Innovation Fund Denmark
RESEARCH, TECHNOLOGY & GROWTH

Analysis of experimental data: The average shape of extreme wave forces on monopile foundations compared to the New Force model

EERA Deepwind '2017

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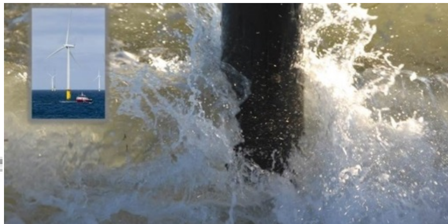
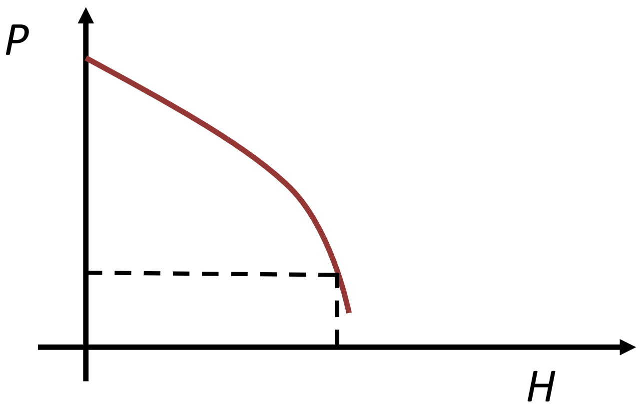
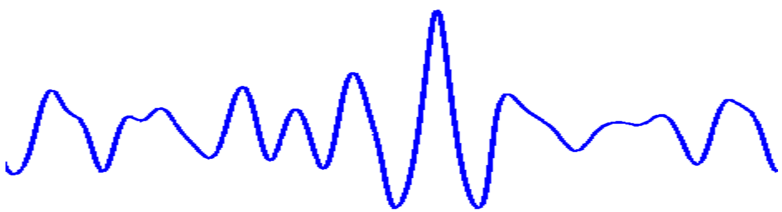
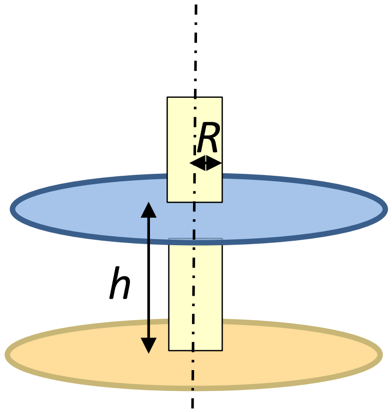


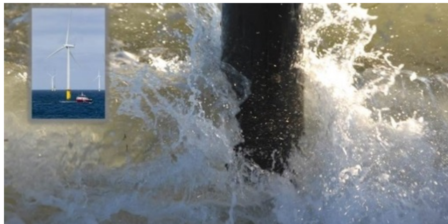
Outset of the anaysis
Extreme load cases







$f=\rho R C_D u\text{^}2+\rho A C_M u_t$



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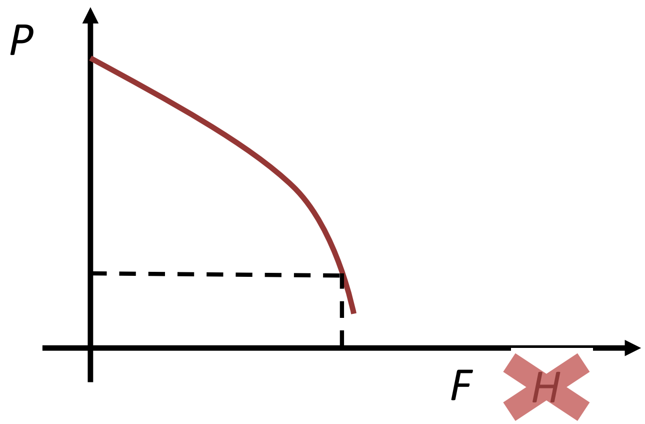
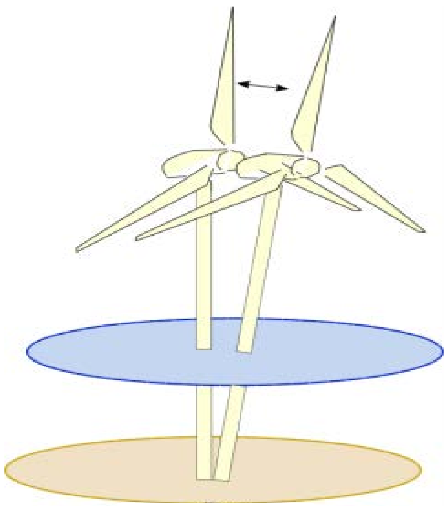
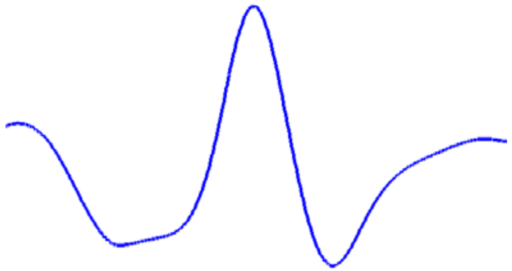
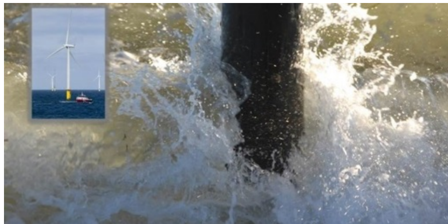




Shape of force?

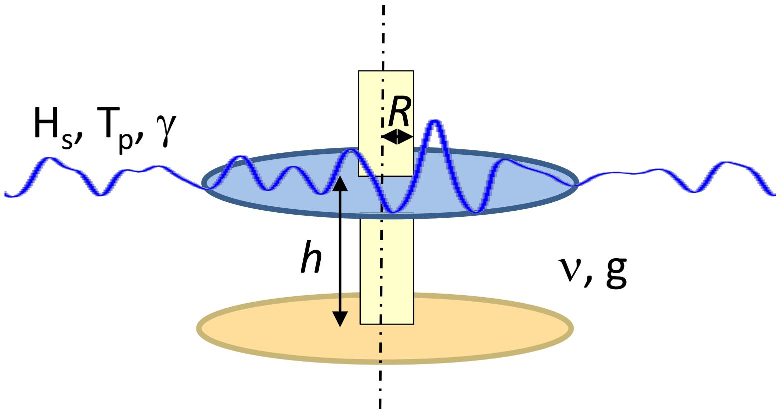




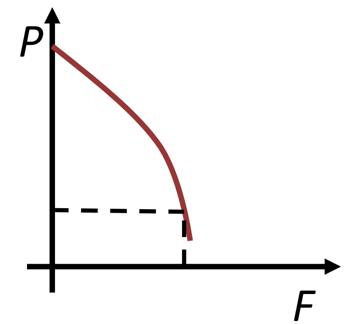
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Outset of the anaysis
Extreme load cases

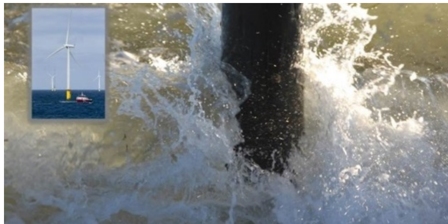
$$\frac{F}{\rho g h R^2} = f\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}, \frac{t}{T_p}, \{x_j\}\right)$$



$$P\left(\frac{F_i}{\rho g h R^2} \le \frac{F}{\rho g h R^2}\right) = f_1\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}\right)$$



$$\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho g h R^2}, \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}, \frac{t}{T_p}\right)$$



