# Effektmålinger på Wave Star i Nissum Bredning

*Afsluttende rapport under PSO-F&U 2008-1-10023*

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AALBORG UNIVERSITY
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by

Peter Frigaard & Thomas Lykke Andersen

April 2009

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# Konklusion på effektmålinger i Nissum Bredning

Wave Star test-maskinen i Nissum Bredning blev sat i kontinuerlig drift den 24. juli 2006. Igennem de seneste 2½ år er den producerede effekt blevet målt kontinuert og kun med mindre afbrydelser. Målingerne dækker over drift på alle årstiderne (forår, sommer, efterår, vinter) i et meget omskifteligt klima. Der er således opnået drifterfaring under vidt forskellige bølge-forhold (bølgehøjder, bølgeperioder, bølgeretninger, ...). Maskinen har i perioden kørt med en simpel form for styring og Power Take Off system (PTO), hvilket danner baggrunden for effektmålingerne med den eksisterende kontrolstrategi vist i figur 1 og beskrevet i Bilag C.

**Målinger. Nissum Bredning skala** **Opskaleret effekt. Nordsø-anlæg**

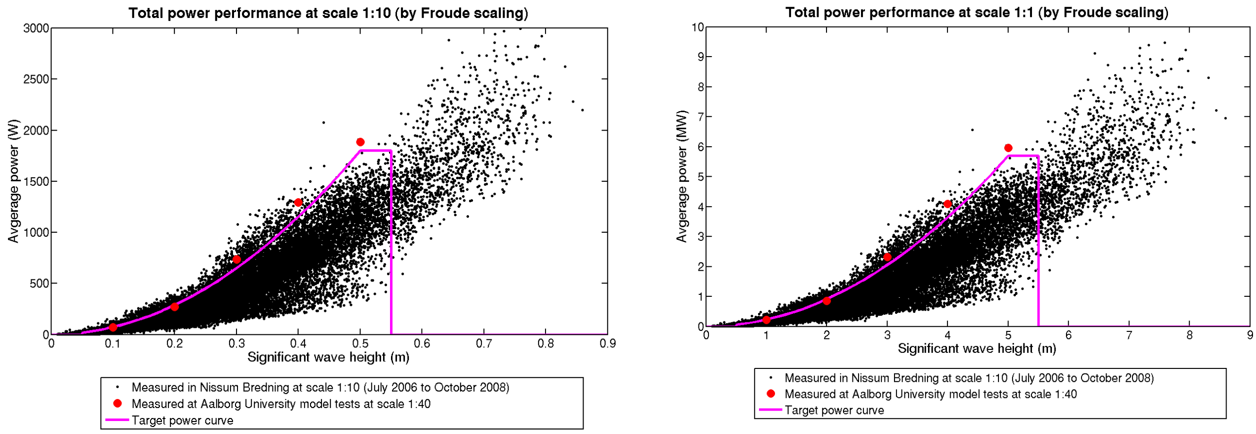



**Figure 1. Målt effekt med 1. generation PTO. Sommer 2006 – forår 2009**

Beregninger har vist, at anvendelsen af mere avancerede styreformer kan øge effekten fra Wave Star markant. Nye styreformer er derfor under fortsat udvikling med det primære formål at øge ydelsen fra anlægget. For at teste og udvikle metoderne er der gennem det seneste år blevet udviklet og konstrueret en ny mini-hydraulikstation med tilhørende 2. generation PTO til afprøvning i Nissum Bredning. Mini-hydraulikstationen er koblet til en enkelt flyder, mens maskinens øvrige 39 flydere stadig er koblet til det eksisterende PTO system. Da det eksisterende PTO system kan anvendes på de 39 flydere samtidigt med, at det nye PTO anvendes på 1 flyder, kan der måles effekt på de to systemer simultant (Bilag D).

Målinger fra marts 2009 viser, at det nye 2. generations PTO øger energiproduktionen til et niveau 3,1 gange så højt som produktionen leveret med det eksisterende PTO.

De første spæde forsøg med det nye 2. generations PTO tegner således særdeles lovende. Under de første målinger foretaget marts 2009 blev der som nævnt med det nye system opnået en gennemsnitlig ydelse på 3,1 gange gennemsnitsydelsen fra en flyder på den eksisterende maskine (Bilag E). I løbet af den kommende tid udføres flere forsøg med mini-hydraulikstationen for at teste det nye PTO i forskellige søtilstande. Da mini-hydraulikstationen kan simulere forskellige former for styring vil sådanne desuden blive testet under virkelige bølgeforhold i Nissum Bredning.

Effektforbedringerne bør fortsat være genstand for en større målrettet indsats, da forbedringer på dette område kan øge energiproduktionen og dermed reducere kWh-prisen på energien fra Wave Star anlæggene.

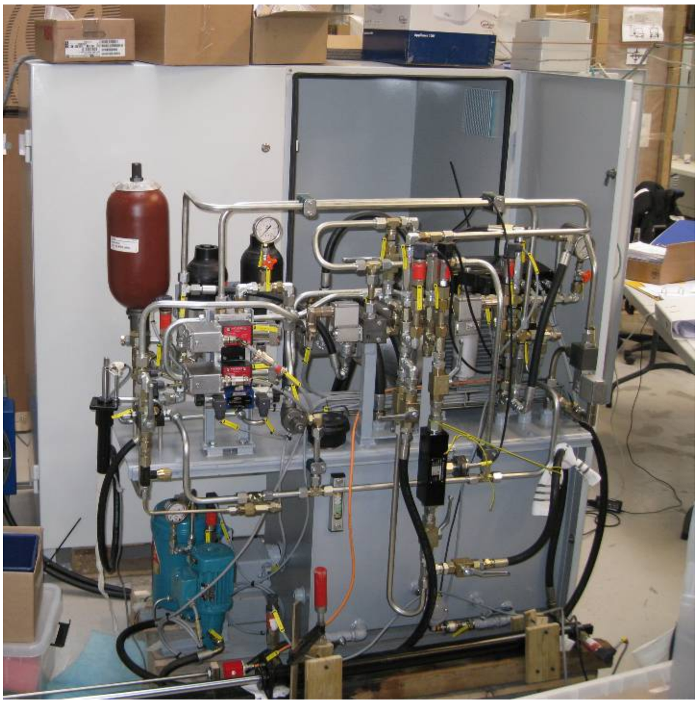
# Indhold af bilag

# A : Billeder af maskinen i Nissum Bredning

# B : Billeder af ny mini-hydraulikstation til Nissum Bredning

**Indledende laboratorie-tests inden døre hos Elkas i Herlev. Februar 2009.**

Nedenstående billede viser mini-hydraulikstationen inden installation i det grå skab i baggrunden.



