HAWC2

Hydrodynamic modeling

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Hydrodynamic model in HAWC2

Hydrodynamic kinematics:

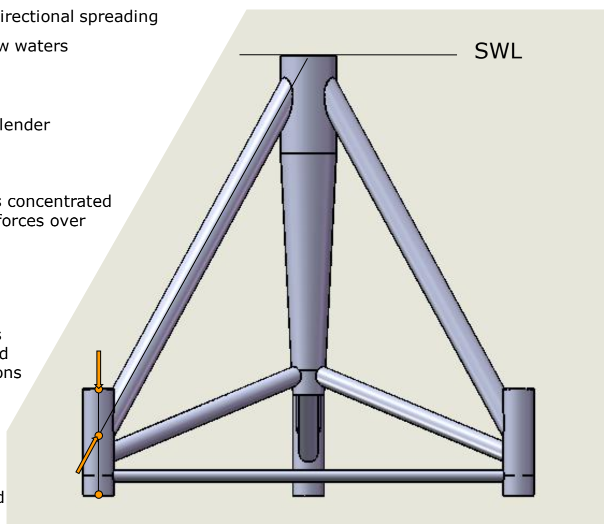
- Regular and iregular Airy waves, directional spreading
- Wheeler stretching used for shallow waters

Hydrodynamic loads:

- Morisons formula (assumption of slender elements)
- Axial damping term in end nodes
- Axial dynamic pressure inserted as concentrated force on end nodes and distributed forces over conical sections

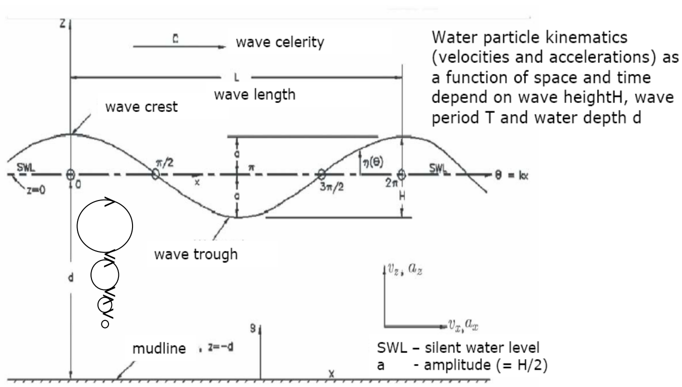
Buoyancy loads from static pressure:

- Axial dynamic pressure inserted as concentrated force on end nodes and distributed forces over conical sections
- Distributed perpendicular force contribution on angled elements
- Restoring moments distribution on conical sections
- Influence of flooded water included



Wave kinematics

Linear wave



Linear wave

The elevation is described as a sinus function

$$\eta_i(t,x) = A_i \sin\left(\omega_i t - k_i x + \varphi_i\right)$$

Where the relation between wave number and frequency is given by the dispersion relation

$$\omega_i^2 = g k_i \tanh(k_i z_0)$$

The horizontal and vertical velocities

$$u_i\left(t,x,z\right) = \omega_i \frac{\cosh\left[k_i\left(z+z_0\right)\right]}{\sinh\left[k_i z_0\right]} \eta\left(t,x\right) \qquad w_i\left(t,x,z\right) = \omega_i \frac{\sinh\left[k_i\left(z+z_0\right)\right]}{\sinh\left[k_i z_0\right]} A_i \cos\left(\omega_i t - k_i x + \varphi_i\right)$$

Linear wave (2)

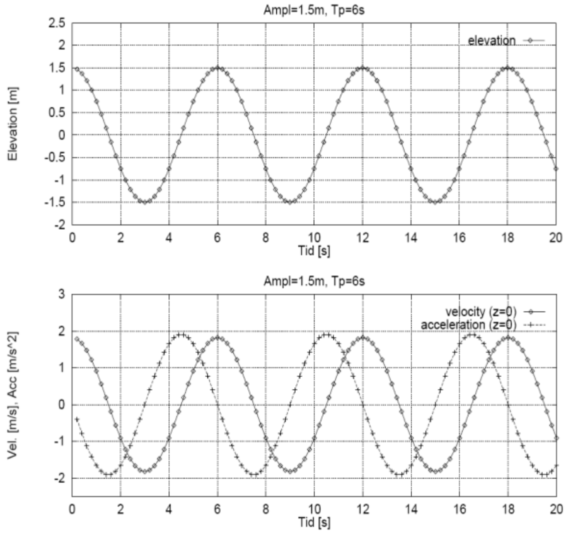
The particle accelerations

$$\dot{u}_i(t,x,z) = \omega_i^2 \frac{\cosh[k_i(z+z_0)]}{\sinh[k_i z_0]} A_i \cos(\omega_i t - k_i x + \varphi_i) \qquad \dot{w}_i(t,x,z) = -\omega_i^2 \frac{\sinh[k_i(z+z_0)]}{\sinh[k_i z_0]} \eta(t,x)$$

