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On the Motions of a Seagoing Cutter Dredge, a Study in Continuity

S.A. Miedema^{*}, J.M.J. Journée^{} and S. Schuurmans^{***}**

^{*} **Delft University of Technology, Soil Movement Lab.**

^{**} **Delft University of Technology, Ship Hydromechanics Lab.**

^{***} **Delft Hydraulics**

Summary

The prediction of the behaviour of cutter dredges in near-shore conditions is important with respect to the construction of the dredge and with respect to the assessment of downtime. To be able to make such a prediction the Chair of the Technology of Soil Movement and the Delft Ship Hydromechanics Laboratory both of Delft University of Technology, together with Delft Hydraulics developed the computer program DREDMO in the early 80's. The behaviour of a seagoing cutter dredge can be described by the Cummins equations, a set of 7 non-linear coupled equations of motion. Because these equations are non-linear, they have to be solved numerically in the time domain.

The Cummins equations require hydromechanical coefficients, retardation functions and wave force time series as input, together with geometrical and operational data on the ship and the working method.

The hydromechanical coefficients and the retardation functions are calculated with a pre-processing program. The wave force time series also calculated with a pre-processing program using the hydromechanical coefficients as input. The Cummins equations can then be solved with the computer program DREDMO. The output of this program consists of a number of files containing time-series of motions of the dredge and forces acting on different locations on the dredge. A post-processing program can be used to interpret these time series graphically, statistically and spectrally.

There have already been a number of publications about the DREDMO program, running on main frames. The pre- and post-processing programs were also running on main frames. A specialist was required to operate the software. To promote the use of the DREDMO package in 1984 Delft Hydraulics decided to develop a PC version. The pre-processing still needed to be carried out on a main frame. Recently pre- and post-processing programs complemented with a user-interface have been developed at Delft University of Technology, permitting non-specialists to work with the DREDMO package.

This paper will describe the philosophy behind and the structure of:

- the DREDMO software package and user interface,
- the program SEAWAY-D used to calculate hydromechanical coefficients, retardation functions and frequency domain wave loads,
- the program WAFOR used to calculate statistically correct wave force time series,
- the program DREDMO used to solve the Cummins equations and
- the program PLOSIM used to process the DREDMO output graphically, statistically and spectrally.

Backgrounds of calculation methods and examples of calculations will be given with respect to the practical use of the software package.

1 Introduction

The behaviour of dredges in off- and near shore conditions is important in relation to the workability of the dredge. To be able to understand this behaviour and the processes involved, at the end of the 70's the Laboratories of Soil Movement and Ship Hydromechanics of the Delft University of Technology and Delft Hydraulics initiated joint research into this subject.

The objective of this research was the development of a computer program with which, the behaviour of seagoing cutter suction dredges could be simulated and thus predicted. In the early 80's the computer program DREDMO was operational on a mainframe. There were several publications in 1983 (Journée, Miedema and Keuning 1983 [4], Keuning and Journée 1983 [7] and de Koning, Miedema and Zwartbol 1983 [8]) published about this subject. The program, written in the language ALGOL, required several pre- and post-processing programs and was only accessible to specialists. In the mid-80's Dutch dredging companies expressed the desire to be able to operate DREDMO themselves. The program was translated to FORTRAN and made operational by Miedema, Koster and Hurdle 1986 [9] for use on MS-DOS computers. The Dutch contractors joined in the CSB research group, purchased DREDMO from Delft Hydraulics in 1986. Since the pre- and post-processing still had to take place on a main frame and because

of the complexity of the programs involved, the use of DREDMO was rather user-unfriendly. Reason for a number of scientists of the Delft University of Technology to develop pre- and post-processing programs and a user-interface for the on personal computers.

These programs became operational in 1990 and are now used by Delft Hydraulics and Delft University. The mathematical modelling and structure of the DREDMO package will be discussed in the following paragraphs.

2 Equations of Motion of a Floating Object

Generally, the equations of motion for the six degrees of freedom of a floating object, influenced by external loads, are written in the frequency domain. In these equations of motions, the hydrodynamic mass and damping coefficients and the external loads depend on the circular frequency of oscillation ω . As a result of the formulation in the frequency domain, any system influencing the behaviour of the vessel should have a linear relation with the displacement, the velocity and the acceleration of the body. Figure 1 shows the six degrees of freedom of a floating object. The rotation of the ladder around the ladder bearings gives the 7th degree of freedom, which will be considered separately from the body motions.

