Gigawind
Universität Hannover

Institut für Strömungsmechanik
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WaveLoads

A computer program to calculate wave loading on vertical and inclined tubes

User Manual

Version 1.01 August 2005

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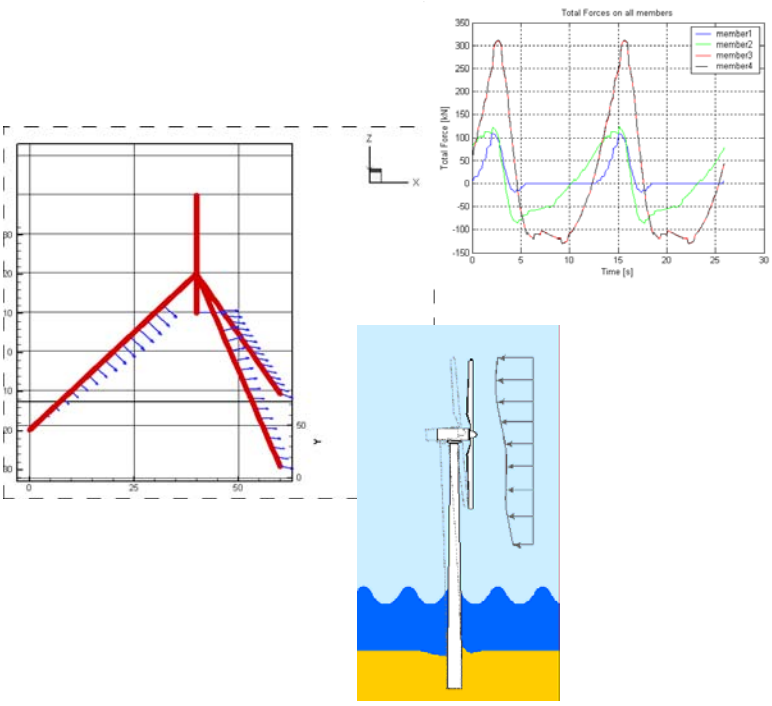

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Introduction

This software for calculating wave induced loading on hydrodynamically transparent structures has been developed by B. Nguyen and K. Mittendorf within the research project “Structure, Design and Environmental Aspects of Offshore Wind-Energy-Converters” (GIGAWIND). This project is supported by the (German) Federal Ministry of Economics and Technology (Bundesministerium für Wirtschaft und Technologie).

The research group GIGAWIND at Hannover University deals with environmental and structural design aspects of offshore wind-energy converters (OWEC). One aim of this research is to develop and improve methods and tools for the design and construction of offshore wind-energy-turbines in order to optimize their design and to reduce construction and operating costs. To reach this aim there is a need for having a reliable tool for calculating wave loading on OWEC support structures. Therefore, the software “WAVELOADS, which includes both regular and irregular wave loading, was developed.

The Fluid Mechanic Institute limits the user support for WAVELOADS. However, questions, remarks, bug reports, suggestions etc. that may contribute to the continued development of WAVELOADS are always welcome and we will try to respond as soon as possible. Please send your bug reports to mdorf@hydromech.uni-hannover.de or nba@hydromech.uni-hannover.de. A current version of WAVELOADS will be available through the GIGAWIND web-site (www.gigawind.de), once the user has signed a licence agreement.

Available Wave Theories

This section gives a short overview of the wave theories available in WaveLoads. The intention is to give the user an idea of what is behind the offered possibilities. For more detailed and comprehensive information, other sources should additionally be consulted. A short list of recommended reading is added.
For calculation of regular waves, eight theories have been implemented; four analytical solutions and four iterative approaches. For irregular waves, wave spectra approaches are available using superposed linear waves. The inclusion of non-linear irregular waves through the Local Fourier Approximation is currently under progress.
Mostly 2D-waves are calculated. Additionally, a 3D-spectral approach is included.

Governing differential equations and boundary conditions

Some general equations have to be fulfilled by the solutions for the wave kinematics. They include the mass conservation law and constraints at the bottom and the free surface.

Laplace's equation: $$\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial z^2}=0$$

ϕ : velocity potential
x : wave propagation direction
z : upward direction, origin in MWL

The velocity potential yields the velocities as:

$$u=\frac{\partial\Phi}{\partial x}; \qquad v=\frac{\partial\Phi}{\partial z}$$

The relation between the velocity potential Φ and the stream function Ψ being:

$$\frac{\partial\Phi}{\partial x}=\frac{\partial\Psi}{\partial z}; \qquad \frac{\partial\Phi}{\partial z}=-\frac{\partial\Psi}{\partial x}$$

follows the Laplace equation for Ψ:

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial z^2}=0$$

For solving the preceding differential equations following boundary conditions are used:

1. bottom boundary condition
   $$-\frac{\partial\Phi}{\partial z}=0 \quad \text{on } z=-d; \quad d: \text{water depth}$$
2. kinematic free-surface boundary condition
   $$-\frac{\partial\Phi}{\partial z}=\frac{\partial\eta}{\partial t}-\frac{\partial\Phi}{\partial x}\frac{\partial\eta}{\partial x} \quad \text{on } z=\eta(x,t); \quad \eta: \text{surface elevation}$$

3. dynamic free-surface boundary condition
$$\frac{p}{\rho}+\frac{(\partial\Phi/\partial x)^2+(\partial\Phi/\partial z)^2}{2}-\frac{\partial\Phi}{\partial t}+gz=B \qquad \text{on } z=\eta(x,t)$$
4. for regular waves: periodic lateral boundary condition
$$\Phi(x,z,t)=\Phi(x+L,z,t)=\Phi(x,z,t+T)$$

Assumptions for solving are that the flow is irrotational and the water is inviscid.

Airy's or linear wave theory

Airy's wave theory describes the propagation of a sine wave. For calculating the kinematics, a solution for the velocity potential is found. As is apparent in the name linear wave theory, only linear terms are considered.
Amplitudes are assumed to be small. The dynamic boundary condition on the surface is thus simplified to:

$$-\frac{\partial\Phi}{\partial t}+gz=B \qquad \text{on } z=0 \text{ (small amplitude)}$$

Thus the solution for a simple sine wave is obtained:

$$\eta(x,t)=\frac{H}{2}\cos(kx-\omega t)\,; \qquad \omega=\frac{2\pi}{T}\,; \qquad k=\frac{2\pi}{L}$$
$$u=\frac{H}{2}\omega\frac{\cosh k(d+z)}{\sinh kd}\cos(kx-\omega t)\,; \qquad w=\frac{H}{2}\omega\frac{\sinh k(d+z)}{\sinh kd}\sin(kx-\omega t)$$
$$\frac{\partial u}{\partial t}=\frac{H}{2}\omega^2\frac{\cosh k(d+z)}{\sinh kd}\sin(kx-\omega t)\,; \qquad \frac{\partial w}{\partial t}=\frac{H}{2}\omega^2\frac{\sinh k(h+z)}{\sinh kh}\cos(kx-\omega t)$$

d : water depth
H : wave height
η : surface elevation
ω : angular frequency
z : coordinate from MWL upward
k :wave number

Stokes 2nd, 3rd and 5th order theory

The Stokes waves are extensions to Airy's theory, still assuming small amplitudes. They give a more realistic surface with higher, narrower crests and lower, broader troughs. For their development, the velocity potential is written as an expansion $\Phi=\varepsilon^0\Phi_1+\varepsilon^1\Phi_2+\varepsilon^2\Phi_3\ldots$, with ε=ka, which is assumed to be small. Therefore, terms of higher order of ε are neglected. The order of the theory is the number of terms considered. For the 1st order, $a=0.5H$ and the equations become the same as in Airy's theory. The expressions for Φ_1, Φ_2, etc. remain the same for each extension. The changes are for ε which is still dependent on the wave height but with increasingly complicated expressions. The solutions which are obtained through successive approximation become more complicated for each expansion.
Here the surface elevation for Stokes 2nd order theory is given:

$$\eta(x,t)=\frac{H}{2}\cos(kx-\omega t)+\frac{\pi H^2}{4L}\left(1+\frac{3}{2\sinh^2 kd}\right)\coth kd\cdot\cos 2(kx-\omega t)$$

For higher order waves, this expression is extended by more cosine terms and altered by other coefficients. The coefficients differ by author, in WaveLoads the ones by Wiegel are used for 2nd and 3rd order, for 5th order the ones after Fenton are used.
Mean water level is lifted by Δh from still water level. For 2nd order theory the lift in mean water level in the formulation after Wiegel is:

$$\Delta h = \frac{\pi H^2}{4L}\left(1 + \frac{3}{2\sinh^2 kd}\right)\coth kd$$

This term differs from that of the commonly used one by the expression in the brackets.
For higher order theories, the wave frequency will become dependent on the amplitude.
Stokes' wave theories are valid for d/L<0.125.

Lagrangian wave in the formulation by Woltering

In contrary to the prior ones, this formulation uses the Lagrangian approach. Thus the water particles are traced over time through space. The surface elevation is viewed as the result of the upper particles' movement along their orbits. The Lagrangian surface contains harmonic components of higher frequency. The equations for the orbits are taken from the Eulerian approaches of Stokes' theory. The time derivatives of the orbit equations give the wave kinematics. The coordinates of the surface particles' orbit origin (x_0, z_0), the vertical correction lift Δh and the belonging wave kinematics are calculated iteratively. The first calculation yields wave induced mass transport of the same amount as Stokes' 2nd order drift velocity, in common formulation, causes. For compensation, the mean water level is lifted by Δh. This is gained from the demand of equal areas under crest and trough.

$$\Delta h = \frac{\pi H^2}{4L}\coth\frac{2\pi d}{L}$$

The formulation for the orbits for 1st order theory uses the orbits of Airy's theory:

$$\xi = -\frac{H}{2}\frac{\cosh(2\pi(z_0+d)/L)}{\sinh(2\pi d/L)}\sin\left(2\pi\left(\frac{x_0}{L}-\frac{t_i}{T}\right)\right)$$

$$\eta = \frac{H}{2}\frac{\sinh(2\pi(z_0+d)/L)}{\sinh(2\pi d/L)}\cos\left(2\pi\left(\frac{x_0}{L}-\frac{t_i}{T}\right)\right)+\frac{\pi H^2}{4L}\coth\frac{2\pi(z_0+d)}{L}$$

x_0 = x-coordinate of orbit origin
z_0 = z-coordinate of orbit origin

The orbit's time derivates give the velocities:

$$u = \frac{d\xi}{dt} = \overline{U} + \frac{H}{2}(\omega - k\overline{U})\cos(xk-\omega t)\frac{\cosh(k(d+z))}{\sinh(kd)}$$

$$v = \frac{d\eta}{dt} = \frac{H}{2}(\omega - k\overline{U})\sin(xk-\omega t)\frac{\sinh(k(d+z))}{\sinh(kd)}$$

$\overline{U}$ =current

In WaveLoads, Lagrangian waves of the first order have been implemented.

Stream function solutions

The stream function theory was first introduced by Dean. These approaches solve the problem for the stream function and derive the wave kinematics from it. There exist several formulations for the stream function: the ones by Dean, Fenton and Sobey are included in WaveLoads. All of them use a Fourier series for calculating the stream function and require that the boundary condition is satisfied at the surface. It is a numeric solution of the problem. Differences between the three approaches are apparent for steep waves; the results for gentle slopes are close. There are no assumptions used; only the number of elements in the Fourier series influences the quality.

The boundary conditions for the stream function are:

1. Bottom boundary condition, no flow through sea floor:
   $\Psi(x,-d) = 0$ at $z = -d$
2. kinematic free-surface boundary condition
   $\Psi(x,\eta) = -Q$ at $z = \eta$ Q: net flow between sea surface and seabed
3. dynamic free-surface boundary condition
   $\frac{1}{2}\left\{\left(\frac{\partial \Psi}{\partial x}\right)^2 + \left(\frac{\partial \Psi}{\partial z}\right)^2\right\} + g\eta = B$ at $z = \eta$ B: Bernoulli constant

The first formulation was by Dean. It is a symmetric stream function theory, which is nonlinear and similar to Stokes' higher order theories due to using same assumptions. Consequently some of its limitations are also inherent in this theory.

$$\Psi(x,z) = \frac{L}{T} z + \sum_{n=1}^{N} C_n \sinh\big(nk(d+z)\big)\cos kx$$

The coefficients C_n are found through a best fit to the dynamic free-surface boundary condition, in the least square sense.

Another formulation of this problem is the one by Fenton. It is similar to Dean's stream function theory but has a broader range of applicability. Another advantage is that this theory requires less complicated calculations.