And the dynamic variation in pressure

$$p_i(t,x,z) = \rho g \frac{\cosh[k_i(z+z_0)]}{\cosh[k_i z_0]} \eta(t,x)$$

Linear wave (3)



Wheeler stretching

The velocity profile is extrapolated to the actual surface level by a stretching technique known as Wheeler stretching.

$$z' = \frac{z+d}{1+\frac{\eta(t)}{d}}$$

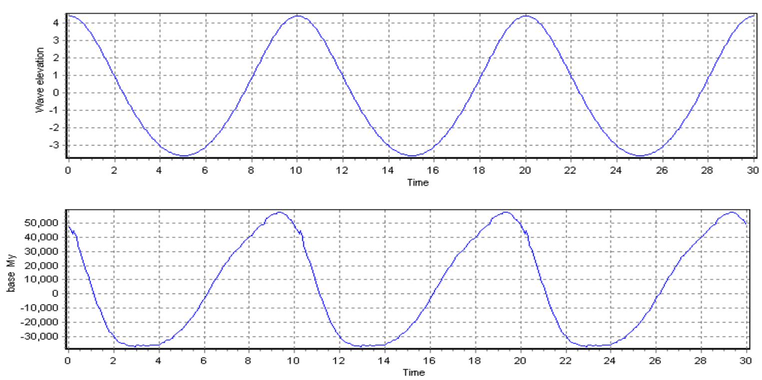
This is inserted in the calculation of velocities instead of z+d. It ensures that the velocities calculated at z=0 without stretching is inserted on the structure at the elevation level.

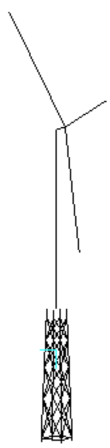
$$u_i(t,x,z) = \omega_i \frac{\cosh[k_i(z')]}{\sinh[k_i z_0]} \eta(t,x)$$

Stream function wave

- Stream function waves now added to the wave kinematics generator. (Missing feature for a long time).
- Method by Chaplin, Southhampton University
  - Dyn. pressure set to zero so far.

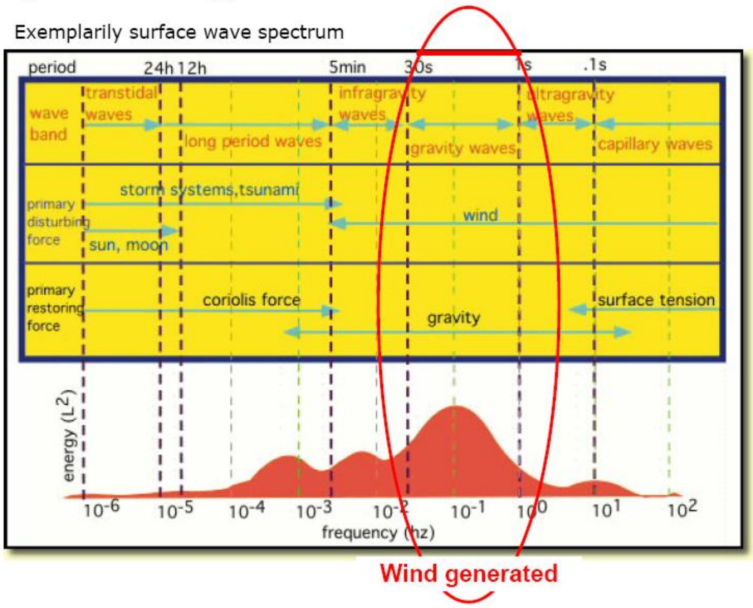
Stream function wave at 44m depth. H=8m, T=10s





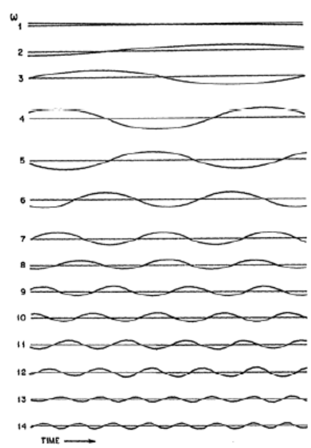
Irregular Waves(I)

