ECN-C--05-028

STREAM FUNCTION WAVE PROGRAM

User's manual

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FEBRUARY 2005

Acknowledgement/Preface

The ECN contribution to this project is funded by the ECN 'samenwerkingsfinanciering' program (project 7.9406).

Abstract

The program *Streamfunction* calculates the wave kinematics of a deterministic nonlinear wave. The wave kinematics can be used in PHATAS for load set calculations on offshore wind turbines. The wave theory used in the program is based on the Fourier approximation given by Fenton (1988). This report is in the first place a user's manual. Also the results of verification tests are discussed.

CONTENTS

LIST OF TABLES

1. INTRODUCTION

For the calculation of extreme loading conditions on offshore wind turbines a deterministic non-linear wave model is needed. Several deterministic non-linear wave models exist. For the design of offshore wind turbines in shallow and finite water depth the stream function wave theory (Dean, 1965; Fenton, 1988) is mostly used. The program *Streamfunction* calculates the wave kinematics based on Fourier series theory (Fenton, 1988). This wave theory is very similar to the stream function wave theory as developed by Dean (1965). In the program *Streamfunction* there is a possibility to include a uniform current.

Main goal of this report is to describe the use of the program. The results of the program *Streamfunction* are compared with the results of other programs. The theoretical background of the used wave theory can be found in Fenton (1988).

2. USING THE PROGRAM

The program *Streamfunction* is based on the FORTRAN program presented in Fenton (1988). The program has been modified to be able to use the results in the dynamic load set calculations of offshore wind turbines. The main modifications are:

1) The program is rewritten in FORTRAN 90
2) The input is read from a (keyword-value) file instead of using a screen input
3) The number and the kind of input is changed
4) The calculation of the wave kinematics for the selected depths (nodes) is added.

The FORTRAN 90 code of the program *Streamfunction* is given in **Error! Reference source not found.**.

2.1 Starting the program

At the moment there is a DOS version of the program *Streamfunction* available. Before starting the program a DOS command prompt should be opened first. The program is started by typing:

steamfunction.exe example.inp

The input file example.inp contains the parameters for the wave calculations. The content of the input file will be explained in the next section.

2.2 Input file

An example of an input file is given in below.

< example.inp 6 september 2004
wave_height 10.0
wave_period 10.0
water_depth 20.0
order 12
< uniform current
current_velocity 1.5
nodes 20
time_step 0.1
simulation_time 10.0
output_filename example.out

In the input file the keywords and their values are given. Comment lines in the input file should start with a '<'. Below the keywords are discussed briefly. The program checks whether all keywords are present in the input file.

wave_height [m]
This is the wave height H of the deterministic wave.

wave_period [s]
This is the wave period T related to wave height H.

water_depth [m]
This is the water depth the wave is calculated for. The water depth is assumed to be constant.

order
This is the order of the stream function. Normally an order of 11 is sufficient. The maximum order to select is 25.

current_velocity [m/s]
This is the velocity of a uniform current.

nodes
This is the number of nodes where the wave kinematics are calculated for. The maximum number of nodes is 100.

time_step [s]
This is the time step where the wave kinematics are calculated for.

simulation_time [s]
This is the length of the wave kinematics times series. The wave is repeated for **simulation_time** longer than the **wave_period**.

output_filename
In this keyword the directory and filename of the output file are given.

2.3 Calculation and output

Before starting the calculation the following three conditions have to be checked:
1) Does the input data correspond with finite water depth or deep water?
2) Is it allowed to use the stream function wave theory for the given wave conditions?
3) Are the wave conditions physical correct?

In the program the calculation of the wave properties is different for finite water depth or deep water. Using the input data the value of kd is estimated. Here k is the wave number and d is the water depth. If kd > π then the input data corresponds with a deep water condition (Sarpkaya et al., 1981).

The program checks whether the wave theory can be used for the selected water depth d and wave length L. For a stream function wave DNV (2000) applies the following criterion:

$$0.1 < \frac{d}{L} \leq 0.3$$

The program *Streamfunction* can also be used for deep water (d/L > 0.3). Therefore the program checks only d/L > 0.1

Finally the physical correctness of the wave input data is checked. In Sarpkaya et al. (1981) the maximum wave height is discussed. For waves of a given length, in water of uniform and given depth, a maximum wave height exists beyond which the waveform is unstable. The wave steepness (wave height H/ wave length L) is used as criterion for the maximum wave height. In deep water the limiting wave steepness is given by (Michell,1893):

$$\frac{H}{L} = 0.142 \approx \frac{1}{7}$$

For finite and uniform water depth the criterion for the limiting wave steepness as proposed by Miche (1944) is used:

$$\frac{H}{L} = 0.142 \cdot \tanh(kd)$$

After the checks the calculation of the wave properties starts. Compared with the original program of Fenton (1988) the calculation of the wave kinematics for different depths (nodes) is added to the program *Streamfunction*. For every time step the given number of nodes is spread equally over the distance between the sea bed and the free surface. For every node the wave kinematics are calculated. The applied equations for the calculation of the wave kinematics can be found in Rienecker et al. (1981).

