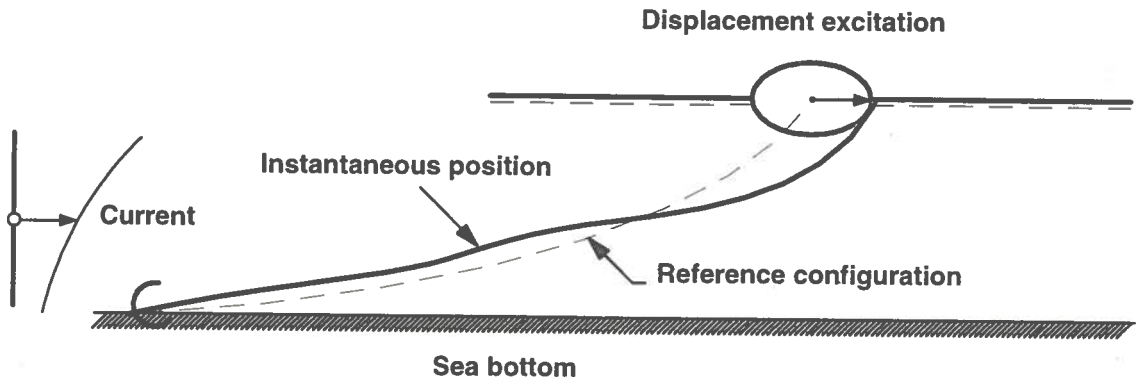
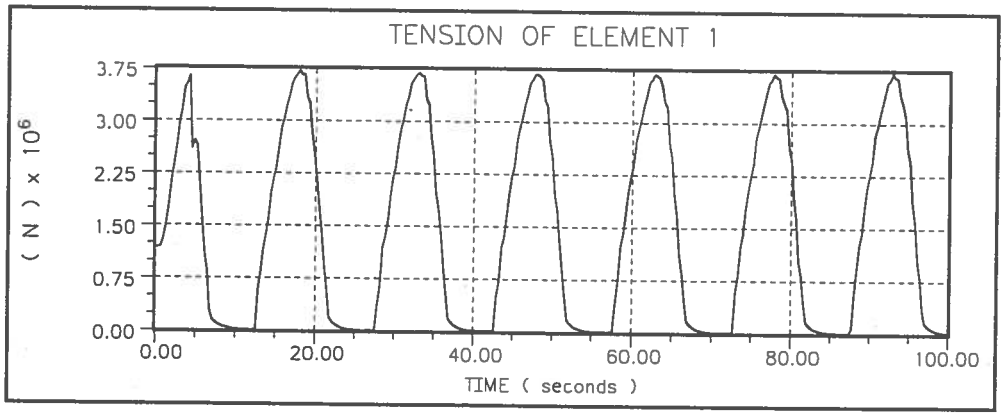
Institutionen för vattenbyggnad
Chalmers Tekniska Högskola

Department of Hydraulics
Chalmers University of Technology

ISSN 0348-1069

MODEX
Version 3
User's Manual





by
Lars Bergdahl

Report Series B:62

Göteborg 1996

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Address: Department of Hydraulics
Chalmers University of Technology
412 96 Göteborg, Sweden

Tel.: +31 772 21 66
Fax: +31 772 21 28
E-mail: lasse@hydr.chalmers.se

PREFACE

MODEX is a finite element program for static and dynamic analysis of cables without bending stiffness. This User's Manual for MODEX (Version 3) replaces the 1987 User's Manual for MODEX - MODIM (Version 2), which was written in connection with the sale of the code to Petroleo Brasileiro SA, Rio de Janeiro. The new manual accounts for improvements made to the code between Version 2 and Version 3 and especially for the improved, interactive input and output for the PC environment. Version 3 can treat cases with buoyant and neutrally buoyant cables, and submerged clump weights and buoys. The main part of the code is written in FORTRAN 90 or FORTRAN 77, but the separate input and output subroutines make use of the GRAPHORIA LIBRARY from Lahey Computer Systems, Inc. and a few subroutines are written in Assembler(PC). The implicit program version MODIM is no longer sustained by development and is therefore excluded from the manual

It should be possible to run the program on any IBM compatible personal computer with at least five megabytes extended memory and provided with VGA graphics adapter. For the plot output, a Laser printer with postscript or plot (HPGL) emulation is necessary.

The original program was developed by Jan Lindahl at the Department of Hydraulics, which retain the proprietary rights. Corrections and additions have been made by Nils Mårtensson, Dynomar AB, and Lars Bergdahl, Martin Asztély and Francisco Herrera at the Department of Hydraulics. Francisco Herrera has created the new input and output routines of the program.

Göteborg, Sweden, December 1996

Lars Bergdahl

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CONTENTS

1 Introduction

MODEX is a finite element computer package for static and dynamic analysis of cables without bending stiffness. The theoretical background to the computer package is accounted for in the reports Dynamic Analysis of Mooring Cables (Lindahl & Sjöberg, 1983) and in Implicit Numerical Solution of the Equations of Motion of a Mooring Cable (in Swedish, Lindahl, 1984). Information from the latter report is included in Appendices B and C of this manual.The finite element method has been used to transform the partial differential equations that describe the motion of the mooring cable into a system of ordinary differential equations, which is solved with an explicit integration in the time domain.

Linear bar elements with constant stiffness and linear, viscous damping are used. See Appendix C. As a result the tension is constant in along each element. Large displacements are taken into account by updating the geometric stiffness matrix at chosen intervals, ordinarily every time step.

The program package contains three separate modules, one helpfile and two drivers.

MODEX.EXE	MOoring Dynamics EXplicit method.
INDATA.EXE	Pre-processor to edit and generate input to the program.
LOOK.EXE	Help program for displaying text files on screen.
DEFAULT.INP	Default file with pre-defined values for a common case.
EPSLDRV.BIN	Driver for PostScript.
HGLDRV.BIN	Driver for HPGL Plotter.

MODEX.EXE is an implementation of the theories of Lindahl and Sjöberg (1983) with the small changes accounted for in Appendices B and C, and complemented with statistics for the calculation of the mean, standard deviation and extreme values of selected quantities. This new version, Version 3, also includes a module of subroutines to handle the graphics output of the program. The graphics can be directly transferred into WINDOWS word processors. Version 3 can treat cases with buoyant and neutrally buoyant cables, and submerged clump weights and buoys.

INDATA.EXE is a self-explanatory pre-processor that will guide through the data groups needed for a specific case of calculation. Some important control functions are implemented to help the user to put in correct data.