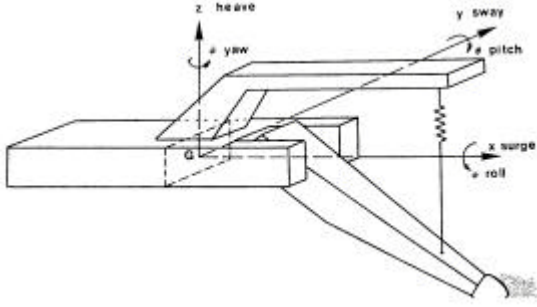


Figure 1 Degrees of Freedom of a Floating Object

The equations of motion for the six degrees of freedom form a system of six coupled differential equations according to:

$$\sum_{j=1}^6 \{ (M_{kj} + a_{kj}(\mathbf{w})) \cdot A_j + b_{kj}(\mathbf{w}) \cdot V_j + c_{kj} \cdot X_j \} = W_k(\mathbf{w}) + F_k(\mathbf{w}) \quad (1)$$

However, in many cases there are several complications, which negate this linear assumption, such as the non-linear viscous damping, non-linear hydrostatic restoring spring terms or non-linear external forces or moments such as cutting forces. Dredging vessels, especially cutter suction dredges and wheel dredges, are in contact with the bottom of the sea by means of the excavating element, mounted on the ladder and by the anchoring system. The excavation process causes strong non-linear effects in the equations of motion and also couples the longitudinal and lateral degrees of freedom of the vessel. To include these non-linear effects in the vessel behaviour at zero forward speed, it is necessary to formulate the equations of motions in the time domain, which relates instantaneous values of forces, moments and motions. Memory functions have to be used to represent the frequency-dependent hydrodynamic mass and damping terms.

Referring to the basic work on this subject by Cummins equations of motions are called the ‘‘Cummins Equations’’, coupled non-linear integral-differential equations:

$$\sum_{j=1}^6 \left\{ (M_{kj} + m_{kj}) \cdot A_j(t) + \int_{-\infty}^t K_{kj}(t-t) \cdot V_j(t) dt + C_{kj} \cdot X_j(t) \right\} = W_k(t) + F_k(A_j, V_j, X_j, t) \quad (2)$$

In this system of coupled equations of motions the following terms can be distinguished:

1. The inertial forces and moments caused by accelerations.
2. The potential damping forces and moments caused by velocities (the convolution integral).
3. The restoring forces and moments as a result of displacements.
4. Wave forces and moments as a function of time acting on the vessel.
5. External forces and moments as a function of the accelerations, velocities and displacements of the vessel and of time.

3 The DREDMO User-Interface

From the previous paragraph it will be clear that solving equation (2) requires much knowledge related to ship hydrodynamics, soil mechanics, mathematics, etc. The objective of the MS-DOS version of the DREDMO package was, however, to have a user-friendly software package. To meet this requirement the DREDMO user-interface was developed. The user-interface has been developed on the basis of the philosophy that the user should not be concerned too much with the theoretical backgrounds of the calculations. The user should also not be concerned with the way the subsequent programs communicate with each other. The only thing the user should be concerned with is the input of the geometry of the cutter suction dredge and operational input like wave spectrum, haulage velocity and type of soil to be dredged. A first step in reaching these requirements was to modify the calculation

programs in such a way that the programs do not communicate with the user by means of the keyboard. Only the user-interface communicates with the user.

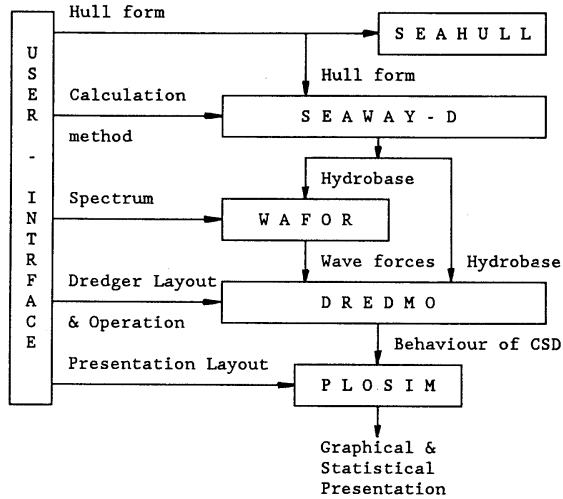


Figure 2 Chart of Information Flow between the Different Programs

The other programs run in the background or obtain essential information from the user-interface. The user-interface also takes care of a correct communication between the calculation programs (see Figure 2). The result of this all is that the user only has to deal with the user-interface.

A calculation should be carried out with the following steps:

1. Enter the hull form in the user-interface.
2. Preview the hull form with the SEAHULL program.
3. Enter data with respect to the calculation method of the hydrodynamic coefficients in the user-interface.
4. Calculate the hydrodynamic coefficients with the SEAWAY-D program. The hydrodynamic coefficients are stored in a so-called Hydrobase.
5. Define a wave spectrum in the user-interface.

6. Calculate wave force time series with the WAFOR program.
7. Enter the dredge layout and the conditions of operation of the cutter suction dredge in the user-interface.
8. Solve the Cummins equations of the cutter suction dredge with the DREDMO program.
9. Enter data with respect to the layout of the graphical output in the user-interface.
10. Create graphical, statistical and spectral output with the PLOSIM program.