Fenton's stream function is valid in deep and shallow water depths, efficient in calculation of numerical coefficient, and uses $\varepsilon = kH/2$ in the perturbation instead of $\varepsilon = ka$, as in Stokes' theories.

$$\Psi(x,z) = -\overline{U}(d+z) + \left(\frac{g}{k^3}\right)^{1/2} \sum_{j=1}^{N} C_j \frac{\sinh jk(d+z)}{\cosh jkd} \cos jkx$$

Sobey's formulation gives better results for waves near breaking than the other approaches. The iteration also aims to fulfil the surface boundary conditions.

$$\Psi(x,z) = -\overline{U}(d+z) + \frac{g^2}{\omega^3} \sum C_j \frac{\sinh jk(d+z)}{\cosh jkd} \cos jkx$$

Irregular waves through wave spectra

Common modelling of irregular waves consists of superposition of linear waves with differing amplitudes and frequencies. WaveLoads supplies a tool for generating such waves out of wave spectra. These are either parameterised JONSWAP spectra or discretised ones. The JONSWAP-spectrum is used in this form:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} e^{-1.25(\frac{\omega_p}{\omega})^4} \gamma^\delta \qquad \delta = e^{-\frac{(\omega-\omega_p)^2}{2\beta^2\omega_p^2}} \qquad \alpha = 0.076\left(\frac{gX}{u^2}\right)^{-0.22} (= 0.0081)$$

X = wind fetch length
u = wind velocity
ω_p = peak frequency
γ = 3.3
for $\omega<\omega_p$: $\beta = \beta_1$ (=0.07)
for $\omega>\omega_p$: $\beta = \beta_2$ (=0.09)

The formulation for the JONSWAP spectrum using significant wave parameters H_s and T_p as given in "*Offshore Standard DNV-OS-J101, June 2004*" has likewise been implemented. This calculates the parameter γ using the above-mentioned values in the following way:

$$\gamma = \begin{cases} 5 & : \frac{T_p}{\sqrt{H_s}} \le 3.6 \\ \exp 5.75 - 1.15\frac{T_p}{\sqrt{H_s}} & : 3.6 \le \frac{T_p}{\sqrt{H_s}} \le 5 \\ 1 & : 5 < \frac{T_p}{\sqrt{H_s}} \end{cases}$$

Observe that the following expressions include some random values. Therefore two calculations using the same parameters will not give the same time series.
The generated waves are linearly superposed by one of the following methods:
For all methods:

$$\eta(t) = \sum_{n=1}^{N} A_n \cos(\omega_n t + \varphi_n)\,; \qquad \varphi_n \text{ is uniformly distributed}$$

1. constant frequency interval, gives periodic waves
$$\Delta\omega = \frac{\omega_{\max} - \omega_{\min}}{N}$$
$$A_n = \sqrt{2S_{zz}(\omega_n)\Delta\omega_n}$$
2. irrational frequency, gives non-periodic waves
$$\Delta\omega_n = \sqrt{n/(n+1)} \cdot \omega_{\max} / \left(\sum_{n=1}^{N} \sqrt{n/(n+1)} \right)$$
$$A_n = \sqrt{2S_{zz}(\omega_n)\Delta\omega_n}$$
3. Webster&Trudell, gives non-periodic waves
$$A_n = \sqrt{2m_0 / N}$$
$$Ar_n = \frac{m_0}{N}; \qquad m_0 = \int_0^\infty S_{zz} d\omega$$

Ar_n is the area under the spectral function for the frequency interval $\Delta\omega_n$

$\Delta\omega_n$ is calculated through the condition that Ar_n is the same for all $\Delta\omega_n$

Furthermore it is possible to give a directional wave spectrum. This gives for each frequency (i.e. wave component) its main direction and spread, in addition to its magnitude. The spectral density is distributed over the direction by multiplying the non-directional spectrum with the spread function *D*.

$$S(\omega,\theta) = S(\omega)D(\theta)$$

S(ω) is calculated according to the above described methods.
Two spread functions are implemented,

1. Cosine model

   $$D(\theta) = \frac{2}{\pi}\cos^2(\theta-\theta_0)\,; \qquad -\frac{\pi}{2} \le \theta \le \frac{\pi}{2}$$

   θ is the frequency direction
   θ_0 is the main peak frequency direction
2. Banner's hyperbolic model

   $$D(\theta,\omega) = \frac{1}{2}\beta\cosh^{-2}(\beta(\theta-\theta_0))$$

   in which $\beta \propto \frac{\omega}{\omega_p}$; ω is the frequency; ω_p is the frequency of the peak

   $$\beta = \begin{cases} 1.24 & : \frac{\omega}{\omega_p} < 0.56 \\ 2.61(\frac{\omega}{\omega_p})^{1.3} & : 0.56 < \frac{\omega}{\omega_p} < 0.95 \\ 2.28(\frac{\omega}{\omega_p})^{-1.3} & : 0.95 < \frac{\omega}{\omega_p} < 1.6 \\ 10^{-0.4+0.8394\exp\left[-0.561\ln(\frac{\omega}{\omega_p})^2\right]} & : \frac{\omega}{\omega_p} > 1.6 \end{cases}$$

When using the non-directional quasi-2D-spectrum, another method for calculating the random numbers is used.

Local Fourier approximation for irregular waves

A new feature of WaveLoads is the Local Fourier Approximation for irregular waves; which also works for regular waves. This is presently not included in the distributed version. Nevertheless a short description is included for future reference.

The local Fourier Approximation (LFA) was developed by Sobey. The wave kinematics are predicted using a given surface time series at a fixed location. The LFA is an extension of the Fourier model for regular waves, finding the solution over a moving time window. For each window, the velocity potential is expressed as:

$$\Phi(x,z,t) = U_E x + \sum_{j=1}^{J} A_j \frac{\cosh jk(d+z)}{\cosh jkd}\sin j(kx-\omega t)$$

with U_E = Euler current [m/s],
d : water depth [m],

A_j : Fourier coefficients,
k: wave number [1/m],
ω : angular wave frequency [1/s]
j = order of Φ

For each window *i,* the kinematic free surface boundary condition is formulated for each surface node:

$$f_i^{kin}(\omega,k,kx,A_j) = gw_i - \frac{D}{Dt}\left(\frac{\partial\Phi}{\partial t}\right)\bigg|_i + u\frac{Du}{Dt}\bigg|_i + w\frac{Dw}{Dt}\bigg|_i = 0$$

and the dynamic free surface condition is formulated for each node as:

$$f_i^{dyn}(\omega,k,kx,A_j) = \frac{\partial\Phi_i}{\partial t} + \frac{1}{2}u_i^2 + \frac{1}{2}w_i^2 + g\eta_i - B = 0$$

with B : Bernoulli constant

These non-linear, implicit equations with the unknown *ω*, *k*, A_j and *kx* are solved numerically.

Mass transport

Mass transport takes into consideration that a mean flux exists in wave direction. It is a non-periodic drift in the direction of wave propagation in the formulation of velocities in the theories of higher order. It influences the wave's length and the velocity in the wave propagation direction. Two approaches for calculating the mass transport are implemented:

- Stokes mass transport due to Stokes' drift velocity or mass transport velocity.
- Eulerian mass transport which is due to asymmetry of velocities at a fixed point.

Stretching

For Airy's theory, the wave kinematics' calculation is only valid up to mean water level. To remedy this, either the values are extrapolated or the results are stretched (or compressed) to the actual water level with Wheeler's stretching function. This transforms the term (k(d+η)) in some hyperbolic trigonometric functions to (kd). For example, in the calculation of the velocity in wave direction, the term $\cosh(k(d+\eta))/\sinh(kd)$ becomes $\cosh(kd)/\sinh(kd)$.

Load Calculation

Morison equation

WaveLoads calculates the loads due to wave impact on defined structures with diameters considerably smaller than the wave length. For that the well known Morison equation is used:

$$dF = c_m\rho\frac{\pi D^2}{4}\frac{\partial v}{\partial t} + c_d\frac{\rho}{2}D|v|v\,.$$

In WaveLoads, ρ is assumed to be 1025 kg/m³.
Lift forces due to wave impact are not considered.

Coefficients in Morison equation

In the Morison equation the parameters c_d and c_m are used. They are dependent upon the state of flow and the structure. These dependencies are expressed by the Reynolds-number Re, by the Keulegan-Carpenter-number KC and the structure's roughness k/D. Extensive experiments have been done by Turgut Sarpakya to obtain values for c_d and c_m. His results are often used and have been curve-fitted for usage in numerical computations.

Adapted Morison equation for inclined tubes

For inclined tubes, an adapted Morison equation is used.
The unit vector in axial direction being

$$e_t^T = (e_x, e_y, e_z) = (\sin\varphi\cos\vartheta, \sin\varphi\cos\vartheta, \cos\varphi)$$

the velocity terms can be written as follows:

$$v_x = u - e_x(e_x u + e_y v + e_z w),$$

$$v_y = v - e_y(e_x u + e_y v + e_z w),$$

$$v_z = w - e_z(e_x u + e_y v + e_z w).$$

This leads to the absolute value for the velocity:

$$|v_N| = \sqrt{u^2 + w^2 - (e_x u + e_z w)^2}$$

The terms for acceleration are formed analogously.
For calculating the wave forces in the respective direction following expressions are used:

$$f_x = c_m \rho \frac{\pi D^2}{4} \frac{\partial v_x}{\partial t} + c_d \frac{\rho}{2} D |v_N| v_x$$

$$f_y = c_m \rho \frac{\pi D^2}{4} \frac{\partial v_y}{\partial t} + c_d \frac{\rho}{2} D |v_N| v_y$$

$$f_z = c_m \rho \frac{\pi D^2}{4} \frac{\partial v_z}{\partial t} + c_d \frac{\rho}{2} D |v_N| v_z$$

Recommended Reading

General:

Dean, R.G., Dalrymple, R.A. *Water Wave mechanics for engineers and scientist*. World Scientific, Singapore, 1984
Massel, S.R. *Ocean surface waves: their physics and prediction.* World Scientific, Singapore, 1996
Wiegel, R.L. *Oceanographic Engineering.* Prentice-Hall, Englewood Cliffs, 1964

Special waves:

Sobey, R.J. A local Fourier approximation method for irregular wave kinematics. *Applied Ocean Research*, Vol. 14 pp. 93-105. 1992
Woltering, S. *Eine LAGRANGEsche Betrachtungsweise des Seeganges*. Dissertation, Franzius-Institut, Universität Hannover, 1996

Loads:

Abdelradi, M.E. *The curve fitting of Sarpkaya's results for inertia draft and lift coefficients.* Dep. of Naval Architecture, University of Glasgow, 1983
Sarpkaya, T. *Mechanics of wave forces on offshore structures.* Van Nostrand Reinholdt Comp. Inc., 1981

WaveLoads in MS-DOS Environment

For all applications, WaveLoads can be started in the MS-DOS environment. WaveLoads consists of a single executable file. Further you need two ASCII-files, one file describing the wave condition and a second one for the structure information. When using the discretised spectrum, an additional file containing the spectrum is required.
To start the program type:

WaveLoads {name of wave parameter file} {name of structure parameter file}

and press return (compare with Figure 1). The calculation will start immediately and the results will be written in several ASCII-files.

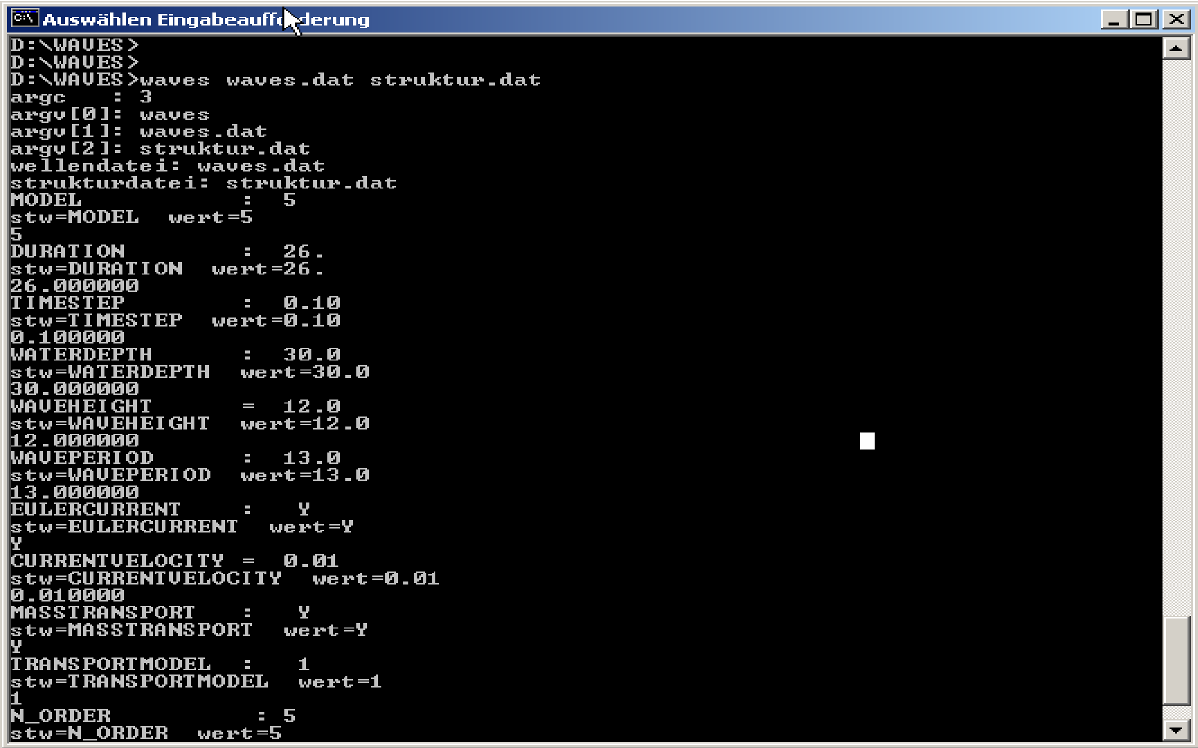

Figure 1 Starting a calculation with WaveLoads in a MS-DOS environment

Graphical User Interface

For most applications, the graphical user interface (GUI) can be used. In this one can create input files or load existing input files and run the program. When the calculation is concluded, the resulting wave elevations, integral forces, and moments will be graphically shown. Figure 3 shows the integrated force on the fourth member of a composed structure. The integrated forces are shown for the specified substructures and moments are shown for the reference points. Additionally all results will be written into output files as described in following sections.
Figure 2 shows the general layout of the GUI. For using, define the wave parameters and the structure, then press the *Calculate* button. To load existing input files or for saving, use the menu *File/Load Wave Parameter* and its equivalents. The button *Graphic* gives a general view of the structure, see Figure 4.
In general the GUI's features are the same as when working in the MS-DOS environment. One exception is that it is not possible for wave spectra to be calculated without use of

direction. Using the directional information enhances calculating time considerably (ca. factor 50). Another limitation with using the GUI is that the maximum number of reference points for which the moment is calculated is three, compared to five when working in the MS-DOS environment.