The organisation of the input data is described in detail in Chapter 3, in order that input can be changed directly in the input file, by use of some text editor, disregarding recommended limits of input parameters.

LOOK.EXE is a fast, assembler program for reading text files. The pre-processor uses this program to invite the user to check values generated by the program.

DEFAULT.INP is a default file which contains a template for input. The content of this file may be changed but its name must not be changed.

EPSLDRV.BIN is a driver that generates files in PostScript format. These files can later be plotted with the DOS command COPY.

HGLDRV.BIN is similar to EPSLDRV, but the generated files are in the format HPGL. This enables the import of the files into a word processor.

1.1 Examples

Figures 1.1 and 1.2 show two typical cases that can be analysed. MODEX has also been used for the preliminary analyses of taut marine risers, tethers of TLP platforms and of flexible risers.

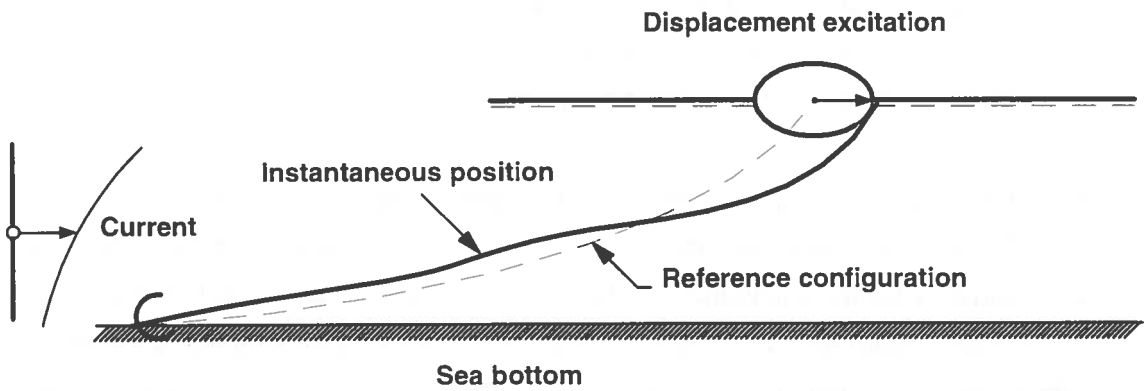


Figure 1.1 A mooring cable

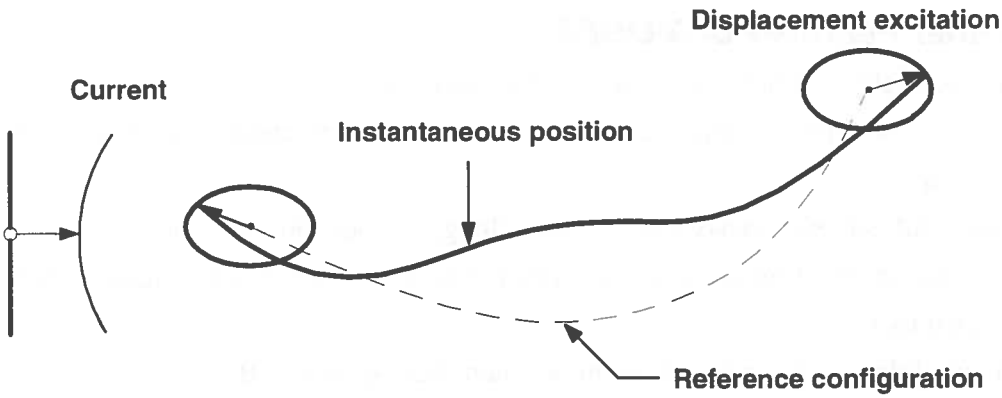


Figure 1.2 A displacement-excited towing cable in a current.

The first case shows the simulation of a displacement-excited mooring cable. Known motions are specified as boundary conditions at the upper end of the cable and the anchor which is regarded fixed. The boundary conditions in the upper end can, for instance, be a time realisation of the expected motion of the fairlead of a floating platform. Further, the presence of the sea bottom and steady currents are taken into account. In the second case a cable is shown that is excited at both ends. This could represent a simulation of a towing cable between a ship and a barge.

In both the figures one instantaneous position of the cable and a reference configuration are shown. The reference configuration is the static equilibrium position of the cable under the influence of weight, buoyancy and the sea bottom. The static equilibrium position is calculated first. This position is then used as an initial condition and a reference configuration in a dynamic analysis. The static position can be associated with the mean position of a floating platform under the exposition of steady current, mean wind, and mean wave drift forces.

1.2 Other Features of MODEX

- Two and three-dimensional calculations can be performed.
- The sea bottom is simulated as rigid and fully energy absorbing for vertical motions.
- Longitudinal and transverse friction along the sea bottom are taken into account in the time-domain simulation but not in the static analysis. See Appendix C.
- Internal damping can be taken into account. See Appendix B.
- Boundary values can be formulated in the form of prescribed forces or motions at the end of the cable. External forces can be prescribed also in nodes along the cable.
- At compressive strain, a choice between alternatives can be made. Either the cable can be allowed to carry compressional forces, or the force in the cable element is set to zero, as long as the distance between the adjacent nodes is shorter than the unstretched length of the element. The calculation is not discontinued in either case.

As stated above the time simulation is performed by an explicit numerical integration. The explicit integration is conditionally stable, which implies that the time increments may not be too large. If too large time increments are chosen, first inaccurate solutions are received, then, for still larger time increments, the solution procedure diverges.

2 How to Run MODEX

There are two ways of running the program MODEX; in batch mode or interactively.

In both cases input files describing the properties of the cable and its excitation must first be created according to the description in Chapter 3 or interactively with the help of a menu-aided input program. See Paragraph 2.2.

The input files has the extension *.inp Excitations can also be given in separate files which shall have the extension *.dpl. Results from the calculations are for each input file produced as one file with the extension *.out and one file with the extension *.grf. The file *.out contains a list of all input data except the external excitation, some key results and error messages, if any. The file *.grf contains all the requested graphic information needed for generating graphs.

2.1 Batch Mode

To the DOS prompt in the appropriate directory, type

modex *filename1*.inp

where *filename1* is the name of an existing input files.

In this mode the program will return to the DOS prompt when the calculation is completed or faults are found in the input file. For running several long simulations in batch mode, a batch file with the following content can be executed:

modex *filename1*.inp
modex *filename2*.inp
modex *filename3*.inp
etc.

Each command must be written on a separate line.