Exemplarily surface wave spectrum

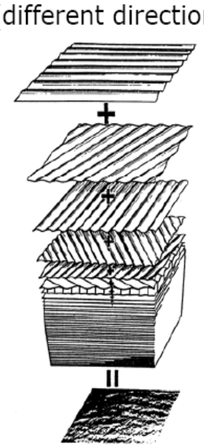


Irregular wave(III)

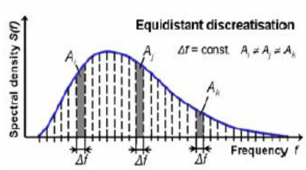
Individual linear waves



Superposition (different directions)



Wave spectrum



1. Discretization
2. Single wave amplitudes from spectrum energy
3. Random phases
4. (Directions)
5. Superposition

Jonswap spectrum for iregular waves:

$$G(\omega)=\frac{\alpha\cdot g^2}{\omega^5}\cdot\exp\left[-\frac{5}{4}\cdot\left(\frac{\omega_p}{\omega}\right)\right]^4\gamma^{\exp\left(-\frac{(\omega-\omega_p)^2}{2\cdot\sigma^2\cdot\omega_p{}^2}\right)}$$

$$\alpha=\frac{5}{16}\frac{H_s^2\omega_p^4}{g^2}(1-0.287\ln(\gamma))$$

$$\omega_p=\frac{2\pi}{T_p}$$

σ=0.07 for $\omega\leq\omega_m$, σ= 0.09 for $\omega>\omega_m$.

Water kinematics, iregular with spreading directions

$$\alpha_i=\omega_i t-k_i x\cos\theta_i-k_i y\sin\theta_i+\varphi_i \qquad \omega_i^2=gk_i\tanh(k_i z_0)$$

$$\eta_i(t,x,y)=A_i\sin\alpha_i \qquad \eta(t,x,y)=\sum_{i=1}^{N}\eta_i(t,x,y)$$

velocity

$$u_i(t,x,y,z)=\omega_i\frac{\cosh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\sin\alpha_i\cos\theta_i \qquad u(t,x,y,z)=\sum_{i=1}^{N}u_i(t,x,y,z)$$

$$v_i(t,x,y,z)=\omega_i\frac{\cosh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\sin\alpha_i\sin\theta_i \qquad v(t,x,y,z)=\sum_{i=1}^{N}v_i(t,x,y,z)$$

$$w_i(t,x,y,z)=\omega_i\frac{\sinh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\cos\alpha_i \qquad w(t,x,y,z)=\sum_{i=1}^{N}w_i(t,x,y,z)$$

acceleration

$$\dot u_i(t,x,y,z)=\omega_i^2\frac{\cosh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\cos\alpha_i\cos\theta_i \qquad \dot u(t,x,y,z)=\sum_{i=1}^{N}\dot u_i(t,x,y,z)$$

$$\dot v_i(t,x,y,z)=\omega_i^2\frac{\cosh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\cos\alpha_i\sin\theta_i \qquad \dot v(t,x,y,z)=\sum_{i=1}^{N}\dot v_i(t,x,y,z)$$

$$\dot w_i(t,x,y,z)=-\omega_i^2\frac{\sinh[k_i(z+z_0)]}{\sinh[k_i z_0]}A_i\sin\alpha_i \qquad \dot w(t,x,y,z)=\sum_{i=1}^{N}\dot w_i(t,x,y,z)$$

pressure

$$p_i(t,x,y,z)=\rho g\frac{\cosh[k_i(z+z_0)]}{\cosh[k_i z_0]}A_i\sin\alpha_i \qquad p(t,x,y,z)=\sum_{i=1}^{N}p_i(t,x,y,z)$$

Directional spreading

The directional spreading distribution function

$$f(\theta)=K_{2s}\cos^{2s}\theta \qquad K_{2s}=\frac{2^{2s-1}s!(s-1)!}{\pi(2s-1)!}$$

$$s := 2$$

$$K2s := \frac{2^{(2\cdot s-1)}\cdot s!\cdot(s-1)!}{\pi\cdot(2\cdot s-1)!}$$

The integrated function is calculated

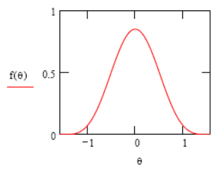
$$F(\theta)=\int_{-\frac{\pi}{2}}^{\theta} f(\theta)d\theta$$

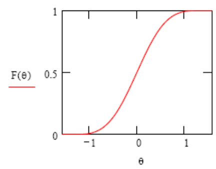
$$f(\theta) := K2s\cdot(\cos(\theta))^{2\cdot s}$$

$$F(\theta) := \int_{\frac{-\pi}{2}}^{\theta} f(\theta)\,d\theta$$

The inverse of this function is calculated so theta can be found with basis of F value.

