Simulation of the ergometer

1. Introduction

Why try to simulate the rowing ergometer on the computer? Through the performance monitor on the erg the user receives immediate feedback that he lacks in the boat. The lack of feedback in the boat is a reason to simulate a boat on the computer. In the boat a number of parameters can be adjusted and their influence can at least qualitatively be analyzed on the computer and more difficult on the water. For the erg only the drag factor can be selected as an erg parameter by the rower and the result is immediately visible on the monitor. Stroke rate and shape of the force curve can also be chosen by the rower but the consequences are also visible on the monitor. Remains to learn about energy production by the rower on the erg that is not visible on the monitor. The results of an exercise with one set of variables are presented below. No parameter variation was performed.

2. Theory and model

2.1 Model

For the time being only ergs of the Concept2 type and clones are considered.
The principal elements of rower and erg are shown in Fig 2.1.
The body of the rower does not rotate. The motion of the pulling bar is the result of the translation of the body and the bending of the arms. The parameters of the erg, the mass moment of inertia and the damping of the wheel are estimates.

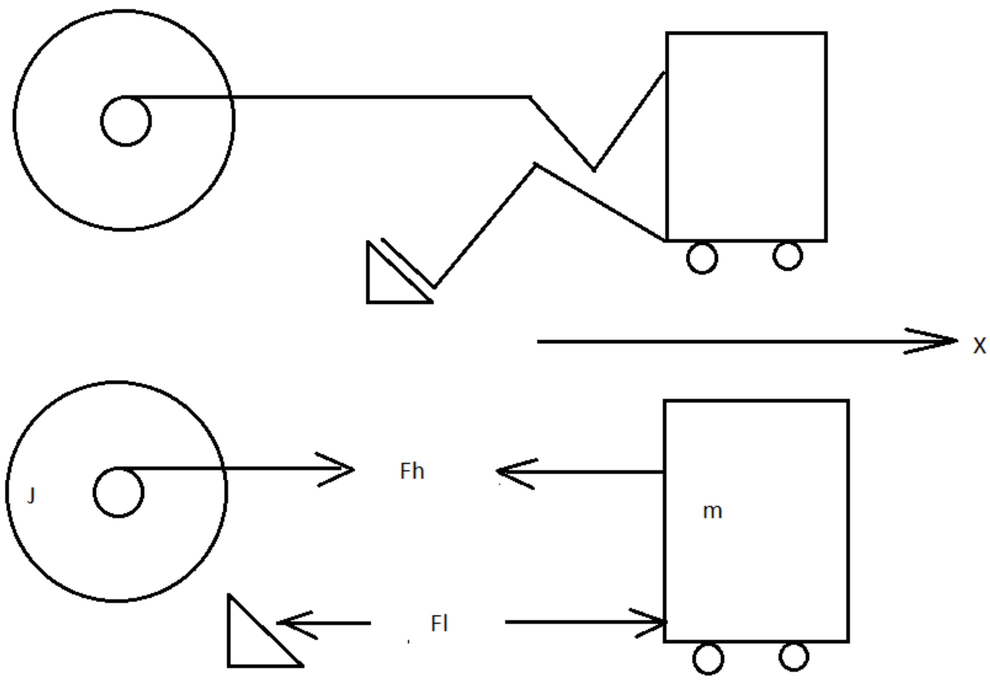

Fig 2.1
Model of the erg

2.2 Parameters

$J = 0.1$ moment of inertia of wheel [kg.m^2]
$k = 0.00022$ damping [N.m.s^2/rad^2]
$r = 0.015$ radius of sprocket [m]
$m = 70$ mass of the rower [kg]
$L_h = 1.5$ path of the hands [m]
$F_1 = 770$ force component #1 [N]
$F_2 = 270$ force component #2 [N]
$dt = 0.001$ time step [s]

I trust that the reader recognizes the elements of the rower and the ergo in Fig 2.1 and the names in the list above.

2.3 Equations of the wheel

The equation of motion of the wheel is:

$$\dot{\omega} = \frac{F_h.r - k.\omega^2}{J}$$

$\dot{\omega}$ = rotational acceleration

ω = rotational speed
F_h = force in the chain
r = radius of the sprocket

The force F_h in the chain = force by the hands, is specified as a function of the position of the hands as:
$F_h = F_1.\sin\left(\frac{\pi}{L_h}.x_h\right) + F_2.\sin\left(\frac{2.\pi}{L_h}.x_h\right)$ with x_h is the distance the hand have covered since the "catch", "path" in the graph.