The generated result files can be studied or plotted later.

All the results of the calculation will be saved in files with the same name as the filename but with different extensions. For example, the file *filename1*.grf contains all the graphic information that the program needs for generating graphs in the computer screen, and for plotting diagrams. The file *filename1*.out contains a detailed explanation of the inputs, error messages, and some important key results.

2.2 Interactive Mode

To the DOS prompt in the appropriate directory, type:

modex

The program will reply with the following menu.

Main menu

```
>> MAIN MENU <<

1.  Edit default file.
2.  Edit old file
3.  See input file
4.  See output file
5.  Run the program
6.  See graphics result
```

Figure 2.1: Main Menu.

Option 1 makes it possible to edit a new input file derived from the default file.

Option 2 makes it possible to edit a new input file derived from a file created earlier.

Option 3 makes it possible to see the input values of a file.

Option 4 makes it possible to see the output results from a calculation.

Option 5 the program will first ask for the name of the input file to be run. Then the program execution will stop after the static reference configuration has been created, and this will be shown on the screen. After the eigenvalue analysis or dynamic simulation is completed the program returns to the main menu.

Option 6 the program will reply with a menu (figure 2.2) which makes it possible to see graphically the output results of a desired case.

Graphics menu

Choosing Option 6 in the main menu leads to the graphics menu, Fig. 2.2. Once in the graphics menu, graphs can be chosen to be displayed in the screen for review.

>>GRAPHICS MENU<<	
1	**Reference configuration**
2	**Static cable tension**
3	**Max Min Tension**
4	**Max Min Displacements**
5	**Displacements**
6	**Velocities**
7	**Accelerations**
8	**Tension**
9	**Strain**
A	**Tangential Forces**
B	**Transverse Forces**
C	**Cable Positions**
D	**Cable Envelop**
E	**Eigenmodes**
P	**Plot out**
M	**Main Menu**

Figure 2.2: Graphics Menu.

Example of displayed graph

In the screen a graph as the one shown in Fig 2.3 is displayed. Below each graph there are different alternatives to be chosen:

M = Menu means, press M to go to the main menu.

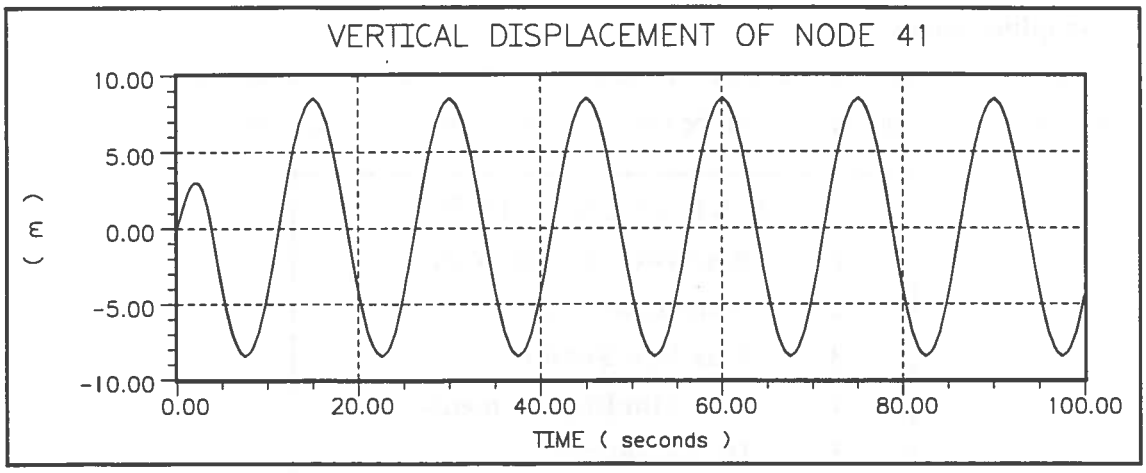
N = Next means press N to go to the next graph.

P = Previous means press P to go to the previous graph.

Space = Save Graph (N)

By pressing space bar, alternately the N in Save Graph (N) changes to Y and Y changes to N. N stands for No and Y stands for Yes. To save a graph to a file choose Y. This file is not generated immediately. To generate it the option plot from the graphics menu must be chosen after all selected graphs have been saved. For further explanation, see the plot menu section below.

T = Tables means, press T to see the values in table form.



Case : Sea floor, buoys, or clumpweights, static and dynamic analysis.
File : case26.inp
Date : 10 MAR 1993

M = Menu N = Next P = Previous Space = Save Graph (N) T = See Tables

Figure 2.3 Example of an option output from the graphics menu.

Plot menu

The **P = plot out** option in the graphics menu responds with a sub menu, Figure 2.4. From this, plot files can be generated in two different formats, PostScript and HPGL. The PostScript files can be plotted with a Laser printer with the DOS command COPY. The HPGL files can be imported into windows word processors.

Options 1 and 2	save the graph only.
Options 3 and 4	save both the graph and the plot valuesin a separate text file with the same name as the input file but with the exension '.txt'.

>> PLOT MENU <<

1 = Save Plot files in POSTSCRIPT format.
2 = Save Plot files in HPGL format.
3 = Save Plot files in POSTSCRIPT format
and plot values in text file.
4 = Save Plot files in HPGL format
and plot values in text files.

Figure 2.4 Plot Menu

The plot files are saved under the same name as the input file but with different extensions.

Filename.rxy :	**R**eference configuration in the **xy** plane.
Filename.rxz :	**R**eference configuration in the **xz** plane.
Filename.rzx :	**R**eference configuration in the **zx** plane.
Filename.ten :	Static cable **ten**sion.
Filename.mmt :	**M**aximum, **m**inimum and standard deviation of the cable **t**ension..
Filename.dxy :	Maximum minimum and standard deviation of the **d**isplacement in the **xy** plane.
Filename.dxz :	Maximum minimum and standard deviation of the **d**isplacement in the **xz** plane.
Filename.dzx :	Maximum minimum and standard deviation of the **d**isplacement in the **zx** plane.
Filename.dxx :	**D**isplacement plot files, where **xx** can be 01 to 10.
Filename.vxx :	**V**elocities plot files, where **xx** can be 01 to 05.
Filename.fxx :	Dynamic tension (**f**orce) plot files, where **xx** can be 01 to 05.
Filename.sxx :	**S**train plot files, where **xx** can be 01 to 05.
Filename.txx :	**T**angential forces plot files, where **xx** can be 01 to 05.
Filename.lxx :	Transversal (**l**ateral) forces plot files, where **xx** can be 01 to 05.
Filename.pxx :	**C**able **p**ositions plot files, where **xx** can be 01 to 20
Filename.exy	**C**able **e**nvelop in the **xy** plane.
Filename.exz	**C**able **e**nvelop the **xz** plane.
Filename.ezx	**C**able **e**nvelop in the **zx** plane
Filename.exx	**E**igenmode plot files, where **xx** can be 01 to 50.