The wave elevation, the horizontal velocity and acceleration at every node are written to the output file for the given time step and simulation time. The data structure has a format compatible with PHATAS IV Lindenburg et al. (2000). The data is written in ASCII format to the output file.

3. VERIFICATION

The results of the program *Streamfunction* are compared with two other stream function programs. One is the in house ECN nonlineairwave program in Matlab (Eecen, 2003). The other stream function program is CW263.exe. The program CW263 includes a uniform current and is developed by Chaplin. Four test runs were performed. An overview is given in Table 3.1 below.

Table 3.1 *An Overview of the test program*

	Test 1	Test 2	Test 3	Test 4
Comparing program	CW263	CW263	CW263	ECN Matlab
Wave height [m]	10.0	10.0	10.0	10.0
Wave period [s]	10.0	10.0	10.0	10.0
Order	12	12	12	7
Current velocity [m/s]	0.0	1.5	-1.5	0.0
Water depth [m]	20.0	20.0	20.0	20.0

In test 1, test 2 and test 3 the wave elevation, the horizontal velocity and acceleration at the free surface are compared for three different current velocities. In order to have results with respect to time the code of CW263 has been slightly modified. Table 3.2, Table 3.3 and Table 3.4 show the results of the program *Streamfunction*. The results correspond very well with the results of CW263.

Test 1, test 2 and test 3 show that the results at the free surface are good. In test 4 results at the different nodes are compared. In this case the comparison is made with the ECN Matlab code. Table 3.5 shows the horizontal velocity at the nodes at the crest and the trough. Node 1 is near the seabed, while node 20 is at the free surface. At a trough the results of the two programs show good correspondence. At the crest a small difference of 2% occurs for nodes near the free surface.

It is concluded that the wave kinematics of a deterministic nonlinear wave calculated with the ECN program *Streamfunction* can be used for wave load calculations of offshore wind turbines.

Table 3.2 *The results of test 1. The results with ECN Streamfunction and CW263 for current velocity 0.0 [m/s]are compared.*

	ECN Stream-function	CW263	ECN Stream-function	CW263	ECN Stream-function	CW263
Time [s]	Elevation [m]		Horizontal velocity [m/s]		Horizontal acceleration [m/s^2]	
0.0	6.77571	6.77600	6.55997	6.56000	0.00000	0.00000
0.5	5.60640	5.60700	5.36517	5.36500	-2.35976	-2.36000
1.0	3.44527	3.44500	3.26851	3.26900	-3.06563	-3.06600
1.5	1.44306	1.44200	1.44498	1.44500	-2.83206	-2.83200
2.0	-0.12405	-0.12200	0.08884	0.08900	-2.25148	-2.25200
2.5	-1.27967	-1.28200	-0.85220	-0.85200	-1.63073	-1.63100
3.0	-2.09082	-2.08800	-1.47645	-1.47700	-1.10714	-1.10700
3.5	-2.63363	-2.63600	-1.87516	-1.87500	-0.70935	-0.70900
4.0	-2.97767	-2.97700	-2.11639	-2.11600	-0.41602	-0.41600
4.5	-3.16460	-3.16500	-2.24498	-2.24500	-0.19139	-0.19100
5.0	-3.22429	-3.22400	-2.28524	-2.28500	0.00000	0.00000
5.5	-3.16460	-3.16500	-2.24498	-2.24500	0.19139	0.19100
6.0	-2.97767	-2.97700	-2.11639	-2.11600	0.41602	0.41600
6.5	-2.63363	-2.63600	-1.87516	-1.87500	0.70935	0.70900
7.0	-2.09082	-2.08800	-1.47645	-1.47700	1.10714	1.10700
7.5	-1.27967	-1.28200	-0.85220	-0.85200	1.63073	1.63100
8.0	-0.12405	-0.12200	0.08884	0.08900	2.25148	2.25200
8.5	1.44306	1.44200	1.44498	1.44500	2.83206	2.83200
9.0	3.44527	3.44500	3.26851	3.26900	3.06563	3.06600
9.5	5.60640	5.60700	5.36517	5.36500	2.35976	2.36000
10.0	6.77571	6.77600	6.55997	6.56000	0.00000	0.00000

Table 3.3 *The results of test 2. The results with ECN Streamfunction and CW263 for current velocity 1.5 [m/s] are compared.*

