Fig. 2 draught of the wider boats is lower and their wetted surface area is bigger to compare with the narrower boats. Sequentially the lower water resistance force is characteristic for narrower boats. The draught and wetted surface area of higher class boats is bigger. The natural frequency of vertical oscillations η is decreased with the increase of boat class and the mass of boat complex m. The increase of damping coefficient of vertical oscillations ν is proportional to the number of rowers in a boat (Fig. 4). For separate boat classes this parameter depends on mass m insignificantly. For narrower boats both η, and ν are lower.

The results of the investigation of vertical oscillations were obtained for the rowing rates range from 21 to 50 1/min and with mean values of masses (106, 207, 412 and 867 kg). The calculated mean values of draught increments – instantaneous and of drawing (t_D) lift (t_{DZ}) and stroke (T_Z) phases are given in Figs. 5-8.

The instantaneous values of draught increments due to vertical oscillations at the time instant corresponding the centre of oar force impulse for the investigated boat classes are summarized in Fig. 5. The greatest change of the draught increment is characteristic for the 1x type boats. The bigger is the boat the less it oscillates.

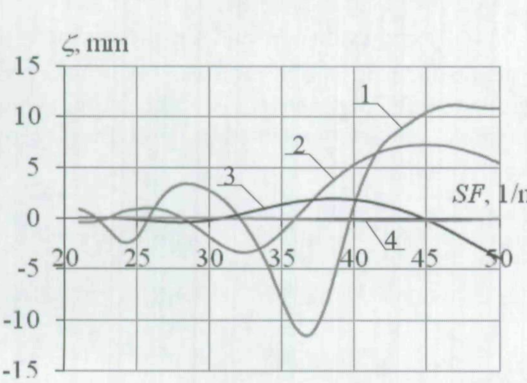

Fig. 5 Dependence of summarized instantaneous draught changes ζ for the boats of different classes on stroke rate SF: *1* – 1x; *2* – 2x/-; *3* – 4x/-; *4* – 8+

The mean values of draught increment $\overline{\varsigma}_D$ at the drawing phase are presented in Fig. 6. The mean values of draught increment change more for narrower boats than for wider boats. For the 1x class boats the lowest mean increment of the draught $\overline{\varsigma}_D$ is at the stroke rate SF of about 35 1/min. With the increase of SF $\overline{\varsigma}_D$ increases also and reaches its maximum at 45 1/min. For the 2x/ class boats the lowest value of $\overline{\varsigma}_D$ is at 30 1/min and the maximum at 40-42 1/min. For the 4x/ class boats the lowest value of $\overline{\varsigma}_D$ is at 35 1/min and decreases with the increase of SF. For the 8+ class boats the increment $\overline{\varsigma}_D$ increases insignificantly with the increase of SF. Such draught increment due to free vertical oscillations changing non proportionally to the stroke rate can be used to perform the drawing phase more effectively. Investigating fatigue of the rowers the researchers [15] have determined that arms become tired in a shorter time period than legs. That's why it is recommended to save arms. Mostly the arms are tired at the drawing phase. So having in mind the draught increment change nonproportional to the rowing rate, the stroke rates at which mean draught is lower can be selected.

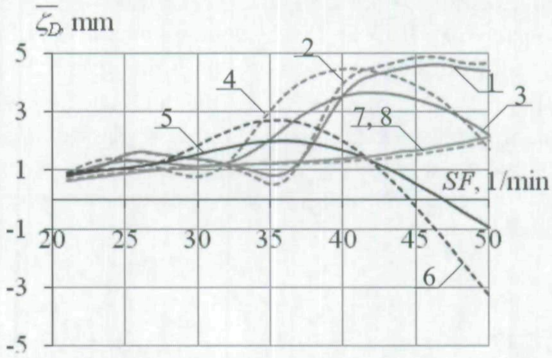

Fig. 6 Dependence of mean values of draught increment $\overline{\varsigma}_D$ at drawing phase on stroke rate SF: *1* – 1x 8303; *2* – 1x 8701; *3* – 2x/- 7606; *4* – 2x/- 8906; *5* – 4x/- 8750; *6* – 4x/- 8650; *7* – 8+ 7801; *8* – 8+ 8585

The mean values of draught increment $\overline{\varsigma}_{DZ}$ at the lift phase are summarized in Fig. 7. Nonlinear change of the draught increment is characteristic for small boats. The greater increment is characteristic for bigger boats. But in this phase the arms do not take part.