The uniformly distributed phase angles are used as input to find a corresponding direction angle for each coefficient.

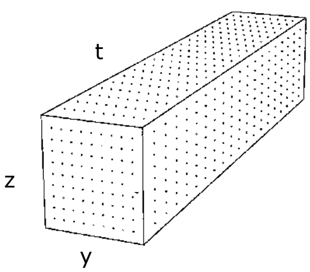




Wave kinematics

- In the previous version all fourrier summations were done in the exact position and time of lookup.
- Now a pregenerated field is created. 3 dimensions when spreading is included. Only height and time resolved for 2D waves.
- 15 points in the height is used. Time resolution is $T_{min}/10$.
- Linear interpolation is used.

- A 10 min time series on a jacket that used to take 2hours for simulations, is now ready after 12minutes!

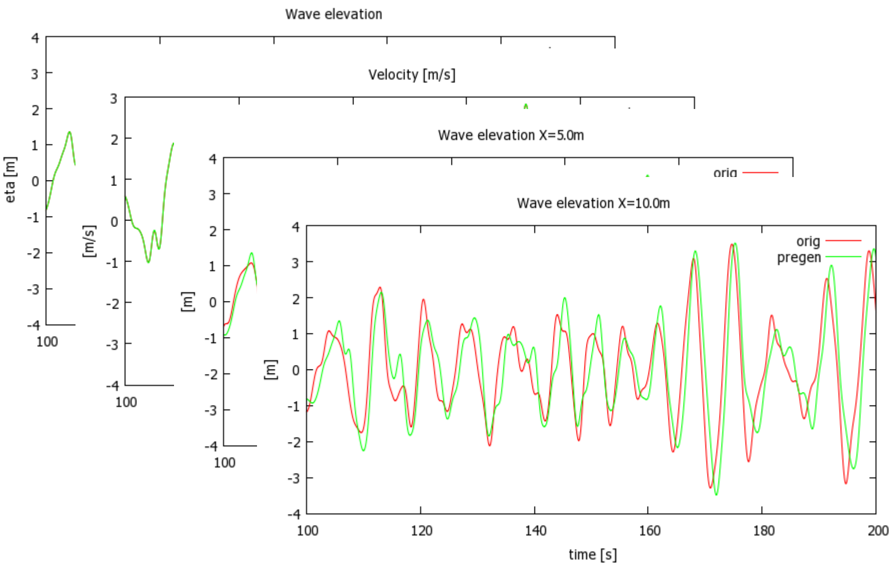


The assumed relation between time and x pos is based on the group velocity of waves.

$$C_G=\frac{1}{2}\sqrt{\frac{g}{k}}\left[\frac{kh+\tanh(kh)-kh\,tanh^2(kh)}{\sqrt{\tanh(kh)}}\right]$$

$$t_{lookup}=t-\frac{x}{C_G}$$

Comparison



Morison formula

For flexible slender structures D/L<0.2

$$dF = \rho A\dot{U} + \rho C_a A_R \dot{U}_{rel} + \tfrac{1}{2}\rho D C_d U_{rel}\left|U_{rel}\right|$$

Froud-Krylov force **water added mass** **drag force**

Which for stiff slender structures decouples to

$$dF = \rho \tfrac{\pi D^2}{4} C_M \dot{U} + \tfrac{1}{2}\rho D C_d U_{rel}\left|U_{rel}\right|, \qquad C_M = 1 + C_a$$

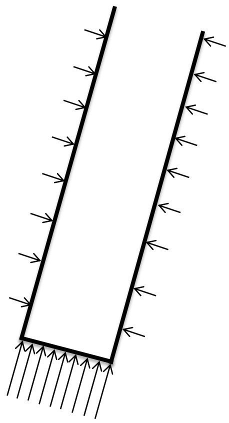
- hydrodynamic drag (cd) and inertia (cm=1+ca) coefficients depend on surface roughness, Reynolds number & Keulegan-Carpenter number
- hydrodynamic damping from drag term relevant only for very flexible structures (e.g. Riser, cable)