With the numbers above the graph of the force looks as in Fig 2.2.
The maximum force of abt. 900 N refers to a strong rower.

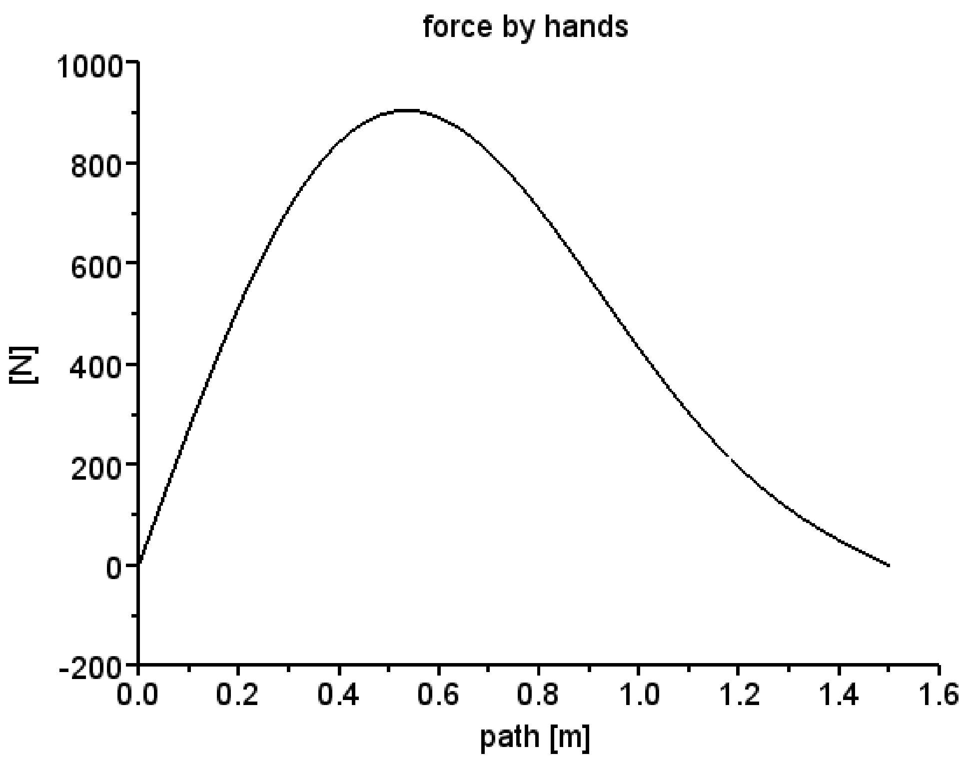

Fig 2.2
Force in the chain as function of the position of the hands. 0.0 m is the catch position.

With the force in the chain the rotational acceleration and speed of the wheel is calculated; quantities in the next step i are derived from those in the previous step i-1 is as follows:
time:

$$t(i) = t(i-1) + dt$$

$$\dot{\omega}_{i-1} = \frac{F_{h,i-1}.\mathrm{r} - \mathrm{k}.\omega_{i-1}^2}{\mathrm{J}}$$

$$\omega_i = \omega_{i-1} + \dot{\omega}_{i-1}.\mathrm{dt}$$

The speed of the hands is $v_{h,i} = \dot{x}_{h,i} = \omega_i.r$

The position of the hands follows from:

$$\mathrm{x}_{h,i} = \mathrm{x}_{h,i-1} + \omega_{i-1}.\mathrm{r.dt} + 0.5.\dot{\omega}_{i-1}^2.\mathrm{r.dt}^2$$

The last term is negligible for sufficient small dt.
The calculation stops when x_h>=L_h, the distance coverd by the hands. The time used for the stroke $T_s = t_{last}$.
During the return no external force works on the wheel.
The time for the recovery $T_r = 1.2*T_s$.
The motion of the wheel follows from:

$$\mathrm{t(i)} = \mathrm{t(i-1)} + \mathrm{dt}$$

$$\dot{\omega}_{i-1} = \frac{-\mathrm{k}.\omega_{i-1}^2}{\mathrm{J}}$$

$$\omega_i = \omega_{i-1} + \dot{\omega}_{i-1}.\mathrm{dt}$$

This calculation continues until $t = T_r$.

For a continuous situation the rotational speed at the catch must be the same as at the end of the recovery. This is obtained by iteration. For a new iteration step the initial speed is taken equal to the mean value of start and end speed of the previous step. This is repeated until start- and end speed are equal.