The mean values of draught increment $\overline{\varsigma}_Z$ during a stroke are presented in Fig. 8. The higher values of the draught increment correspond to the bigger boats. They increase with the stroke rate increase. The change of mean value of the draught increment practically is linear. The draught increment of the narrower boats changes more than that of the wider boats.

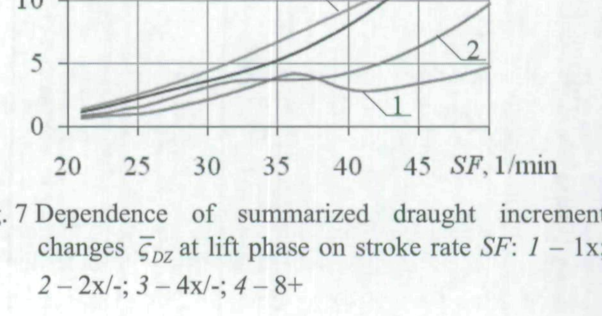

Fig. 7 Dependence of summarized draught increment changes $\overline{\varsigma}_{DZ}$ at lift phase on stroke rate SF: *1* – 1x; *2* – 2x/-; *3* – 4x/-; *4* – 8+

The strength of the vertical action is evaluated by calculating the values of mean draught increments changing force $F_S(t)$ in the limits from $0.5F_S(t)$ to $1.5F_S(t)$. The draught increments are proportional to the magnitude of acting force $F_S(t)$. The shape of their dependences is similar to the ones presented in Figs. 5-8.

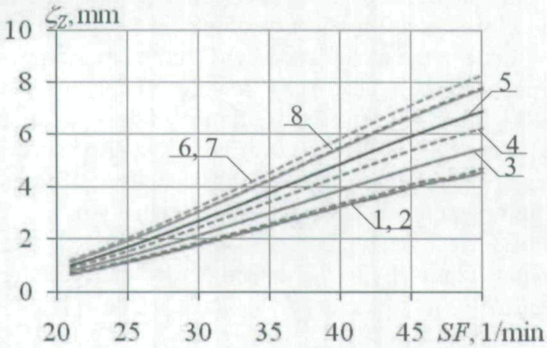

Fig. 8 Dependence of mean values of draught increment $\overline{\varsigma}_D$ at a stroke on stroke rate *SF*: *1* – 1x 8303; *2* – 1x 8701; *3* – 2x/- 7606; *4* – 2x/- 8906; *5* – 4x/- 8750; *6* – 4x/- 8650; *7* – 8+ 7801; *8* – 8+ 8585

Practical data on the dependences of boat rowing effectiveness EK_S on stroke rate [6] are presented in Fig. 9. They are grouped according specifics of sweep and sculling and do not reflect peculiarities of boat classes and the magnitude of vertical force action on the seat. The latter factor can be used to define the data spread. As a result of our investigations rowing effectiveness EK_S dependences for the boat classes' determined according formula (11) are presented in Fig. 9. Rowing effectiveness for the boat classes 1x, 2x/- and 4x/- almost coincides, rowing effectiveness of the 8+ boat class is higher. Rowing effectiveness for all boat classes decreases with the rowing rate increase. The difference of the two dependence families is predefined by different force action onto the seat (for higher dependences – $F_S(t)$, for lower $1.5F_S(t)$). The higher is $F_S(t)$ the lower is the effectiveness EK_S. The data of theoretical dependences of the effectiveness on the rate are in satisfactory agreement with experimental data. Summarizing it could be stated that the existence of free vertical oscillations could be the reason of the change of rowing