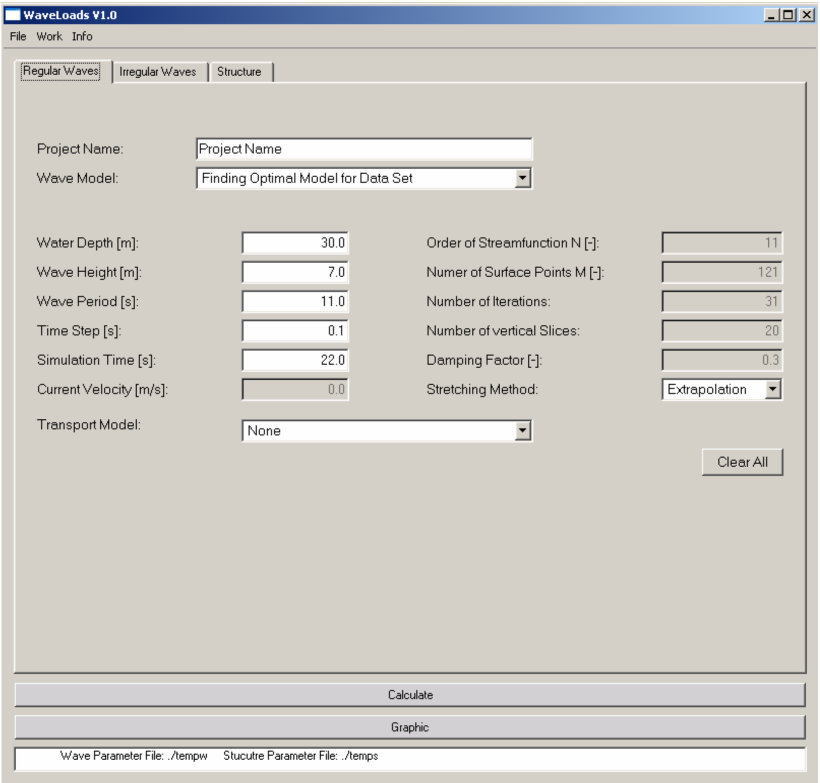

Figure 2 Graphical User Interface

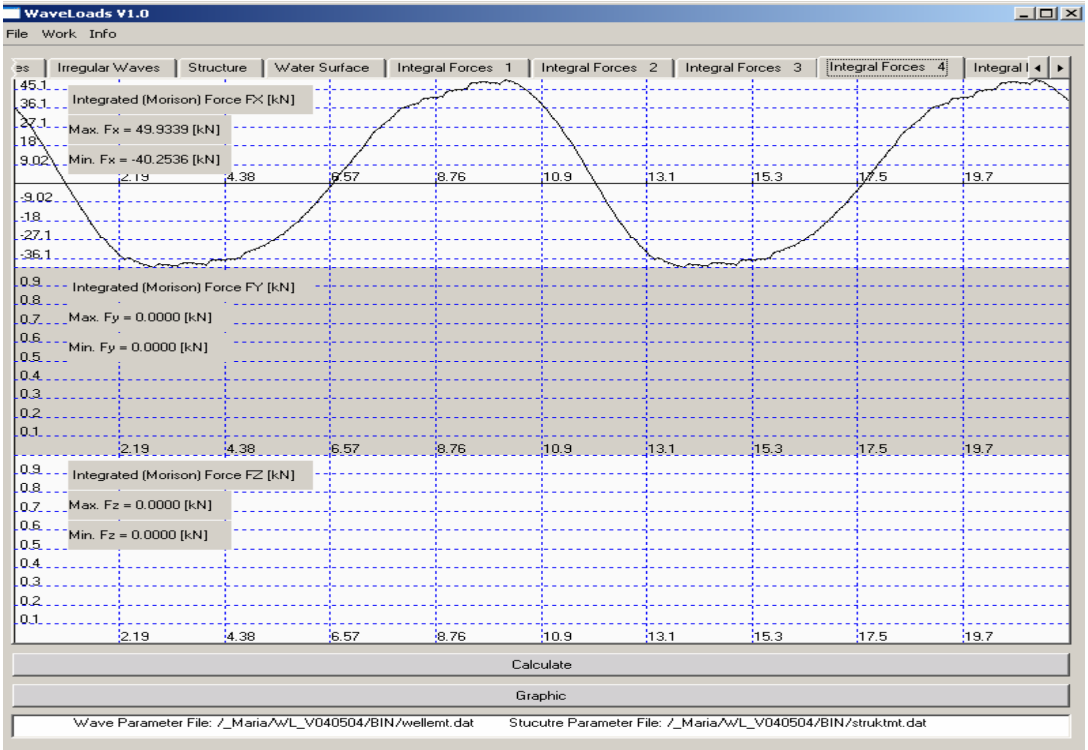

Figure 3 Graphical output of results

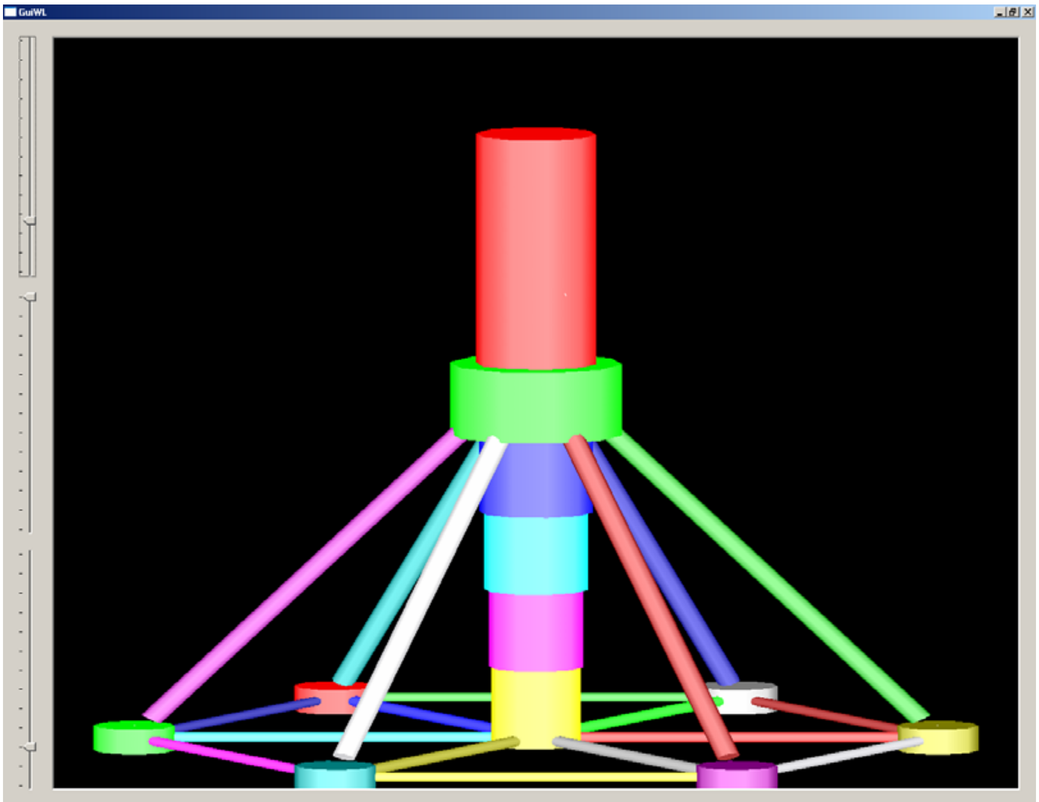

Figure 4 Graphic for complex structure in GUI

Input Files

Every line beginning with *'#'* is a comment und will be ignored. The parameters, which can be defined by a user, always start with a special keyword followed by ":" and the value which is to be given in SI-units ([m],[kg],[s]).

Note: When a spectrum is defined by parameters the frequency is given as the angular frequency $\omega=2\pi f$. If the spectrum is defined through a file containing the discretised spectrum, this spectrum uses *f* as frequency.

Input file for wave parameters

Here is a list with all possible keywords.

MODEL following wave theories can be chosen

- 0 Calculation and comparison of boundary conditions errors for the wave models Airy, Stokes 1-5
- 1 Stokes First Order Theory (Airy)
- 2 Stokes Second Order Theory
- 3 Stokes Third Order Theory
- 4 Lagrangian formulation by Woltering
- 5 Stokes Fifth Order Theory
- 6 Stream function Theory in Formulation by Sobey
- 7 Stream function Theory in Formulation by Fenton
- 8 Stream function Theory in Formulation by Dalrymple
- 9 Wave Spectra Approach

LABEL here a name for the problem can be defined

DURATION defines the simulation time in seconds - only for regular wave models

TIMESTEP defines the time step

WATERDEPTH the fixed water depth in meters

WAVEHEIGT wave height in meters

WAVEPERIOD wave period in seconds
only if WAVELENGTH is not active,
you can decide whether you want to describe the wave by period or by wavelength

WAVELENGTH wave length in meter
only if WAVEPERIOD is not active,
you can decide whether you want to describe the wave by period or by wavelength

EULERCURRENT The calculation can be performed with or without a constant (basic) current component

Y for YES, calculation with current
N for NO, calculation without current

CURRENTVELOCITY (Basic) current velocity in meter/second, value > 1 in direction of wave propagation, value < 1 opposed to wave propagation, if calculation shall be performed with constant current

MASSTRANSPORT Calculations can be performed with or without mass transport

Y for YES, calculation with mass transport
N for NO, calculation without mass transport

TRANSPORTMODEL If mass transport is activated you can chose between two ways for the series expansion of high order WaveLoads of the non-periodic component.
0 no mass transport
1 Stokes transport model
2 Euler transport model

STRECHINGSMODE Method for finding the wave kinematics above mean water level
0: Extrapolation of Airy results from mean water level
1: Wheeler's stretching method

Only necessary for Stream Function Theories:

N_ORDER Order of the Fourier series, maximum order is 15

MPUNCT Number of segments on wave profile, must be odd, default 121, for Fenton it must be larger than 100, for others a value of about 20 suffices

KMAX The upper limit for the number of iterations

DEANDAMPING Damping coefficient for the iteration default 0.3

If stream function theory by Fenton is chosen:

FENTONSTEP: Subdividing the vertical direction in N zones for calculation default N=10

Only necessary for Wave Spectrum Approach:

SEEGANG_3D_OBERFLAECH 1: a file with a time dependent 3D surface profile will be generated for Tecplot file name `Seegang_3DXYZOberflaech.plt`

	0: no water surface file will be generated
SEEGANG_DURATION	duration for the sea state simulation in seconds
SEEGANG_TIMESTEP	defines the time step for the simulation
SEEGANG_TIEFE	the fixed water depth in meters
X_SEASTREAM	current velocity in meter/second in x-direction
Y_SEASTREAM	current velocity in meter/second in y-direction
SEEGANG_SPECTRUM_MODE	0: parameterised JONSWAP Spectrum using coefficients 1: discretised spectrum given by data file 2: parameterised JONSWAP Spectrum with H_s and T_p
SEEGANG_SPECTRUM_DATAFILE	file name for a discretised spectrum (*if* SEEGANG_SPECTRUM_MODE=1)
SEEGANG_N_OMEGA	number of grid points for dividing the wave spectrum
SEEGANG_SUPERPOS_MODE	1: Mode 1, constant $\Delta\omega$ 2: Mode 2, irrational ω 3: Mode 3, Webster & Trudell

for details look into section: *Irregular waves through wave spectra*

SEEGANG_OMEGA_MIN	lowest frequency ω_{min}
SEEGANG_OMEGA_MAX	highest frequency ω_{max}

If no discretised spectrum file is defined you have to give all recommended parameters for a JONSWAP spectrum

SEEGANG_ALPHA	Phillips Alpha constant for high frequency tail
SEEGANG_BETA1	relates respectively to the widths of the left side of the spectral peak
SEEGANG_BETA2	relates respectively to the widths of the right side of the spectral peak
SEEGANG_GAMMA	peak enhancement factor
SEEGANG_OMEGA_M	peak frequency

SEEGANG_STAT	name of gauging station
SEEGANG_MART	kind of measurement, e.g. buoy
SEEGANG_DATUM	date of measurement, YYYYMMDD
SEEGANG_UHRZEIT	time of measurement, hhmm
SEEGANG_DIRECTION_MODEL	-1 : non-directional spectrum 0 : directional spectrum (JONSWAP
parameterised	SEEGANG_SPECTRUM_MODE =0) based on a cosine power model. 1 : directional spectrum (JONSWAP
parameterised	SEEGANG_SPECTRUM_MODE =0) based on Banner's hyperbolic type model.
SEEGANG_PEAK_THETA0	if SEEGANG_DIRECTION_MODEL = 1 the peak wind direction angle has to be defined in radian ($-\pi$ – + π)
SEEGANG_SPREAD	if SEEGANG_DIRECTION_MODEL = 0 the spreading angle theta in radian has to be defined. ($-\pi$ – + π)
SEEGANG_HS	if SEEGANG_SPECTRUM_MODE = 2 the significant wave height has to be defined
SEEGANG_TP	if SEEGANG_SPECTRUM_MODE = 2 the the peak period has to be defined

A simple wave input file for regular waves could look like this:

```
# WAVELOADS STEERING FILE
#
MODEL         :  5
# 5  STOKES FITH ORDER THEORY
#
DURATION       :  30.
# simulating 30 seconds
#
TIMESTEP       :  .1
# time step is 0.1 second
#
WATERDEPTH      :  30.0
# water depth 30 m
#
WAVEHEIGHT      =  12.0
# wave height 12 m
```

```
#
WAVEPERIOD      :  13.0
# wave period 13 s
#
# alternative
#WAVELENGTH      :  200.
# switched off
#
EULERCURRENT    :   N
# without Euler- current
#
CURRENTVELOCITY =  0.01
# will be ignored, because EULERCURRENT is switched off
#
MASSTRANSPORT   :   N
# without mass transport
#
TRANSPORTMODEL  :   0
# no mass transport
#
# THE END
```

Input file for discretised spectrum

The input file for a discretised spectrum is structured as follows:
Information about where and when the spectrum was measured is specified in the first line. The second line contains the peak frequency, the energy of the peak frequency, its direction and spread, the significant wave height, height of long waves(T>10s), mean period, zero-crossing period, wave length and the number of values. Significant among those are the peak frequency and its energy as the first two values and the last value, the number of following value groups. The following value groups are written in the order frequency, energy, main direction, spread. The latter two are only of significance if directional sea state is considered.