**Mini-hydraulikstation installeret på test-maskinen i Nissum Bredning. Marts 2009.**

Nedenstående billede viser placeringen af det grå skab med den nye mini-hydraulikstation.


Billedet nedenfor viser *måleflyderen*, som den nye mini-hydraulikstation er koblet på. *Måleflyderen* adskiller sig fra de øvrige ved at være instrumenteret med mere målegrej.

# C : Målinger på hele maskinen i Nissum Bredning

*Power production performance - Wave Star, Nissum Bredning. 16 January 2009.*

## Contents



## C.1 Introduction

The purpose of the present memo is to describe the measured power production performance for the Wave Star test converters, in particular results from the scale 1:10 converter in Nissum Bredning which has now been in operation for more than two years.

## C.2 History overview of tests

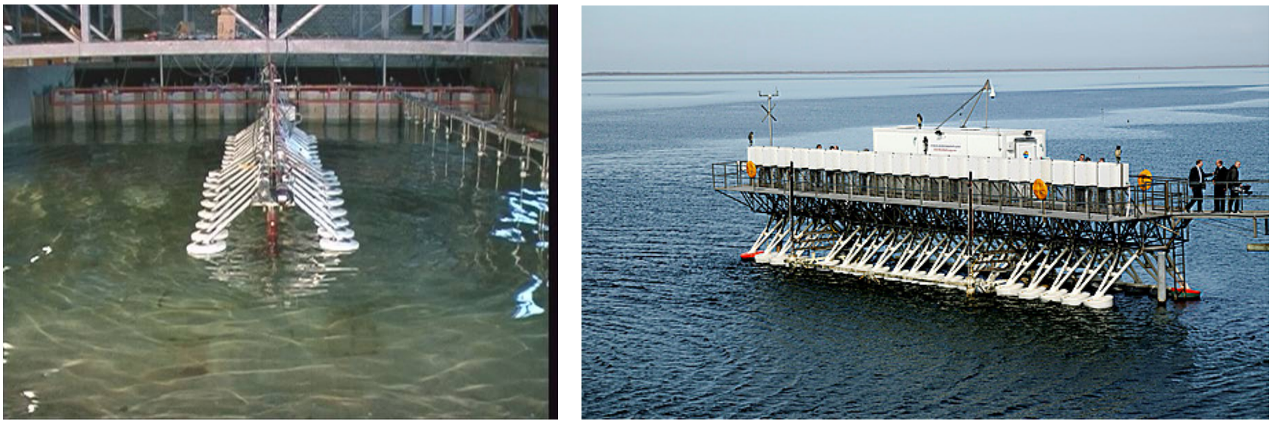


**Figure 2. Scale 1:40 converter at Aalborg University (left), and scale 1:10 converter at Nissum Bredning (right).**

**Year 2004, scale 1:40, Aalborg University**

In 2004 wave tank testing in scale 1:40 was carried out at Aalborg University, Denmark. The main goal was to optimize the basic geometrical configuration of the wave energy converter. The power take off (PTO) consisted of a mechanical transmission system. Results of the small scale model tests are descrided in detail in [1], [2] and [3].

**Year 2006-2009, scale 1:10, Nissum Bredning**

In 2005 a scale 1:10 converter was designed and built with a hydraulic transmission system and grid connection. On the 6$^{th}$ of April 2006 the scale 1:10 converter was installed in the sea at Nissum Bredning, close to Thyborøn in the North West of Denmark. After testing of all control systems the converter was put into daily operation on the 24$^{th}$ of July 2006. The converter has been in daily operation in Nissum Bredning since, and has been supplying electricity to the grid during the last 30 months. Over this period it has demonstrated a high reliability with more than 17,000 operational hours and has survived 12 storms. The technology has proven to be a safe solution in the harsh marine environment. Numerous tests and performance have been documented, e.g. in [4]-[7].

**Year 2009 -, scale 1:2, Hanstholm**

A scale 1:2 converter is under development, see [8] and [9].

## C.3 Measured power variations over time, Nissum Bredning

The yearly average wave power have been found using recorded wave data during two years (13 July 2006 to 3 October 2008). The wave power $P_W$ (kW/m) is calculated from measurements of the significant wave height $H_S$ (m) and the mean wave period $T_m$ (s) by $P_W = 0.577 \cdot H_S^2 T_m$ .

As shown in Figure 3 there is a large variation in the wave power at the site. In a large part of the year the wave power is close to zero, while wave power up to almost 10 kW/m have been measured during storms. As the wave power varies over time it is clear that the power production $P_{WS}$ also must vary over time, see Figure 4.

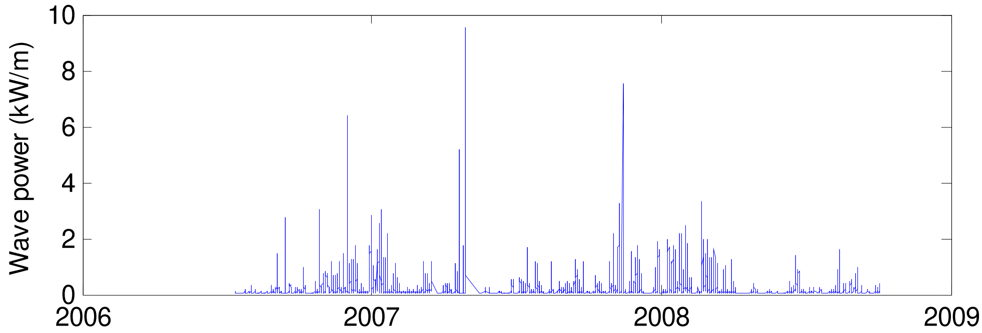



**Figure 3. Incoming wave power at the site (30 minute average values). Total average is 0.13 kW/m.**

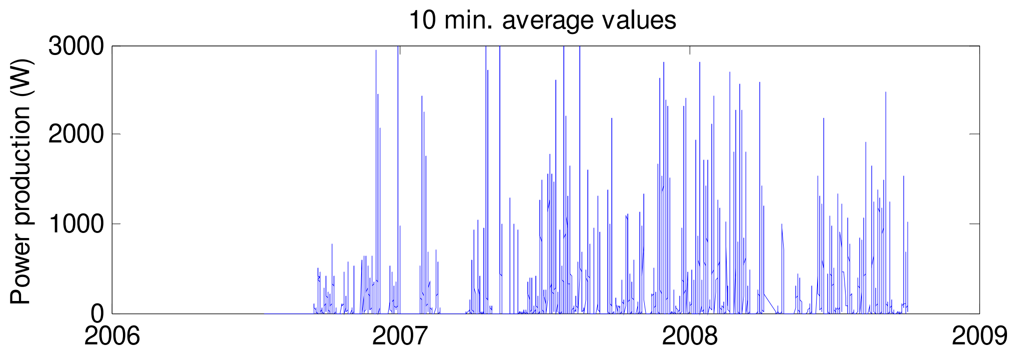



**Figure 4. Power production for Wave Star, Nissum Bredning. Total average is 129 W.**

The natural variations in wave power may be compared to the variations in the power production by comparing the standard deviation $\sigma$ in the signals normalized by the average values.