Outset of the anaysis

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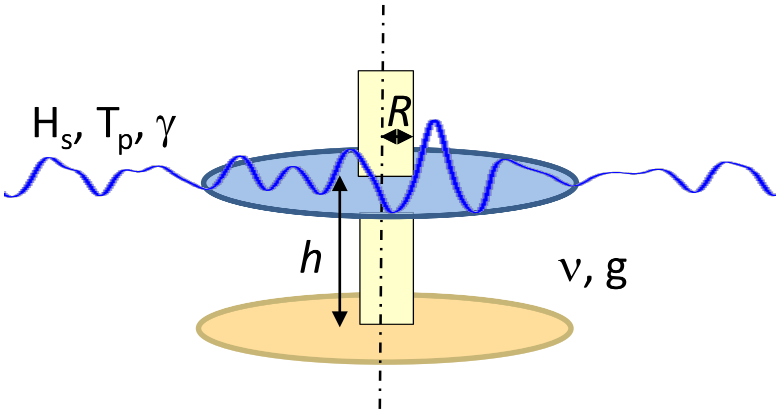
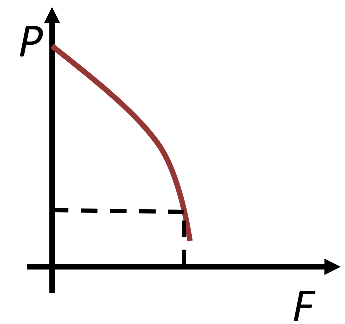
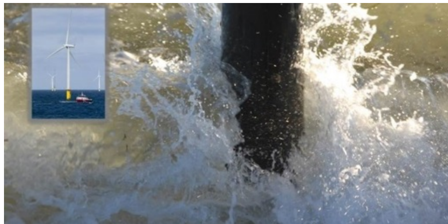


$$P\left(\frac{F_i}{\rho g h R^2} \leq \frac{F}{\rho g h R^2}\right) = f_1\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \cancel{\gamma}, \cancel{\frac{R}{gT_p^2}}, \cancel{\frac{\nu}{\sqrt{ghR^2}}}\right)$$



$$\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho g h R^2}, \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \cancel{\gamma}, \cancel{\frac{R}{gT_p^2}}, \cancel{\frac{\nu}{\sqrt{ghR^2}}}, \frac{t}{T_p}\right)$$



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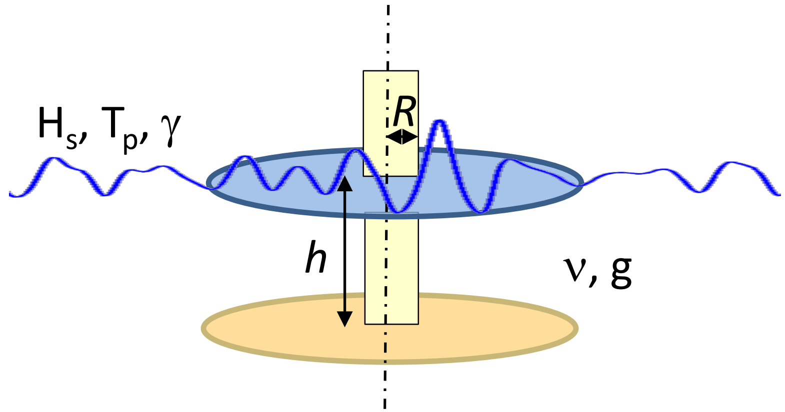
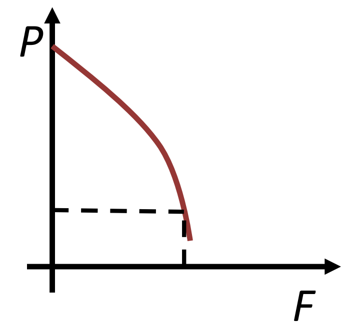
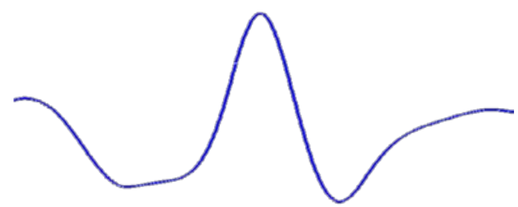
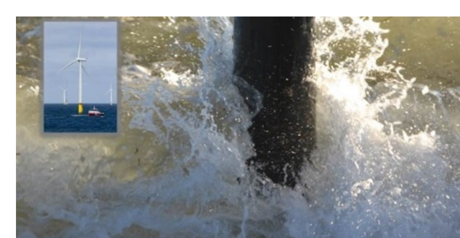


$$P\left(\frac{F_i}{\rho g h R^2} \le \frac{F}{\rho g h R^2}\right) = f_1\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}\right)$$



$$\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho g h R^2}, \frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \frac{t}{T_a}\right)$$





Outset of the anaysis

Extreme load cases

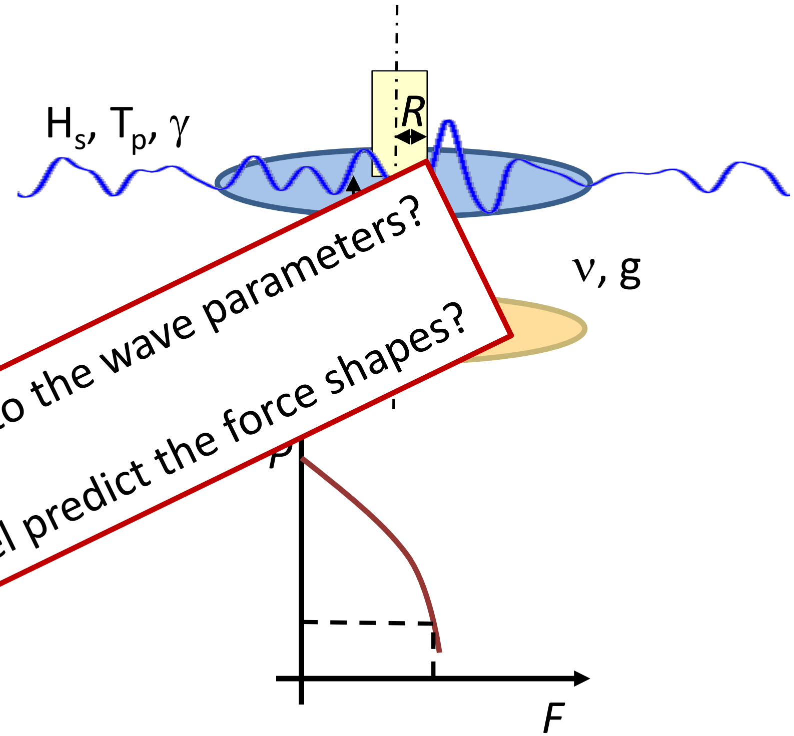
$$\frac{F}{\rho g h R^2} = f\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}, \gamma, \frac{R}{gT_p^2}, \frac{\nu}{\sqrt{ghR^2}}, \frac{t}{T_p}, \{x_j\}\right)$$

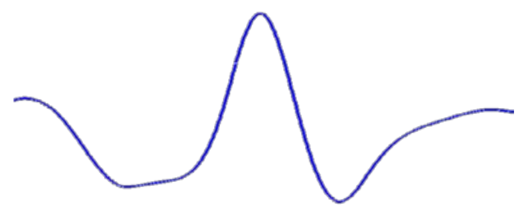
$$P\left(\frac{F_i}{\rho g H_s R^2} \leq \frac{F}{\rho g H_s R^2}\right) = f_1\left(\frac{H_s}{\cdots}\right.$$

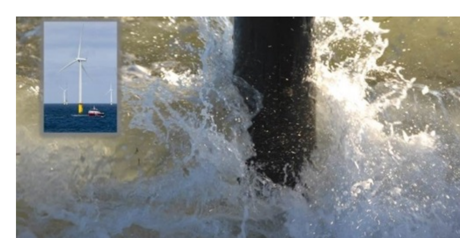
$$\frac{F}{F_i} = f_2\left(\frac{F_i}{\rho g h R^2}, \cdots, \frac{h}{gT_p^2}, \frac{t}{T_a}\right)$$

Functional dependencies of f_1 and f_2 to the wave parameters?

How well can the New Force model predict the force shapes?

