Rolling Cylinder Phase 1bis

long model testing in irregular waves

Margheritini, Lucia

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Rolling Cylinder Phase 1bis: long model testing in irregular waves

by

L. Margheritini

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Preface

This report has been prepared under the contract agreement between Aalborg Universitet and Storper Innovation ApS.
The report has been written by Lucia Margheritini (lm@civil.aau.dk) who is also responsible for the data analysis. This report is the continuation of the previous report "Rolling Cylinder Phase 1: proof of concept and first optimization", DCE report 115, ISSN 1901-726X, and it is recommended that the two are consulted together as they were firstly agreed to be in one document. The present report aims at estimate the efficiency of the Rolling Cylinder long model (previously optimized), by mean of physical tests in irregular waves.
Several difficulties have been encountered during the testing, the biggest of witch being the extremely unfriendly torque measuring system.

Contents

1. Objectives

The objectives of the present study are:

- Construction of full length model of the Rolling Cylinder wave energy device in scale 1:25.
- To design of the torque measuring equipment.
- To test the long model of the rolling cylinder in irregular waves in scale 1:25.
- Estimation of power production.

Results are presented first in Chapter 3 in laboratory scale (1:25) in terms of power production, torque and rotational speed; at the end of the Chapter the results are normalized and in Chapter 4 resultas are presented in term of power production in scale 1:1.

Test in irregular waves have been conducted using Jonswap Spectrum 3.3. Different load conditions have been tested in 3 different wave conditions. Sample frequency = 20 Hz. The data from the torque measuring equipment was handled by a matlab routine (Appendix A).

2. Laboratory set up

The main body of the long model has been realized with three tube of aluminum steel of 1400 mm and Ø=120 mm, with two hard plastic cones fixed at the two extremities of 120 mm each. The fins have been fixed to the main body by mean of an "L" element rigidly connected to the tube by mean of two screws. The total length of the device is 4440 mm with 11 set of fins of 0.75 mm thickness, 6 fin´s par set and distance between one set and the other of 400 mm. Each set allocates 6 fins. The device was placed in the middle of the deep wave basin at AAU laboratory with d=0.65 m water depth (Fig 1).

Figure 1. Laboratory setup for Rolling Cylinder long model in scale 1:25.

The device was rigidly fixed to the two bridges above the basin and constrained to two spherical bearings on the small rod (Ø=17 mm) at the two endings.

The measuring equipment consisted of:

- No. 3 wave gauges to measure incident and reflected waves
- No. 1 potentiometer to measure the angular velocity
- No. 2 load cells to measure the two forces induced on the strip around the cylinder by the cylinder rotation.

All the signals passed through amplification and low pass filter and were finally acquired by Wavelab at 20 Hz.
Prior to the start, the static friction was measured *sf*= 0.24 N on the main body.

2.1   Friction based measuring system

The first measuring system is of a friction based kind (Fig 2). It includes two load cells attached to a stripe passing around the cylinder rod. By a mechanism it is possible to adjust the load on the cylinder. The cylinder rotation generates then 2 forces. The instantaneous resultant of F1 and F2 multiplied by the radius of the rod R = 8.5 mm gives the instantaneous momentum or torque M(t). In addition, a potentiometer connected to the small rod measures the rotational speed *v* (rad/s). The power in this case is instantaneously calculated from the equation:

4

$$P(t) = M(t) * v(t) \tag{1}$$

The system had to be implemented with two springs (compared to the solution suggested in the report "Rolling Cylinder Phase 1: proof of concept and first optimization") in order to reduce its stiffness. The data is collected by Wavelab and a Matlab routine handles the analysis plotting instantaneous power and giving average power, efficiency and rotational speed.
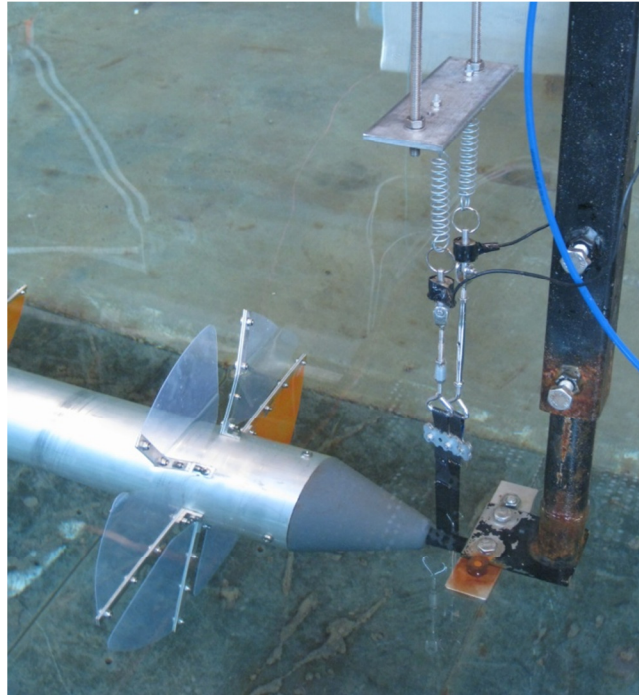