In the following paragraphs the programs used will be discussed. The different steps of the calculation will be illustrated with graphs in the frequency and time domain.

3.1 The SEAWAY-D Program

When carrying out time domain calculations with a program like DREDMO, first the potential mass coefficients for an infinite frequency have to be calculated. Then the potential damping coefficients for a range of frequencies have to be calculated, followed by the determination of the retardation functions. These calculations have to be carried out by an external program.

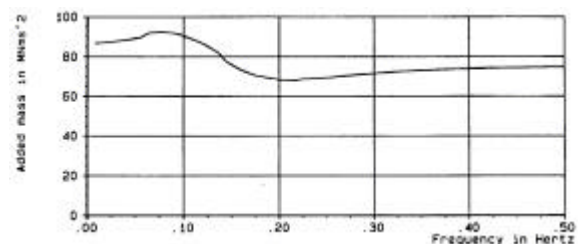


Figure 3 Added Mass of Roll In the Frequency Domain

For this a new pre-processing program, named SEAWAY-D, has been written, which calculates the hydrodynamic mass coefficients and the retardation functions

at zero forward speed. The program has been derived from the frequency domain ship motions personal computer program SEAWAY, Journée 1990 [6], which has recently been made suitable for twin-hull ships and semi-submersibles too.

The use of the pre-processing program SEAWAY-D makes no high demands on the ship hydromechanical knowledge of the user of the DREDMO program.

The ship hull form and some parameters concerning the calculation method are input to the program. The program first calculates the hydrodynamic coefficients in the frequency domain.

Figure 3 shows the added mass of the roll motion as a function of the frequency.

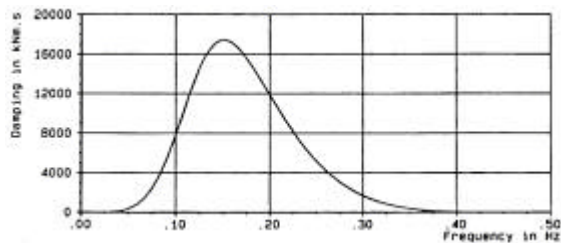


Figure 4 Damping of Roll in the Frequency Domain

Figure 4 shows the potential damping of the roll motion as a function of the frequency.

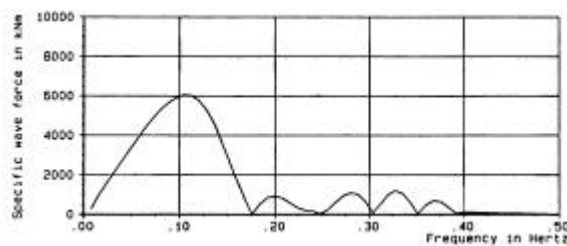


Figure 5 Wave Force Transfer Function in Roll (Amplitude Operator)

The wave loads (wave force transfer function) of the roll motion as a function of the frequency are illustrated in Figure 5. The linear restoring spring coefficients follow from the underwater geometry of the ship. It may be noted that this approach

leads to linear left-hand sides of the time domain equations (2).

To calculate the frequency-depending hydrodynamic mass and damping coefficients of a ship, two- or three-dimensional potential theories can be used. Here use has been made of the relatively simple two-dimensional or strip theory method to calculate the sectional sway, heave and roll coefficients. For the determination of the two-dimensional coefficients of ship-like cross-sections that are not fully submerged, the cross sections are conformably mapped to the unit circle by a two- or three-parameter Lewis transformation or by a N -parameter Close Fit conformal mapping technique.

The advantage of conformal mapping is that the velocity potential of the fluid around an arbitrarily shape of a cross section in a complex plane can be derived from the more convenient circular section in another complex plane. In this manner hydrodynamic problems can be solved directly with the coefficients of the mapping function only. The theory for the calculation of the two-dimensional hydrodynamic potential coefficients is given by Ursell 1949 [18] and Tasai 1959-1961 [16, 17]. All algorithms, necessary to derive these coefficients, are described in detail by Journée 1990 [5].

Another very suitable method is the Frank Close Fit method (Frank, 1967 [2]), especially advised for fully submerged cross-sections. This method determines the velocity potential of a two-dimensional cross section by an integral-equation method, utilising the Green's function, which represents a pulsating source below the free surface. To suppress the so-called "irregular frequencies" in the operational frequency range, not fully submerged cross sections have to be closed at the free surface with some additional points. This results into a shift of these irregular frequencies towards a higher frequency region. A separate method determines the two-dimensional potential surge coefficients.

Then, according to the strip theory, the total hydrodynamic potential coefficients of the ship for surge, sway, heave and roll can be found easily by integrating the sectional values over the ship length. The pitch and yaw coefficients follow from an integration of the moments caused by the sectional surge, sway and heave coefficients over the ship length. Studies, carried out in the past on this subject, have shown that this approach leads to a fairly well prediction of the hydrodynamic potential coefficients.