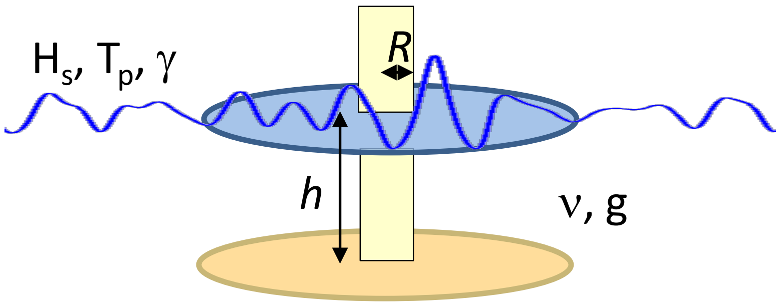




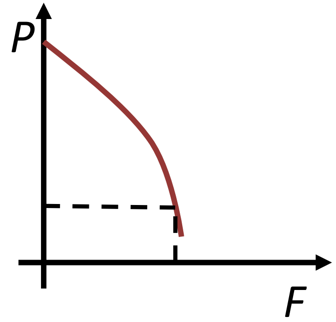


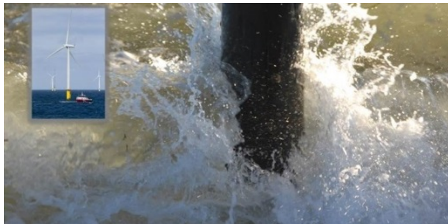
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Agenda



- The New Force model
- Experimental data
- Exceedance probability distributions of the free surface elevation and force signal
- Average shape of measured inline forces
- Comparison to the New Force model
- Conclusion

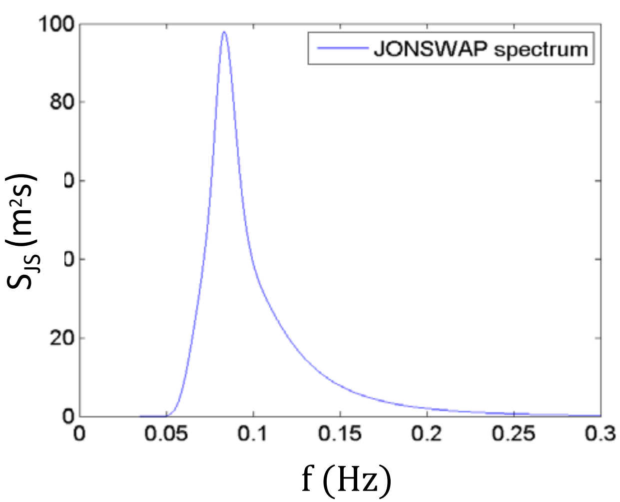


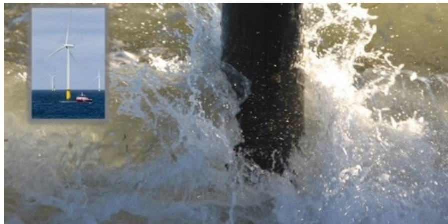


DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

The New Force model

$$\eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma_\eta^2} \sum_j \mathrm{Re}\left\{S_\eta(\omega_j)\Delta\omega \exp\left(\mathrm{i}\left(\omega_j(t-t_0) - k_j(x-x_0)\right)\right)\right\},$$ [Lindgren (1976), Boccotti (1983), Tromans (1991)]





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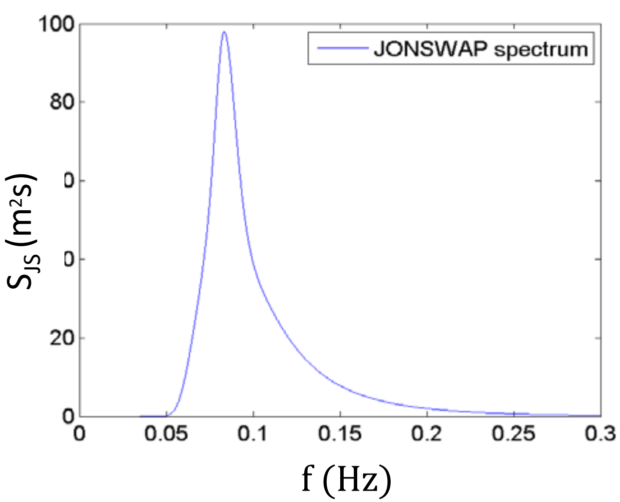
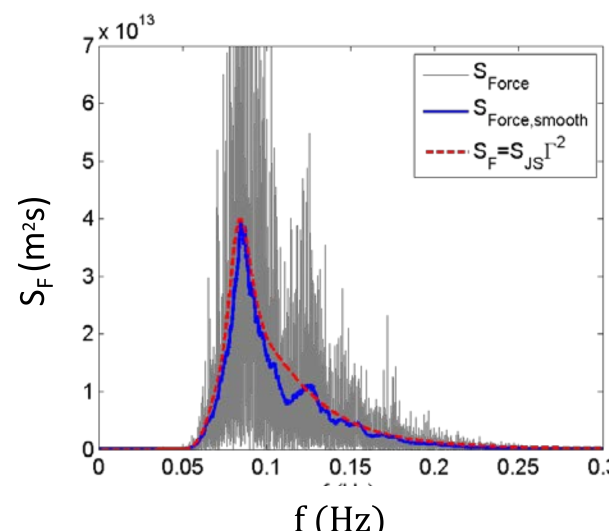
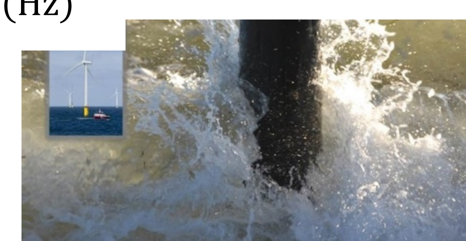
$$\Gamma(\omega) = \mathrm{i}\rho\pi R^2 C_M \omega^2 / k \qquad S_F(\omega) = |\Gamma(\omega)|^2 S_\eta(\omega)$$







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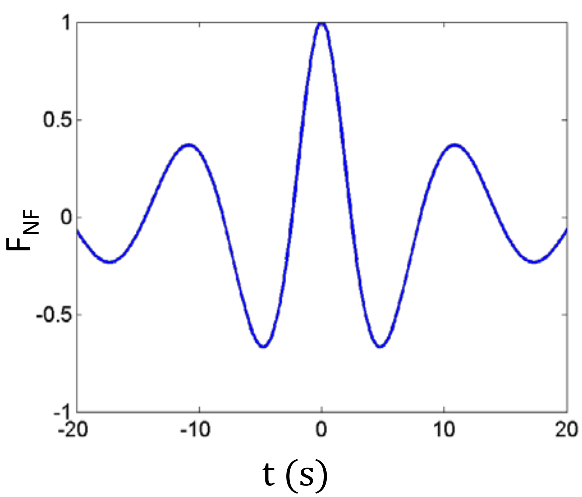
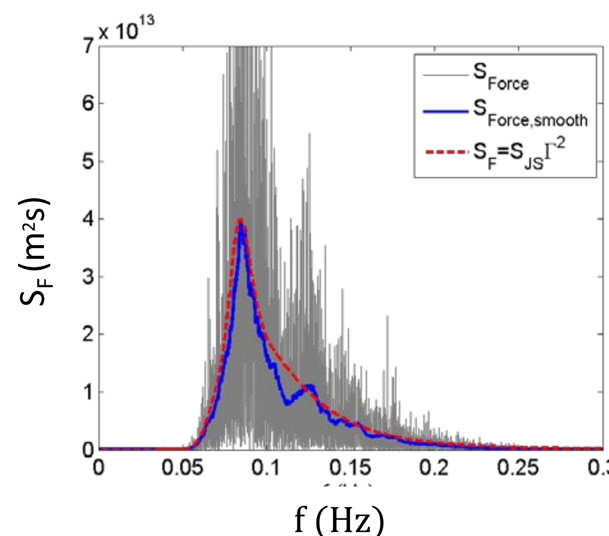
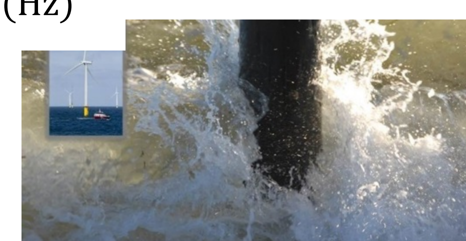
$$\Gamma(\omega) = \mathrm{i}\rho\pi R^2 C_M \omega^2 / k \qquad S_F(\omega) = |\Gamma(\omega)|^2 S_\eta(\omega)$$

$$F_{\text{New Force}} = \frac{\alpha_F}{\sigma_F^2} \sum_i \mathrm{Re}\left\{ \left|\Gamma(\omega_j)\right|^2 S_\eta(\omega_j)\Delta\omega \exp\left(\mathrm{i}\left(\omega_j(t-t_0) - k_j(x-x_0)\right)\right)\right\}$$







DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

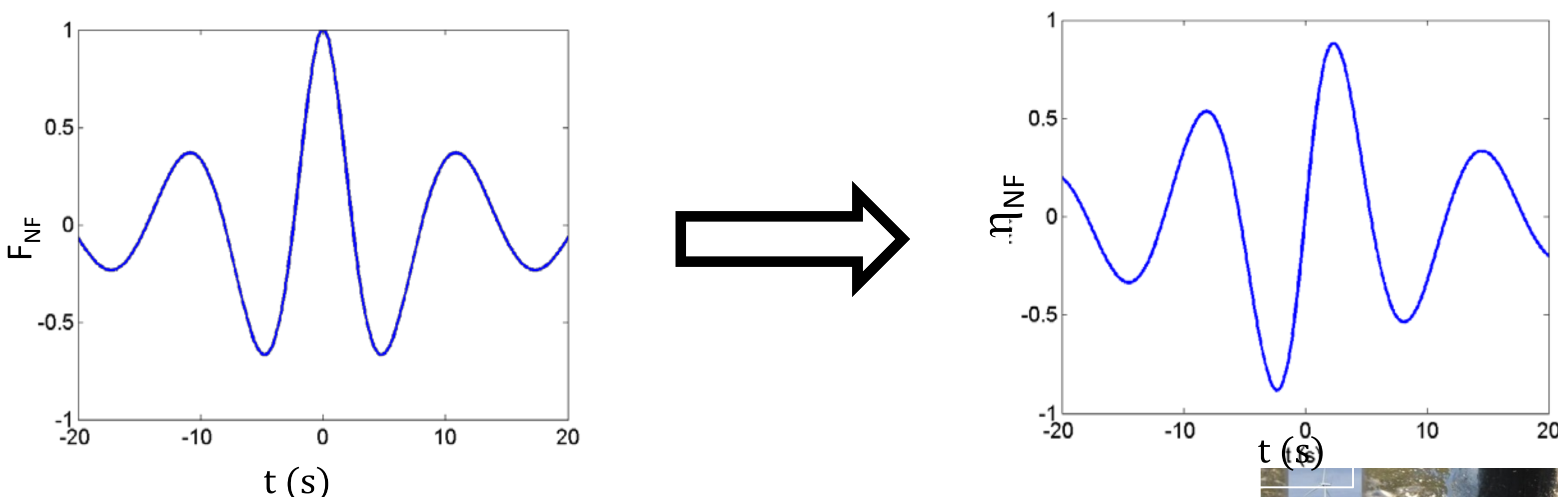
The New Force model

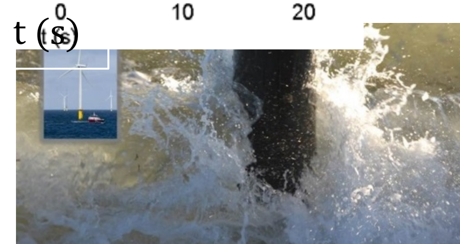
$$\eta_{\text{New Wave}} = \frac{\alpha_\eta}{\sigma_\eta^2} \sum_j \mathrm{Re}\left\{ S_\eta(\omega_j)\Delta\omega \exp\left(\mathrm{i}\left(\omega_j(t-t_0) - k_j(x-x_0)\right)\right)\right\}$$

$$\Gamma(\omega) = \mathrm{i}\rho\pi R^2 C_M \omega^2/k \qquad S_F(\omega) = |\Gamma(\omega)|^2 S_\eta(\omega)$$

$$F_{\text{New Force}} = \frac{\alpha_F}{\sigma_F^2} \sum_i \mathrm{Re}\left\{ \left|\Gamma(\omega_j)\right|^2 S_\eta(\omega_j)\Delta\omega \exp\left(\mathrm{i}\left(\omega_j(t-t_0) - k_j(x-x_0)\right)\right)\right\}$$

$$\eta_{\text{New Force}} = \frac{\alpha_F}{\sigma_F^2} \sum_j \mathrm{Re}\left\{ \Gamma^*(\omega_j) S_\eta(\omega_j)\Delta\omega \exp\left(\mathrm{i}\left(\omega_j(t-t_0) - k_j(x-x_0)\right)\right)\right\}$$



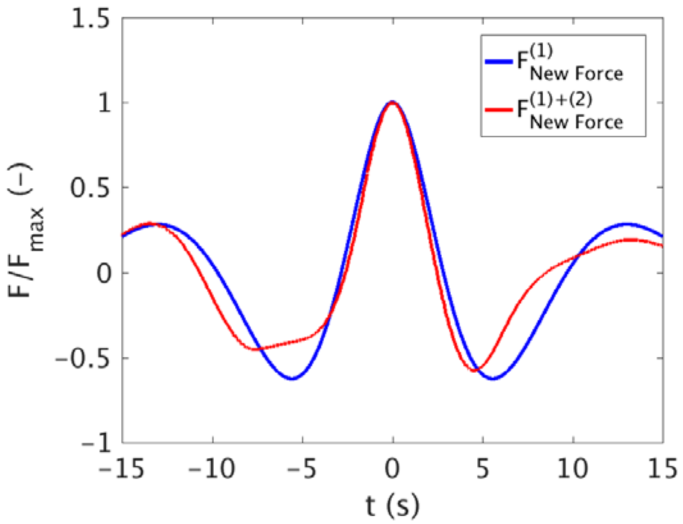


DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

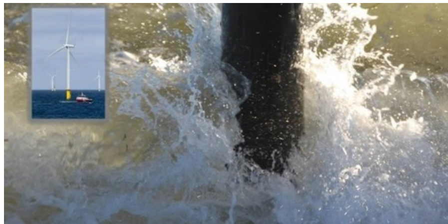
The New Force model – 2nd order contribution

$F^{(1)+(2)} = +F^{(1)} + F_M^{(2)}$

$$F_M^{(2)} = \rho\pi R^2 C_M \int_{-h}^{0} (u_t^{(2)} + u^{(1)}u_x^{(1)} + w^{(1)}u_z^{(1)})dz + \rho R C_D \int_{-h}^{0} u^{(1)}|u^{(1)}|dz$$
$$+\rho\pi R^2 (C_M - 1) \int_{-h}^{0} (u^{(1)}w_z^{(1)})dz + \rho\pi R^2 C_M \eta_{NF}^{(1)} u_t^{(1)}.$$

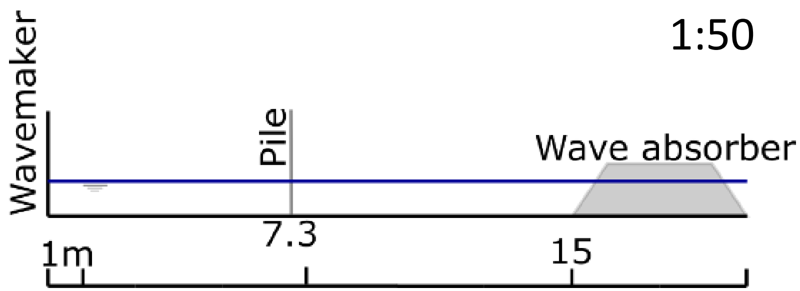


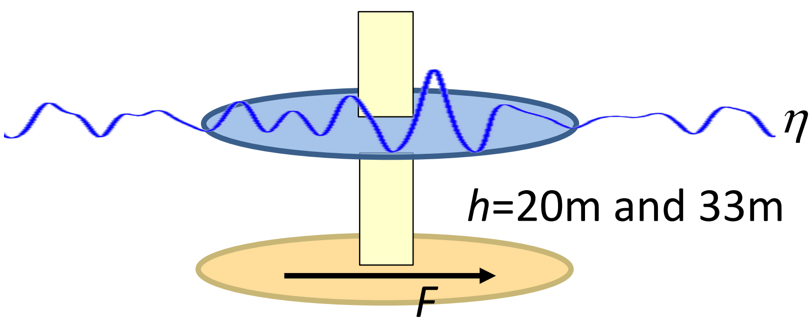
Second order wave kinematics based on second order wave theory of Sharma and Dean (1981)