Buoyancy model in HAWC2

Boyancy implemented as the result of integration of external pressure

- Buoyancy, distributed load contributions:

$$\vec{F}_b = -g\rho \begin{Bmatrix} A_{3,1}S \\ A_{3,2}S \\ -\dfrac{\partial S}{\partial z}(z-z_0) + \dfrac{\partial S}{\partial z} p_{dyn} \end{Bmatrix} \qquad \vec{M}_b = -g\rho \begin{Bmatrix} -A_{3,2}\dfrac{\partial r}{\partial z}\pi r^3 \\ A_{3,1}\dfrac{\partial r}{\partial z}\pi r^3 \\ 0 \end{Bmatrix}$$



- Buoyancy and drag contributions at end nodes

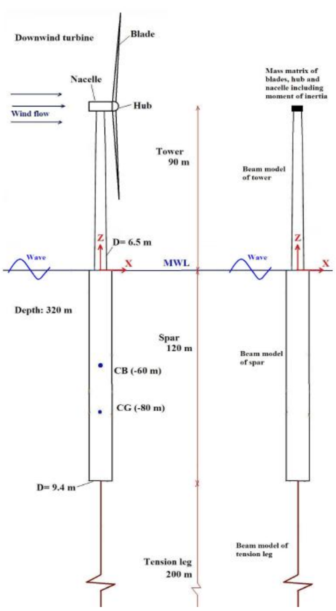
$$F_{b,end}(3) = \underbrace{\rho g S(z-z_0)}_{\text{Static pressure}} + \underbrace{S\, p_{dyn}}_{\text{Dynamic pressure}} + \underbrace{\frac{1}{2}\rho C_{d,axial} S\, u_{rel}|u_{rel}|}_{\text{Viscous drag}}$$

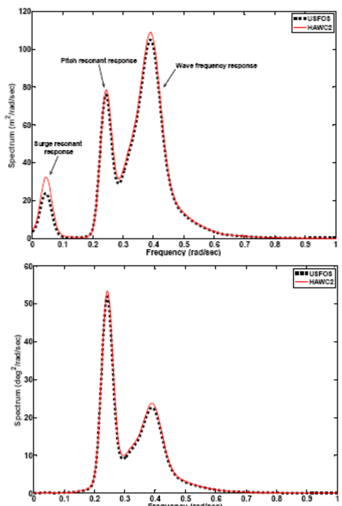
A : orientation matrix
S : area
r : radius

g : gravity
P : pressure
ρ : density

z : vertical pos
u : velocity
dr/dz : conicity

Validation for a spar bouy



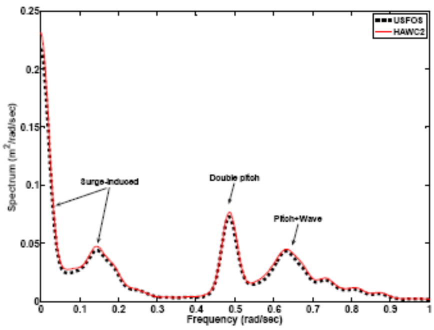


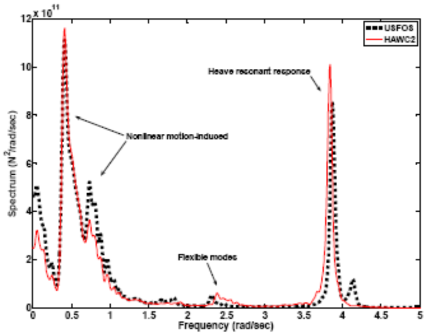
Surge

Pitch

Madjid Karimirad, Quentin Meissonnier, Zhen Gao, Torgeir Moan. HYDROELASTIC CODE-TO-CODE COMPARISON FOR A TENSION LEG SPAR-TYPE FLOATING WIND TURBINE. Submitted to Marine Structures journ. 2011.