For the path of the body L_b a fraction f of the path of the hands L_h has been assumed.

$$\mathrm{f} = \frac{\mathrm{L_b}}{\mathrm{L_h}}$$

2.4 The motion of the body.

The speed of the body during the stroke has been chosen as:

$$\mathrm{v_{bs}} = \frac{\mathrm{L_b}}{\mathrm{T_s}}.\left[1 - cos\left(\frac{2\pi}{T_s}t_s\right)\right]$$

and the acceleration is:

$$a_{bs} = \frac{2\pi . L_b}{T_s^2} . \sin\left(\frac{2\pi}{T_s} t_s\right)$$

These functions give zero speed and –acceleration at the start and finish of the body during the recovery and avoids extreme acceleration forces.

For the recovery the same function has been chosen with an opposite sign and T_s and t_s replaced by T_r and t_r.

2.5 Leg force

Leg force during the stroke is:

$$F_{ls} = m . \dot{v}_{bs} + F_h$$

And during the recovery:

$$F_{lr} = m . \dot{v}_{br}$$

3. Energy considerations

Energy delivered to the wheel is:

$$E_w = \int_0^{L_h} F_h . dx_h$$

Or alternatively via the power to the wheel P_w:
$P_w = F_h . v_h$ and:

$$E_w = \int_0^{T_s} P_w . dt$$

The mean power during one cycle P_c analogous to the power as displayed on the monitor of the real ergo is:

$$P_c = \frac{E_w}{T_c}$$

The cycle time is the sum of the stroke time and the recovery time $T_c = T_s + T_r$
The energy delivered by the legs has been calculated from:
Power of the leg during the stroke is: $P_{ls} = F_{ls} . v_b$
and $E_{ls} = \int_0^{T_s} P_{ls} . dt$
The legs produce "negative work" when leg force is needed to decelerate the body. Force and speed then have opposite signs and the product is negative. In the computer program this negative energy diminishes the amount of energy delivered. In a conservative system this is correct but in this case we cannot use this energy and it is lost (converted to heat in the rower's body). Therefore in the final energy balance this negative energy is again added to the energy calculated by the computer as energy delivered by the rower.

Some authors are of the opinion that this is not enough. Their argumentation is that the not only the kinetic energy accumulated in the body is lost (my opinion) but that the body must deliver again energy to withdraw the kinetic energy from the system. They add twice the negative energy.

Besides the legs the arm are a source of energy. As the arms are considered as massless the force at the hands and at the connection to the body are equal. During the stroke the arms bend or contract. The contraction speed v_c is the relative speed of the hand with respect to the body: $v_c = v_h - v_{bs}$

The power delivered by the arms is: $P_a = F.v_c$ and the energy: $E_a = \int_0^{T_s} P_a \, .dt$.

4. Results

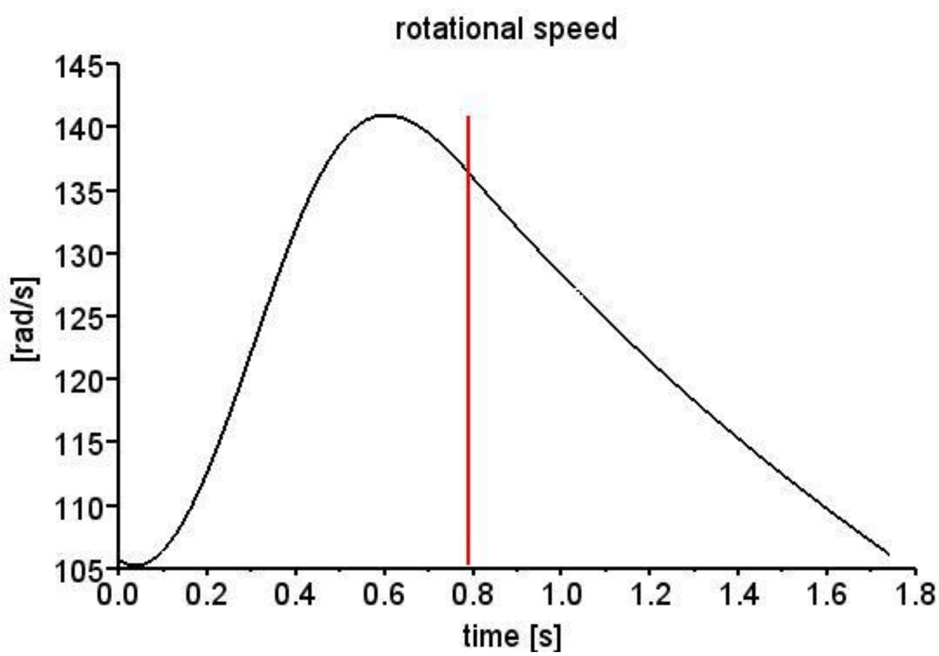

Fig 4.1
Rotational speed of the wheel during the cycle.
The red vertical marks the transition between stroke (left) and recovery.