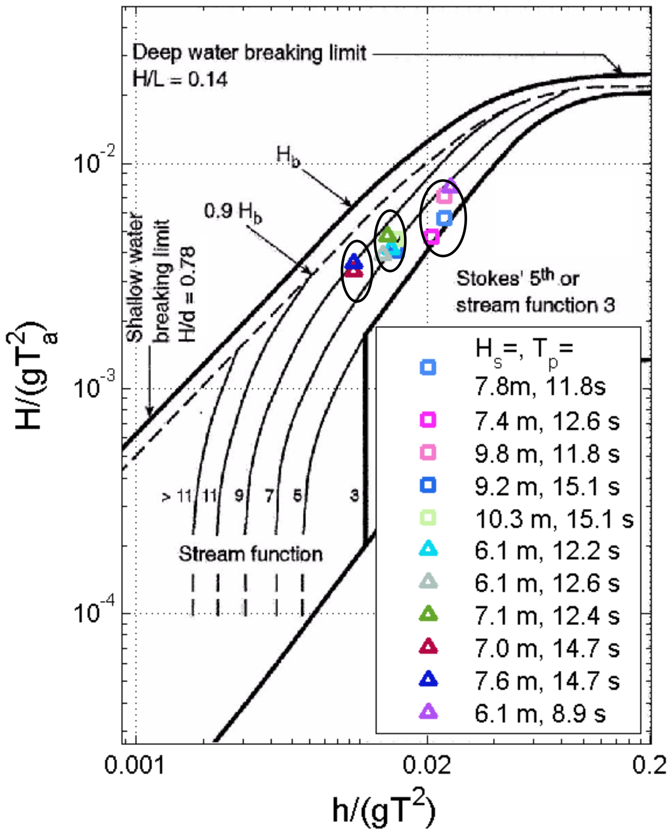


DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Model tests







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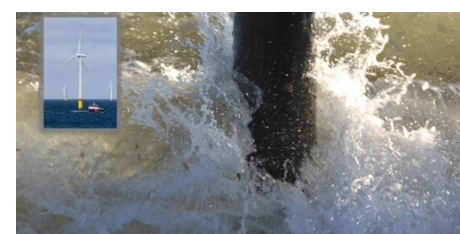
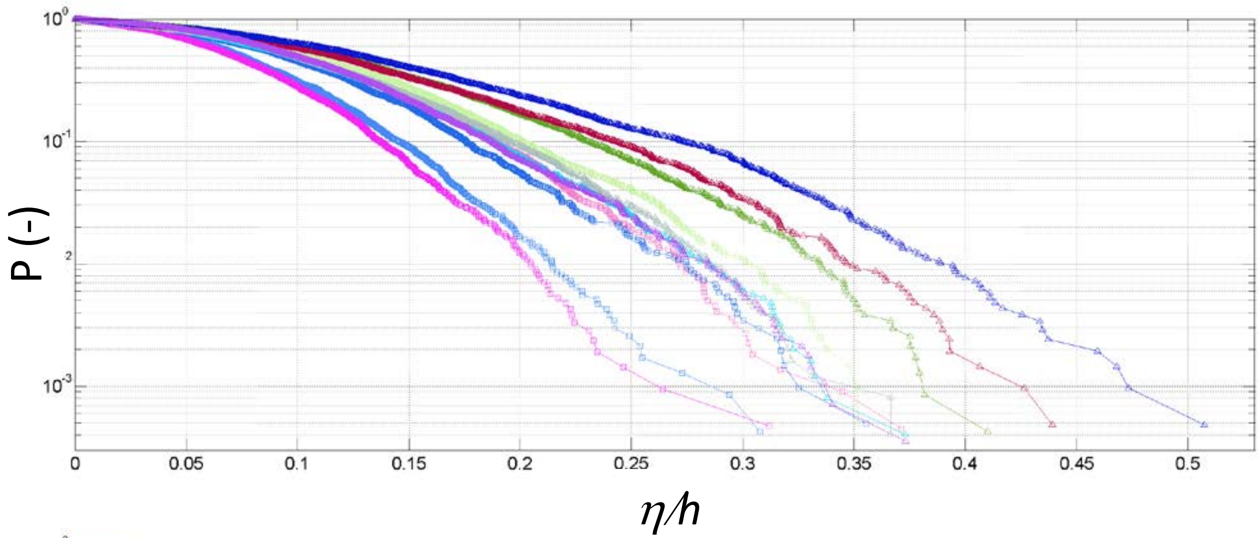
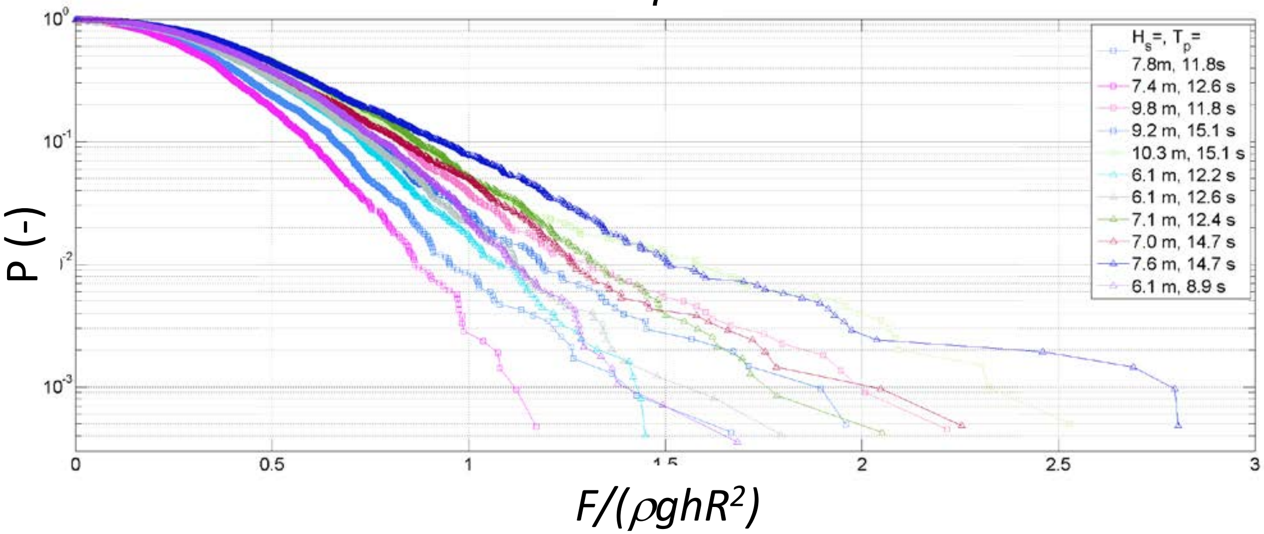
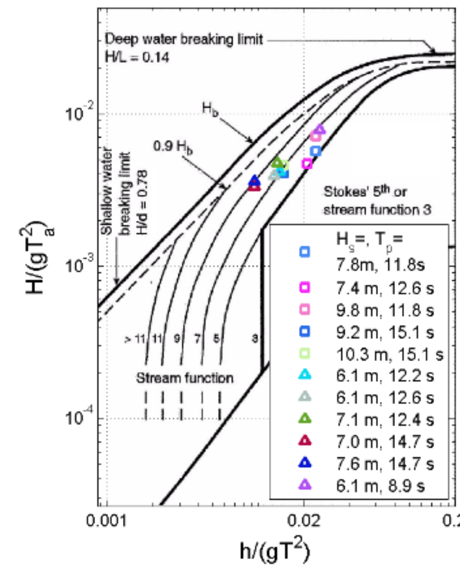
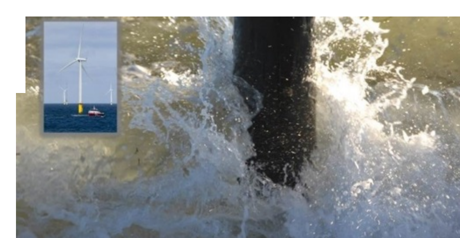


Exceedance probability distributions of the free surface elevation and force signal