Spar bouy (2)





Heave

Tension

Morison formula
Modified for flooded members

$$F = \rho A\dot{U} + \rho C_a A_R \dot{U}_{rel} + \tfrac{1}{2}\rho D C_d U_{rel}|U_{rel}|$$

The external forces of a section in balance with acceleration of cylinder and internal flooded water

$$F = m_{cyl}\,\dot{u}_{cyl} + \rho A_i \dot{u}_{cyl}$$

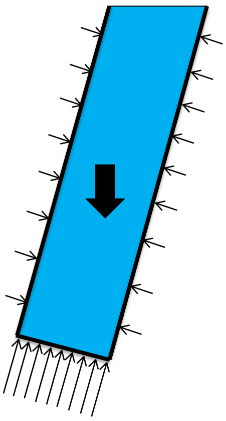
$$\Rightarrow \rho A\dot{u} + \rho C_m A\dot{u}_{rel} + \tfrac{1}{2}\rho D C_d u_{rel}|u_{rel}| = m_{cyl}\,\dot{u}_{cyl} + \rho A_i \dot{u}_{cyl}$$

This can be put on same form as the Morisons equation where the effect of the acceleration of flooded water is included in the external force contribution.

$$\Rightarrow \rho(A - A_i)\dot{u} + \rho(C_m A + A_i)\dot{u}_{rel} + \tfrac{1}{2}\rho D C_d u_{rel}|u_{rel}| = m_{cyl}\,\dot{u}_{cyl}\,, \qquad \dot{u}_{cyl} = \dot{u} - \dot{u}_{rel}$$

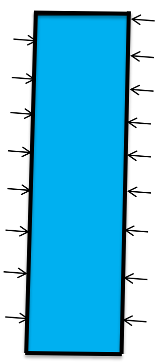
What about flooded members?

Important for piles in the jacket



- Classical approach in existing aeroelastic codes
  - Internal water applied as extra ”steel” mass to ensure correct inertia
- This is not correct since eg. gravity force will accumulate wrongly in the steel structure
- Another method is proposed that is valid for flooded members in compartments without free inner surfaces.

Flooded members – added mass



We start with the Morisons formula and include the flooded water

$$F_{waves} = m_{steel}\dot{u}_{cyl} + m_{water}\dot{u}_{cyl}$$

$$\Rightarrow \rho A\dot{u} + \rho C_m A_R \dot{u}_{rel} + \tfrac{1}{2}\rho D C_d u_{rel}\left|u_{rel}\right| = m_{steel}\dot{u}_{cyl} + \rho A_i \dot{u}_{cyl}$$

$$\dot{u}_{rel} = \dot{u} - \dot{u}_{cyl}$$

$$\rho(A - A_i)\dot{u} + \rho(C_m A_R + A_i)\dot{u}_{rel} + \tfrac{1}{2}\rho D C_d u_{rel}\left|u_{rel}\right| = m_{steel}\dot{u}_{cyl}$$

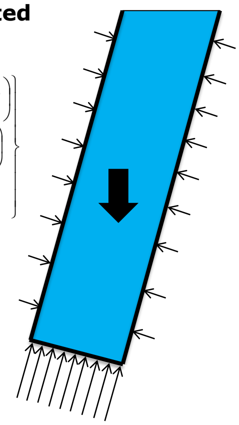
And end with a new modified Morisons formula for flooded members

The benefit is an added mass not affected by gravity.

Buoyancy for flooded members

- **The boyancy is still a result of integration of external pressure**
- **The flooded water will apply an internal pressure at same location as outer pressure from water**
- **The result is that the inner area should be subtracted**
  - Buoyancy, distributed load contributions:

$$\vec{F}_b = -g\rho\begin{Bmatrix} A_{3,1}(S-S_i) \\ A_{3,2}(S-S_i) \\ -\frac{\partial S}{\partial z}(z-z_0)+\frac{\partial S_i}{\partial z}(z-z_0)+\frac{\partial S}{\partial z}p_{dyn} \end{Bmatrix} \qquad \vec{M}_b = -g\rho\begin{Bmatrix} -A_{3,2}\pi\left(\frac{\partial r}{\partial z}r^3-\frac{\partial r_i}{\partial z}r_i^3\right) \\ A_{3,1}\pi\left(\frac{\partial r}{\partial z}r^3-\frac{\partial r_i}{\partial z}r_i^3\right) \\ 0 \end{Bmatrix}$$



  - Buoyancy and drag contributions at end nodes

$$F_{b,end}(3) = \rho g(S-S_i)(z-z_0) + S\,p_{dyn} + \tfrac{1}{2}\rho C_{d,axial} S u_{rel}|u_{rel}|$$

Static pressure

Dynamic pressure

Viscous drag

Also applied at inner nodes when jump in plate thickness occurs

g : gravity
P : pressure
ρ : density

Dynamic pressure assumed not to change inner pressure (depends on design though)

Improvements of solver

A.M. Hansen

- External hydro added mass derived as an analytical integration of the external load.
- Separation of effects from large rotations/movements and local deformation.