Note: Be careful to have the same amount of letters and digits as in the example. The first frequency in the discretised file must be larger than zero. All frequencies are in [Hz] and the angles are in [°].

```
HEL WR  199503221800
0.160  4.37200  44  -1  1.81  6.25  5.60  5.40  6.08  33
0.030  0.03322  80  -10
0.040  0.01275  12  -12
0.050  0.01438  65  -15
0.060  0.00987  18  -18
0.070  0.01442  70  -20
0.080  0.02476  22  -22
0.090  0.05182  25  -25
0.100  0.08146  28  -1
0.110  0.24910  30  -1
0.120  0.25330  33  -1
0.130  0.62340  35  -1
0.140  2.95000  38  -1
0.150  3.69400  41  -1
0.160  4.37200  44  -1
0.170  1.92300  45  -1
0.180  0.73890  48  -1
0.190  0.51770  55  -1
0.200  0.55240  54  -1
```

0.210 0.89860 56 -1
0.220 0.75430 57 -1
0.230 0.47660 60 -1
0.240 0.30280 -01 -1
0.250 0.31520 -03 -1
0.260 0.26500 -04 -1
0.270 0.16110 -07 -1
0.280 0.14690 -10 -1
0.290 0.17340 -08 -1
0.300 0.11790 -12 -1
0.310 0.11710 -15 -1
0.320 0.12920 -18 -1
0.330 0.11000 -21 -1
0.340 0.06794 -22 -1
0.350 0.06085 -29 -1

Input file for structure parameters

In this file the number of circular structure components and their location will be defined. The user has to enter the inertia and drag coefficients as well as the diameter. The coordinate system is a right handed system.

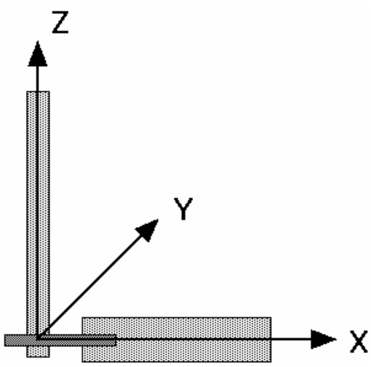

Figure 5 WAVELOADS uses a right handed coordinate system

The x-axis is the wave propagation direction. The origin in z-direction is located on the mean water level. Up is positive and down is negative on the scale; so the sea bottom is at the negative water depth.
To define a structure the ending points of its components are specified, as well as their diameter and the Morison coefficients to be used for each part. Additionally the number of elements or nodes for the calculating is given. As loads are calculated for the defined structures, the number of nodes influences the calculated integral forces and moments.
It is necessary to define at least one reference point for which the moment will be calculated.

The list of all available keywords and their meanings:

NSUBSTRUCT defines the number of structure components

SUBSTRUCTINDEX index of a substructure, always starting with 0, so the first index of the first member is 0

XU	x-coordinate of the upper endpoint of the current member
YU	y-coordinate of the upper endpoint of the current member
ZU	z-coordinate of the upper endpoint of the current member
XL	x-coordinate of the lower endpoint of the current member
YL	y-coordinate of the lower endpoint of the current member
ZL	z-coordinate of the lower endpoint of the current member
RADIUS	radius of the circular member in meter
CD	drag coefficient [default=0.7]
CM	inertia coefficient [default=2.0]
NELEMENT	number of elements, in which the structure is divided
NNODES	instead of NELEMENT Number of nodes, in which the structure is divided NNODES = NELEMENT+1

According to the number of members this block must be repeated!

NUMBMOMTREF	Number of reference points for calculating the moment (limited to max. 5 points)
MOMTREFINDEX	Index of a reference point, always starting with 0
XM	x-coordinate of the node for moment calculation
YM	y-coordinate of the node for moment calculation
ZM	z-coordinate of the node for moment calculation

According to the number of nodes for moment calculation this block must be repeated!

A structure input file describing two members could look like this:

```
NSUBSTRUCT     :   2
#
SUBSTRUCTINDEX :   0
#
XU             :   0.0
#
YU             :   0.0
#
```

ZU : 20.0
#
XL : 0.0
#
YL : 0.0
#
ZL : -30.0
#
RADIUS : 0.455
#
CD : 0.7
#
CM : 2.1
#
NELEMENT : 50
#
SUBSTRUCTINDEX : 1
#
XU : 0.
#
YU : 0.
#
ZU : 10.0
#
XL : 10.
#
YL : 0.
#
ZL : -30.
#
RADIUS : 0.455
#
CD : 0.700
#
CM : 2.0000
#
NELEMENT : 40
NUMBMOMTREF : 2
#Number of reference points on the structure, where the moments of Morison forces must be calculated
#
#Coordinates of the first point: (index from 0 up to NUMBMOMTREF-1)
MOMTREFINDEX : 0
#
XM : 0.0
 # [m]
YM : 0.0
 # [m]
ZM : -30.0
 # [m]
#
#Coordinates of the second point: (index from 0 up to NUMBMOMTREF-1)
MOMTREFINDEX : 1
#
XM : 0.0
 # [m]
YM : 0.0
 # [m]
ZM : 10.0

 # [m]
#
 # End of the input block

Output Files

In the file `*_integralkraft.plt` the integrated force is saved specified for substructures for all models except model 0.

Model 0 output files

1. **Allwaves_Fskindynbc.plt** file including water surface profiles, orbital velocities, orbital accelerations and kinematic and dynamic free surface boundary condition errors for the Airy and Stokes wave theories.

Airy theory output files

1. wellenpar.dat ASCII-FILE containing general information about the calculated wave
1. **w_moris.fem** File prepared for processing with ANSYS
2. **w_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
3. w_fskindynbc.plt All calculated parameters in Tecplot-style for surface
4. **w_morissubstr.plt** All calculated parameters over structure in Tecplot-style
5. w_surface.plt The calculated surface depending on time
6. **w_structmoment.plt** The calculated moments at (a) chosen point(s)

Stokes 2nd order output files

1. **zstokes2_moris.fem** File prepared for processing with ANSYS
2. **zstokes2_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
3. **zstokes2_substr.plt** All calculated parameters over structure in Tecplot-style
4. zstokes2_surface.plt The calculated surface depending on time
5. zstokes2_param.plt All calculated parameters in Tecplot-style

6. **zstokes2_structmoment.plt** The calculated moments at (a) chosen point(s)

Stokes 3rd order output files

1. stokes3_par.dat parameters for Stokes wave
2. **dstokes3_moris.fem** File prepared for processing with ANSYS
3. **dstokes3_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
4. **dstokes3_substr.plt** All calculated parameters over structure in Tecplot-style
5. dstokes3_surface.plt The calculated surface depending on time
6. **dstokes3_structmoment.plt** The calculated moments at (a) chosen point(s)
7. dstokes3_fskindynbc.plt All calculated parameters on surface over time

Stokes 5th order output files

1. wellenpar.dat ASCII-FILE containing general information about the calculated wave.
2. **stokes5_moris.fem** File prepared for processing with ANSYS
3. **stokes5_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
4. stokes5_accexz.plt A time series of the acceleration in x- and z-direction. Tecplot –style
5. **stokes5_substr.plt** All calculated parameters over structure in Tecplot-style
6. stokes5_surface.plt The calculated surface depending on time
7. stokes5_oberfl.plt The calculated surface depending on space
8. stokes5_xvelo.plt The calculated horizontal velocities depending on time
9. stokes5_zvelo.plt The calculated vertical velocities depending on time
10. **stokes5_structmoment.plt** The calculated moments at (a) chosen point(s)
11. stokes5_fskindybc.plt All calculated parameters on surface over time

12. stokes5_param.dat Parameters for Stokes wave

Lagrangian approach by Woltering output files

1. wellenpar.dat ASCII-FILE containing general information about the calculated wave
2. Oberflach.fil surface over time
3. **lgr_moris.fem** File prepared for processing with ANSYS
4. **lgr_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
5. lgr_surface.plt The calculated surface depending on time
6. lgr_oberfl.plt The calculated surface depending on space
7. lgr_fskindynbc.plt All calculated parameters at surface in Tecplot-style
8. **lgr_substr.plt** All calculated parameters over structure in Tecplot-style
9. **lgr_structmoment.plt** The calculated moments at (a) chosen point(s)

Stream function by Dean-Dalrymple output files

1. **dalrymple_moris.fem** File prepared for processing with ANSYS
2. **dalrymple_substr.plt** All calculated parameters over structure in Tecplot-style
3. dalrympletest.dat Test file containing STREAM FUNCTION COEFFICIENTS
4. **dalrymple_structmoment.plt** The calculated moments at (a) chosen point(s)
5. dalrymple_surface.plt The calculated surface over time
6. **dalrymple_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
7. dalrymple_velo_acce.plt Calculated velocities, accelerations and water surface elevation in Tecplot-style
8. wavepar.dat empty file

Stream function by Fenton output files

1. **fenton_moris.fem** File prepared for processing with ANSYS
2. **fenton _substr.plt** All calculated parameters over structure in Tecplot-style
3. testfenton.dat Test file
4. **fenton_structmoment.plt** The calculated moments at (a) chosen point(s)
5. **fenton_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
6. fenton_surface.plt Calculated water surface elevation in Tecplot-style, note: time not in seconds, but in time steps!
7. fenton_oberfl.plt calculated water surface over space
8. wavepar.dat ASCII-FILE containing general information about the calculated wave
9. Fentontest.dat empty file

Stream function by Sobey output files

1. **sobey_substr.plt** All calculated parameters over structure in Tecplot-style
2. **sobey_structmoment.plt** The calculated moments at (a) chosen point(s)
3. **sobey_moris.fem** File prepared for processing with ANSYS
4. **sobey_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
5. sobey_surface.plt Calculated water surface elevation in Tecplot-style
6. sobey_info.dat parameters of Sobey wave

Wave spectrum approach output files

When using the wave spectrum approach it depends on the kind of spectrum chosen which output files are written.

1. **seegang_integralkraft.plt** This file contains a time series of the integrated Morison-forces in [kN] in all possible directions
2. **seegang_moris.fem** File prepared for processing with ANSYS
3. seegang_param.dat File with all wavelets, if discretised spectrum
4. **seegang_structmoment.plt** The calculated moments at (a) chosen point(s)
5. **seegang_substr.plt** All calculated parameters over structure in Tecplot-style
6. seegang_2DXZoberfl.plt 2D water surface elevation in Tecplot style
7. seegang_dataspec.plt Input spectrum in Tecplot style, if discretised spectrum
8. seegang_spectrum.plt Spectrum of the calculated sea state in Tecplot style
9. *optional* Seegang_3DXYZOberflaech.plt 3D time dependent water surface elevation in Tecplot style
10. surf.dat empty file

Effects of Using different Wave Theories

In this section the different wave theories are applied to one exemplary wave on a monopile. The following pictures show the calculated surface elevations and the accumulated forces.

<u>The parameters</u>:

Wave height	17.5 m
Water depth	34.0 m
Wave period	15.0 s
Euler current	0.00 m/s
Stokes Mass transport	

Pile diameter	6.0 m
Pile length	54.0 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	501 [-]

For this wave, with an $H/d \approx 0.5$, the calculated surface elevations for the stream functions are practically identical, see Figure 7. The results for Stokes' fifth order are similar to these. Stokes' 2nd order is apparently now longer valid, as is visible in the trough region, see Figure 6. Interesting in the calculation of accumulated force is the fact that the results for the stream function differ somewhat, see Figure 9, even as the surface elevation is practically the same.

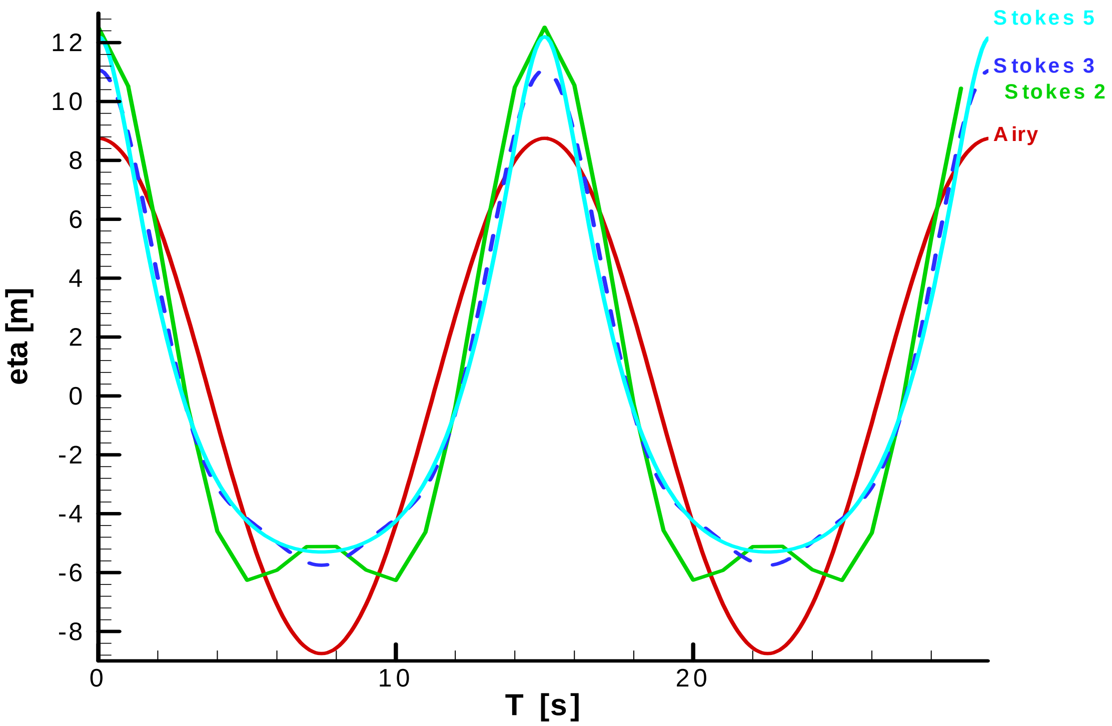

Figure 6 Surface elevation for Airy, Stokes 2nd, Stokes 3rd and Stokes 4th order theories