When comparing the linear frequency domain equations (1) with the time domain equations (2), the time domain coefficients can easily be found from the frequency domain coefficients.

It is found that the hydrodynamic mass coefficients in the time domain equations are defined by:

$$m_{kj} = a_{kj} + \frac{1}{\omega} \cdot \int_0^{\infty} K_{kj}(\mathbf{t}) \cdot \sin(\omega \mathbf{t}) \cdot d\mathbf{t} = a_{kj}(\omega = \infty) \quad (3)$$

and the retardation functions by:

$$K_{kj}(\mathbf{t}) = \frac{2}{\pi} \cdot \int_0^{\infty} b_{kj}(\omega) \cdot \cos(\omega \mathbf{t}) \cdot d\omega \quad (4)$$

Figure 6 shows the retardation function of the roll motion as a function of time. The calculated data are stored in the required format in a file named "hydrobase" and DREDMO and WAFOR can read this file.

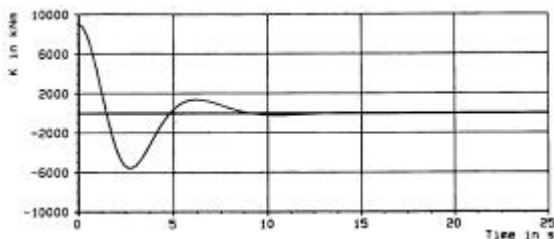


Figure 6 Retardation Function of Roll in Time Domain

Verifications of time domain calculations with results of frequency domain calculations have been carried out for the linear case at zero forward speed. Wave loads, calculated by the frequency domain program, have been input in the time domain program. In spite of errors caused by numerical integration, truncations and differences expected by using two different techniques to solve the differential equations of motions, the two approaches showed a remarkably good agreement. The differences between the amplitudes calculated in two manners, of the harmonic surge, sway, heave, roll, pitch and yaw motions are within 1.0 percent. The differences between the calculated phase lags belonging to these motions with respect to the exciting wave loads are within 1.0 degrees.

3.2 The WAFOR Program

As described above, the wave force transfer functions are computed in the frequency domain with the program SFAWAY-D. Based on these transfer functions, the user can compose time-series of the wave excitation forces on the barge by means of the program WAFOR.

In the computational process to obtain the time series of the wave forces, the following steps can be distinguished:

- Determination of the wave spectrum.
- Determination of the wave force spectra (6 components).
- Determination of the wave force time series.

The wave conditions at the dredging location are defined by a wave spectrum. WAFOR is able to generate a Pierson-Moskowitz spectrum, a JONSWAP spectrum or regular waves. It is also

possible to use a file containing a user-defined spectrum.

The Pierson-Moskowitz spectrum is derived for a fully developed sea and originally has the wind speed as the only free parameter (Pierson 1964 [15]). For engineering purposes however, it is more convenient to have the significant wave-height and the peak-period as free parameters. WAFOR applies this two-parameter Pierson-Moskowitz spectrum.

The JONSWAP spectrum has been derived from a large volume of data in a major international project (Hasselmann 1973 [3]). This spectrum uses three free parameters, the significant wave height, the peak period and the peak enhancement factor g . The peak enhancement factor defines the shape of the spectrum. For $g = 1.0$ the JONSWAP spectrum is equal to the Pierson-Moskowitz spectrum. Factors larger than 1.0 will enhance the shape of the peak and characterise the stage of development of a sea.

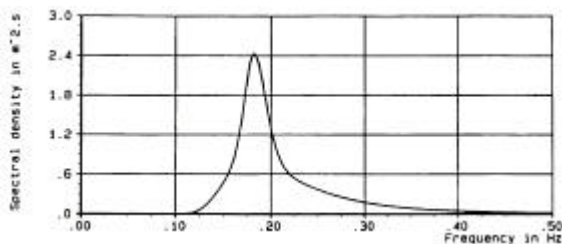


Figure 7 JONSWAP Wave Spectrum

Figure 7 shows the wave energy density of a JONSWAP spectrum with a significant wave height, $H_s = 1.5$ m, a period of the peak of spectral density, $T_p = 5.5$ s, and a peak enhancement factor, $g = 3.3$. The peak enhancement factor used is applicable for a sea in development.

If a user-defined spectrum originating for instance from measurements in the operational field is to be used, the user has to create a file containing a tabulated wave spectrum. WAFOR will read this file to generate a wave spectrum.

If the wave spectrum has been calculated, the spectra of the wave forces have to be determined. Since the natural frequencies of response of cutter suction dredges are usually close to the peak of the wave spectrum, only first-order wave forces are considered.