The vertical red line marks the transition between stroke and recovery. The wheel speed decreases immediately after the catch. The chain force is then not yet big enough to accelerate the wheel.

In reality this is also the case because of the dead space in the coupling of the sprocket to the wheel axle. The maximum speed is reached before the end of the stroke because of the diminishing chain force.

The leg force is shown in Fig 4.2.

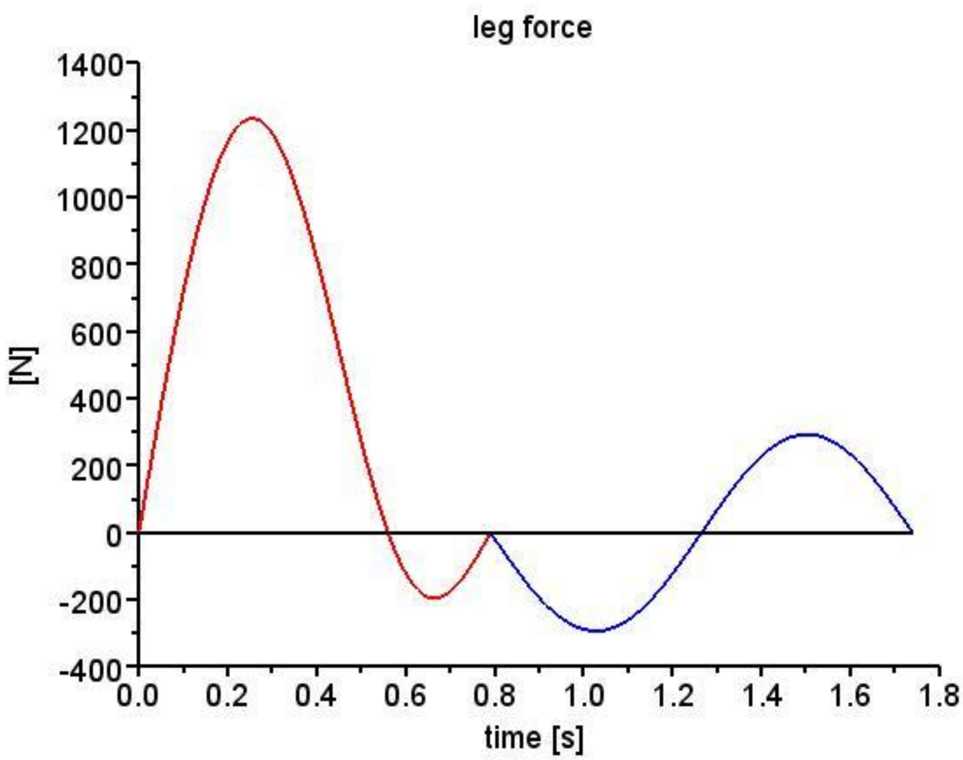

Fig 4.2
Leg force during the cycle. Stroke: red, recovery: blue

During the stroke the body velocity is positive. When the force curve sinks below the line force = 0, negative work is done. During the recovery the body velocity is negative. When the force curve raises above the line force = 0, negative work is done.

Fig 4.3 shows the power fed to the wheel and the power delivered by legs. Negative power is rather small and the negative leg energy (during the stroke) is represented by the area enclosed by the horizontal zero power line and the blue line below the zero power line.