Wave power variation: $\frac{\sigma_{P_W}}{|P_W|} = \frac{0.26\,kW/m}{0.13\,kW/m} = 2.00$ , || denotes average value

Power production variation: $\frac{\sigma_{P_{WS}}}{|P_{WS}|} = \frac{291\,W}{129\,W} = 2.25$

It is seen, that the power production variation is only slightly larger than the natural variation of the incoming wave power. It may thereby be concluded that the variations in average power production is just due to natural variations in the wave climate. This conclusion is in agreement with the results from the scale 1:40 tests at Aalborg University [10].

## *C.4 Measured power performance figures*

Measurements can be scaled up or down by the use of Froude scaling law, it is possible to compare results from scale 1:40 and 1:10. Further expected power production at larger scale can be calculated, see Figure 5. The measurements from Nissum Bredning shows a large scatter (the big cloud of black dots in the figure) which is caused by influence of wave direction and wave period.

Simple numerical calculations for a scale 1:2 prototype with a passive control system without individual controlling of the floats have showed a yearly production of 1.2 GWh at 4 kW/m wave energy flux [11], see Table 1. The measurements at scale 1:40 and 1:10 have validated these numbers, but significantly higher production is expected by more optimal control using individual active control of the floats [12] & [13].

| Platform | Location | Water depth | Floaters | | Length of structure | Cut-off production | Installed power | Avg. Wave energy flux | Annual produc-tion |
|---|---|---|---|---|---|---|---|---|---|
| | | | Diameter | Number | | | | | |
| | | m | m | | m | MW | MW | kW/m | GWh |
| WAVESTAR1 (Prototype 1:10) | Nissum Bredning | 2 | 1 | 40 | 24 | 0,0018 | 0,0018 | 0,13 | - |
| WAVESTAR3 (Prototype 1:2) | North Sea, Horns Reef | 10 | 5 | 40 | 120 | 0,5 | 0,5 | 4 | 1,2 |
| Conceptual study | Atlantic (Portugal) | 20 | 10 | 40 | 240 | 6 | 6 | 12 | 14,0 |

**Table 1. Power production depending on size of structure [8].**

The expected power production numbers given here are without taking account of losses in the PTO. The reason is that the efficiency of the components in the PTO not yet are known at larger scale (scale 1:2 or 1:1).

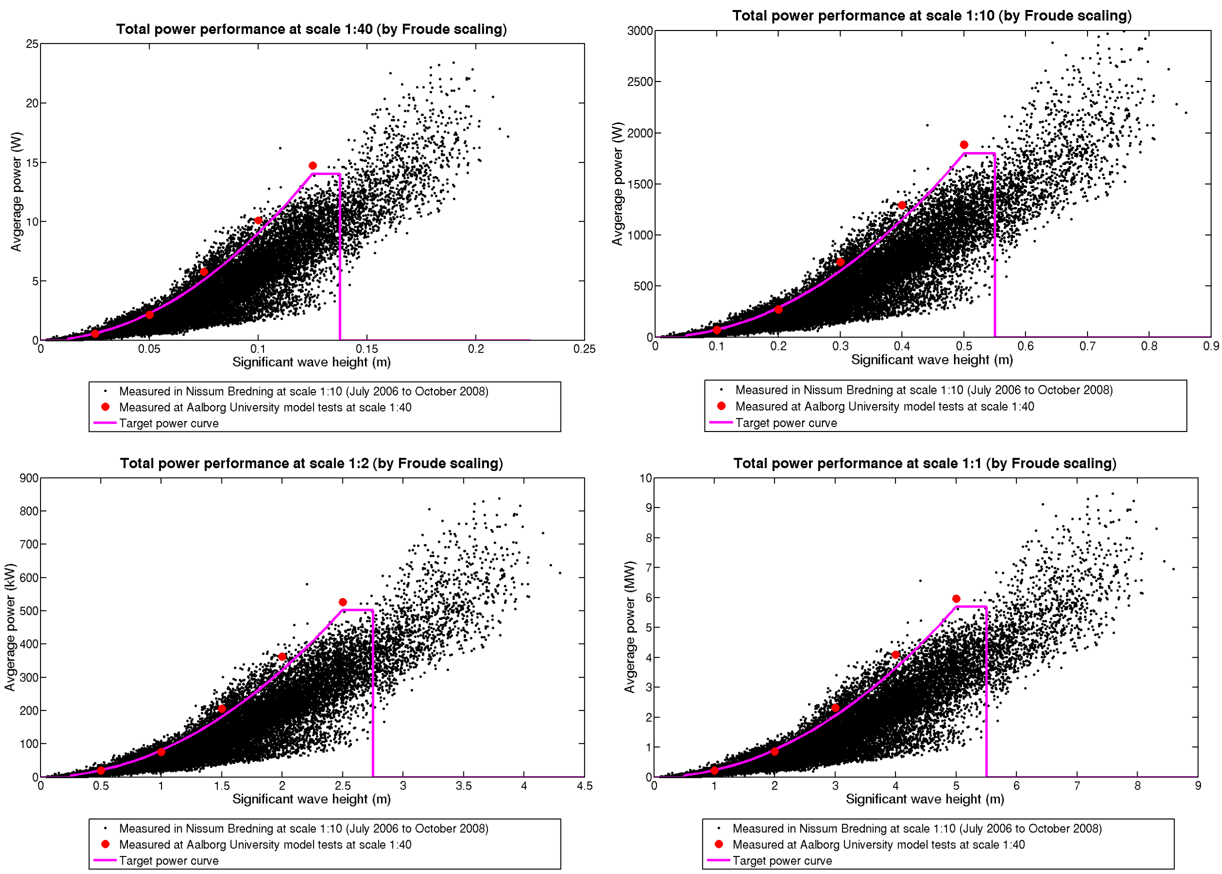



**Figure 5. Measured power performance at different scales.**

## C.5 References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[13] Bjerrum, A. (2008). *The Wave Star Energy Concept*. ICOE 2008 (International Conference on Ocean Energy), 15-17 October 2008, Brest, France, www.icoe2008.com.