Figure 2. Friction based measuring system.

This system demonstrated not to be optimal for this kind of device and contributed to the overall delay of the project. With some extra time and money, it would have been important to look for a better, more reliable measuring system. For example, the system did not allow a complete arbitrary choice of the load to be applied on the rod, but instead a "close to desired value" where the margin was several Newtons of difference from the desired one.

2.2   Sea states

All the irregular sea conditions presented in Figure 3 have been used to test the full length model of the Rolling Cylinder in scale 1:25, under different loads. For W1 and W2 the model wan not moving *because of relatively high friction in the bearings) and therefore the results are not reported. 2D Jonswap Spectrum (3.3) has been used as an input in the wave generation program AWASYS6. Each test lasted 25 minutes, corresponding to 800-1000 waves.

(W)	Hs [m]	Tp [s]	Prob. Occur. [%]
1	1.0	5.6	46.8
2	2.0	7.0	22.6
3	3.0	8.4	10.8
4	4.0	9.8	5.1
5	5.0	11.2	2.3

Scale 1:25 irregular waves (W)	
Hs [m]	Tp [s]
0.04	1.12
0.08	1.4
0.12	1.68
0.16	1.96
0.2	2.24

Figure 3. Sea states target for irregular wave tests of the Rolling Cylinder.

3. Results and analysis – Irregular Waves

The discussion and presentation of the results will be done in laboratory scale (1:25) while in the conclusions the power production values will be presented for the full scale case.

In the following chapter the results from the irregular wave (W) tests will be presented. Find here the definition of the main entities presented further.

The efficiency is:

$$Eff. = \frac{P}{P_{wave}\,D} = [\%] \tag{2}$$

Where:

D is the diameter of the rotor = 0.44 m;

P is the power calculated as in Eq. 1 and *Pwave* is the power of the specific sea state calculated as:

$$P_{wave} = \frac{\rho g^2 H_{mo}^2 T_P}{64\pi} = [W/m] \tag{3}$$

Where:

P = is the water density = 1000 [kg/m^3];

g = gravity acceleration = 9.82 [m/s^2];

$H_{m0} = \sqrt{4m_0}$ [m], with m_0 is the zero order moment of the wave spectra, i.e. the total energy from the frequency domain analysis; $H_{m0}=H_s$ for Rayleigh distributed waves.

T_p= [s] peak period, corresponding to the frequency where the spectra is maximum.

The instantaneous torque 8or momentum) is calculated as:

$$M(t) = [(F1(t) - F2(t)) * 0.0085] + sf = [Nm] \tag{4}$$

Where:

F1(t) – F2(t) is the instantaneous difference of the signal coming from the load cells [N];

0.0085=diameter of the rod where the friction measuring system is installed [m];

sf is the static friction = mass*g*radius = 0.4*9.82*0.06 = 0.24 [Nm].

Because of the problems faced during the testing, it was not possible to run more than the tests in Table 1 because of time restrictions. Nevertheless, the obtained results allowed the extrapolation of further data that will also be presented below.

Table 1. Tested conditions.

Input		WaveLab results		
wavecondition	Load	H_{m0} [m]	T_p [s]	P_{wave} [W/m]
W3	L1	0.10	1.60	8.614
W4	L1	0.14	1.97	18.3
W5	L1	0.17	2.23	30.66
W2	L2	0.07	1.42	2.911
W3	L2	0.10	1.60	9.046
W4	L2	0.14	1.90	18.24
W3	L3	0.10	1.65	8.858
W4	L3	0.14	1.97	19.4
W3	L4	0.10	1.60	8.583
W4	L4	0.15	1.97	20.48
W5	L4	0.17	2.23	30.34

In order to b able to present the test results in a way so that they are comparable and easy to scale, the found P, M and v have been normalized as follow:

$$M_{norm} = \frac{M}{\rho g H_{mo}^2 R^2} \tag{5}$$

$$P_{norm} = \frac{PT_P}{\rho g H_{mo}^2 R^2} \tag{6}$$

$$v_{norm} = vT_P \tag{7}$$

3.1 Performance analysis

As previously mentioned, the device was not moving (or moving very little) under wave conditions number two (W2) even with no load, and result is presented for only one test.