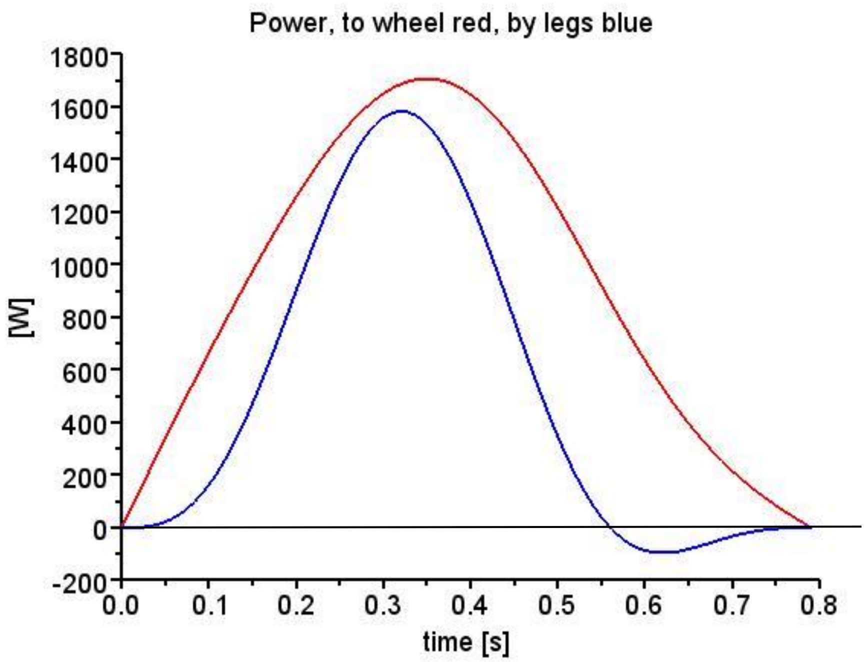

Fig 4.3
Power to the wheel and power delivered by the legs.

Further results are shown in the next tables. Work done on the wheel is always positive. The legs do mainly positive work during the stroke (fortunately) but do some negative work at the end of the stroke to decelerate the body. In the ideal case all the kinetic energy of the body should be transferred to the wheel. The computer program has in calculating the net work taken the algebraic sum of positive and negative work

Energy to the wheel [J]	
net	735.3
negative	0
positive	735.3

Table 4.4

Energy by the arms [J]	326.5

Table 4.3

Energy legs in the stroke [J]	
Net	408.8
Negative	-10.3
Positive	419.1
Energy legs in the return	
Net	0
Negative	-55.9
Positive	55.9

Table 4.2

Energy Balance: energy to the wheel = net energy legs during stroke + energy of arms = 735.3 = 408.8 + 326.5

Power as displayed on the monitor [W]	423.1
Total power delivered by the rower [W]	554.9
Cycle time [s]	1.738
Stroke rate [strokes/min]	34.5

Table 4.4

5. Conclusion

The results above show at least some similarity with the real erg. Maybe improvement is possible when the parameters are measured on the metal erg.

The contraction speed of the arms is not as can be expected from a good rower. See Fig 5.1.
It is the result of the choice of the velocity function of the body. Maybe this will be improved in the future.

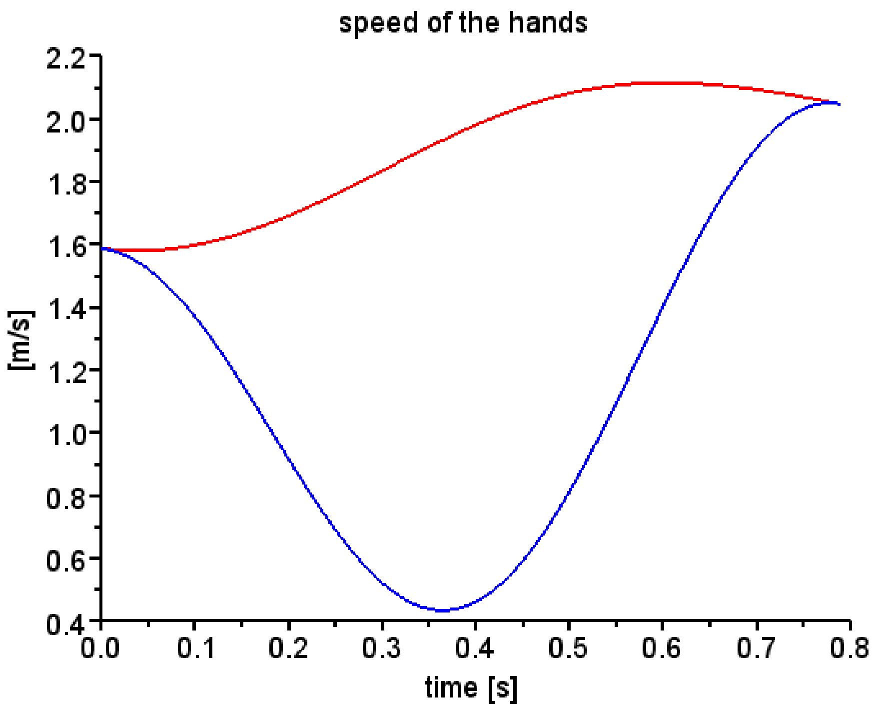

Fig 5.1

red: absolute speed of the hands.

blue: relative speed of the hands with respect to the body = contraction speed of the arms.