3 Input to MODEX

In the following section a complete description of the input file and the contained variables is given. It is possible to write the input file directly with a text editor, but it is recommended that the first input file for a series of calculations of a class of problems is written in the interactive mode as described in Chapter 2.2. The interactive input program will help in choosing variables and posing a numerically correct problem.

The file must be given in Data Groups as explained below. All values are given in free format.

- Data Groups number 1 to 5 are needed to perform a static calculation.
- Data Groups number 1 to 6 are needed for a calculation of eigenmodes and eigenperiods.
- Data Groups number 1 to 30 are needed to study time dependent load cases.

SI-units without prefixes (kg, m, s, N) are used consistently in the input file. (In the interactive input sometimes the prefix M = 10^6 is used for convenience.)

Data Group 1. Basic geometry and type of problem

STRING1
STRING2
XL1, XL2, ND, NS, ICASE, IEIG , IEXCIT

STRING1			Identification of the problem or blank line
STRING2			Explanation of the kind of data or blank line
XL1			Horizontal co-ordinate (m) of the cable end at static equilibrium.
XL2			Vertical co-ordinate (m) of the cable end at static equilibrium.
			See Figure 3.1, 3.2, 3.3
ND	=	2	Two-dimensional calculation Z = 0.
	=	3	Three-dimensional eigenmode or dynamic calculation. The cable is able to sway out of its plane of equilibrium Z=0. The static equilibrium calculation is performed two-dimensionally also when ND = 3.
NS			Number of cable segments. The cable is divided into segments with different properties. The numbering of the segments are shown in Figure 3.3. NS ≤ 20.

ICASE = 1 No sea floor, static analysis. (See Fig. 3.1)

= 2 No sea floor, dynamic calculation. The static equilibrium configuration (See Fig. 3.1) is used as the reference configuration.

= 3 With sea floor, static analysis. (See Fig. 3.2)

= 4 With sea, floor, dynamic calculation. The static equilibrium configuration (See fig. 3.2) is used as the reference configuration.

= 5 With sea floor, submerged buoys, clump weights and/or one surface buoy , static analysis (See fig. 3.3).

= 6 With sea floor, submerged buoys, and/or clump weights, dynamic calculation. The static equilibrium configuration (See fig. 3.3) is used as the reference configuration. (No surface buoy.)

IEIG = 0 if ICASE = 2, 4, 6

= k if ICASE = 1, 2 ,5

$0 < k \leq$ number of degrees of freedom.

Then the k greatest eigenperiods with corresponding eigenmodes are calculated assuming small oscillations around the equilibrium configuration. Neither drag nor internal damping is taken into account.

IEXCIT = 0 External excitation is given directly in Data Groups 12 to 14 in this file.

= 1 External displacement excitation in three dimensions is given for the uppermost node in one external file

= 2 External displacement excitation in three dimensions is given for the uppermost and lowermost node in two external files

= 3 For the uppermost node external displacement excitation in three dimensions is given in an external file, and external force excitation in the Y direction is given in another external file. The displacement excitation in the Y direction is not used. This option is suitable for the preliminary calculation of dynamics of TLP-tendons or marine (taut) risers.

Restrictions on XL1 and XL2 and examples of configurations.

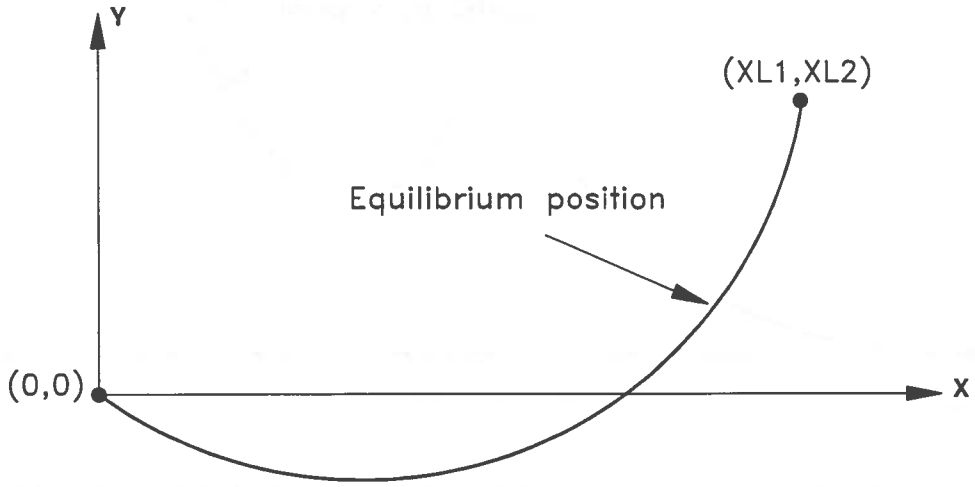


Figure 3.1 Static equilibrium of the cable in the cases ICASE = 1 and 2 for co-ordinates XL1, XL2

In the case (ICASE = 1 and 2) shown in Fig. 3.1 the condition XL1 > 0 must hold. The cable is hanging in the plane defined by the co-ordinate axes X and Y

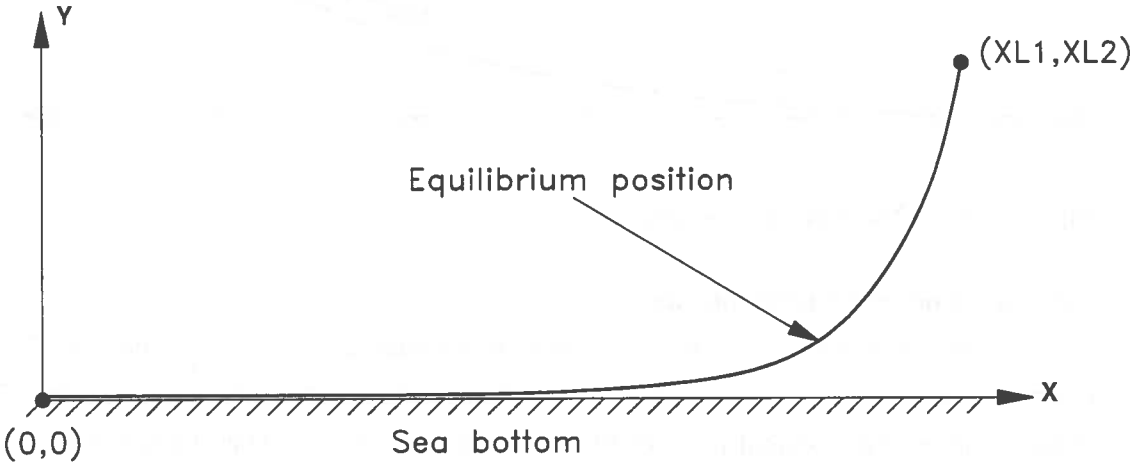


Figure 3.2 Static equilibrium of the cable in the cases ICASE = 3 and 4 for co-ordinates XL1, XL2.