By adjusting the load on the rid, it was possible run tests with optimal loads for W3, W4 and W5 (Fig. 4). Arguably, the only presented efficiency for W2 is the maximum corresponding to 0.082 for Hs=0.07 m and Tp=1.40 s. The maximum efficiency recoded was 0.111, for Hs=0.10 m and Tp=1.60 s (target W3). For Hs=1.15 m and Tp=1.97 s. (Target W4) the maximum efficiency was 0.101 while for target wave W5 the result was found by extrapolation and the maximum efficiency was calculated to be 0.079.

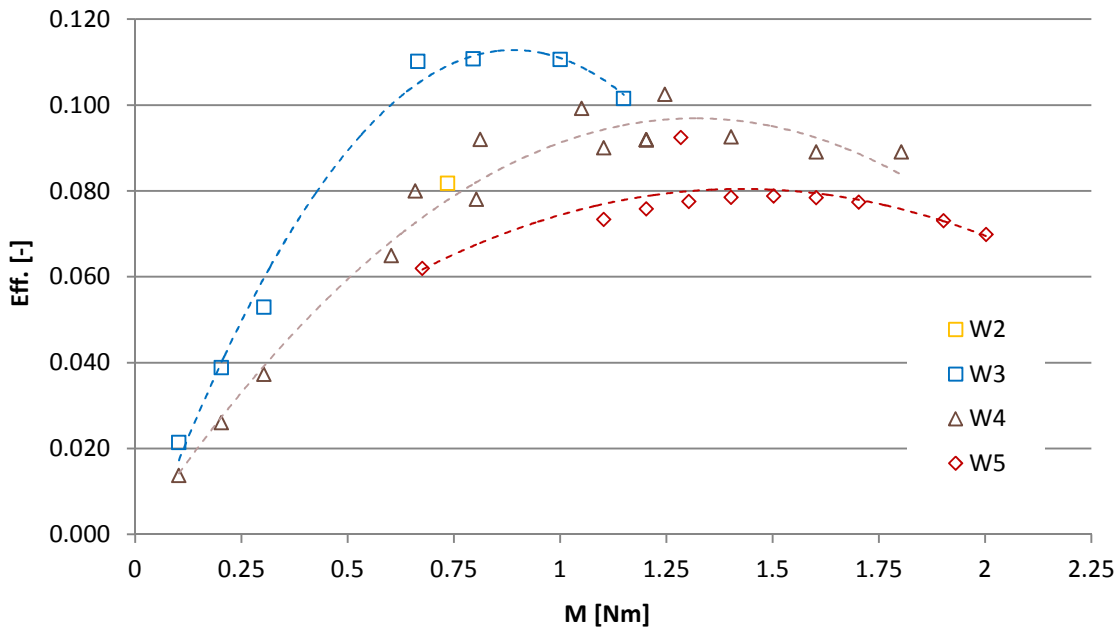The device is performing better for W3, which is also the highest in Power*Prob.

Figure 4. Efficiency depending on the mean torque for different wave conditions in scale 1:25.