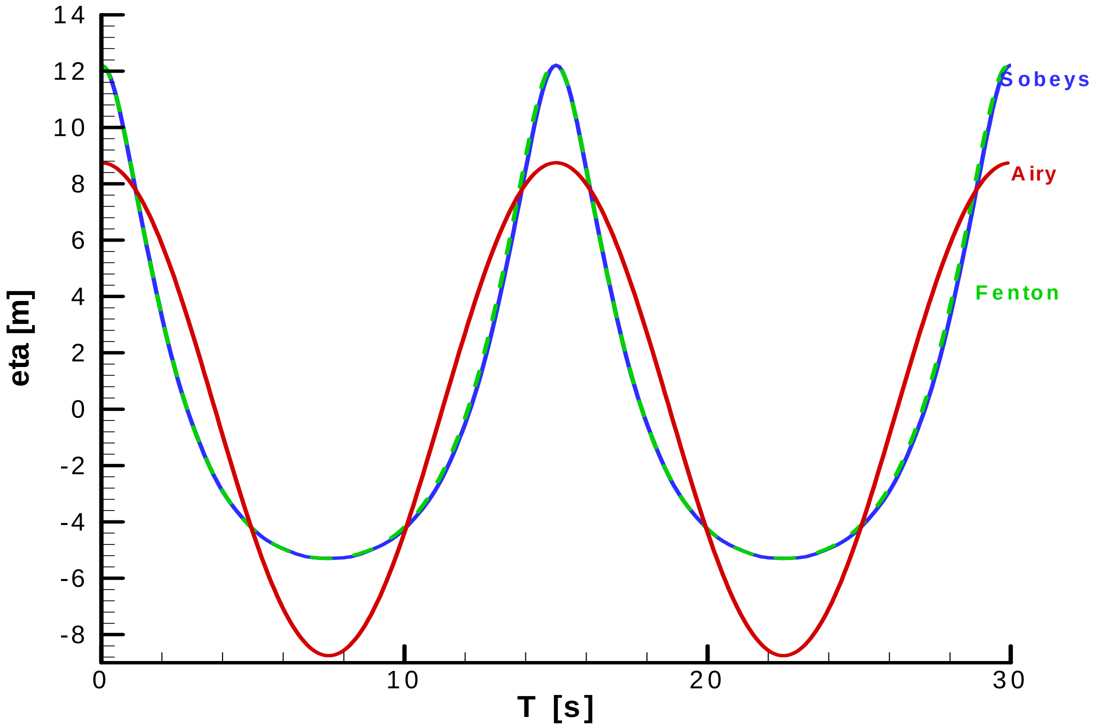

Figure 7 Surface elevation for Airy's theory and stream function solutions after Fenton and Sobey

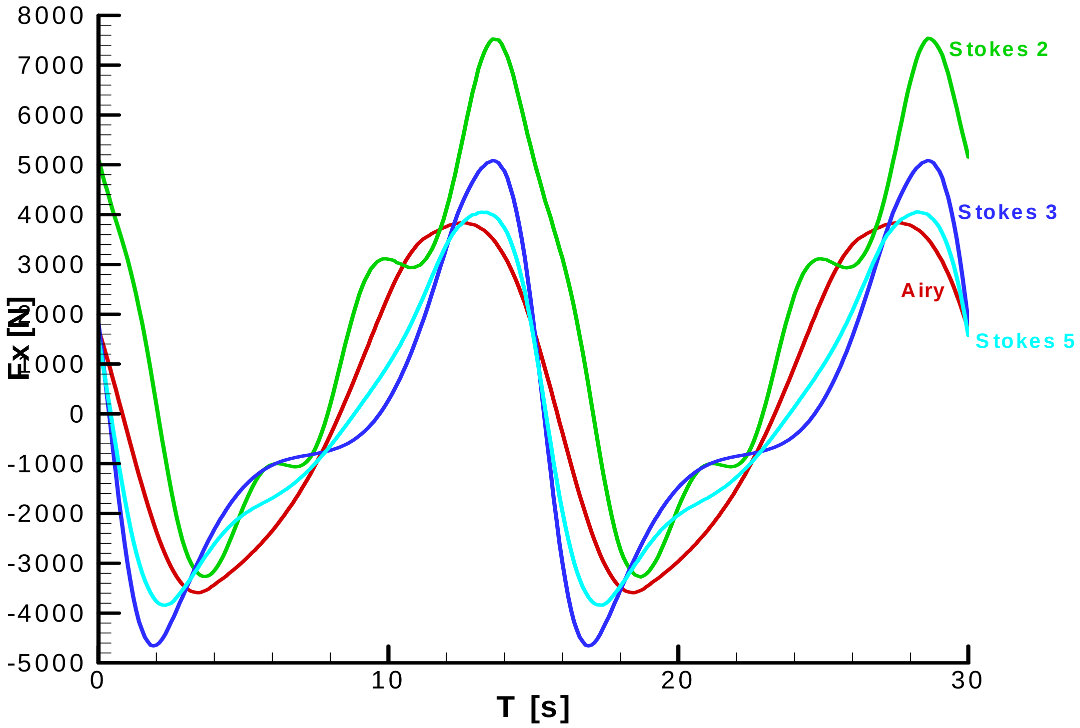

Figure 8 Accumulated force for Airy, Stokes 2nd, Stokes 3rd and Stokes 4th order theories

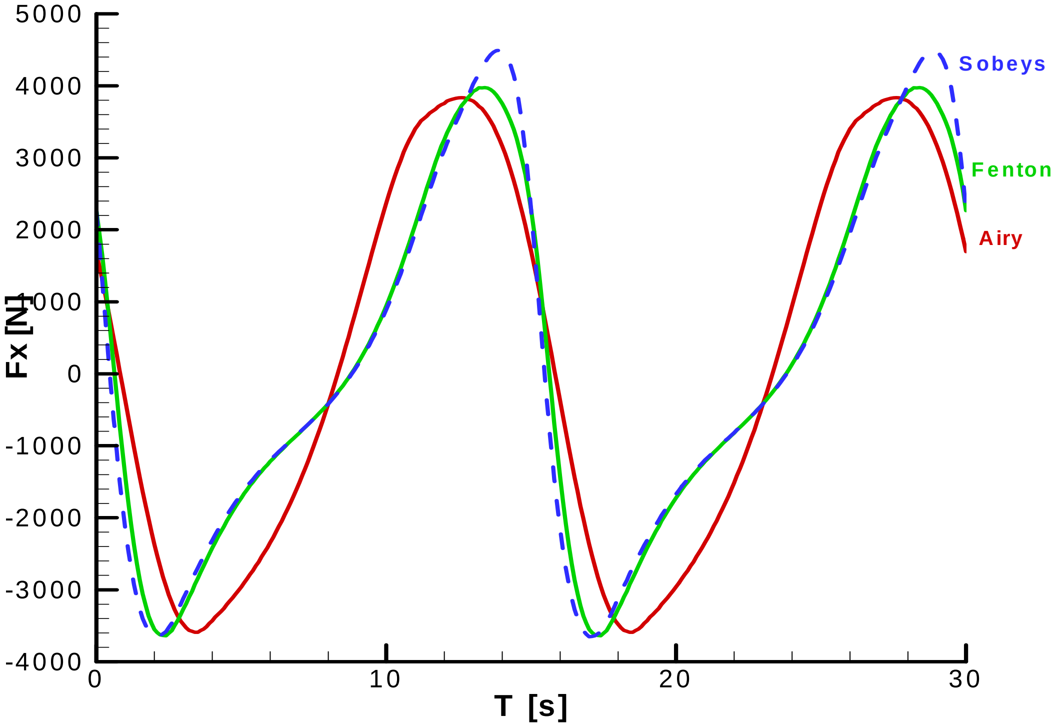

Figure 9 Accumulated force for Airy's theory and stream function solutions after Fenton and Sobey

Appendix

Example 1 – Morison forces on a monopile – Stokes' 5th order

<u>The parameters</u>:

Wave height	10.0 m
Water depth	34.0 m
Wave period	15.0 s
Euler current	0.01 m/s
Stokes Mass transport	
Pile diameter	6.0 m
Pile length	54.0 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	501 [-]
Wave theory:	Stokes 5th order

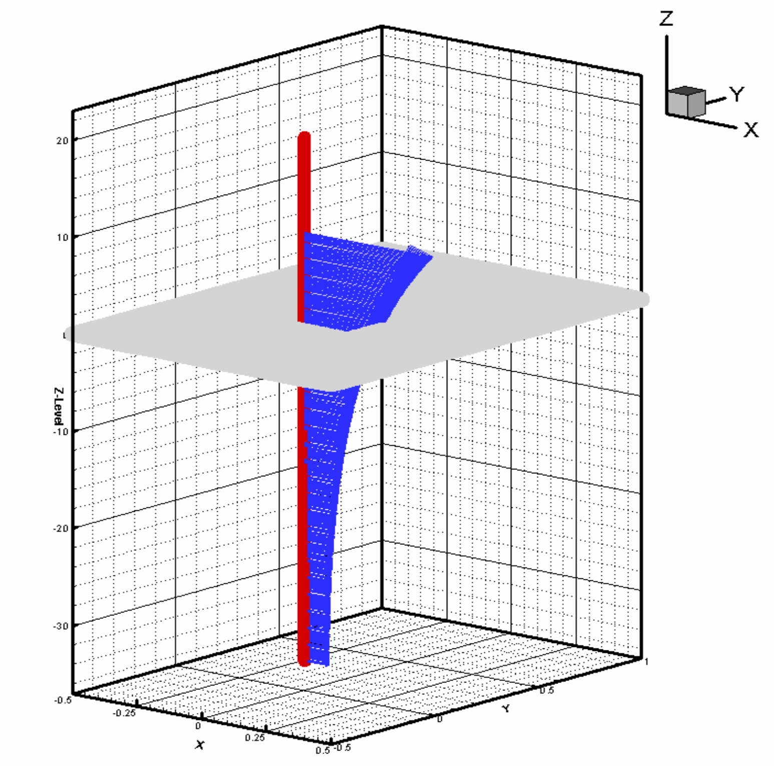

Figure 10 Node forces on a monopile

The wave input file:

```
# Stokes 5
MODEL           :     5
#
DURATION        :    30
#
TIMESTEP        :     0.10
#
WATERDEPTH      :    34.0
#
WAVEHEIGHT      =    10.0
#
WAVEPERIOD      :    15.0
#
EULERCURRENT    :     Y
#
CURRENTVELOCITY =     0.01
#
MASSTRANSPORT   :     Y
#
TRANSPORTMODEL  :     1
```

The structure input file:

```
NSUBSTRUCT       :     1
#
SUBSTRUCTINDEX   :     0
#
XU               :     0.000000
#
YU               :     0.000000
#
ZU               :    20.000000
#
XL               :     0.000000
#
YL               :     0.000000
#
ZL               :   -34.000000
#
RADIUS           :     3.000000
#
CD               :     0.700000
#
CM               :     2.000000
#
NELEMENT         :   500
#
NUMBMOMTREF      :     1
#
MOMTREFINDEX     :     0
#
XM               :     0.000000
#
YM               :     0.000000
#
ZM               :   -30.000000
```

The results:
The integrated maximum force is 2787 kN at 12.8 s.

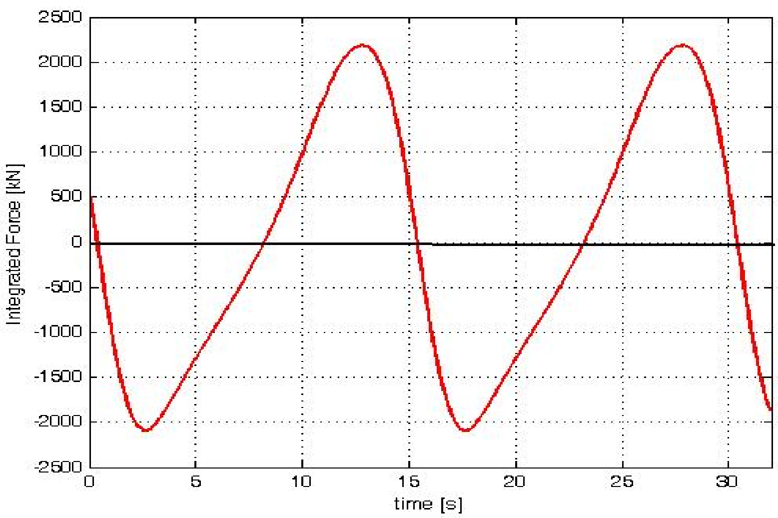

Figure 11 Total Morison force

In Figure 12 the calculated water surface elevation over time is shown.

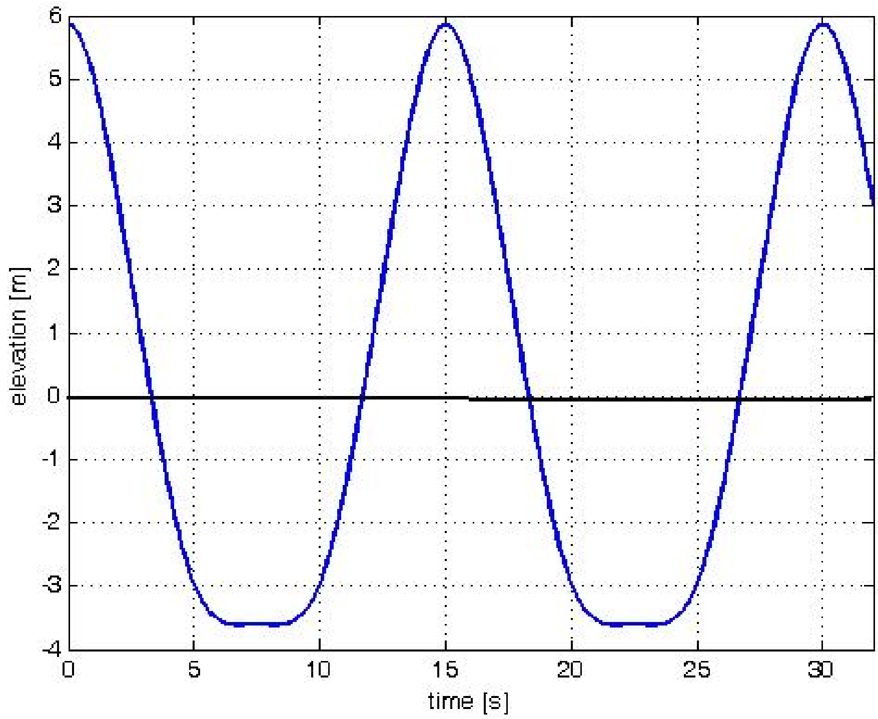

Figure 12 Calculated water surface elevation with Stokes 5 theory

The next image (Figure 13) shows the particle velocity in x- and z-direction at the surface.