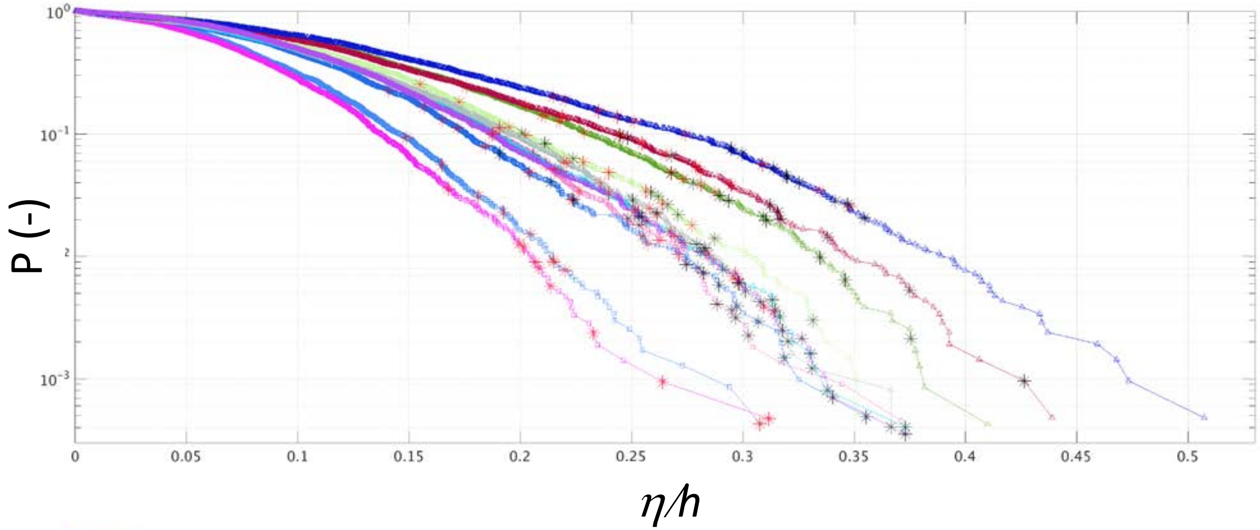


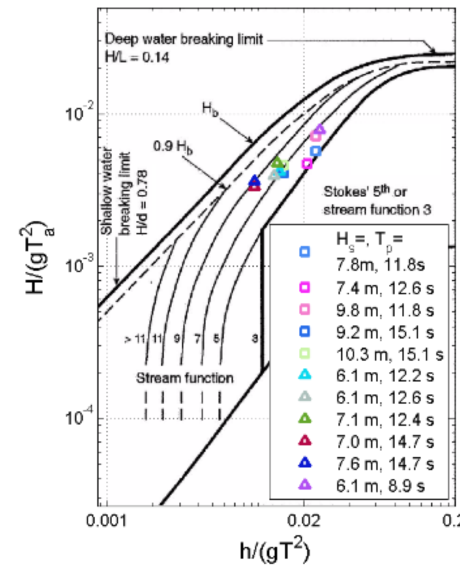


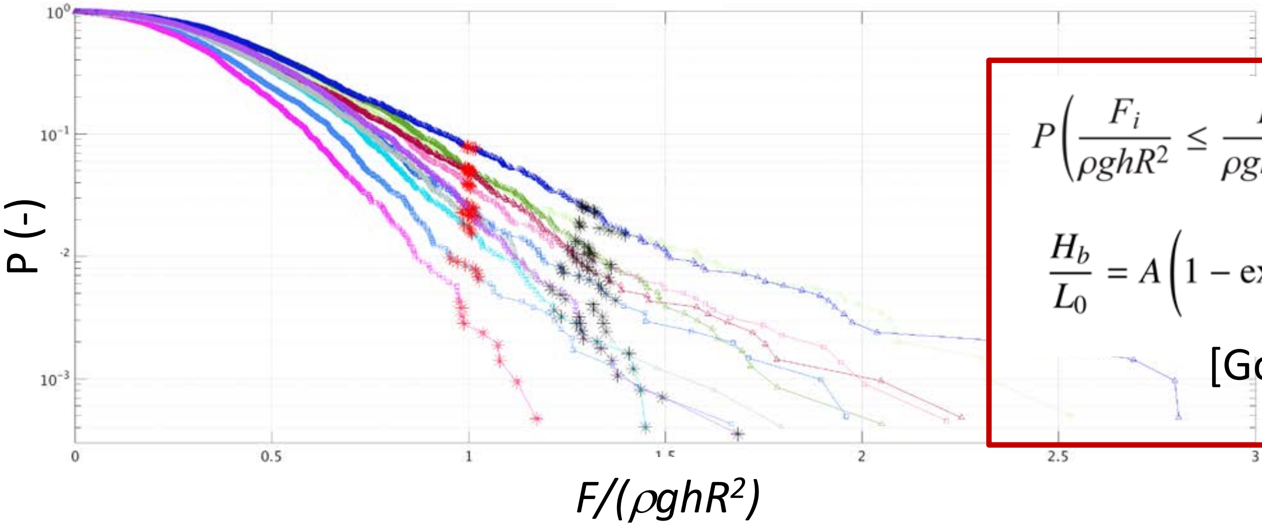


DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

Exceedance probability distributions of the free surface elevation and force signal



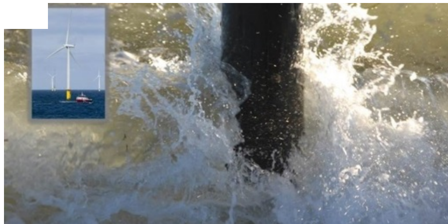




$$P\left(\frac{F_i}{\rho g h R^2} \leq \frac{F}{\rho g h R^2}\right) = f_1\left(\frac{H_s}{gT_p^2}, \frac{h}{gT_p^2}\right)$$

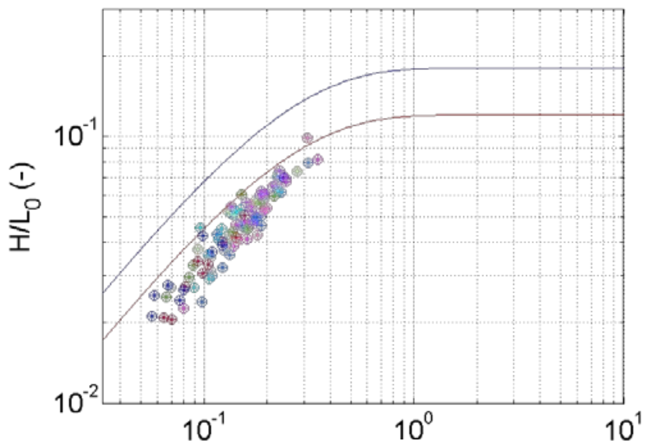
$$\frac{H_b}{L_0} = A\left(1 - \exp\left(-1.5\pi\frac{h}{L_0}\right)\right)$$

[Goda et al. 1976]

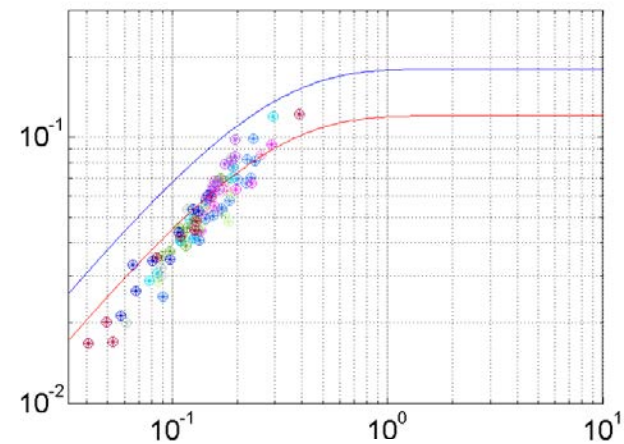


Exceedance probability distributions of the free surface elevation and force signal