The angular velocity decreases when increasing the torque as expected (Fig. 5). By comparing the values of the angular velocities with the results in regular waves, it is possible to notice that the ones presented here are lower. This could be the consequence "down time" (when the device is not rotating) that does not occur in regular waves, because the angular velocity presented in the results is a mean over the test´s duration.
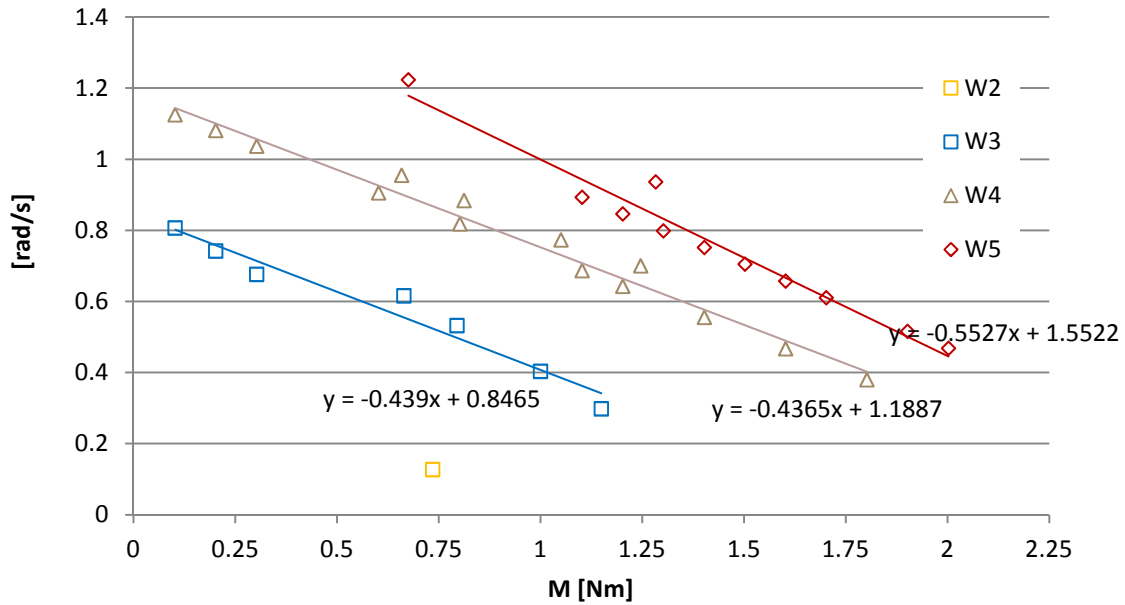
Figure 5. Angular speed as function of the mean torque, for the tested wave conditions with trend lines and corresponding equations. Scale 1:25.

In order to have results that are easily scalable, the results are also reported normalized (Fig 6 and 7). The highest power production occurs under sea state five (W5), then sea state four (W4) and finally three and two (W3 and W2). This is reverse order if compared to the efficiency as previously shown in fig. 4. The normalized power depending on the normalized significant wave height obtained by dividing it with the device length *L* shows a logarithmic trend of the power to increase with wave height.
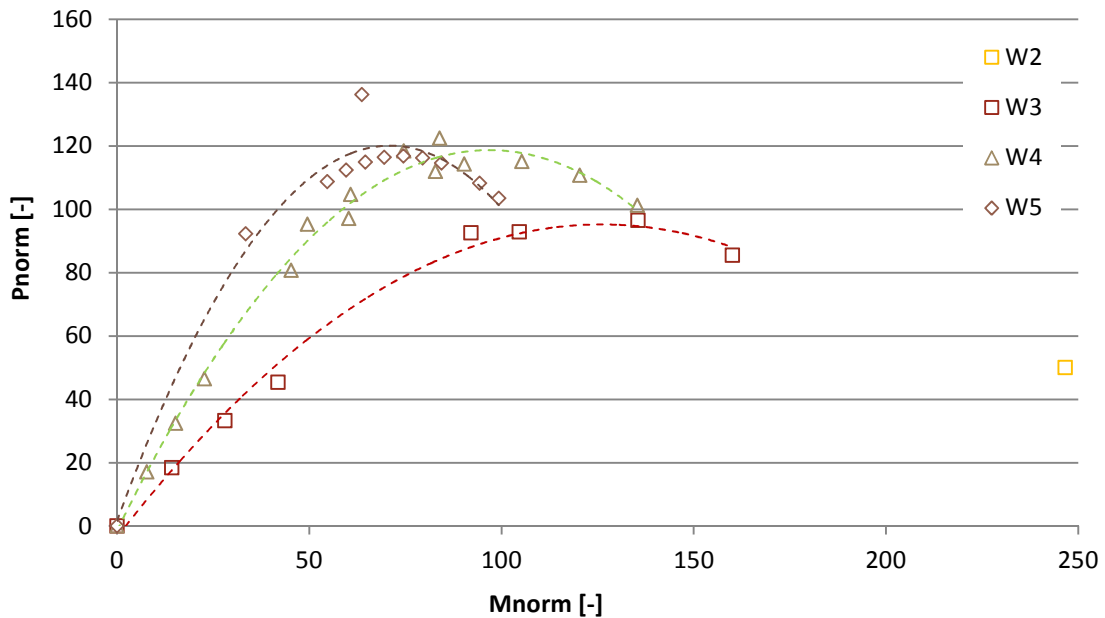