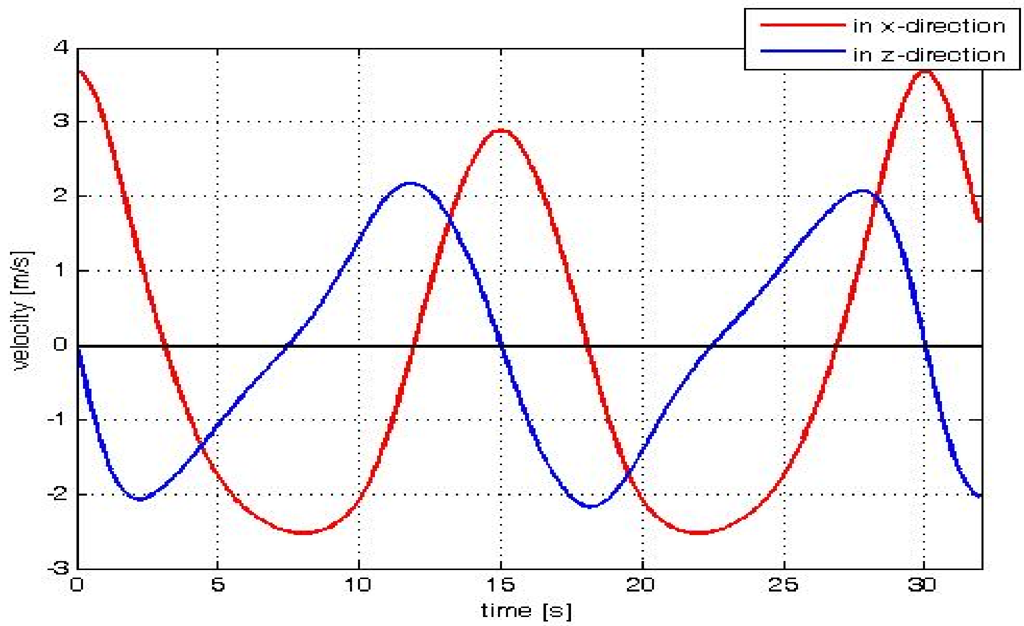

Figure 13 Particle velocities at the surface

Example 2 – Morison forces on a monopile – Fenton stream function

The parameters:

Wave height	6.9 m
Water depth	22.0 m
Wave period	14.0 s
Euler current	0.0 m/s
Pile diameter	0.8 m
Pile length	27.0 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	271 [-]
Wave theory:	Fenton stream function

```
MODEL                :    7
#Fenton Stream Function Model
DURATION             :   22.0
TIMESTEP             :    0.10
WATERDEPTH           :   22.0
WAVEHEIGHT           :    6.90
WAVEPERIOD           :   14.0
EULERCURRENT         :    N
CURRENTVELOCITY      :    0.0
MASSTRANSPORT        :    N
TRANSPORTMODEL       :    0
STRECHINGSMODE       :    0
#Extrapolation
N_ORDER              :   11
MPUNCT               :  121
KMAX                 :   31
DEANDAMPING          :    0.30
FENTONSTEP           :   20
```

The calculated surface elevation:

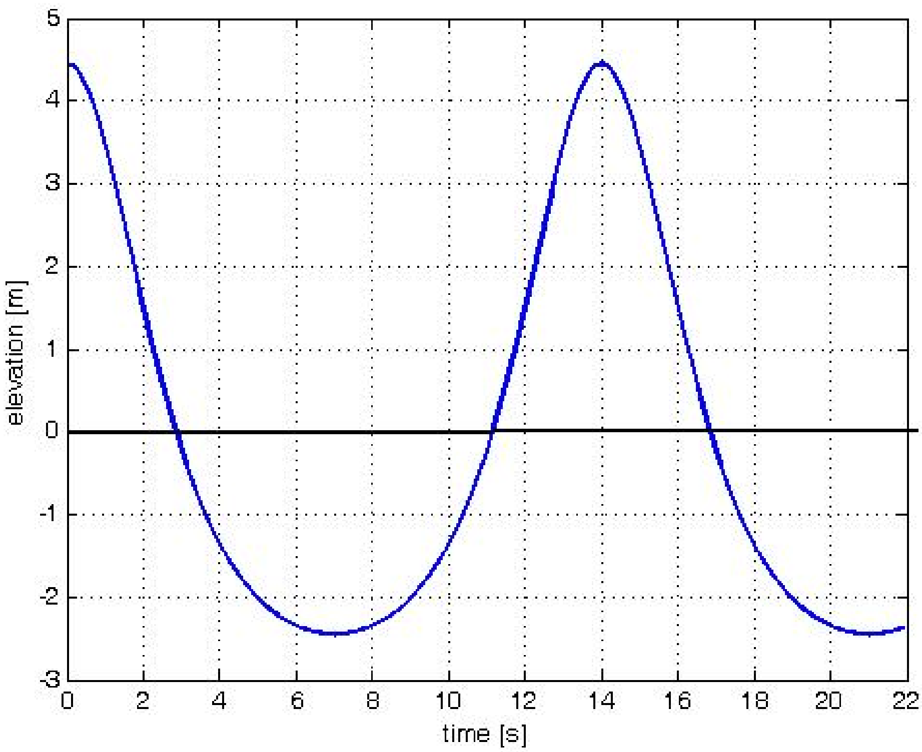

Figure 14 Surface elevation – Fenton stream function

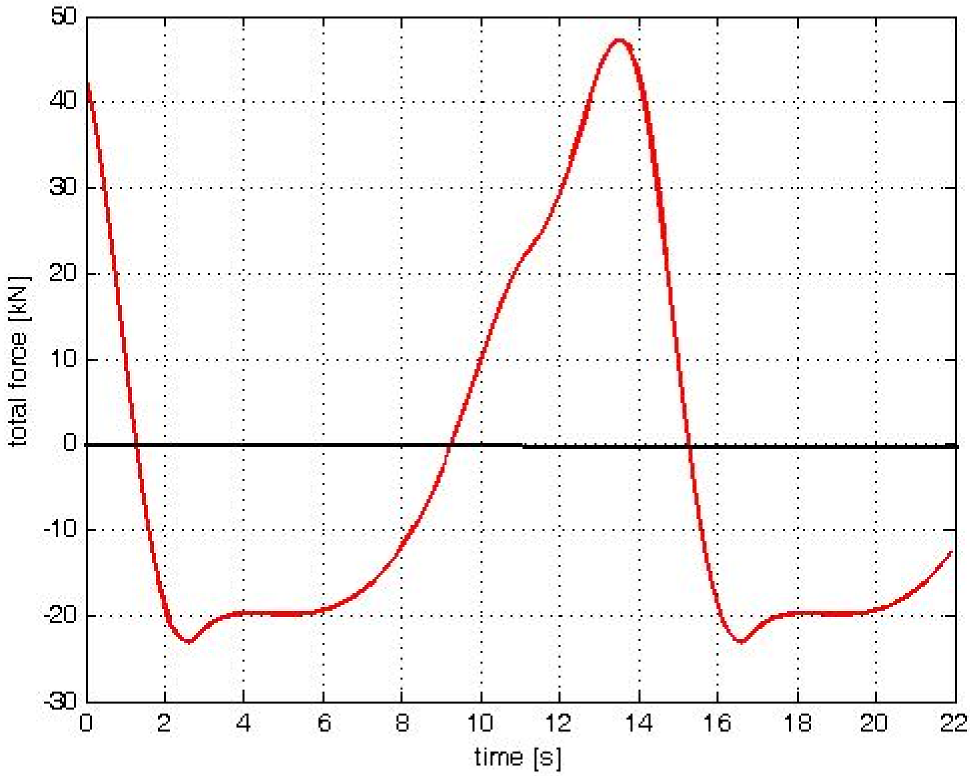

Figure 15 Total Morison force – Fenton stream function

In Figure 15 the total Morison force is shown, its maximum is 47.2 kN at 13.5 s.

Example 3 – Moment on monopile – Lagrangian wave

The parameters:

Wave height	7.0 m
Water depth	22.0 m
Wave period	12.0 s
Euler current	0.02 m/s
Stokes mass transport	

Pile diameter	0.9 m
Pile length	29.0 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	291 [-]

Wave theory: Lagrangian wave

The resulting surface elevation:

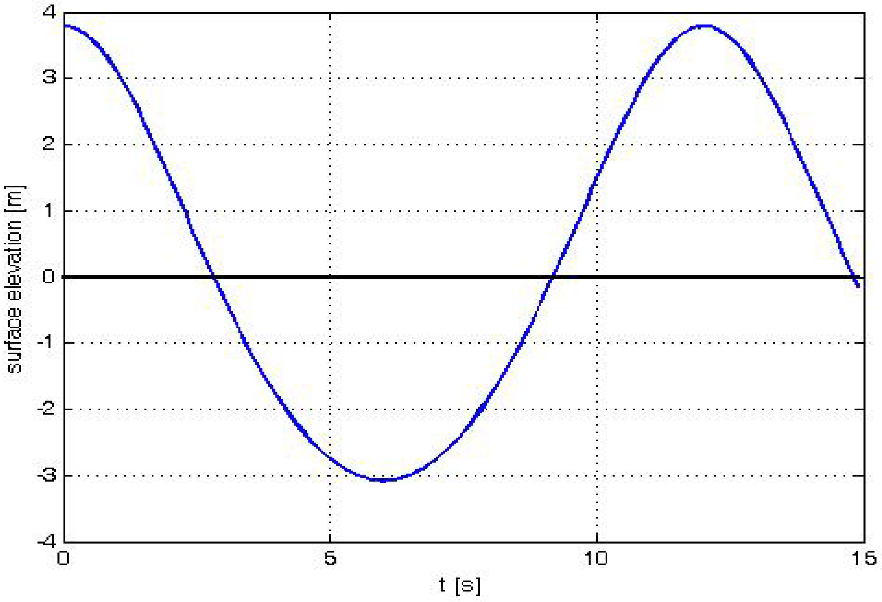

Figure 16 surface elevation – Lagrangian wave

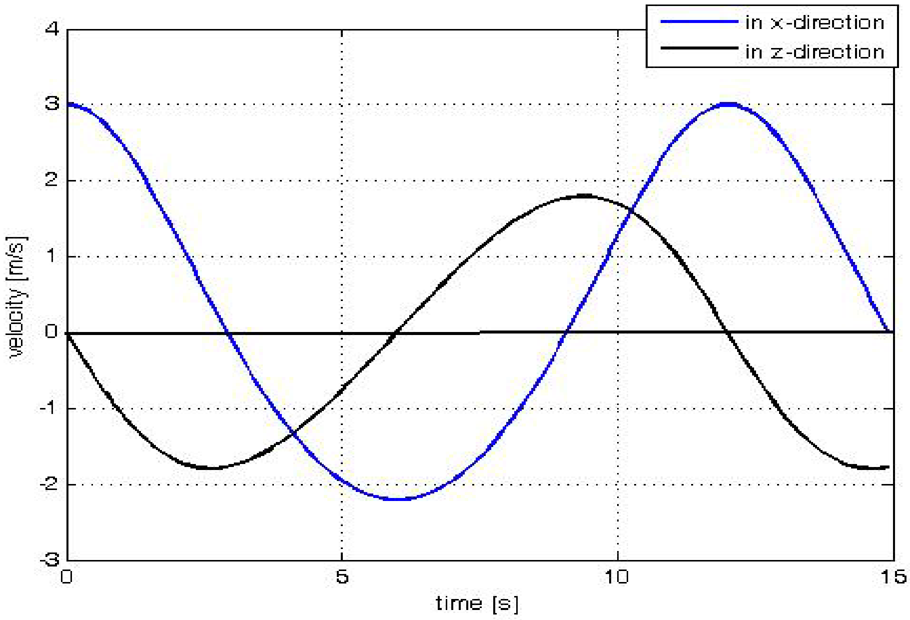

Figure 17 surface velocities

In Figure 17 the velocities on the surface are shown. The curve for the moment at the sea bottom due to the Morison loads is plotted in Figure 18.