# D : Målinger på én flyder i Nissum Bredning

*Power production performance of a single float - Wave Star, Nissum Bredning. 17 February 2009.*

### Contents



## D.1 Introduction

The purpose of the present memo is to describe the measured power production performance for a single Wave Star float using the existing power take off (PTO).

A new PTO for Wave Star is under development, with the initial primary focus on optimizing the power from a single float in Nissum Bredning. When the new control system for a single float is tested, the power production can be measured and compared to the earlier measures, and thereby the possible increase in performance using the new system can be estimated.

## D.2 Previous work

Measured power production from real sea scale tests of Wave Star with 40 floats are extensively documented, see Chapter C above. However, not much focus has been on the performance of the single floats.

Measured power production performance of a single Wave Star float in Nissum Bredning has only been analysed and documented for short test periods to date. Some general results from tests at Nissum Bredning are given in [1 & 2] with details about the distribution of individual power performance in [3, page 77-92].

In 2004-2005 small scale tests were performed at Aalborg University [4 & 5]. Some main results from measurements of the individual performance at scale 1:40 are included in Appendix 2 of this note.

Numerical calculations of the individual performance and the shadowing effects for the whole system with 40 floats are described in [6 & 7], and some more detailed numerical calculations with a system of 5 floats are described in [8 & 9]. Numerical and experimental measurements of the hydrodynamic interactions have not been compared so far. This task is left to future investigations.

Recently a numerical model of the new hydraulic PTO with one float was developed [10]. The model combines a numerical model of the float energy transfer and an empirical model of the efficiency of the hydraulic pump. Simulations with a typical irregular wave shows an optimum over all efficiency of the pump itself of $\eta_{pump}$ = 0.75 (i.e. excluding losses in overflow system, hydraulic cylinder, valves and pipes, generator, converter and other electrical systems).

## D.3 Existing and new power take off

The **existing PTO** at Nissum Bredning is a *passive* and *one-way* hydraulic system:

- *Passive* is here used to symbolize that the hydraulic pressure in the PTO fluid line remains almost constant during a certain wave climate. The pressure is constant during a time span of several wave periods. As the pressure in the fluid line does not change when a wave passes, the float must always overcome this pressure before the float will move and produce power. Small waves will only cause small pressures in the hydraulic cylinder, which may possibly not overcome the pressure in the hydraulic main line, and in this case the existing PTO will not produce any power.
- *One-way* is describing the way the existing cylinder is transferring the oil into the main hydraulic line. Only when the float is moving upward the cylinder pumps hydraulic oil into the main line. When the float goes down it moves freely back into the sea as if the cylinder was not there. So power can only be produced when the floats are moving upward.

The **new PTO** at Nissum Bredning is an *active* and two-*way* hydraulic system:

- *Active* is used to describe a system which is able to control and adjust the pressure and velocity during the passing of a single wave. As an example such a system can act as a damper on the motion by setting the pressure in system proportional to the velocity (recall the fundamental physics in a classic mass-spring-damper system using a viscous damper with damping coefficient c). Such a system is capable of producing power even in very small waves.
- *Two-way* system is denoting that power can be produced both when the float moves up and down. This obviously requires the float to have enough mass to drive the system downwards, as the wave can only apply positive pressure on the float shell.

As explained in Chapter D.2 the efficiency of the hydraulic pump in the new PTO is likely to be lower than for a pump in the existing PTO. However, as more energy presumably will be transferred into the new hydraulic system, a net power profit by using the new PTO is expected. The drawback is a more complicated and thereby more expensive system. However, the increase in performance is expected to justify the investment in the more complicated PTO.

## D.4 Measurements from Nissum Bredning

The logging system at Nissum Bredning does not calculate and store average power for the individual floats (the system was designed, but it was never implemented on the computers in Nissum [11]). However, timeseries of individual power production exist in stored so-called *fastlog files* (one file per day). Fastlog data are available from October 2006 until present (February 2009). It takes long computational time to load and analyse the data for all the months of operation, so for this reason only individual power from 2007 is documented below. The average values are calculated as ten minute values for the same time intervals as used in the existing SQL database with average ten minute values. Hereby it is possible e.g. to correlate the calculated power performance with parameters such as wave climate (e.g. significant wave height, mean wave period, and wave direction) and PTO setup (e.g. pressure and flow in hydraulic line).

Float number 1 will have the new hydraulic PTO installed. Float number 1 is the most Western one in the Northern line, see description of the numbering in Appendix 1. The float is only in operation during special manual tests, and only few measurements are therefore available for this float as it has mostly been in storm protection. Time series of power from the first three floats in the Northern line is shown in Figure 6. From the data it is concluded that the three floats produces approximately the same amount of power when they are in operation. Float number 2 has been in operation in a large part of the time, and it has been the most Western float in the Northern line, which have been in operation. Measurements from float number 2 are therefore used in the following as the reference for the power produced by one float with the existing PTO.

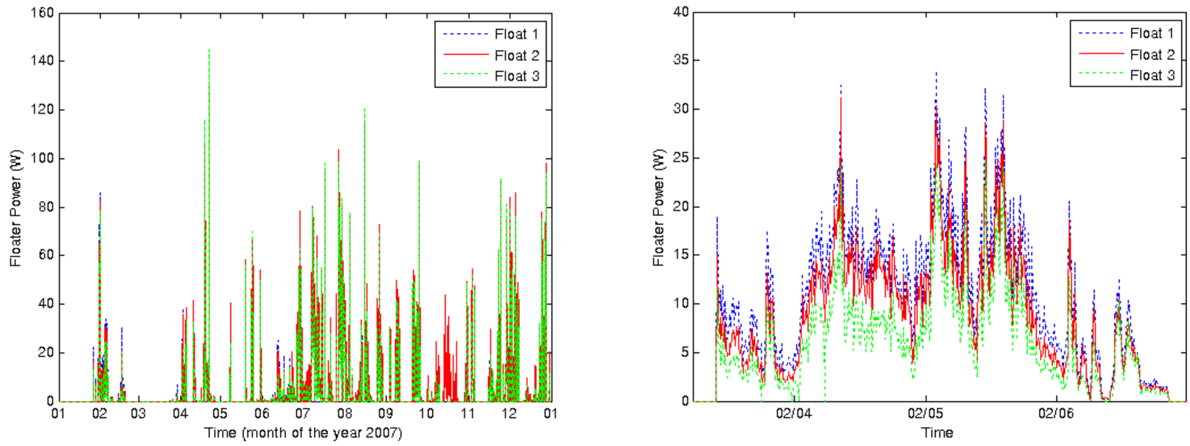


**Figure 6. Time series of floater power from the first three floats in the Northern line. Left graph is for whole 2007, right graph is an example with data from four days.**

The power strongly depends on the significant wave height, see Figure 7. In the figure the scaling of the y-axis is different on the left and right graph; the maximum value of the y-axis on the left graph is 120 W (power from float number 2), and on the right graph it is 3000 W (power sum from all floats). Hereby a simple estimate is, that float number 2 produces approximately the following part of the total power: 120W/3000W = 1/25, i.e. 4% of the total power comes from float number 2.