Figure 6. Adimensionalized power depending on the adimensionalized moment, for different sea states.
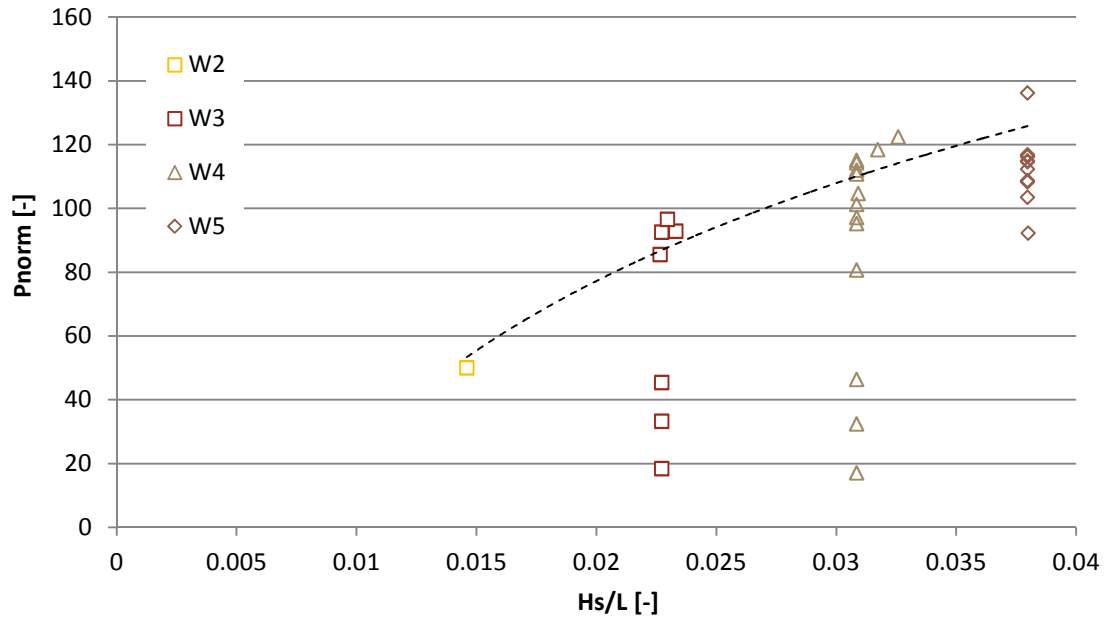
Figure 7. Normalized power as a function of the normalized wave height, for different sea states. Trend curve for the Pnorm corresponding to optimal load (best case) for each wave condition is added.

3.2   Discussion

The efficiency is therefore lower than what expected when calculating it for regular waves with the optimistic assumption that a three times longer device would be three times more efficient than in regular waves. Indeed, in regular waves there was not the start up problem that seems to influence the overall behavior of the device: once a small wave with not enough force to rotate the cylinder comes, the device is steady: not producing and it then requires a wave that will be strong enough to win the static forces and induce rotation every time a stop occurs. This means that the total force $F_{tot}(t) = F_1(t) - F_2(t)$ is equal to zero many times during a test (Fig. 8).

It can definitely be said that the stops and start cycles showed to be not negligible and are probably the major reason for lack of production. Indeed, by making the device longer the condition for having continuous rotation it is only partially granted because even for Hs = 4 m, it is possible that a group of 1-2 m waves occur, stopping the device.

In addition, the device it is not exactly 3 times longer than the short model previously tested in regular waves. Indeed, the short model had 4 sets of fins of 0.75 mm, 6 fins each set, for a length of 1400 mm + 240 mm. But for the long model we don´t 3 times the amount of fins as we only have 11 sets of fins and not 12. This could also be a reason for the smaller recorded efficiencies.