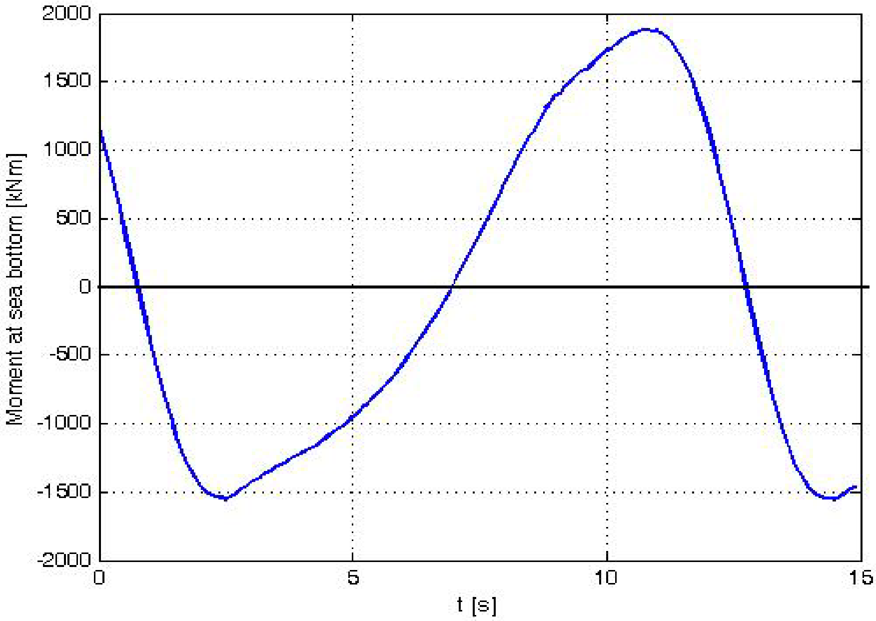

Figure 18 Moment at sea bottom due to Morison loads

Calculated wave characteristics:

Wave parameters Lagrangian model		
Wave height	[m]	= 7.000000
Wave period	[s]	= 12.000000
Water depth	[m]	= 22.000000
Wave length [m] (Fenton Approach)		= 160.072201
Wave length [m] (Iteration IWB)		= 161.003994
Wave amplitude	[m]	= 3.500000
angular frequency	[Hz]	= 0.523599
frequency	[1/s]	= 0.083333
Wave number	[-]	= 0.039025
W_Group velocity	[m/s]	= 13.339350
L/d		= 13.416999
Wave characteristics:		
(w_height/(g*w_period^2))		= 0.004955
steepness		= 0.043477
H/d		= 0.318182
H/L		= 0.043477
d/L		= 0.136643
Eulerian current		= 0.020000
gravity		= 9.810000
density		= 1.025000
Stretchingsmode		= 0
wave nodes in x-direction		= 100
wave nodes in z-direction		= 50
time nodes per wave period		= 120
Number of time steps		= 150

Example 4 – Morison forces on an inclined tube – Stokes’ 3rd order

The parameters:

Wave height	12.0 m
Water depth	30.0 m
Wave period	13.0 s
Euler current	0.00 m/s
Pile diameter	0.91 m
Pile length	46.1 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.1 [-]
Number of Nodes	51 [-]
Wave theory:	Stokes 3

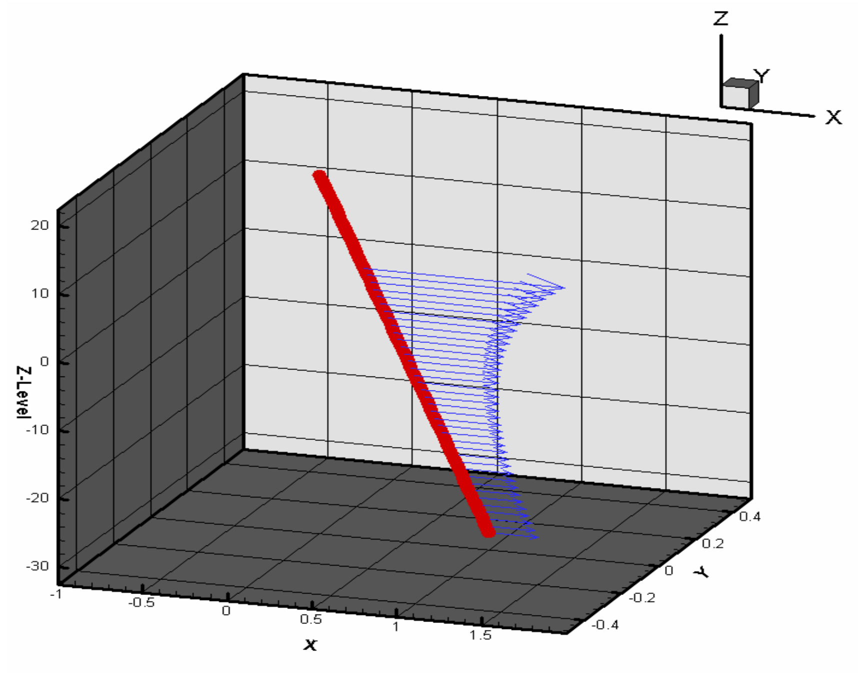

Figure 19 Forces on an inclined tube

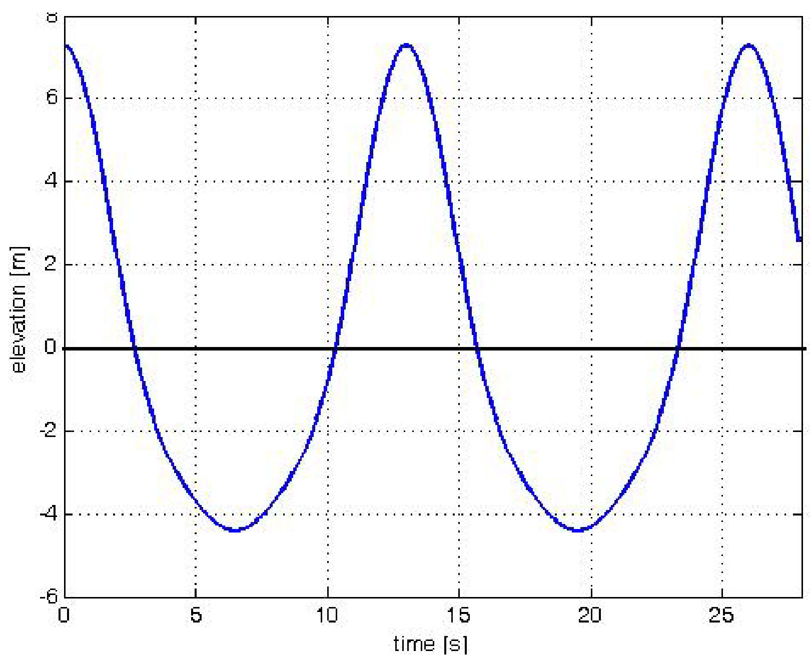

Figure 20 Calculated Surface – Stokes 3 wave theory

```
NSUBSTRUCT       :  1
SUBSTRUCTINDEX   :  0
XU               :  0.0
YU               :  0.0
ZU               : 16.090
XL               :  0.90
YL               :  0.10
ZL               :-30.0
RADIUS           :  0.455
CD               :  0.70
CM               :  2.0
NELEMENT         : 50
NUMBMOMTREF      :  1
MOMTREFINDEX     :  0
XM               :  0.000
YM               :  0.000
ZM               :-30.000
```

Calculated wave characteristics:

Calculated Wave Parameter		
Wave height	[m]	= 12.0000
Wave Period	[s]	= 13.0000
Water Depth	[m]	= 30.0000
Wave length[m] (Fenton Approach)		= 198.1978
Wave amplitude	[m]	= 5.8404
ω	[1/s]	= 0.4833
f	[Hz]	= 0.0769
k		= 0.0317
c	[m/s]	= 15.2460
L/d		= 6.6066
$H/(g*T^2)$		= 0.0072
steepness		= 0.1851
H/d		= 0.4000
H/L		= 0.0605
d/L		= 0.1514

The calculated forces are shown in Figure 21. As the tube is merely slightly inclined, the main force is in x-direction. Its maximum is 135.3 kN at 12.6 s.

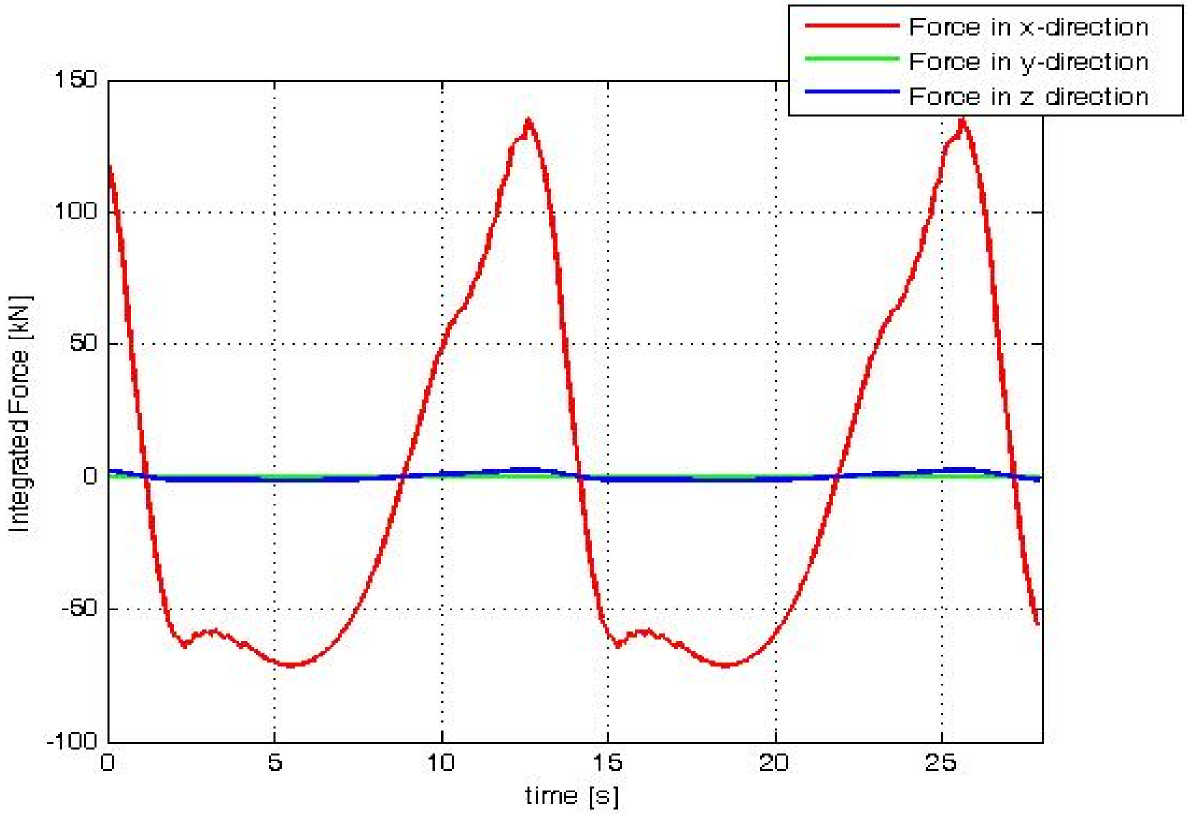

Figure 21 Total forces on inclined member

Example 5 – Morison forces on an inclined tube – Sobey stream function

<u>The parameters</u>:

Wave height	4.0 m
Water depth	17.0 m
Wave period	9.0 s
Euler current	0.0 m/s
Pile diameter	0.8 m
Pile length	23.1 m
Pile angle	18.5°
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	271 [-]

Wave theory: Sobey stream function

```
NSUBSTRUCT       :     1
SUBSTRUCTINDEX   :     0
XU               :     7.0
YU               :     0.0
ZU               :     5.0
XL               :     0.0
YL               :     0.0
ZL               :   -17.0
RADIUS           :     0.40
CD               :     0.70
CM               :     2.0
NELEMENT         :   270
NUMBMOMTREF      :     1
MOMTREFINDEX     :     0
XM               :     0.0
YM               :     0.0
ZM               :   -17.0
```

Calculated wave characteristics:

Wave Length [m]:	101.937140
C_Phase:	11.326349
Wave Number k:	0.061638

The resulting surface elevation:

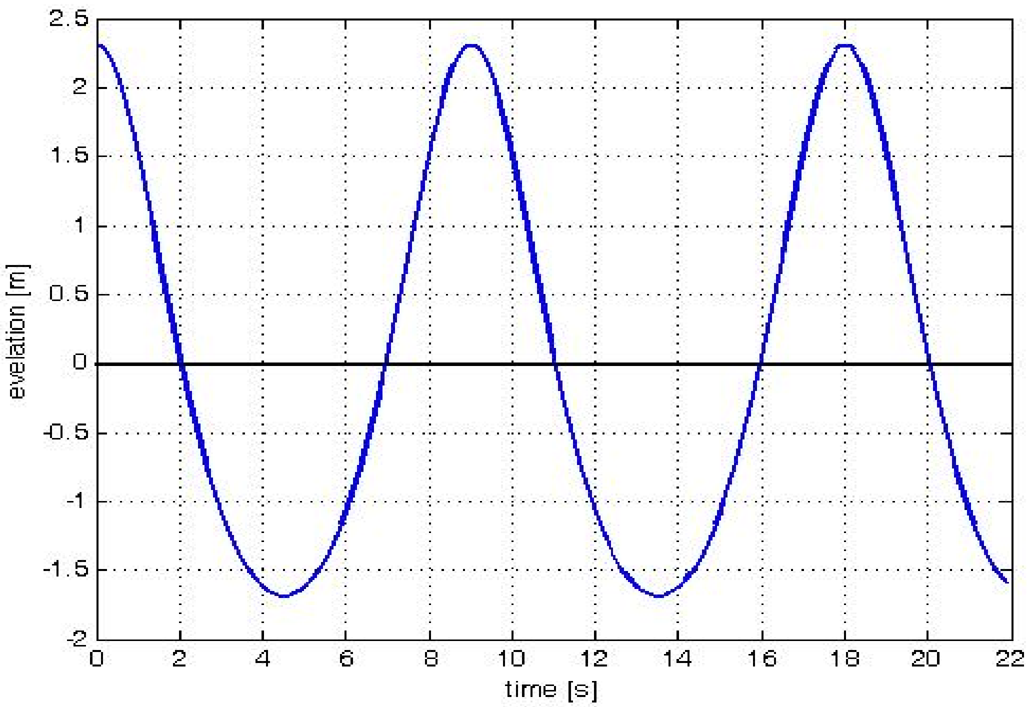

Figure 22 Surface elevation – Sobey stream function

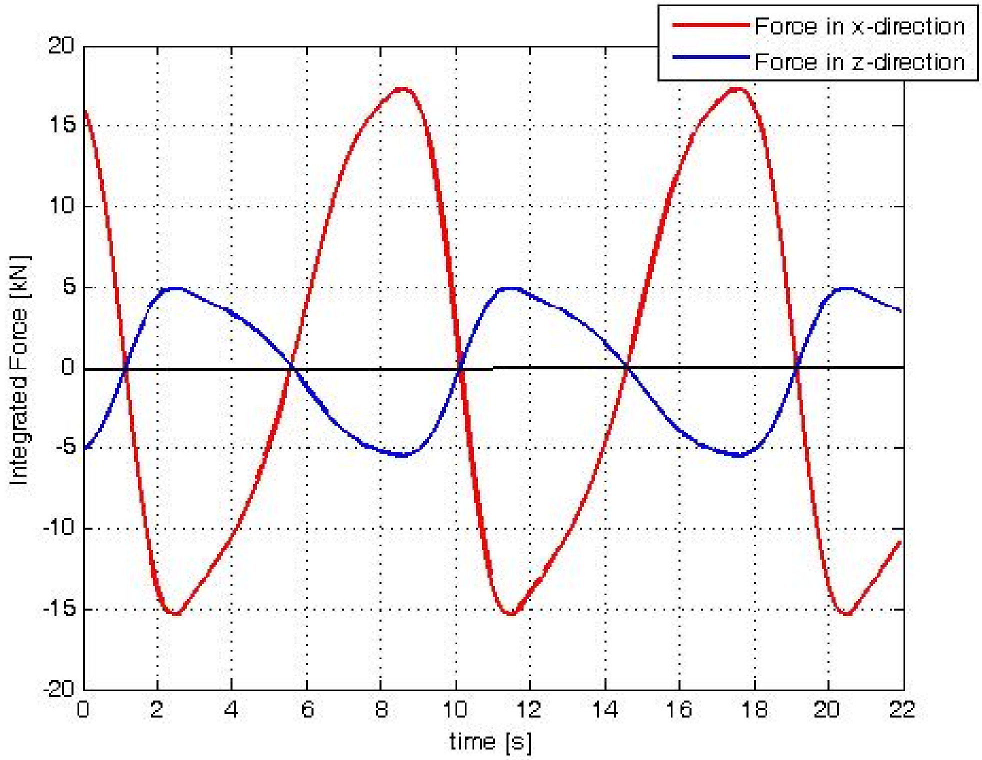

Figure 23 total Morison force – Sobey stream function

The maximum force in x-direction is 17.2 kN at 8.6 s, the maximum in y-direction is 4.9 kN at 2.4 s.