In the case (ICASE = 3 and 4) shown in Fig. 3.2 XL1 + XL2 must be greater than the length of the unstretched cable. The cable is hanging in the plane defined by the co-ordinate axes X and Y, and is partly resting on the sea floor.

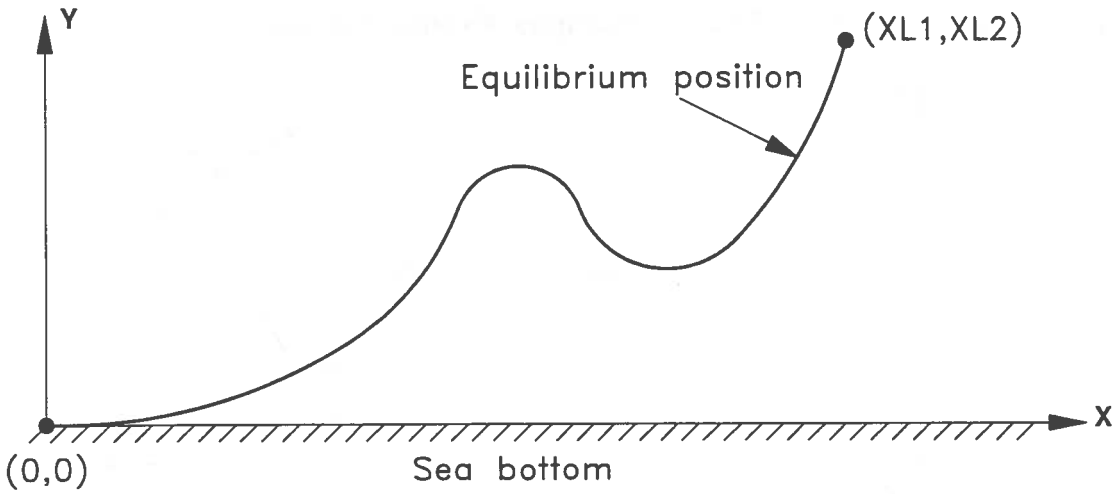


Figure 3.3 Static equilibrium of the cable in the cases ICASE = 5 and 6 for co-ordinates XL1, XL2.

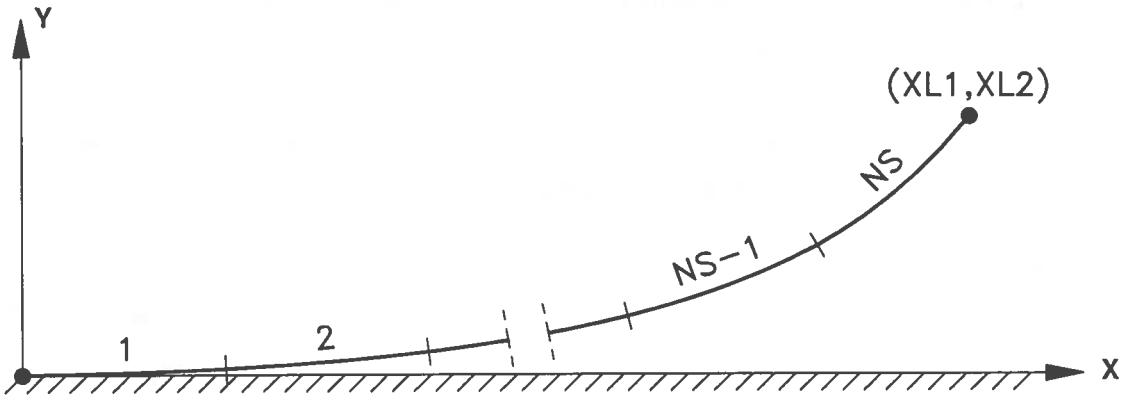


Figure 3.4 Numbering of segments.

Comments on eigenfrequency analysis

In the case of ICASE = 3, the sea floor is simulated with linear springs. The stiffnesses of the springs are calculated by letting the cable sink a given vertical distance below the nominal level of the sea floor (Y = 0). See Data Group No 4. In the three-dimensional calculation of eigenmodes (also in the case of ICASE = 5) these spring constants are also used to suppress oscillations, that are transverse to the plane of equilibrium, along the sea floor.

The calculation of eigenmodes and eigenperiods are thus founded on a series of assumptions. The hydrodynamic drag has, for example, been shown to have great influence on the properties of the system. One should therefore not draw too far-reaching conclusions from the calculated eigenmodes, as damped systems are being examined.

External excitation files, IEXCIT

If IEXCIT = 1 give on line 4

FILENAME1

else if IEXCIT = 2 or 3 give on line 4 and 5

FILENAME1

FILENAME2

FILENAME1 The name of the external file where prescribed displacement excitation for the uppermost node is given.

FILENAME2 The name of the external file where prescribed displacement or force excitation is given.

The values given in FILENAME1 always refer to the uppermost node of the cable. The values given in FILENAME2 refers to the lowermost node of the cable if they are displacements or to the uppermost node if they are forces.

The external excitation files for displacements are freeformatted, contain the displacements and shall be organised as follows

Line No	Variable	Type	Meaning
1	IDENTINP	String (A80)	Identification of input data
2	NTF	Integer	Number of time steps
3	DELTAT	Real	Time increment (sec)
4 etc.	PSX, PSY, PSZ	Real	NTF lines of displacements of node in X, Y and Z directions.

The external excitation files for force are freeformatted, contain one force in the Y direction (vertical) and shall be organised as follows:

Line No	Variable	Type	Meaning
1	IDENTINP	String (A80)	Identification of input data
2	NTF	Integer	Number of time steps
3	DELTAT	Real	Time increment (sec)
4 etc.	F	Real	NTF lines of vertical force in upper attachment point in the Y direction.