Due to the problems with the friction based system, it is here stated that the accuracy and the precision of the results is uncertain (maybe between ±5-25%).
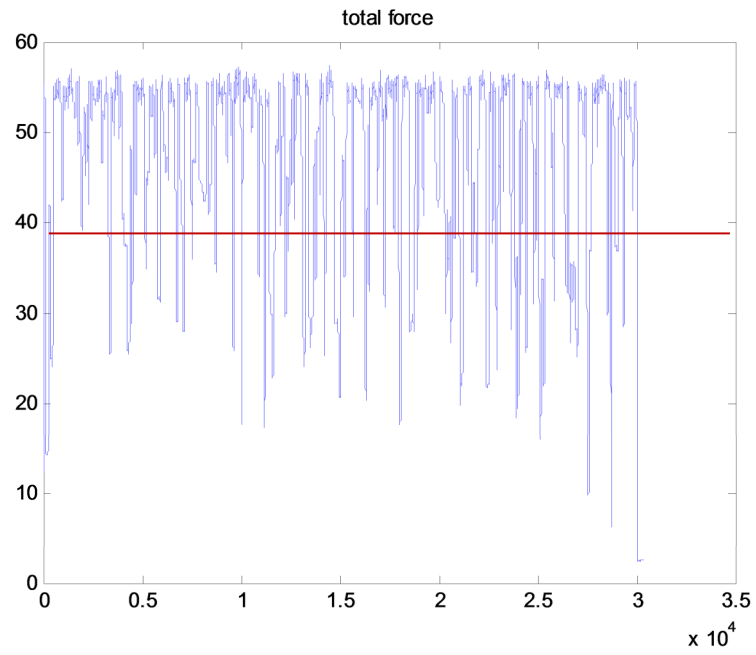
total force

Figure 8. Total force for W2L2. Offset not removed: red line=zero line, load =39.6 N, scale 1:25.

4. Yearly power production estimate

Supposing that the torque can be controlled so to be adjusted to the optimum for each wave condition, the overall power production has been estimated and presented in table 2. The installed capacity for an 110 m long device, with a rotor diameter of 11 m, 11 sets of fins, 6 fins each set is rated 11, 24 kW.

The yearly energy power production is then around 100 MWh/y (98.46 MWh/y) for an overall efficiency of 8%.

Table 2. Summary of rolling cylinder expected performance in irregular waves, full scale. For 110 m length, with 11 sets of fins, 6 fins each set for a total rotor diameter of 11 m.

W	Hmo [m]	Tp [s]	Pwave [kW]	Prob. [-]	Pwave*Prob. [kW]	Eff. [-]	Pgen. [kW]	Pgen.*Prob. [kW]
1	1	5.6	23.1	0.468	10.811	0.000	0.000	0.000
2	2	7	127.6	0.226	28.838	0.082	8.188	1.850
3	3	8.4	352	0.108	38.016	0.111	34.469	3.723
4	4	9.8	715	0.051	36.465	0.103	72.195	3.682
5	5	11.2	1254	0.024	30.096	0.079	82.704	1.985
					Tot 144.225			**Tot 11.240**

5. Conclusions

A long model of 4440 mm the rolling cylinder (scale 1:25) has been constructed and tested in irregular waves.

A specific measuring system for the device has been design, but it demonstrated itself not to be optimal. Nevertheless the results showed clearly, especially during visual examination, that the "down time" has a considerable negative influence of the overall performance.

Based on the obtained results, a calculation of the expected power production for 110 m long device, with 11 m rotor diameter, 2 m of witch emerging from the water, 11 sets of fins with 6 fins each, fixed to the bottom would generate around 100 MWh/y in the North Sea with an overall efficiency of 8%. The power take off losses are not taken into account.

It is suggested that if the developer considers that it is worth going on with a second phase of investigations, this should focus on:

1. Power take-off design, possibly with the collaboration of experts from the wind sector. Indeed, it seems that there may be synergies between wind turbines power takeoff and the one of the Rolling Cylinder and a power take off with adjustable load could improve the "down time" issue.
2. It is suggested that the fin´s geometry and position is further investigated with a numerical model, for ex. CFD.
3. Finally it is recommended that the dialog with experts on materials it is started in order to find which material could provide the same fin´s flexibility than that in scale 1:25, required for the best functioning of Rolling Cylinder working principle.
4. At any time, tests on forces is also required prior construction of a larger model (for ex. 1:10 and larger).

References

Margheritini, L. and Taraborelli V. 2011: "Rolling Cylinder Phase 1: proof of concept and first optimization", DCE report 115, ISSN 1901-726X, Aalborg : Aalborg University. Department of Civil Engineering, 36 s.