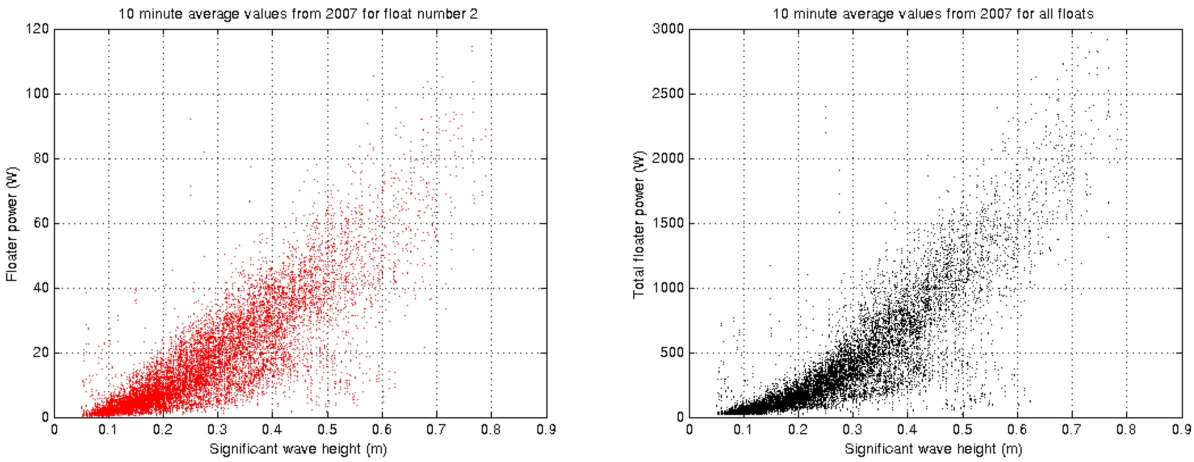


**Figure 7. Measured floater power as a function of measured significant wave height. Left graph: Float number 2. Right graph: Sum of floater power for all the floats in operation.**

When looking at the total power production it is essential to know how many floats that have been in operation. In Figure 8 it is seen that a significant amount of data exist with 30 or more floats in operation. In the following only data are included for which more than 30 floats are in action.

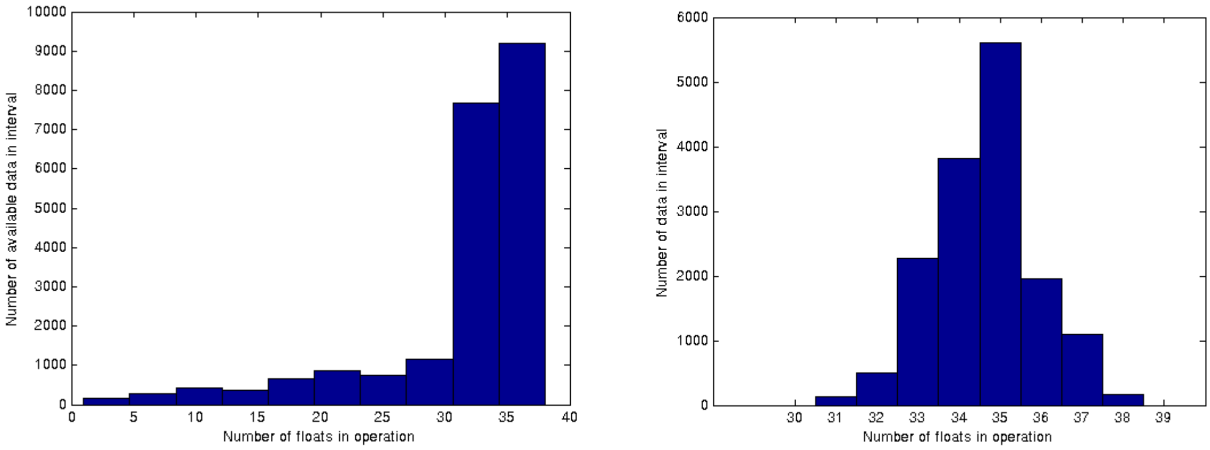


**Figure 8. Number of floats in operation. The right graph shows details about the distribution when many (>30) floats are in operation.**

A power factor is defined by the following:

$$\text{Average power from one float} = \frac{\text{Total summarized power from all floats}}{\text{Number of floats in operation}}$$

$$\text{Power factor} = \frac{\text{Power from a specific single float}}{\text{Average power from one float}}$$

In Figure 9 it is seen that the power factor for float number 2 varies a lot (between 0 and 6). The average for all the data is an average power factor = 1.64. However, the distribution is rather crooked and the most probable value is approximately 1.4. The numbers are in agreement with the scale 1:40 tests explained in Appendix 2 (at scale 1:40 the power factors were measured to 1.3 to 2.0 depending on wave climate).

The reason for the large variation in the power factor is obviously, that the factor is influenced by several parameters such as wave climate and pressure in the hydraulic line. By doing more detailed analysis it is most likely possible to correlate the factor to parameters for wave climate and machine control. This task is left to future investigations.

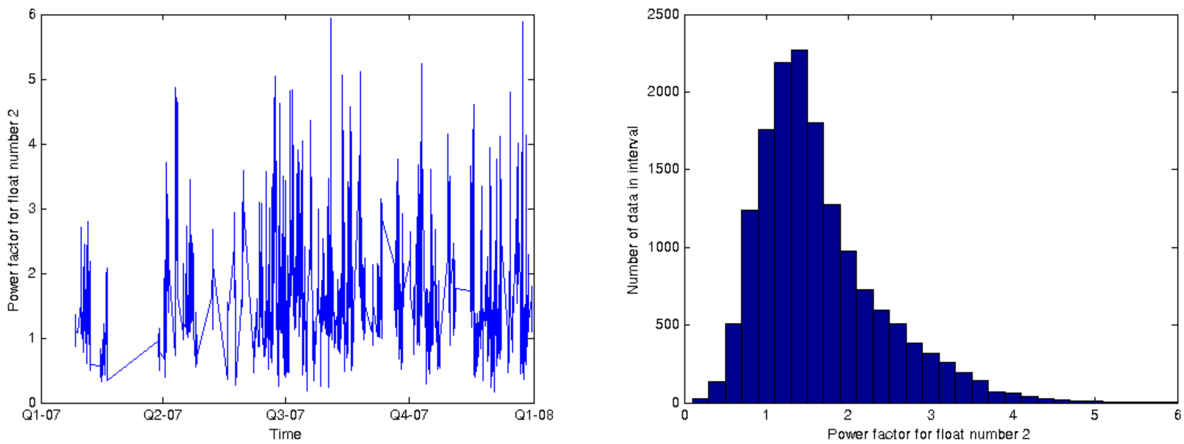


**Figure 9. Measured power factor for float number 2. Left: Time series. Right: Distribution.**

For the time being it is recommended to do measurements with both the new and the existing PTO at the same time (i.e. same wave conditions). The measured performances can then be directly compared.