The wave forces acting on the body of the dredge consist of six components:

- F_x , wave force acting in the longitudinal (surge) direction.
- F_y , wave force acting in the transversal (sway) direction.
- F_z , wave force acting in the vertical (heave) direction.
- M_x , wave moment about the longitudinal (roll) axis.
- M_y , wave moment about the transversal (pitch) axis.
- M_z , wave moment about the vertical (yaw) axis.

The energy density spectra of these six components of the wave force can be obtained by multiplying the energy densities of the waves by the square of the amplitude operator of the wave force transfer functions at the required frequency:

$$S_{FF}(f) = S_{zz}(f) \cdot A_{zF}^2(f) \quad (5)$$

An example of the amplitude operator is given in Figure 8.

Figure 9 shows the resulting energy density spectrum of the wave-forces when the amplitude operator of Figure 8 is applied to the wave spectrum of figure 7.

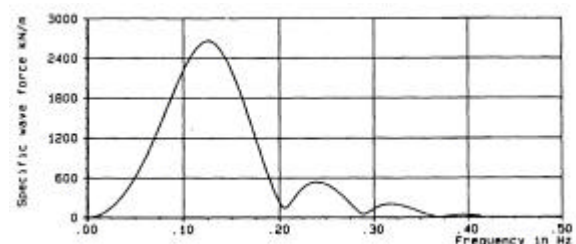


Figure 8 Amplitude Operator of Wave Force for Sway

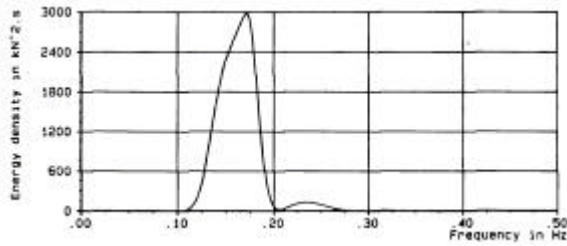


Figure 9 Energy Density Spectrum of Sway Wave Forces

The final step in the computation of the wave forces concerns the determination of the wave force time series. The fundamental obtain time series from a energy density spectrum is:

$$W(t) = \sum_{n=1}^M \sqrt{2 \cdot S_{FF}(f_n) \cdot \Delta f_n} \cdot \cos(2\mathbf{p} \cdot f_n + \mathbf{e}_n) \quad (6)$$

The phase angle \mathbf{e}_n is determined on the basis of a random phase shift for the wave frequency components and the phase operator of the wave-force transfer functions.

Special care should be taken to avoid the time-series repeating themselves within the required computation interval. This repetition can be avoided in the following ways:

- The use of non-equidistant frequencies in equation (6). This method has the advantage that a relatively small number of frequencies may be used. The determination of the time series however has to be carried out in the time domain and is relatively inefficient (time consuming). Moreover, the set of frequencies should be dense enough to cover the frequency band of interest.

Figure 10 shows a typical example of this method using a frequency step too large. In this figure, the amplitude spectrum of a typical ship movement is illustrated for a case where the energy of the waves is concentrated in a small number of frequencies (in total 20 frequencies). These frequencies can be deduced from the amplitude spectrum of the ship movements.

- Using a large number of equidistant frequencies (M frequencies with a constant step Δf) in equation (6). The time series will repeat themselves with a period equal to $1/\Delta f$, so the frequency step can be adjusted with respect to the required time interval of the time-domain computations. Since the frequency step Δf is constant, a Fast Fourier Transform can be used to solve equation (6).

WAFOR offers the user a dense representation of the spectrum that is efficiently used to create wave force time-series, which are statistically correct, with a minimum on input from the user-interface. The wave force time-series are stored in a file named the “wavebase”.

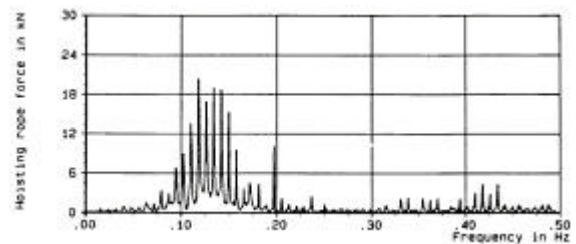


Figure 10 Response on a Small Number of Non-Equidistant Frequencies

3.3 The DREDMO Program

The DREDMO program solves the Cummins equations. DREDMO reads the mass, added mass, restoring spring coefficients and retardation functions from

the “hydrobase”. The wave force time series are read from the “wavebase”. The dredge geometry and the operational parameters are read from a file produced by the user-interface.

This file contains information with respect to:

- the current,
- the dynamics and kinematics of the ladder,
- the geometry of the cutter head,
- the geometry of the face,
- the spud or X-mas anchoring system,
- the swing wires and hoisting wire,
- the type of soil to be dredged,
- the operational parameters and
- the calculation.