Position of a point on a structure

$$\mathbf{u} = \mathbf{R} + \mathbf{A}(\mathbf{r_c} + \mathbf{N_c q})$$

Acceleration of point

$$\ddot{\mathbf{u}} = \ddot{\mathbf{R}} - \mathbf{A}\,[\{\mathbf{r_c}\}\times\mathbf{I}]\,\dot{\vec{\omega}} + \mathbf{A N_c}\ddot{\mathbf{q}}$$

External force

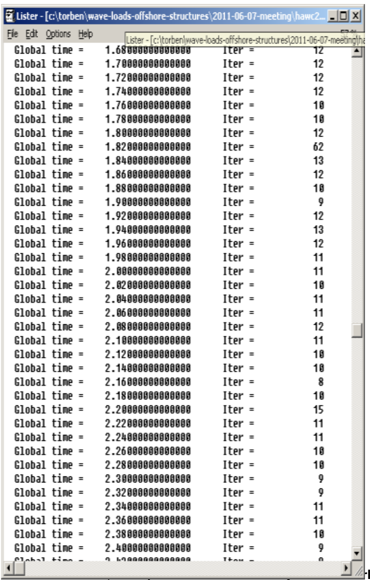
$$\mathbf{Q} = -\mathbf{A T_{AS} C_M T_{AS}}^T \mathbf{A}^T \ddot{\mathbf{u}}$$

$\mathbf{C}_M$ is the section added mass matrix

$$\mathbf{M_A} = \int_L \begin{bmatrix} \mathbf{A C_M^S A}^T & \mathbf{A C_M^S}\,[\{\mathbf{r_c}\}\times\mathbf{I}] & \mathbf{A C_M^S N_c} \\ & -[\{\mathbf{r_c}\}\times\mathbf{I}]\,\mathbf{C_M^S}\,[\{\mathbf{r_c}\}\times\mathbf{I}] & [\{\mathbf{r_c}\}\times\mathbf{I}]\,\mathbf{C_M^S N_c} \\ sym & & \mathbf{N_c}^T\mathbf{C_M^S N_c} \end{bmatrix} dz$$

where $\mathbf{C_M^S} = \mathbf{T_{AS} C_M T_{AS}}^T$. Since $\mathbf{A}$ is part of the added mass matrix and $\mathbf{A}$ is time dependent, the added mass matrix also becomes time dependent, however, $\mathbf{A}$ is the *only* time dependent part of the matrix. This means that the added mass matrix have to be updated each time step, but only by pre- and post multiplication by $\mathbf{A}$ - the remainder of the matrix is integrated only once.

Better convergence from version 10.4



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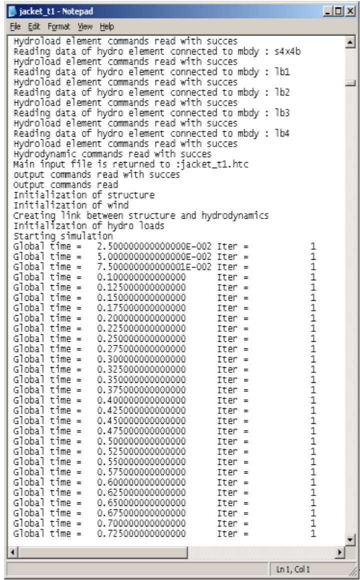

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jacket_t1 - Notepad
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Hydroload element commands read with succes
Reading data of hydro element connected to mbdy : s4x4b
Hydroload element commands read with succes
Reading data of hydro element connected to mbdy : lb1
Hydroload element commands read with succes
Reading data of hydro element connected to mbdy : lb2
Hydroload element commands read with succes
Reading data of hydro element connected to mbdy : lb3
Hydroload element commands read with succes
Reading data of hydro element connected to mbdy : lb4
Hydroload element commands read with succes
Hydrodynamic commands read with succes
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output commands read with succes
Output commands read
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Initialization of wind
Creating link between structure and hydrodynamics
Initialization of hydro loads
Starting simulation
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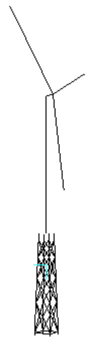
Global time =   0.600000000000000      Iter =           1
Global time =   0.625000000000000      Iter =           1
Global time =   0.650000000000000      Iter =           1
Global time =   0.675000000000000      Iter =           1
Global time =   0.700000000000000      Iter =           1
Global time =   0.725000000000000      Iter =           1
Ln 1, Col 1
```



HAWC2 example