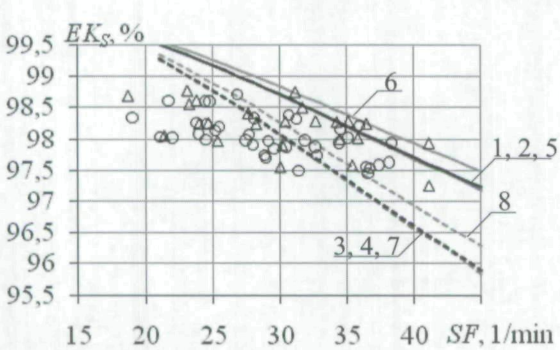

Fig 9 Dependence of boat rowing effectiveness on stroke rate *SF*: *o* – sculling; *Δ* – sweep; *1* – 1x; *2* – 4x/-; *3* – 1x $1.5F_S(t)$, *4* – 4x/- $1.5F_S(t)$, *5* – 2x/-; *6* – 8+; *7* – 2x/- $1.5F_S(t)$, *8* – 8+ $1.5F_S(t)$

effectiveness in dependence on the rate. The phenomenon is expedient to be taken into account when analyzing the factors influencing rowing techniques of highly skilled rowers.

4. Conclusions

1. The change of rowing effectiveness based on the theory of vertical free oscillations in dependence on stroke rate practically corresponds with experimental data obtained by other researchers.

2. As the reason of the change of rowing effectiveness in dependence on stroke rate the fact of the existence of free vertical oscillations can be considered.

3. When force action on the seat is strengthened the rowing effectiveness is reduced proportionally.

4. Recommendation to save arms during rowing can be related to the selection of stroke rate, when the possibilities of reduction of mean draught increment at drawing phase are known.

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LAISVAS VERTIKALUSIS AKADEMINĖS VALTIES SUPIMAS

R e z i u m ė

Nagrinėjama akademinių valčių vertikaliojo supimo įtaka irklavimo efektyvumo rodikliams, kurie apibrėžiami kaip valties drėkinamo paviršiaus ploto pokytis dėl vidutinio valties grimzlės prieaugio. Apskaičiuoti įvairių klasių akademinių valčių irklavimo efektyvumo rodikliai, sąlygojami valties komplekso laisvo vertikaliojo supimo, nustatyta šių rodiklių priklausomybė nuo kai kurių valties korpuso parametrų ir irkluotojų vertikalaus poveikio sėdynėlei intensyvumo, pateikta praktinių rekomendacijų, kaip padidinti irklavimo efektyvumą.

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FREE VERTICAL OSCILLATIONS IN ROWING

S u m m a r y

The influence of the factor of vertical oscillation of academic boats on rowing effectiveness parameters defined as the change in the area of wetted surface of the boat caused due to the mean its draught increment is analysed in the paper. The indicators of rowing effectiveness conditioned by the factor of free oscillation of the boat are calculated for academic boats of different classes; the dependences of the effectiveness indicators on some of the different hull parameters of boats and on intensity of the rowers vertical effect on to the seat were determined; practical recommendations for the effectiveness increase are presented.

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СВОБОДНАЯ ВЕРТИКАЛЬНАЯ КАЧКА ЛОДОК В АКАДЕМИЧЕСКОЙ ГРЕБЛЕ

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Рассматривается влияние фактора вертикальной качки академических лодок на показатели эффективности гребли. Показатели эффективности определяются как изменение площади смачиваемой поверхности корпуса лодки вследствие увеличения погружения лодки. Рассчитаны показатели эффективности для различных типов академических лодок, обусловленные фактором свободной вертикальной качки комплекса лодки, определены зависимости показателей эффективности от некоторых параметров корпуса лодки, интенсивности вертикального воздействия гребца на подвижное сиденье, представлены практические рекомендации по увеличению эффективности гребли.

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