Example 6 – Composite structure – Dean-Dalrymple stream function

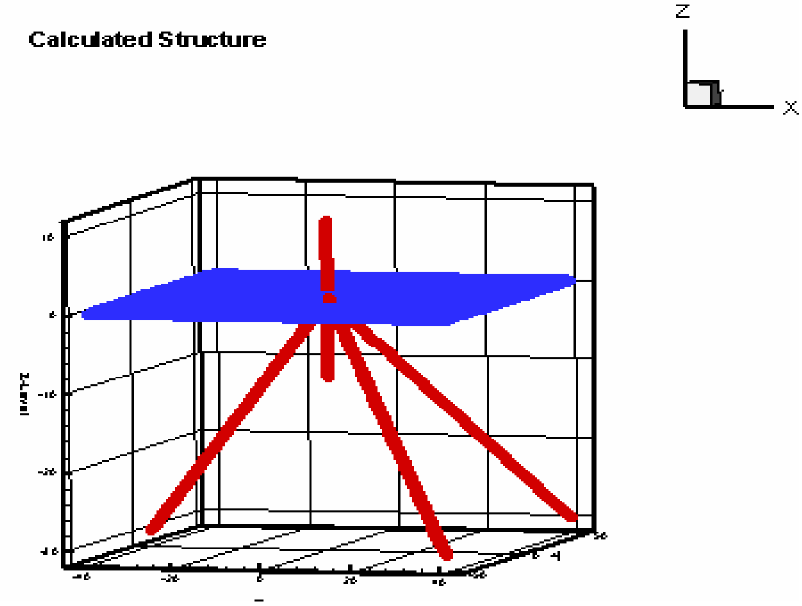

Figure 24 Composite Structure

The parameters:

Wave height	15.0 m
Water depth	30.0 m
Wave period	16.0 s
Euler current	0.00 m/s
Pile diameter	0.91 m
Pile length 0	20.0 m
Pile length 1	50.0 m
Pile length 2	70.71 m
Pile length 3	70.71 m
Drag coefficient	0.7 [-]
Inertia coefficient	2.0 [-]
Number of Nodes	31 [-]

Wave theory: Dean-Dalrymple stream function

The resulting integrated forces in x-direction for each structure member:

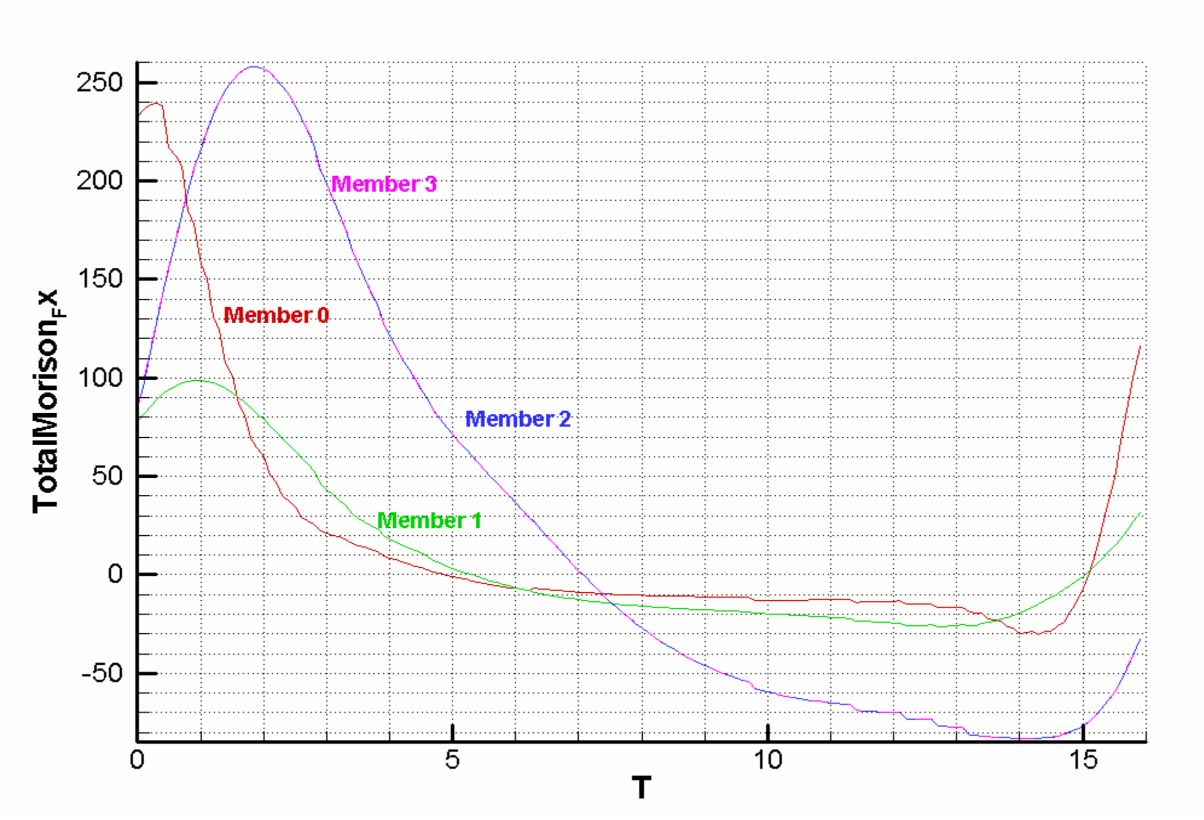

Figure 25 Integrated wave loads in x-direction

Example 7 – Wave spectrum approach method

<u>The parameters:</u>

Monopile
Pile diameter 0.91 m
Pile length 40.0 m
Drag coefficient 0.7 [-]
Inertia coefficient 2.0 [-]
Number of Nodes 20 [-]

Water depth 30.0 m
Input spectrum: 22.03.1995, 06:00 pm, NSB

Figure 27 shows the resulting time series of water surface elevation which are generating from a spectrum by using following methods:

Method 1: constant delta omega
Method 2: irrational omega
Method 3: Webster and Trudell

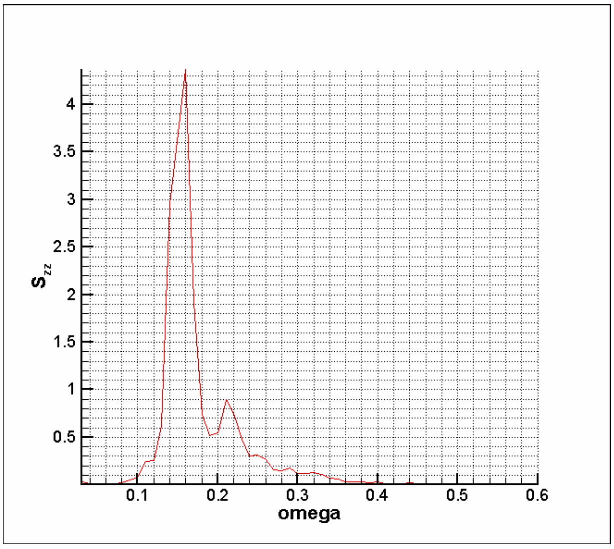

Figure 26 Input Spectrum

The discretised spectrum is read from the file `HEL1995.SPC`.

The wave parameter input file:

```
MODEL:                    9
LABEL: 22.03.95 18UhrNSB
SEEGANG_3D_OBERFLAECH:    0
SEEGANG_DURATION:       100
SEEGANG_TIMESTEP:         0.1
SEEGANG_TIEFE:           30
X_SEASTREAM:              0.0
Y_SEASTREAM:              0.0
SEEGANG_SPECTRUM_MODE:    1
SEEGANG_SPECTRUM_DATAFILE:    HEL1995.SPC
SEEGANG_N_OMEGA:         58
SEEGANG_SUPERPOS_MODE:    1
SEEGANG_OMEGA_MIN:        0.05
SEEGANG_OMEGA_MAX:        3.00
# end of the Waves-Input
```

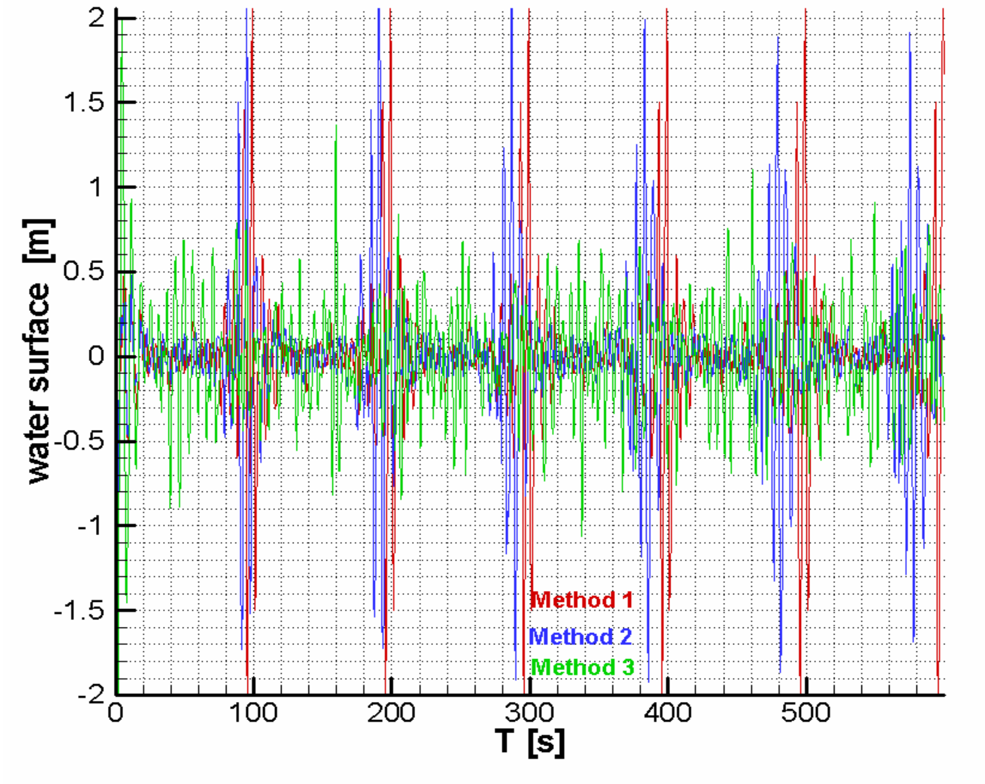

Figure 27 Generated water surface elevation

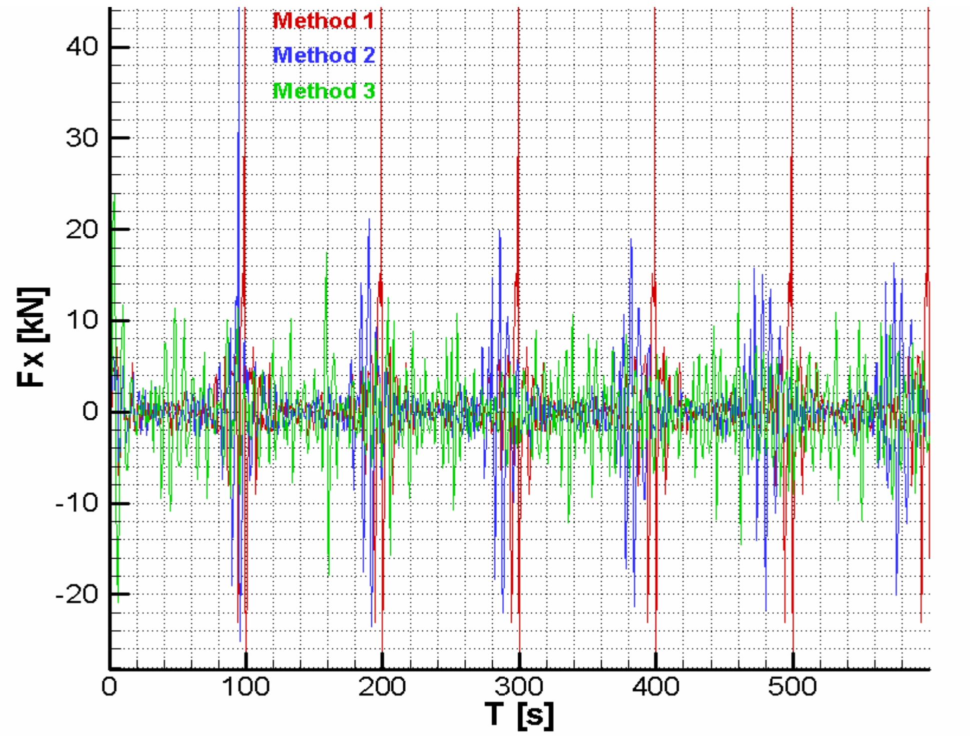

Figure 28 Generated Load Series

Figure 28 shows the resulting loads in x-direction using the available methods for superposition of waves.