	ECN Stream-function	CW263	ECN Stream-function	CW263	ECN Stream-function	CW263
Time [s]	Elevation [m]		Horizontal velocity [m/s]		Horizontal acceleration [m/s^2]	
0.0	6.90747	6.90700	7.90376	7.90400	0.00000	0.00000
0.5	5.66608	5.66600	6.69239	6.69200	-2.24808	-2.24800
1.0	3.38096	3.38100	4.55821	4.55800	-2.87591	-2.87600
1.5	1.30998	1.30900	2.73509	2.73500	-2.55861	-2.55800
2.0	-0.25716	-0.25500	1.42733	1.42700	-1.93344	-1.93400
2.5	-1.36727	-1.37000	0.55953	0.56000	-1.32732	-1.32700
3.0	-2.11427	-2.11200	0.00918	0.00900	-0.85779	-0.85800
3.5	-2.59416	-2.59600	-0.32846	-0.32800	-0.52734	-0.52700
4.0	-2.88812	-2.88700	-0.52616	-0.52600	-0.29975	-0.30000
4.5	-3.04352	-3.04400	-0.62910	-0.62900	-0.13520	-0.13500
5.0	-3.09253	-3.09300	-0.66094	-0.66100	0.00000	0.00000
5.5	-3.04352	-3.04400	-0.62910	-0.62900	0.13520	0.13500
6.0	-2.88812	-2.88700	-0.52616	-0.52600	0.29975	0.30000
6.5	-2.59416	-2.59600	-0.32846	-0.32800	0.52734	0.52700
7.0	-2.11427	-2.11200	0.00918	0.00900	0.85779	0.85800
7.5	-1.36727	-1.37000	0.55953	0.56000	1.32732	1.32700
8.0	-0.25716	-0.25500	1.42733	1.42700	1.93344	1.93400
8.5	1.30998	1.30900	2.73509	2.73500	2.55861	2.55800
9.0	3.38096	3.38100	4.55821	4.55800	2.87591	2.87600
9.5	5.66608	5.66600	6.69239	6.69200	2.24808	2.24800
10.0	6.90747	6.90700	7.90376	7.90400	0.00000	0.00000

Table 3.4 *The results of test 3. The results with ECN Streamfunction and CW263 for current velocity -1.5 [m/s] are compared.*

	ECN Stream-function	CW263	ECN Stream-function	CW263	ECN Stream-function	CW263
Time [s]	Elevation [m]		Horizontal velocity [m/s]		Horizontal acceleration [m/s^2]	
0.0	6.68048	6.68000	5.42565	5.42600	0.00000	0.00000
0.5	5.51570	5.51600	4.13209	4.13200	-2.63862	-2.63900
1.0	3.44491	3.44500	1.99297	1.99300	-3.36830	-3.36800
1.5	1.52374	1.52200	0.15835	0.15800	-3.17633	-3.17600
2.0	-0.01225	-0.01000	-1.23593	-1.23600	-2.63558	-2.63600
2.5	-1.18709	-1.19100	-2.24181	-2.24200	-2.00916	-2.00900
3.0	-2.04460	-2.04100	-2.93882	-2.93900	-1.43431	-1.43400
3.5	-2.64035	-2.64300	-3.40273	-3.40300	-0.95960	-0.96000
4.0	-3.03150	-3.03000	-3.69299	-3.69300	-0.58160	-0.58200
4.5	-3.24903	-3.24900	-3.85153	-3.85200	-0.27313	-0.27300
5.0	-3.31952	-3.32000	-3.90179	-3.90200	0.00000	0.00000
5.5	-3.24903	-3.24900	-3.85153	-3.85200	0.27313	0.27300
6.0	-3.03150	-3.03000	-3.69299	-3.69300	0.58160	0.58200
6.5	-2.64035	-2.64300	-3.40273	-3.40300	0.95960	0.96000
7.0	-2.04460	-2.04100	-2.93881	-2.93900	1.43431	1.43400
7.5	-1.18709	-1.19100	-2.24181	-2.24200	2.00916	2.00900
8.0	-0.01225	-0.01000	-1.23593	-1.23600	2.63558	2.63600
8.5	1.52374	1.52200	0.15835	0.15800	3.17633	3.17600
9.0	3.44491	3.44500	1.99297	1.99300	3.36830	3.36800
9.5	5.51570	5.51600	4.13209	4.13200	2.63862	2.63900
10.0	6.68048	6.68000	5.42565	5.42600	0.00000	0.00000

Table 3.5 *The results of test 4. The horizontal velocity at different nodes between ECN Streamfunction and ECN Matlab is compared. Node 1 is near the sea bed, node 20 is at the free surface.*

	Crest		Trough	
Node	ECN Streamfunction	ECN Matlab	ECN Streamfunction	ECN Matlab
1	2.49403	2.49555	-1.91769	-1.91619
2	2.51543	2.51694	-1.92057	-1.91912
3	2.55133	2.55283	-1.92538	-1.92386
4	2.60210	2.60357	-1.93211	-1.93045
5	2.66823	2.66967	-1.94074	-1.93890
6	2.75042	2.75181	-1.95127	-1.94955
7	2.84951	2.85083	-1.96368	-1.96172
8	2.96654	2.96776	-1.97795	-1.97570
9	3.10277	3.10091	-1.99408	-1.99200
10	3.25969	3.25714	-2.01203	-2.00958
11	3.43908	3.43564	-2.03179	-2.02889
12	3.64301	3.63834	-2.05331	-2.04989
13	3.87391	3.86748	-2.07659	-2.07330
14	4.13465	4.12557	-2.10157	-2.09760
15	4.42856	4.41535	-2.12822	-2.12343
16	4.75957	4.73979	-2.15649	-2.15164
17	5.13228	5.10192	-2.18636	-2.18036
18	5.55213	5.50459	-2.21775	-2.21034
19	6.02557	5.95004	-2.25062	-2.24147
20	6.56026	6.42889	-2.28491	-2.27357

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