The cutting forces are implemented for the cutting of water saturated sand according to Miedema 1987-1989 [12, 13, 14]. The Cummins equations are solved in the time domain by an implicit Newton-Raphson method for the prediction and correction of the acceleration vector. Integrating the accelerations and velocities can derive velocities and displacements. For numerical stability the “teta” integration method is used. Figure 11 shows a flow chart of the solution method. At $t=0$ the dredge is considered to be in a static equilibrium. For $t>0$ the dredge is excited by the wave-forces (depending on time only). For each time-step the iteration process, as illustrated in Figure 11, is repeated until the predicted acceleration vector A_p and the calculated acceleration vector A_c match within the convergence criterion. Then the next time step is executed. This is repeated until the behaviour of the dredge is calculated for the required time interval.

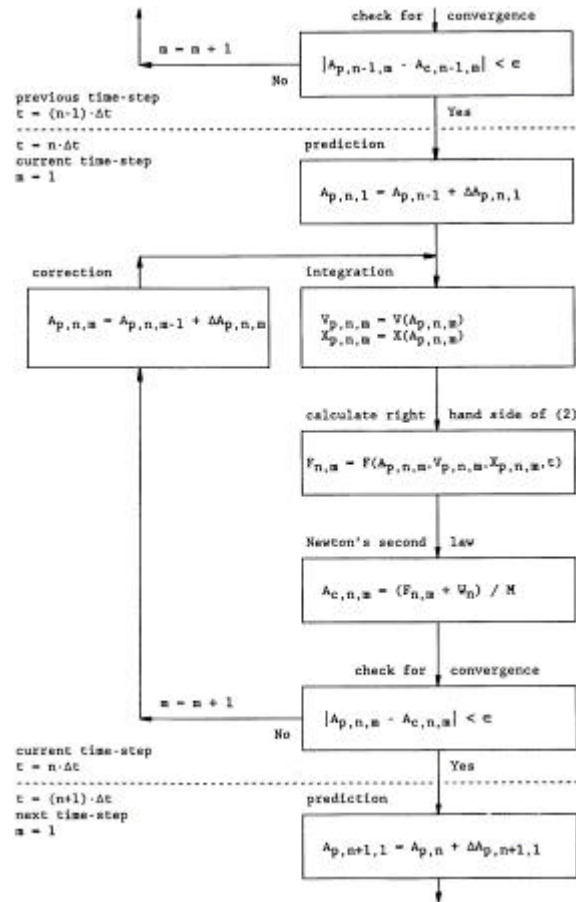


Figure 11 Flow Chart of Solution Method in DREDMO

In DREDMO the ladder is not considered as the 7th degree of freedom, but as an external influence on the body of the dredge. To achieve this the non-linear equilibrium equation of the ladder is solved by an implicit Newton-Raphson method every iteration step of the main program. The reason for this is, that different ladder constructions can be used while the main program remains unchanged.

The output of DREDMO consists of a number of files containing time-series of:

- the motions of the dredge,
- the motions of the ladder,
- the motions of the cutter head,
- the forces on the cutter head and the cutter torque,
- the loads on the spud keepers or the forces in the X-mas tree wires,
- the loads on the ladder bearings,

- the forces in the swing wires and hoisting wire,
- the swing velocity at the cutter position,
- the number of revolutions of the cutter head and
- the production.

Figure 12 illustrates the DREDMO output for the motions of a dredge during 30 seconds simulation.

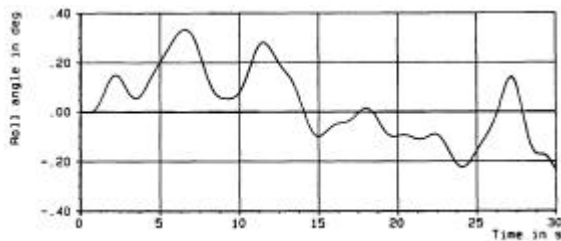


Figure 12 Roll Motions Obtained by DREDMO

3.4 The PLOSIM Program

As mentioned in the previous paragraph, the results of the DREDMO program are stored in a number of files. To evaluate the results of the calculations the results have to be made visible for interpretation. For this purpose the PLOSIM program is added to the DREDMO package. All graphs in this paper have been created with PLOSIM. Except for creating graphs, PLOSIM is also able to smooth signals, apply a low pass filter on a signal, carry out linear and non-linear curve fitting and perform spectral analysis (amplitude spectrum) on signals with a varying time step. Figure 10 illustrates the spectral analysis.

PLOSIM can process files with up to 100 channels and up to 16000 samples per channel. Graphs can be produced with a maximum of 12 view ports and 6 channels maximum per view port on A4 or A3 format. A spread sheet function is added, which permits operation with deduced variables. The size of the graphs can be

adjusted as required as is being used in this paper.