Example of content of external file for three-dimensional displacements

```
File: RIG.DPL Spectrum type: 1  Hs=10    Tz= 9.  RARG=0
900
0.2
 -0.735200      1.37900      0.132900
 -0.659700      1.28800      0.146400
 -0.581000      1.19200      0.159200
 -0.499400      1.09300      0.171000
 -0.415200     0.989500      0.181800
 -0.328800     0.884300      0.191100
 -0.240500     0.777700      0.199000
 -0.150800     0.670500      0.205100
 -0.601200E-01  0.563700     0.209300
  0.308300E-01  0.458000     0.211300
  0.121500     0.354200      0.211200
  0.210900     0.253100      0.208700
  0.298700     0.155300      0.203800
  0.383700     0.614200E-01  0.196300
  0.465200    -0.278900E-01  0.186600
  0.542000    -0.112300      0.174400
  0.613600    -0.191300      0.160000
  0.679000    -0.264600      0.143600
  0.737100    -0.332200      0.125500
  0.787400    -0.393700      0.106000
  0.829100    -0.449000      0.854300E-01
  0.861600    -0.497900      0.642100E-01
  0.884600    -0.541200      0.427700E-01
  0.897600    -0.578500      0.214100E-01
  0.900600    -0.610000      0.575000E-03
  0.893800    -0.636100     -0.193500E-01
  0.877500    -0.657300     -0.380700E-01
  0.852000    -0.673500     -0.555900E-01
  0.818000    -0.685000     -0.716100E-01
  0.776400    -0.692700     -0.860500E-01
  0.728000    -0.697000     -0.990100E-01
  0.674000    -0.697900     -0.110600
  0.615300    -0.696100     -0.121000
  0.553300    -0.692100     -0.130300
  0.489000    -0.686600     -0.138800
  0.423600    -0.680100     -0.146500
  0.358100    -0.673100     -0.153800
  0.293600    -0.666400     -0.160600
  0.230900    -0.660400     -0.166900
  0.170800    -0.656000     -0.172900
  0.114000    -0.653900     -0.178200
  0.611700E-01 -0.654700    -0.182700
  0.126900E-01 -0.659100    -0.186200
 -0.310500E-01 -0.668200    -0.188200
 -0.697500E-01 -0.681400    -0.188500
 -0.103200    -0.700100     -0.186700
 -0.131000    -0.725700     -0.182400
 -0.153300    -0.756100     -0.175300
 -0.169700    -0.795200     -0.165400
 -0.180300    -0.839400     -0.152300
etc.
```

Data Group 2 Segment properties

For each segment I = 1, NS give:
STRING
DM, DENSC, EK, CCV, TLS, NES
MBUOY, DBUOY, HI, DSBUOY, WB, FOB, FEK

The numbering of the cable segments is shown in Fig. 3.4. Each segment is divided into NES number of elements. The properties for each segment I is given by:

STRING	Explanation of the kind of data or blank line
DM	Cable mass per unit unstretched length (kg/m).
DENSC	Density of cable (kg/m^3). For ICASE = 1 to 4 DENSC > DENS, where DENS is the density of water). Cases equivalent to ICASE 1 to 4 can be run by ICASE 5 or 6 if the cable is lighter than the ambient water.
EK	Stiffness of cable (N). Elasticity times cross sectional area.
CCV	Internal damping of cable (Ns). See Appendix B
TLS	Unstretched length of segment (m).
NES	Number of elements in segment No I. Must be an even integer NES ≥ 2. The length of elements becomes TLS/NES (m). In the interactive input program the number of elements is given for the first segment. The number in the following segments are automatically calculated to give an optimal solution.
MBUOY	Mass of buoy or clump weight (kg).
DBUOY	Diameter of buoy or clump weight. This submerged buoy or clump weight is attached to the upper end of segment No I and is assumed to be spherical.
HI	Height (m) of surface buoy. If HI is set to zero, there is no surface buoy and the rest of the parameters will not be read. The dynamics of this buoy is not implemented (May 1996).
DSBUOY	Diameter (m) of cylindrical surface buoy. If DSBUOY is set to zero the surface buoy is assumed spherical with diameter HI.
WB	Mass of surface buoy (kg).
FOB	Length of attachment line (m) between the surface buoy and the cable.
FEK	Stiffness (N) of attachment line.

Observe : Only one surface buoy can be given for the whole cable.

The total number of elements becomes NE = $\sum$ NES and the number of nodes NE+1.

The numbering of nodes and elements is shown in Fig. 3.5. The present arrays allow 96 elements.

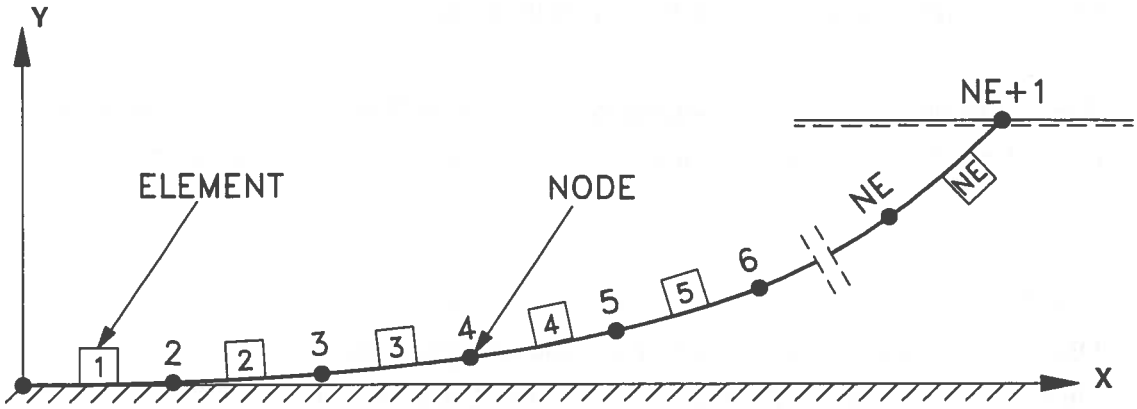


Figure 3.5 Numbering of nodes and elements

Data Group 3 **Parameters for numerical solution of static configuration**

STRING
DELL, EFAC

This data group is needed for the calculation of the static reference configuration.