## D.5 References

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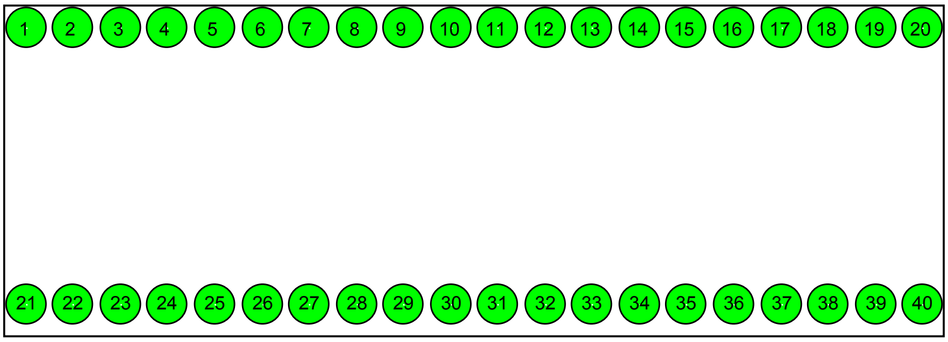
## *D.6 Appendix 1: Numbering of floats*




## *D.7 Appendix 2: Small scale tests at Aalborg University*

Some scale 1:40 tests were performed at Aalborg University in 2005 to describe the "shaddowing effects" of the floats [4 & 5]. Results documented in [5, page 18-20 & 46-47] shows that the measured optimum average power from the first float in the line is approximately 1.3 to 2.0 times higher than the average production from all the floats, see the table below. The factor depends on the physical configuration (mainly float diameter, gap and draft) and the wave climate (mainly wave direction and wave period).

| Description | Wave | Power from machine $P_{tot}$ (kW/float) | Power from a single float $P_1$ (kW) | $P_1/P_{tot}$ |
|---|---|---|---|---|
| Tests with Ø200 spherical floats, gap = 0.5xD. (*) | Short and low *UR II* | 17.1 | 23.9 | 1.40 |
| | Long and high *UR III* | 39.1 | 52.4 | 1.34 |
| Tests with Nissum float shape "*Afskåret kuglehat*", gap and approximate weight. (**) | Short and low *UR II* | 21.5 | 43.0 | 2.00 |
| | Long and high *UR III* | 58.1 | 79.0 | 1.36 |
| Tests with Ø200 spherical floats, gap = 0.5xD. (***) | Short and low *UR II* | 17.1 | 23.9 | 1.40 |
| | Long and high *UR III* | 39.2 | 52.2 | 1.33 |

**Notes for the table above:**

(*) Reference to [5, page 18, table 12]

(**) Reference to [5, page 46, Appendix D, last row in tables]

(***) Total float power is found in [4, page 43, table 23, power for test 253 & 258]. Single float power is found in [5, page 33, table 20, power for test 712 & 713c].

(***) Total float power is found in [4, page 43, table 23, power for test 253 & 258]. Single float power is found in [5, page 33, table 20, power for test 712 & 713c]. The single float measures in this series are with a PTO consisting of a single float "alone in basin".

All reported tests above are for wave direction 0°. The tests in the wave basin for 20° and 60° showed slightly lower shaddowing effects. Power numbers are average optimum values at full scale (1:1). D is float diameter.

# E : Målinger på flyder med nyudviklet PTO

*Nissum forsøg – Resume af effektmålinger med variabel dæmpningskoefficient. 18/3-2009.*

## Indhold



## E.1 Formål

Give en oversigt over målt middeleffekt ud fra de første egentlige effektmålinger på det nyudviklede PTO med minihydraulikstyring. Styring på denne flyder er forbedret, men er stadig foretaget med en simpel variabel dæmpningskoefficient.

## E.2 Konklusion

Resultaterne er opnået gennem forsøg med en samlet varighed på en time, og resultaterne vil indeholde en del naturlig variation. Bølgerne var stejle og korte og kom fra Nordvestlig retning, hvilket gav specielle og ugunstige bølgeforhold i testperioden.

Forsøgene viser, at den maksimale effekt optræder ved tilladelse af ret store flyderbevægelser (lille belastning og store bevægelser er fordelagtigt for effekten). Flyderne bevæger sig ikke ret meget på den eksisterende maskine, hvilket indikerer at den eksisterende kontrolstrategi ikke fungerer optimalt.

I testperioden blev der opnået en målt middeleffekt på måleflyderen med minihydraulikstyring på 26,1 W. I den tilsvarende testperiode ydede flyder nr. 2 i den eksisterende maskine en middeleffekt på 8,5 W. Det nyudviklede PTO ydede således 3 gange så meget effekt i gennemsnit i perioden.

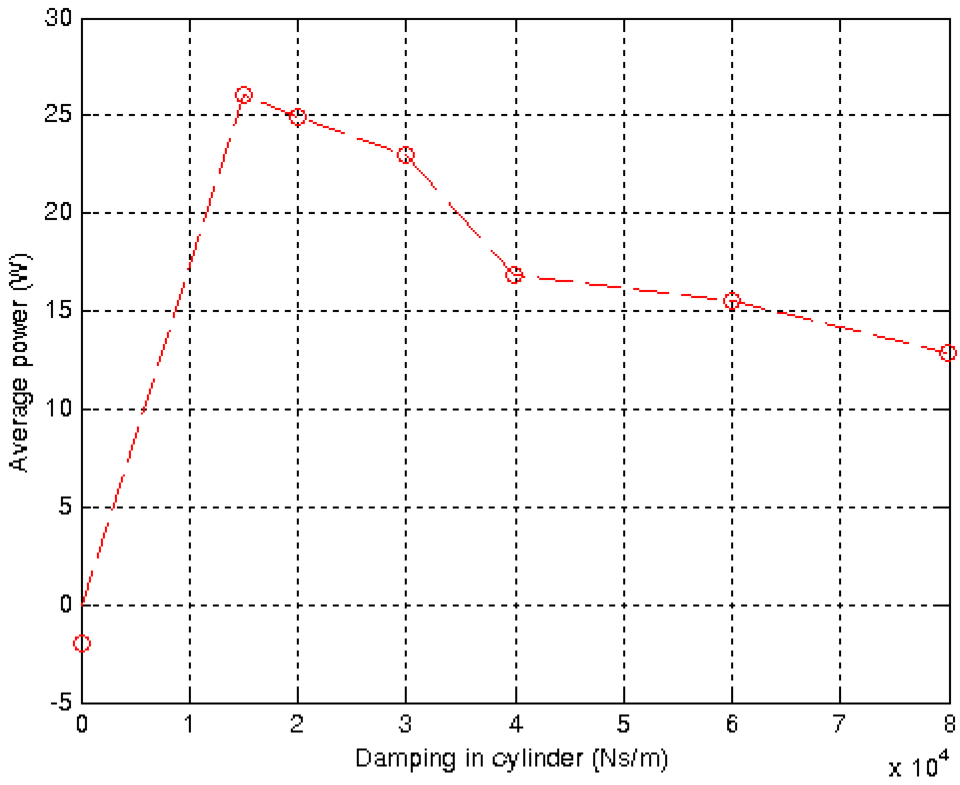
Den voldsomme effektforøgelse skyldes dels, at ydelsen på den eksisterende maskine var specielt lav i testperioden. Dels, at kontrolstrategien i det eksisterende anlæg ikke er optimeret. Dette er forklaret nærmere i kapitel E.7.