Figure 13 illustrates the motions of a dredge, anchored on a spud pole, as a function of time, during 100 seconds simulation. Figure 14 illustrates the amplitude spectra of the motions. As can be seen, the heave, roll, pitch and surge motions have most of the energy concentrated in a small area around their natural frequencies following from the hydrostatic restoring spring stiffness and the anchoring system. The behaviour of the sway and the yaw motions depend on the anchoring system and the cutting process and has more natural frequencies.

4 Conclusions

The separation of the communication of a user with application programs by means of a user-interface has proven to allow non-specialists to operate the DREDMO package and make them use it. This should however also be valid for other software packages.

The DREDMO package is now a self-contained software package, so no external programs have to be used.

The different programs, the DREDMO package consists of, can also be used for other applications.

5 List of Symbols

- $a(\omega)$ Frequency dependent added mass matrix in kg, kgm or kgm²
- A Acceleration vector in m/s² or rad/m²
- A_{zF} Amplitude operator of wave force transfer function in N/m or Nm/m
- b Frequency dependent potential damping matrix in Ns/m or Nms
- C, c Spring coefficient matrix in N/m or Nm/rad
- m Frequency independent added mass matrix in kg or kgm²

| | |
|----------|---|
| f | Frequency in Hz or rad/s |
| F | External loads in N or Nm |
| H_s | Significant wave height in m |
| K | Retardation functions in N/m or Nm |
| M | Mass matrix in kg, kgm or kgm ² |
| S_{FF} | Spectral density of wave forces in N ² s |
| S_{zz} | Spectral density of wave energy in m ² s |
| t | Time in s |
| T_p | Peak period in s |
| V | Velocity vector in m/s or rad/s |
| W | Wave loads in N or Nm |
| X | Displacement vector in m or rad |
| e | Phase shift in rad |
| g | Peak enhancement factor |
| t | Time in s |
| ∞ | Infinite |

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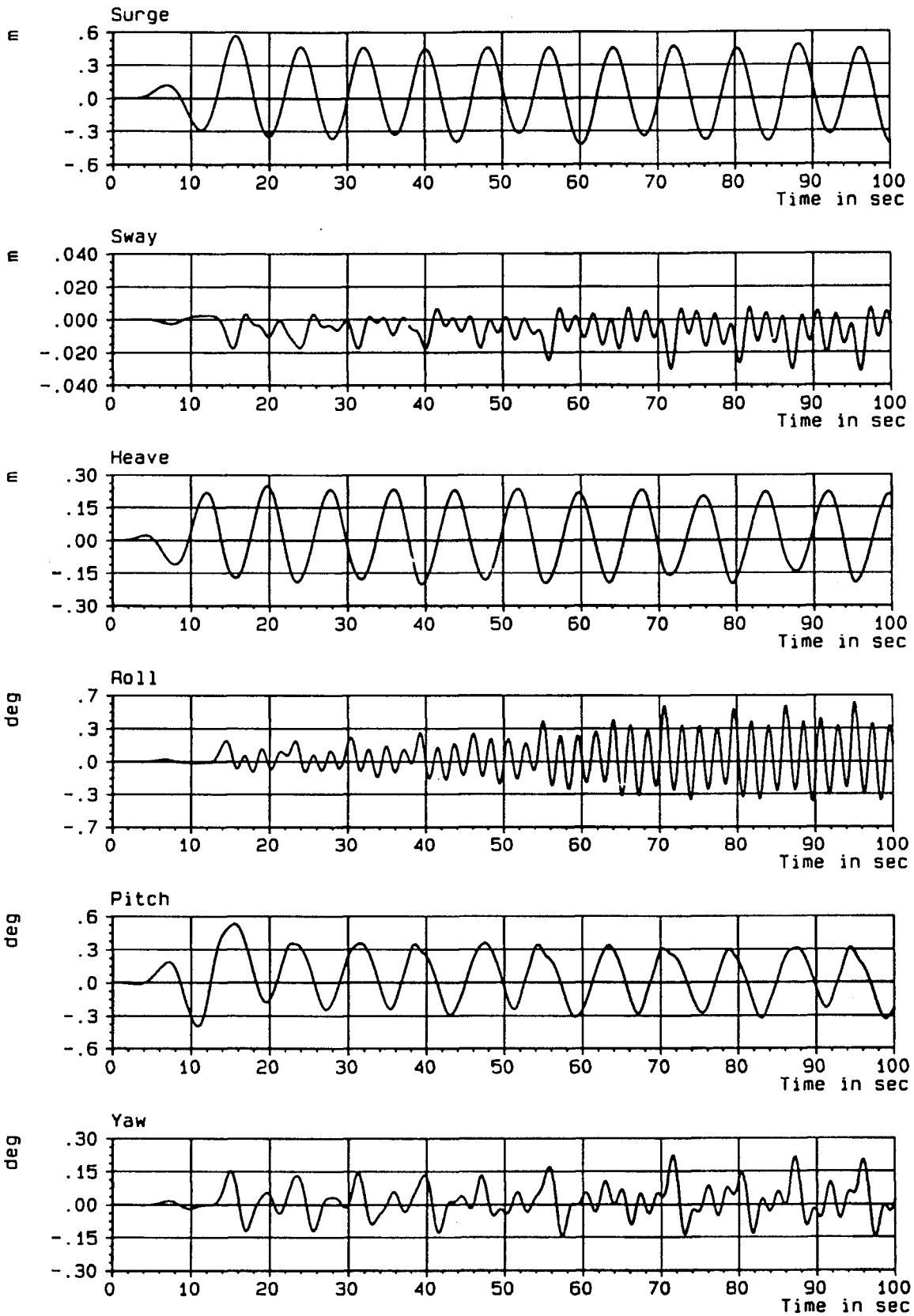