STRING Explanation of the kind of data or blank line

DELL Defines the number of load increments 1/DELL, 0.0 < DELL ≤ 1.0. The total effect of gravity will be gradually increased for 1/DELL number of load increments. Each load level is associated with an intermediate reference configuration. After the last load increment, the weight and buoyancy have reached their full values. For a cable with uniformly distributed mass and stiffness it is ordinarily sufficient to use DELL = 0.05 to 0.10. For a cable with segments with different properties a lower value is needed. DELL = 0.01 is usually sufficient, but also lower values must sometimes be used.

In the latter case weight and buoyancy is applied with equal increments along the whole cable until the load on any one segment has reached its full value. Thereafter, this segment will not get further contributions but only the other segments until any one of these segments has reached its full load etc. The procedure is continued until the final equilibrium position is reached.

EFAC Fictitious elastic stiffness factor. At the first load increment the reference configuration is established from the equation of "inelastic or elastic catenary". In order to reach the next reference configuration smoothly it is necessary to give the cable an extra stiffness, which is applied as linear springs in the nodes. EFAC gives the stiffness of these springs in relation to the mean stiffness of the cable segments. The spring stiffnesses are all set to

$$\left(\frac{EFAC}{NE}\right)\sum_{i=1}^{NE}\frac{K_i}{l_i}$$

where l_i is the length of elements and K_i the stiffness of elements. NE is the total number of elements. For a cable with equal element lengths, uniform mass and stiffness distribution EFAC = 0.01 has given converging solutions. The stiffnesses of the springs are reduced for each load increment and are nil when the cable reaches its equilibrium.

If there are problems with the convergence a value greater than 0.01 should be used, in extreme cases EFAC = 1 has been used.
If $XL1^2 + XL2^2 > TL^2$, EFAC can be given to zero .

If ICASE = 1 or 3, continue at Data Group 5.

Data Group 4 Stiffness of sea floor.

STRING
BDIS

STRING Explanation of the kind of data or blank line
BDIS The sinking (m) of the cable below the nominal level of the sea floor (Y = 0) at vertical equilibrium. BDIS > 0.0 m. The stiffness of the sea floor is calculated from BDIS, and is applied as vertical and transverse linear springs in nodes resting on the sea floor. These springs are used in the static analysis and at the calculation of eigenperiods and eigenmodes.

Data Group 5 Water density

STRING
DENS

STRING	Explanation of the kind of data or blank line
DENS	Density of water (kg/m^3).

In the program the weight per unit length of the submerged cable is calculated as g*DM*(DENSC – DENS)/DENSC with DM and DENSC from Data Group No 2.

> If ICASE = 1, 3 or 5 and IEIG = 0, a calculation of static equilibrium can be performed.

Data Group 6 Hydrodynamic coefficients and cable diameter

For each segment I = 1, NS give

STRING
CDN, CDT, CNM, DIAM, CDBUOY, CMBUOY

These lines give cable diameter and hydrodynamic coefficients for each cable segment and must, therefore, be as many as the number of segments NS according to Data Group No 2. For each segment give:

STRING	Explanation of the kind of data or blank line
CDN	Drag coefficient for transverse flow.
CDT	Drag coefficient for tangential flow.
CNM	Coefficient of added mass transverse to the cable.
DIAM	Cable diameter.
CDBUOY	Drag coefficient of the buoy (spherical)
CMBUOY	Coefficient of added mass of the buoy

The properties given in this data group are only used to calculate hydrodynamic forces. The added mass of the cable is for instance calculated as CNM*π*DIAM^2/4 for any segment be it steel rope, synthetic rope or chain. It is thus up to the user to

define consistent coefficients. For a rope the nominal diameter is normally used. Also for a chain the authors of this report have chosen to use the nominal diameter, and as the volume per unit of length of a steel chain is around $3.8*\pi*DIAM^2/4$ the coefficient of added mass is set to CNM = 3.8. Another convention could be to use the equivalent diameter for a cylinder containing all the steel of the chain and coupled to this CNM = 1.

Note that the tangential drag force per unit length of the cable is defined as :

CDT*DIAM*|UT|*UT,

where UT is the tangential relative velocity.

If IEIG > 0 and ICASE =1, 3 or 5 eigenmodes and eigen-periods can be calculated.

Data Group 7 Specification of steady current

STRING
NST, TRS

STRING		Explanation of the kind of data or blank line	
NST	=	0	No specified current.
	>	2	Number of points where the current is specified.
TRS		Reduction of current velocity according to Fig. 3.5 during a part TRS (s) of the simulation time.	

Through this data group and the next one an oblique horizontal current can be imposed. The current is parallel to the sea bottom and is specified at vertical levels along the Y axis. The current must be given so that the cable at all times is between the outermost specified levels, because the used subroutine does not extrapolate the current velocities.

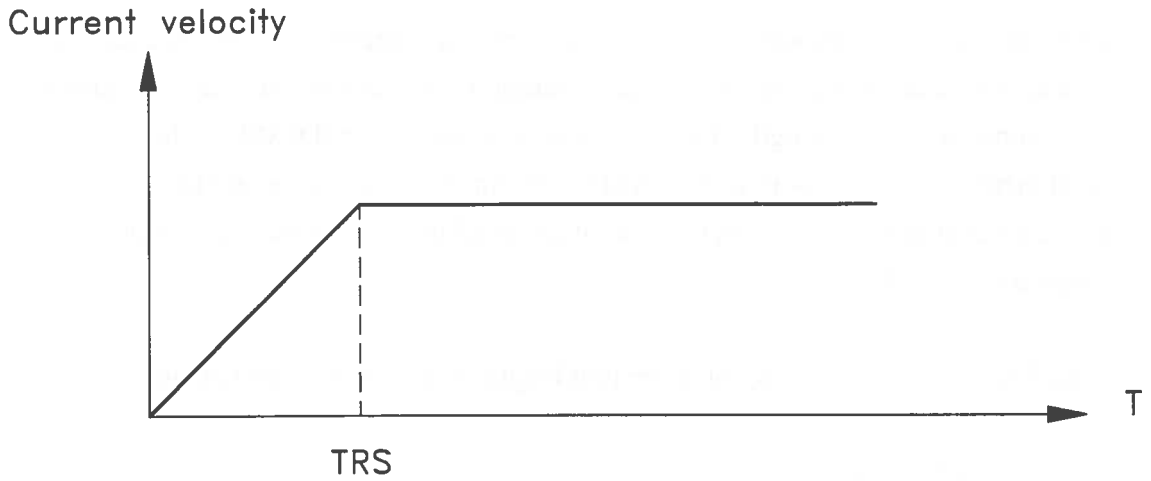


Figure 3.6 Reduction of current velocity.