## E.3 De udførte forsøg

Der er udført forsøg med forskellig belastning. Belastning er påført i trin fra nul (friløb) til stor belastning (næsten fastholdt flyder). Der er udført forsøg med 7 lasttrin med en varighed hver især på cirka 10 minutter. Angivelser af middeleffekten er således over ca. 10 minutter. Belastning er foretaget med en dæmpningskoefficient for hydraulikcylinderen. Stempelkraft er derved proportional med stempelhastigheden (kraft = dæmpning * hastighed).

## *E.4 Effektkurve for middeleffekt*

Resultaterne for forsøgene med de 7 belastningstrin er at finde som 7 røde cirkler på figuren herunder.




Forklaring på effektkurve:

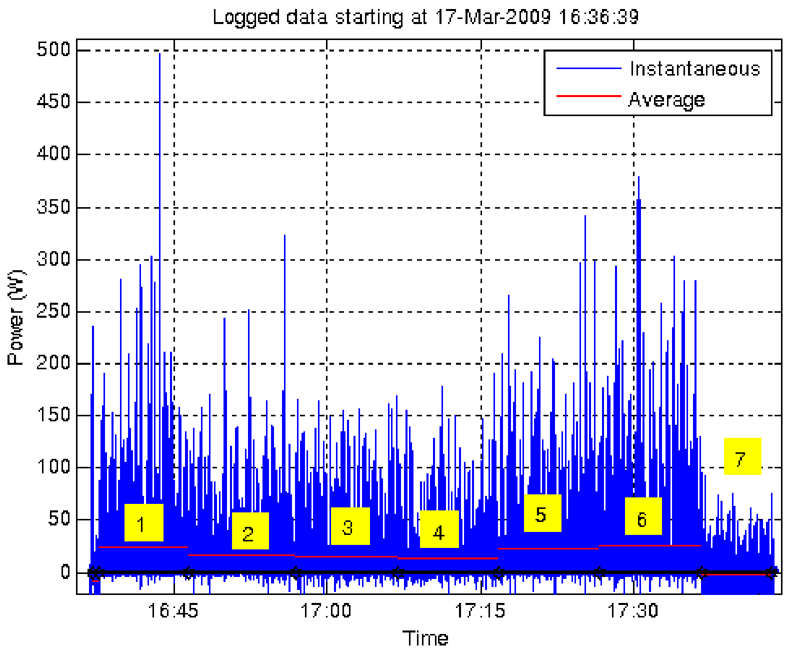
- Når belastningen er nul bevæger flyderen sig meget, men der ydes ingen effekt.
- Når belastningen er tilstrækkelig stor er flyderen fastholdt, og der ydes ingen effekt
- Den belastning som giver størst effekt ligger mellem de to ovenstående grænser

Kommentarer til effektkurve:

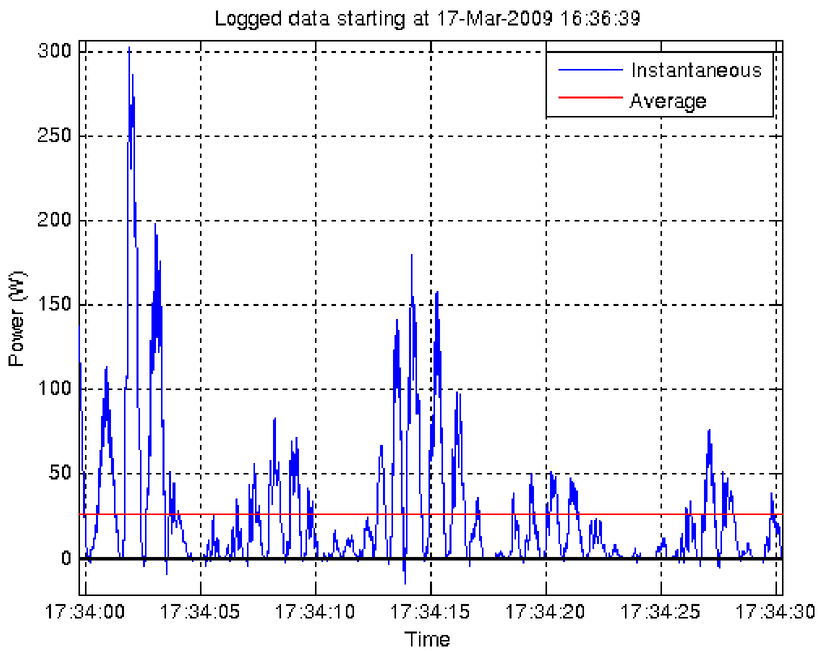
- Maksimal effekt er målt til 26,1 W.
- Maksimal effekt optræder ved ret lille dæmpning, dvs. optimal effekt optræder ved tilladelse af ret store flyderbevægelser
- Effektkurven er ret bred (intervallet for dæmpning på x-aksen er meget stort)

## E.5 Tidslig variation i effekten fra måleflyderen

Hele tidsserien for effekten er vist herunder (hele forsøget med de 7 lasttrin varede cirka 1 time og 10 minutter). Gennemsnitseffekten er vist med rød kurve for de 7 perioder med forskellig belastning. I periode nummer 6 er målt den største gennemsnitseffekt (26,1 W). I periode 7 er belastningen nul og flyderen kører i friløb.