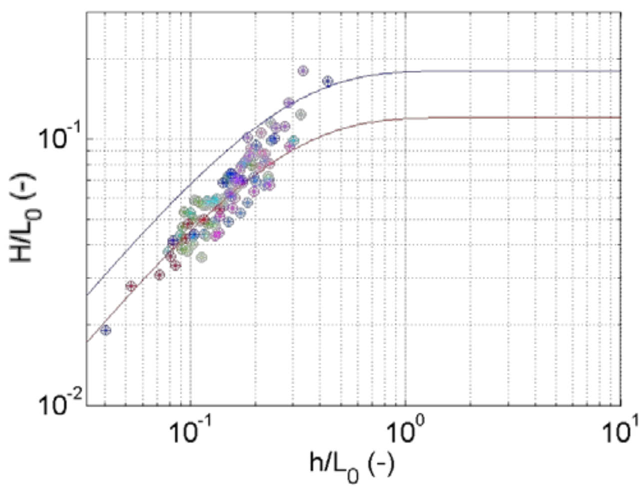
$F/(\rho g h R^2)=0.8$



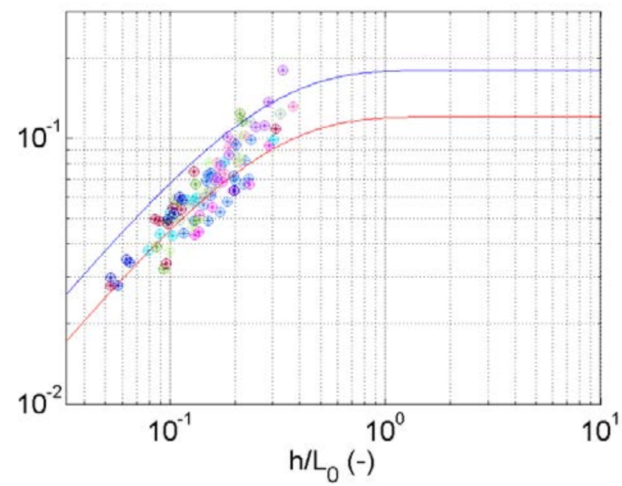
$F/(\rho g h R^2)=1.0$

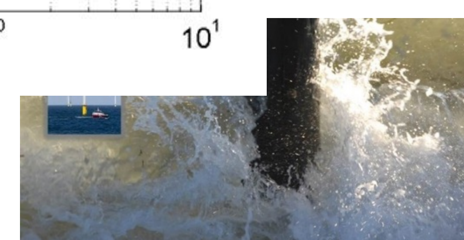


$F/(\rho g h R^2)=1.3$



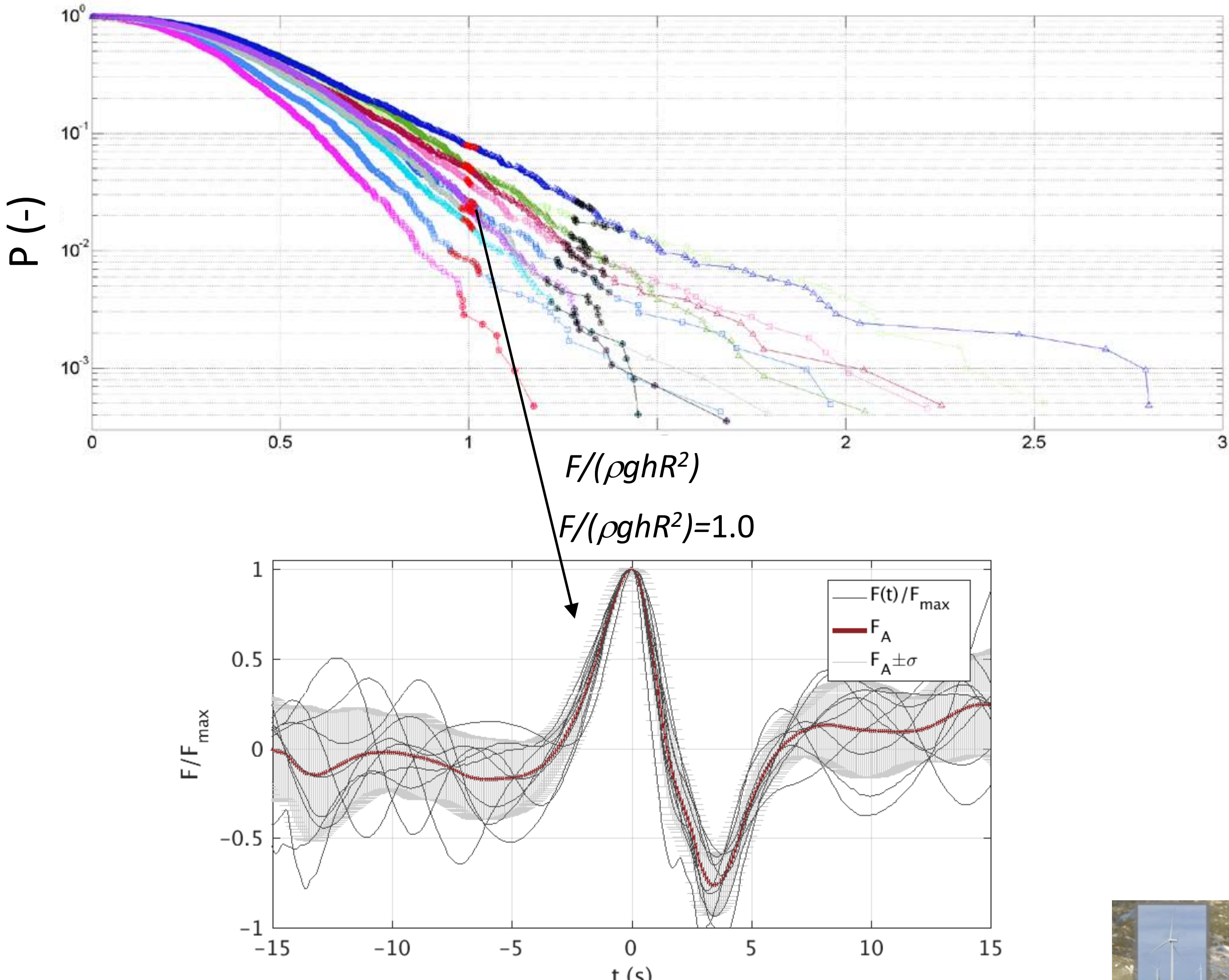
$F/(\rho g h R^2)=1.6$

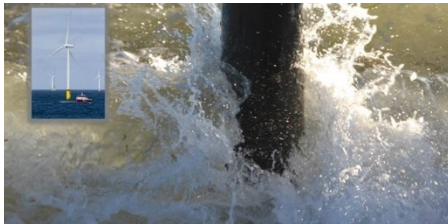




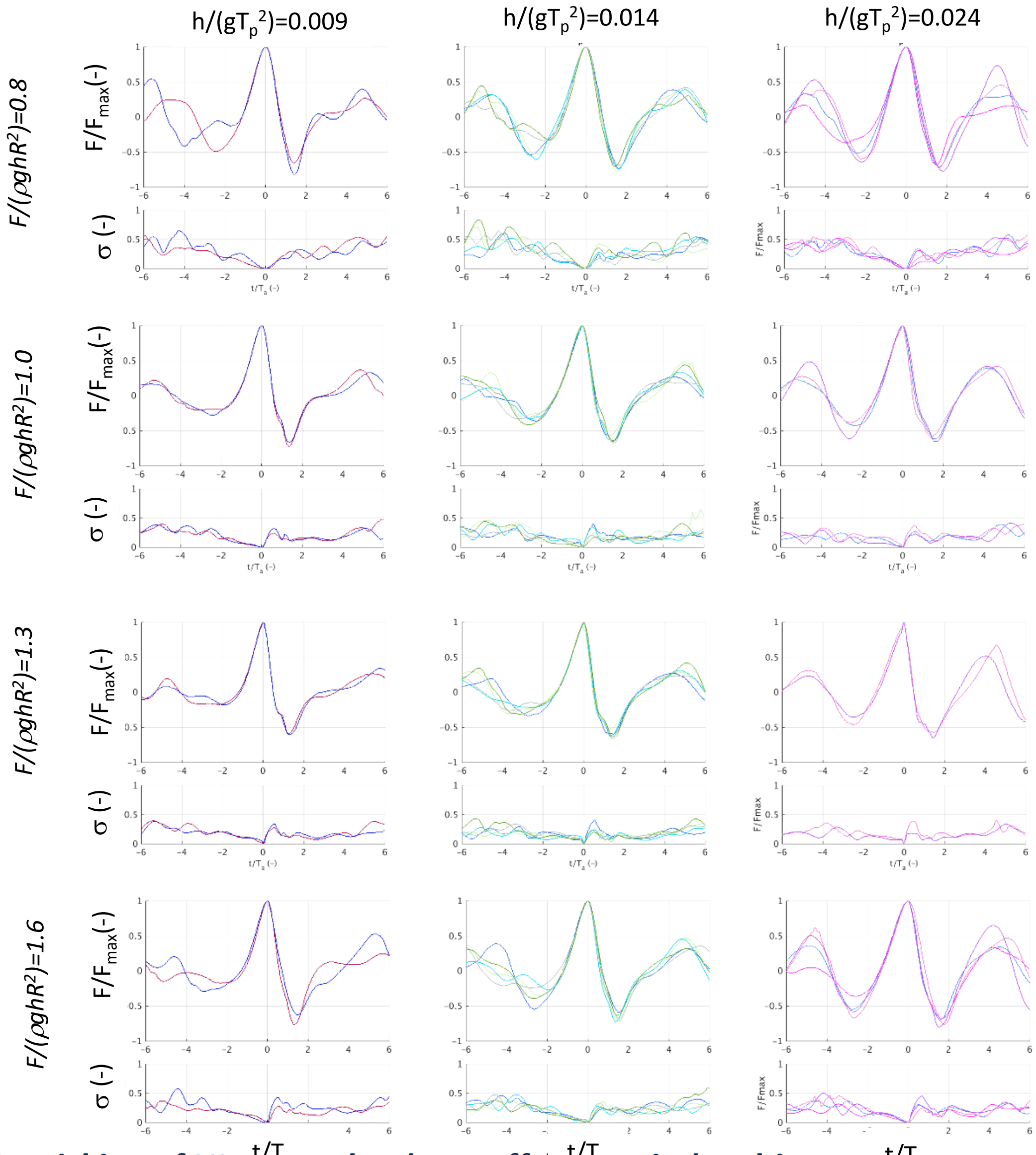
DeRisk – De-risking of ULS wave loads on offshore wind turbine structures