Appendix A

```matlab
function [L Fmean Mm Pm rpm_m eta par] =newsimple27102011

% try rolling cylinder data analysis

[filename, pathname]=uigetfile({'*.dat'},'File Selector');
[FT1, FT2, WG1, WG2, WG3, PT] = textread([pathname filename],'%f %f %f %f %f
%f','headerlines',56);
% ---------------------------------------------
%%%%%%%%% ANALYSIS PARAMETERS %%%%%%%%%%
sf=20;  par.sf=sf;              %[Hz] sample frequency
ro=1000; par.ro=ro;             %[kg/m^3] water density
g=9.82; par.g=g;                %[m/s^2] gravity;
st_fr=0.400*g*0.07;par.st_fr=st_fr; %[Nm] static friction
gearD=4.2/8.3;par.gearD=gearD;       %gearing
m=6;par.m=m;                    %nr of channels
wgd=0.65; par.wgd=wgd;          %[m] water depth
Pw= XXXXX; par.Pw=Pw;    %input from WaveLab
par.filename=filename;
%---------------------------------------------
%plot(data);
A=FT1;         %F1 signal (Lower)
%plot(A);
B=FT2;         %F2 signal (Higher)
%plot(B);
C=PT;
%plot(C);          %Potentiometer signal


%------------%peak detection

for Sind=length(A):-1:1
   Ainv(length(A)-Sind+1)=A(Sind);
end
for si=2:length(A)
%     DifA(si)=A(si)-A(si-1);
%     DifAinv(si)=Ainv(si)-Ainv(si-1);
   if si>6

       CurrAvgA=mean(A(si-6:si));
       CurrStdA=std(A(si-6:si));
       MovAvgA(si)=mean(A(1:si));
       MovStdA(si)=std(A(1:si));
       CurrAvgAinv=mean(Ainv(si-6:si));
       CurrStdAinv=std(Ainv(si-6:si));
       MovAvgAinv(si)=mean(Ainv(1:si));
       MovStdAinv(si)=std(Ainv(1:si));
       if abs(CurrAvgA-MovAvgA(si))>2*MovStdA
           peak(si)=si;
           if peak(si-1)==0
             Fpeak(si)=1;
           end
       end
       if abs(CurrAvgAinv-MovAvgAinv(si))>2*MovStdAinv
           invpeak(si)=si;
           if invpeak(si-1)==0
             Finvpeak(si)=1;
           end
```

```matlab
        end
        MovAvgA=mean(A(1:si));
        MovStdA=std(A(1:si));

        breakpoint='break';
    end
end
a=find(Fpeak>0);
ainv=find(Finvpeak>0);
t1=a(1);


t2=length(A)-ainv(1)+1;



T1=1:t1-6;
T2=t1-6+1:t2;
T3=t2+1:length(A);

%figure, plot(A),
%plot(T2,A(T2),'r')

  %CELL1----------
A1=A(T1);        % selection of initial values for evaluation of load from F1
%figure, plot(A1)
l1=mean(A1);        %initial mean value load on cell 1
A3=A(T3); % selection of final values for evaluation of load from F1
%figure, plot(A3)
l2=mean(A3);        %final mean value load on cell 1
L1=(l1+l2)/2;        %load on load cell 1

  %CELL2----------