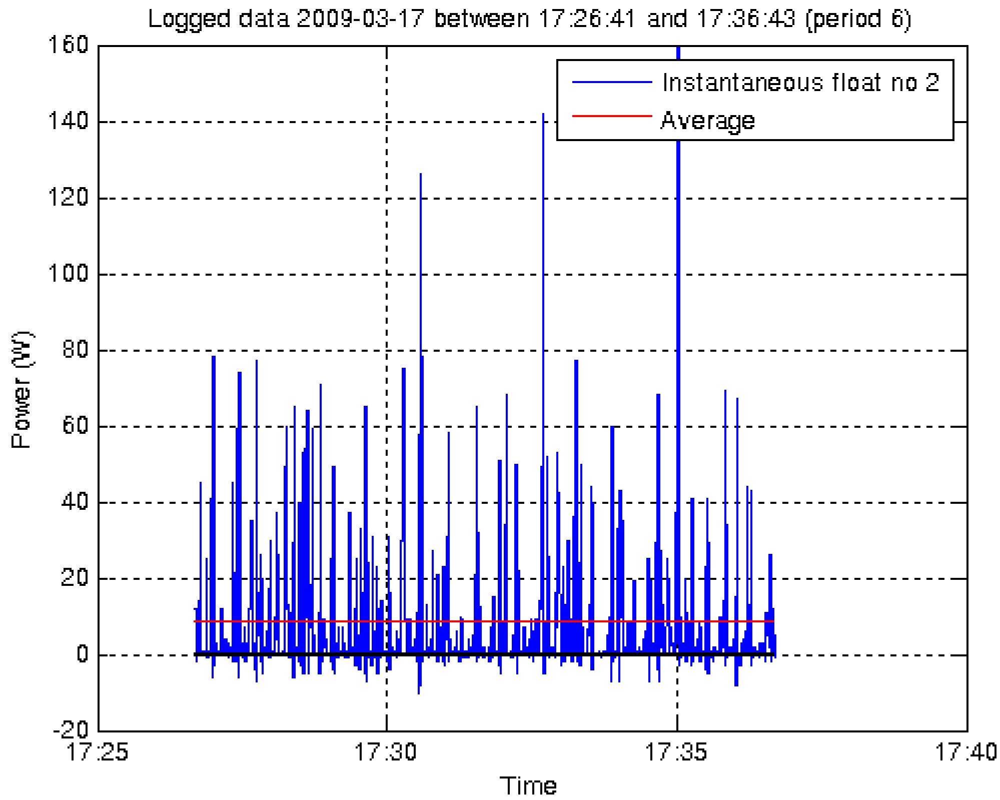



Efterfølgende figur viser et udpluk på 30 sekunder fra periode 6 (dæmpning på 15000 Ns/m, middeleffekt for hele periode 6 på 26,1 W).



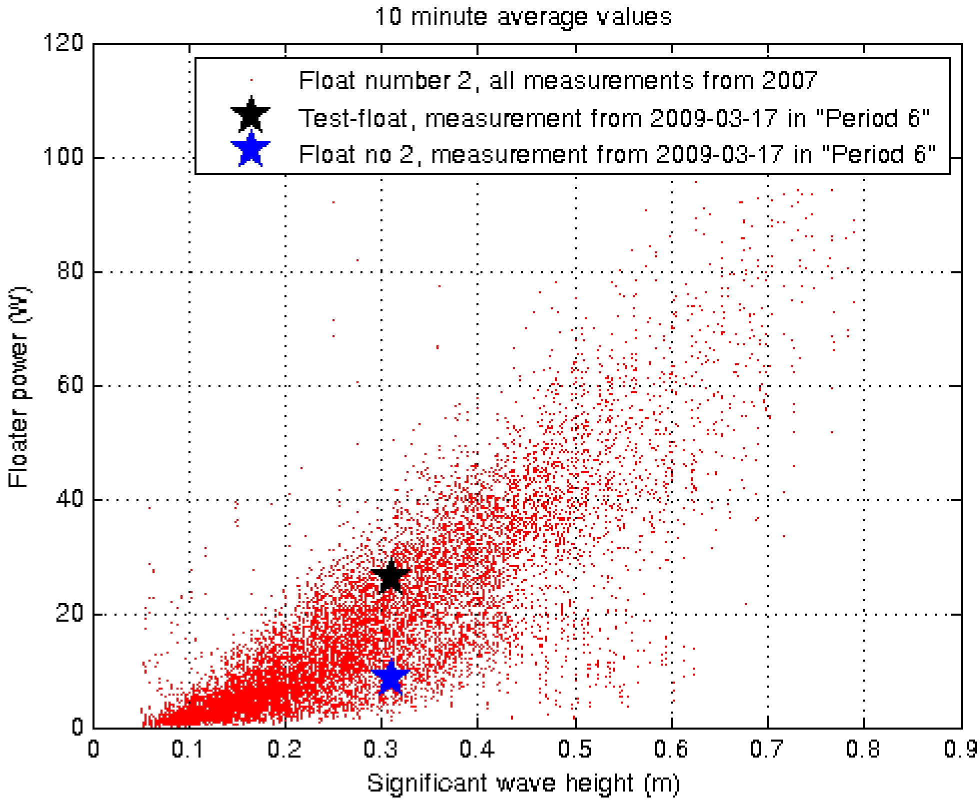
## E.6 Tidslig variation for flyder nummer 2 (eksisterende maskine)

Figuren nedenfor viser effektmålingen for flyder nummer 2 (flyderen ved siden af måleflyderen). Data er fra de såkaldte "fastlog-data" som logges kontinuerligt på I-Box'en. I gennemsnit ydede flyder nummer 2 kun 8,52 W i perioden.



## E.7 Effektmålingerne i lidt større perspektiv

Den signifikante bølgehøjde i periode 6 var 0,31 m.
Der er tidligere udarbejdet en effektfigur for den målte ydelse af flyder nummer 2, se figur 6 i kapitel D.4. De nærværende måleresultater for "Periode 6" er plottet med de to stjerner på denne effektfigur, se nedenfor.




Figuren ovenfor viser tre forskellige datasæt. De røde punkter viser alle gennemsnitsværdier for 2007. Den blå stjerne (flyder 2) ligger lavt i forhold til de samlede data, hvilket indikerer at den valgte måleperiode bestod af af en søtilstand hvor produktionen har ligget i underkanten af det forventelige. Den sorte stjerne viser produktionen fra test flyderen med den nyudviklede kontrol. Der er målt en klækkelig forbedring af effekten fra flyderen med det nye kontrolsystem.

Det står stadig tilbage at dokumentere, at den målte effektforbedring kan implementeres for alle søtilstande, men det ser lovende ud.

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