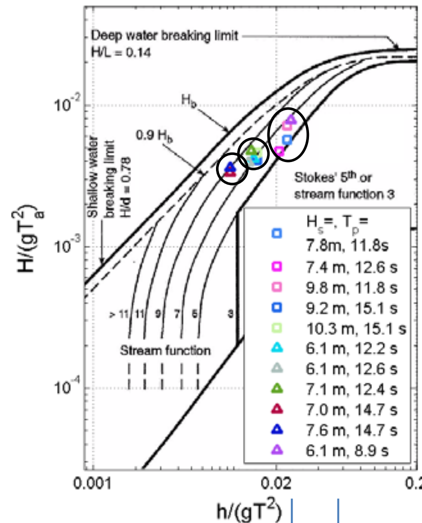
The average force shape

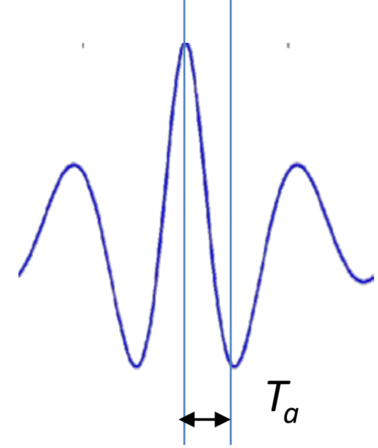


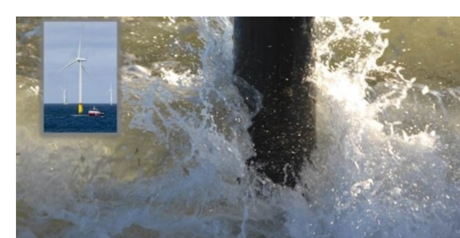


The average force shape









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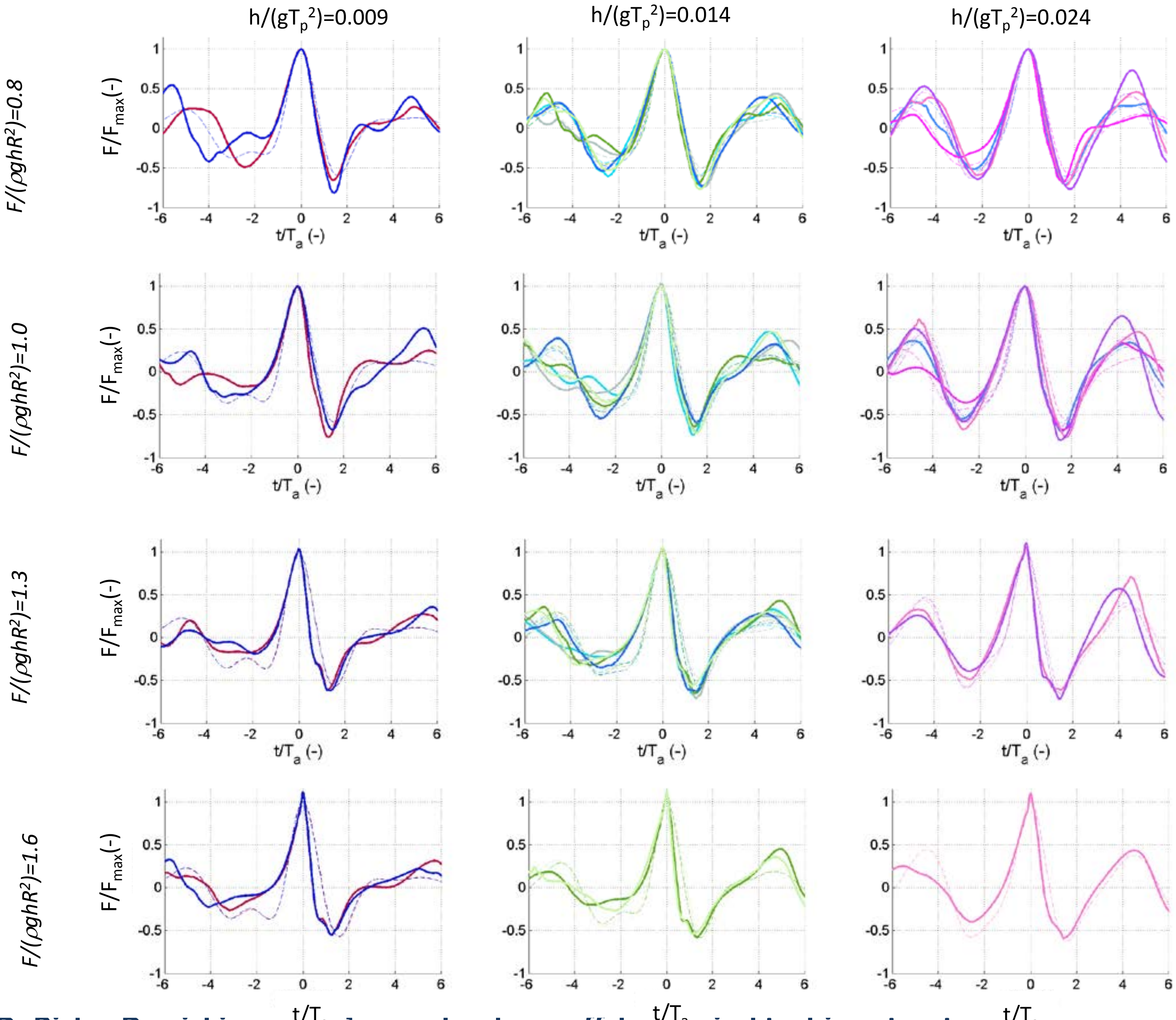
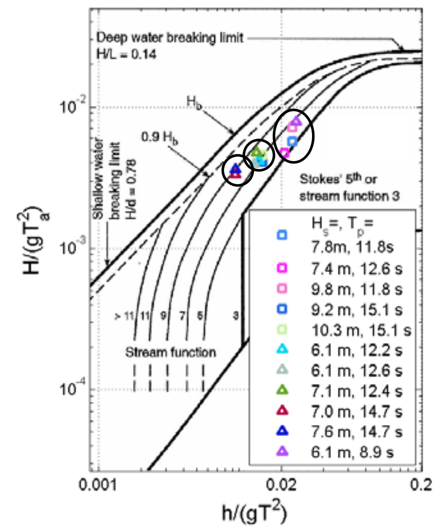
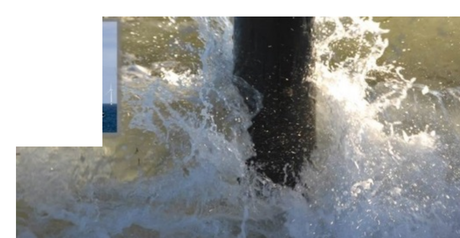
The average force shape







Conclusion

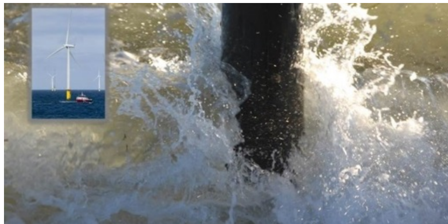
For the considered sea states

- The probability distributions of the force peaks are function of $F/(\rho g h R^2)$, $H_s/(gT_p^2)$, $h/(gT_p^2)$ $\rightarrow$ possible to estimate the probability distributions of the force peaks from stocastic variables of the sea states.

- The normalised force shapes are function of $F/(\rho g h R^2)$, $h/(gT_p^2)$, t/T_a.
- For moderate nonlinear waves The New Force model of second order predicts the shapes of well.

Planned future work

- To predict force shapes of more nonlinear waves, more advanced wave models should be used together with the New Force model.
- Include multidirectional waves in the analysis



Thank you

sigs@dtu.dk

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