B1=B(T1);        % selection of initial values for evaluation of load from F2
 %plot(B1)
h1=mean(B1);        %initial mean value load on cell 2
B3=B(T3); % selection of final values for evaluation of load from F2
 %plot(B2)
h2=mean(B3);        %final mean value load on cell 2
L2=(h1+h2)/2;        %load on load cell 2

L=(L1+L2)/2;        %INITIAL LOAD

%-----------------------power calculations

F1=A(T1(end)+1:T2(end));
%figure, plot(F1)
F2=B(T1(end)+1:T2(end));
%figure, plot(F2)

%-----------------------rpm calculations

amp=max(PT)-min(PT)  ;  %potentiometer amplitude
%figure, plot(1:length(PT),PT)
%title('PT')
nbfiles=size(PT,2);
```

```matlab
    for k=1:nbfiles  % velocity calculation
        V=PT(T2);
        for j=1:(length(V(:,k)))-1
            if (V(j,k)-V(j+1,k))<-1  %-1 rapresents the critiria for chosing
the peak
                ofV(j,k)=V(j,k)-V(j+1,k);
                V(j:end,k)=V(j:end,k)+ofV(j,k);
                V(j,k)=V(j,k)-ofV(j,k);
            elseif (V(j,k)-V(j+1,k))<0 & (V(j,k)-V(j+1,k))>-3
                V(j+1,k)=V(j,k);
             else
             end
        end
        plot(1:length(V),abs(V))
        rpm(:,k)=gearD*[(((diff(abs(V(:,k))))*2*pi))*sf;0];;
        for j=1:length(rpm)        % remove the values <0 from rpm
          if rpm(j)<0
            newvalue=0;
             rpm(j) = newvalue;
          end
        end
        rpm_m(k)=mean(rpm(:,k));                   %[rad/s] mean value of
rpm

   %------------------ Operation to zero set and calculate the force and rpm
values

        %%%Calculation of the force and power
        P=zeros(length(T2),1);
        for z=1:length(F1(:,k))
            F(z,k)=abs(F2(z,k)-F1(z,k));            %[N] instantaneous force
            P(z,k)=(0.01*F(z,k)+st_fr)*rpm(z,k);            %[W]
instantaneous power
            M(z,k)=((0.01*F(z,k)+st_fr));
        end

        Pm(k)=mean(P(:,k));                         %[W] mean value of
measured power
        eta(k)=Pm(k)/Pw(k);                         %[-] efficiency
        Mm(k)=mean(M(:,k));
        % Load estimation

        Fmean(k)= mean(F(:,k));

    end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure, plot(1:length(F1),F1)
title('F1')
figure, plot (1:length(F2), F2)
title('F2')
figure, plot(1:length(F),F)
title('total force')
figure, plot(1:length(P),P)
title('power')
figure, plot(1:length(rpm),rpm)
```
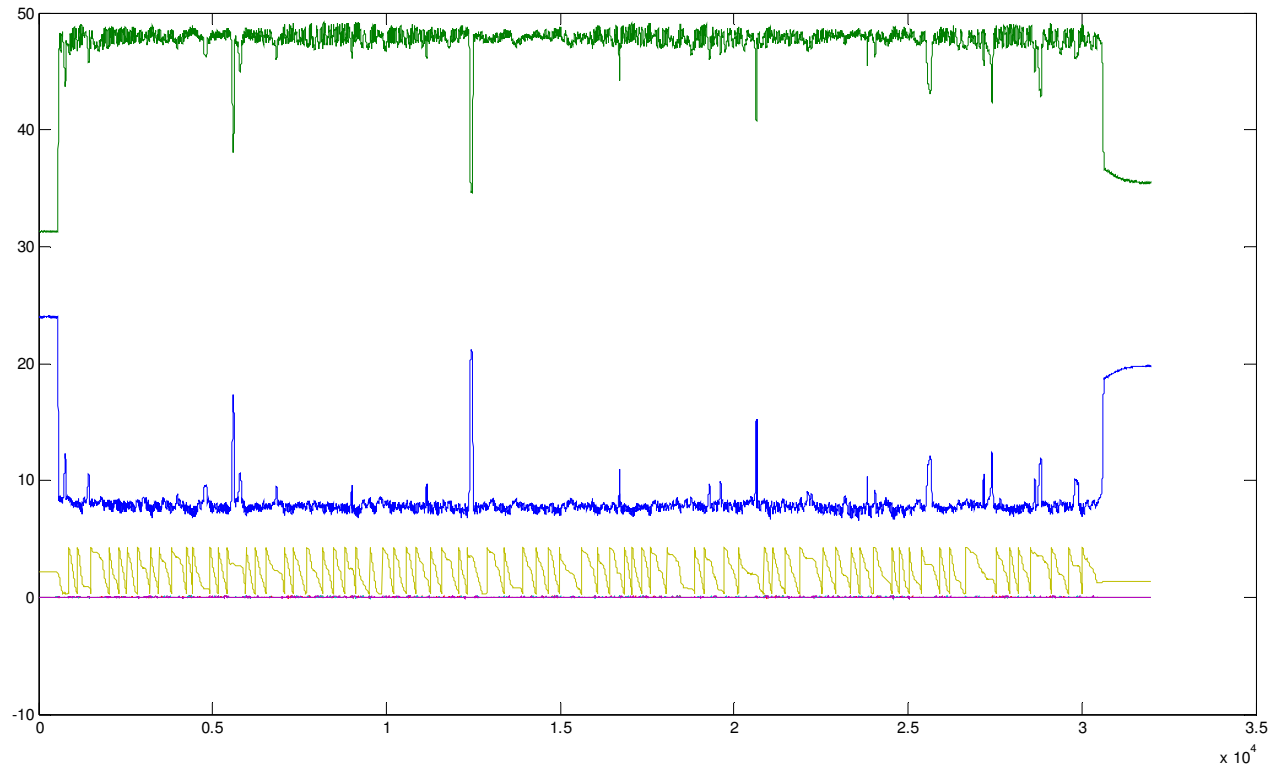
```
title('rpms')

end
```


Figure 9. Data imported to matlab (test W3L1).