```
begin HYDRO ;
   begin WATER_PROPERTIES ;
    rho 1025 ; [kg/m^3]
    gravity 9.816 ; [m/s^2]
    mwl 0.000; [m]
    mudlevel 14.500 ; [m]
    water_kinematics_dll ./wkin_dll.dll   ./hydrohtc/reg_airy_1.htc ;
   end WATER_PROPERTIES  ;
;
 begin HYDRO_ELEMENT ;
    mbdy_name L1 ;
     buoyancy 1 ;
     update_states  1 ; (0: no dynamic interaction, 1: fully coupled solution
     hydrosections auto 4 ; dist, of hydro calculation points from 1 to nsec
    nsec  9 ;  z     Cm   Cd    A          Aref        width dr/dz Cd_a_(quad) Cm_a Cd_a_lin Ai
      sec     0.000   1    1    1.1309734   1.1309734   1.20  0.0 0.0 0.0 0.0    0.9503318 ;
      sec     5.005   1    1    1.1309734   1.1309734   1.20  0.0 0.0 0.0 0.0    0.9503318 ;
      sec     5.015   1    1    1.5393804   1.5393804   1.40  0.0 0.0 0.0 0.0    0.9503318 ;
      sec    20.408   1    1    1.5393804   1.5393804   1.40  0.0 0.0 0.0 0.0    0.9503318 ;
      sec    20.418   1    1    1.5393804   1.5393804   1.40  0.0 0.0 0.0 0.0    1.0028749 ;
      sec    43.046   1    1    1.5393804   1.5393804   1.40  0.0 0.0 0.0 0.0    1.0028749 ;
      sec    43.056   1    1    1.1309734   1.1309734   1.20  0.0 0.0 0.0 0.0    1.0028749 ;
      sec    49.431   1    1    1.1309734   1.1309734   1.20  0.0 0.0 0.0 0.0    1.0028749 ;
      sec    61.215   1    1    1.1309734   1.1309734   1.20  0.0 0.0 0.0 0.0    1.0028749 ;
   end HYDRO_ELEMENT ;
end HYDRO ;
```

Wkin_dll input file example, regular airy

```
begin wkin_input ;
  wavetype 0 ; 0=regular, 1=irregular, 2=deterministic
  wdepth 220.0 ;
;
  begin reg_airy ;
    stretching 0; 0=none, 1=wheeler
    wave 9 12.6;  Hs,T
  end;
end;
;
exit ;
```


Wkin_dll input file example, irregular airy

```
begin wkin_input ;
  wavetype 1 ; 0=regular, 1=irregular, 2=deterministic
  wdepth 220.0 ;
;
  begin ireg_airy ;
    stretching 0;   0=none, 1=wheeler
    spectrum   1;  (1=jonswap)
    jonswap    9 12.6 3.3 ; (Hs, Tp, gamma)
    coef       200 1 ; (coefnr, seed)
    spreading 1 2; (type(0=off 1=on), s parameter (pos. integer min 1)
  end;
end;
;
exit ;
```

Wkin_dll input file example, deterministic airy

```
begin wkin_input ;
  wavetype 2 ; 0=regular, 1=irregular, 2=deterministic
  wdepth 220.0 ;
;
  begin det_airy ;
    stretching 0; 0=none, 1=wheeler
    file ..₩waves₩elevation.dat ;
    nsamples 32768 ;
    nskip 1 ;
    columns 1 2 ; time column, elevation column
  end;
end;
exit ;
```

..\waves\elevation.dat   file example

```
time, elevation
0.0   0.0
0.1   0.2
0.2   0.4
0.3   0.6
0.4   0.8
0.5   0.9
0.6   1.0
0.7   0.9
0.8   0.8
0.9   0.6
```


Wkin_dll input file example, stream function

```
begin wkin_input ;
  wavetype 3 ; 0=regular, 1=irregular, 2=deterministic, 3=stream function
  wdepth 40.0 ;
;
 begin strf ;
    wave 8.0 10.0 0.0 ;     Hs,T,current
  end;
end;
;
exit ;
```