Figure 13 Example of Dredge Motions

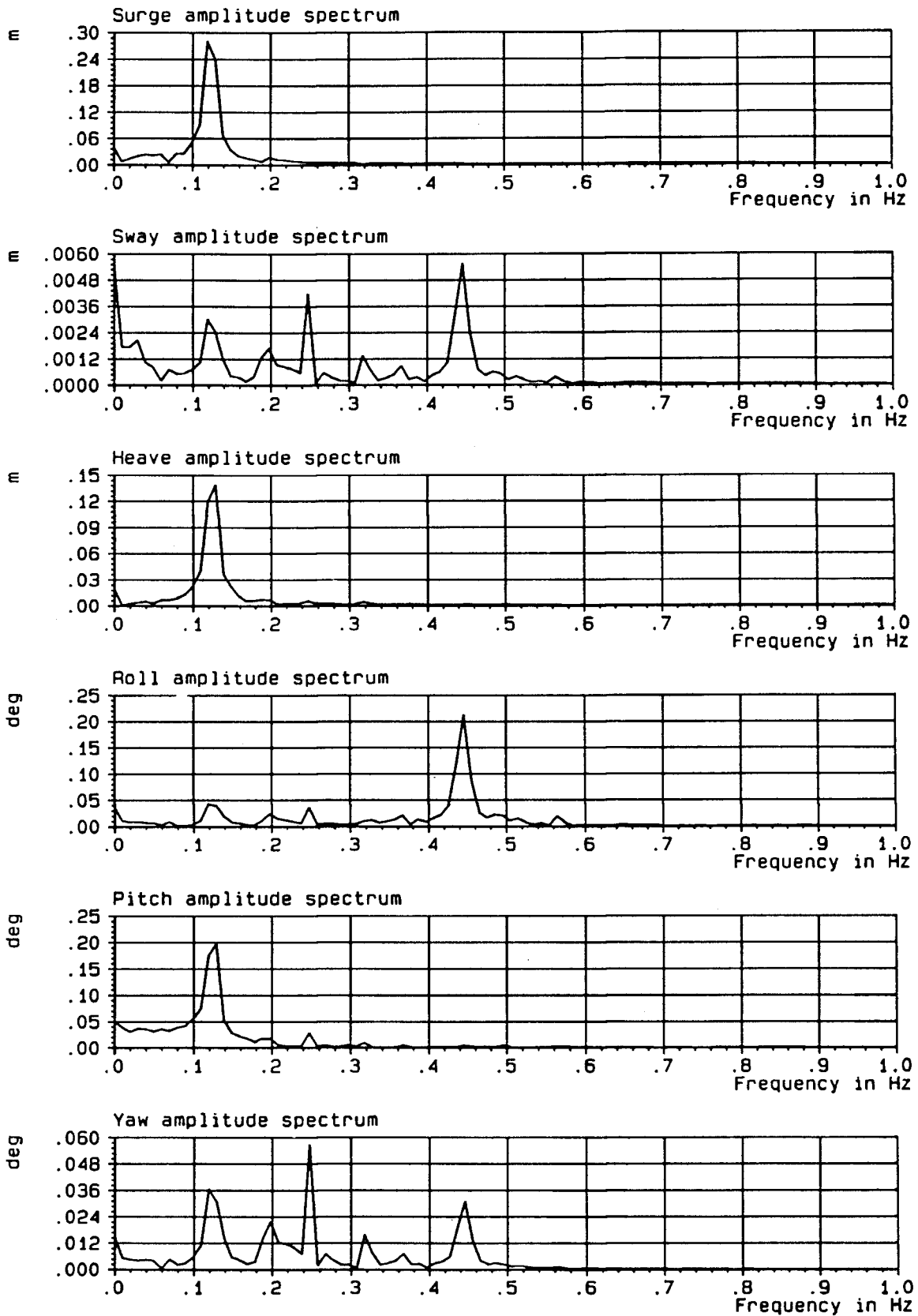


Figure 14 Example of Dredge Motions Amplitude Spectra