If NST = 0 continue at Data Group No 9.

Data Group 8 **Horizontal current velocities**

STRING
For I = 1, NST give:
YST, (VST(J), J = 1, ND-1)

STRING Explanation of the kind of data or blank line
YST Level along the Y axis (m) where the current is specified. Must be given from below in increasing order with the lowest level at least BDIS (See Data Group 4) below the sea bottom and well below the lowest point of the cable motion, and well above the uppermost point of the cable motion.

VST(J) Current velocity (m/s) at the level YST. For a two-dimensional case (ND = 2) give VST(1) where VST(1) is the component in the direction X. For a three-dimensional case (ND = 3) give VST(1) and VST(2) where VST(2) is the component in the direction Z.

Data Group 9 Time integration data

STRING
DELT, TMAX, TS, TR, TVA, IPOL, NUPM

STRING Explanation of the kind of data or blank line

DELT Time increment (s). In order to get a stable calculation the time increment DELT must be smaller than the smallest value of lj/cj where lj is the element length and cj is the longitudinal celerity of elastic waves in cable segment No j. To get a good solution only half that time increment should be used. Thus the smallest value of
DELT = 0.5*TLS*SQRT(DM/EK)/NES
along the cable is recommended. (Notations at Data Group No 2). The interactive input program will help the user to choose time increment and element lengths so that approximately the same accuracy will be obtained for the segments.

TMAX Time of simulation. The time integration is started at the time zero and is terminated at the time TMAX.

TS Point of time at which exciting forces or displacements shall start (s). TS ≥ 0.0. See Fig 3.7 at Data Group No 11.

TR The length of time (s) during which the excitations are gradually increased to their full values. See Fig 3.6.

TVA The point of time after which maxima, minima, standard deviations and mean values are calculated for demanded parameters. These characteristic values are calculated between TVA and TMAX.

IPOL = 0 The drag forces are set to zero in the analysis even if drag coefficients are given in Data Group 6.

= 1 to 5 The drag forces are evaluated by integration along the elements. A greater number yields better accuracy. See comments below.

NUPM causes the global mass matrix (including the added mass) to be updated each NUPM'th time increment. It can, at least for ND = 2, be given the value 1. At a three-dimensional analysis calculation efforts can be saved by assigning a higher value depending on the magnitude of the oscillations.

When the finite-element method is used the integrals (Eq. 3.18 and 3.19 in Lindahl, Sjöberg, 1983) that give the drag forces on the elements must be evaluated numerically. The integrals are evaluated with Newton-Cotes equation as given by

Harold et al. (1973). Values of IPOL > 0 indicate with which order of accuracy the integrals is evaluated. 1st order is equivalent to a linear interpolation between the nodes:

IPOL = 1 1st order approximation
= 2 1st "
= 3 2nd "
= 4 3rd "
= 5 4th "

The evaluation of the integrals of te drag forces constitutes a considerable part of the calculation effort. The greater value of IPOL that is used the greater accuracy will be obtained for the same division into elements. This will, however, use considerably more computing time. Therefore it can be more efficient and equally accurate (as to drag forces) to choose shorter elements and a low value of IPOL. IPOL = 1 and 2 are numerically equivalent but IPOL = 1 is more efficiently coded. IPOL = 1 is recommended in combination with a rather dense division into elements. Then a better representation of the cable is also gained.

If ICASE = 2 continue at Data Group No 11

Data Group 10 Bottom friction.

STRING
CFR, CVTOL

STRING Explanation of the kind of data or blank line
CFR Coefficient of friction between cable and sea floor.
CVTOL Tolerance (m/s) given in order to avoid numerical problems when the model of friction is used in time-domain dynamic analysis. The value 0.3 m/s has been used in most simulations and has recently proven to give results agreeing with frequency-domain analyses. (Liu and Bergdahl, 1997).

The model of friction has been changed somewhat in comparison to what was accounted for in Lindahl, Sjöberg (1983). See Appendix C. There is no bottom friction implemented in the static analysis.

Data Group 11 Specification of excitation and compressional behaviour

STRING
NTF, NDF, NDP, NC, NSS

STRING Explanation of the kind of data or blank line

NTF Number of points of time for which force or displacement excitations are specified. Both types must be specified at the same points of time. At most 500 points. Not used for excitation from external files although an arbitrary value must be given.

NDF Number of specified exciting force functions in the nodes of the cable. At most 6 functions. Must be given also for excitation from external files.

NDP Number of specified displacement functions in the nodes of the cable. At most 6 functions. Must be given also for excitation from external files.

NC Number of nulled displacements in the nodes of the cable. At most 6 displacements. Must be given also for excitation from external files.

NSS = 0 The internal forces in the cable are to follow assumed constitutive relations also for compression (staving).
1 The internal forces are set to zero at compression (staving).

Forces or displacements can act in nodes of the cable.

Usually the displacements for a mooring cable are given to zero at the anchor i.e. node No 1 and to some functions of time at the fairlead i.e. node No NE+1. (For node numbering see Fig 3.4.) For a two-dimensional case then NC = 2 and NDP = 2.

It is rather meaningless to specify a displacement somewhere along the span of the cable, but this can be done. Calculation errors can result if the cable is prescribed to move below the sea floor.

By a specified exciting force is meant a force that is known prior to the analysis and that shall be added to other forces acting in the node (gravity, buoyancy, drag etc.). It is not permitted to specify an exciting force and an exciting displacement in the same direction in a node.

Specified forces and displacements are specified at NTF points of time TP(I). The points of time can thereafter be scaled to TC(I) = AMPT * TP(I) (Data Group 13) and the specified forces and displacements are assumed to vary linearly between the

"scaled" points of time. See Fig 3.6. Forces and displacements are specified in the data groups Nos. 14 to 17 or in external files, (See Data Group 1).

Specified forces or displacements commence at the point of time TS, and if the time of integration (TMAX) is greater than TS+TC(NTF) the functions will be repeated. For such cases periodic boundary conditions are obtained, and it is recommended that the specified displacements have the same values at the points of time TC(1) and TC(NTF). Otherwise discontinuous displacements are obtained, which causes calculation problems. The prescribed displacement need not be given the value zero at point of time TC(1), because the displacement (as a function of time obtained through data groups Nos. 16 to 17) can be gradually increased from zero by PS* TC/TR by giving a tapering time TR, so that an abrupt start is avoided. See Fig 3.6.

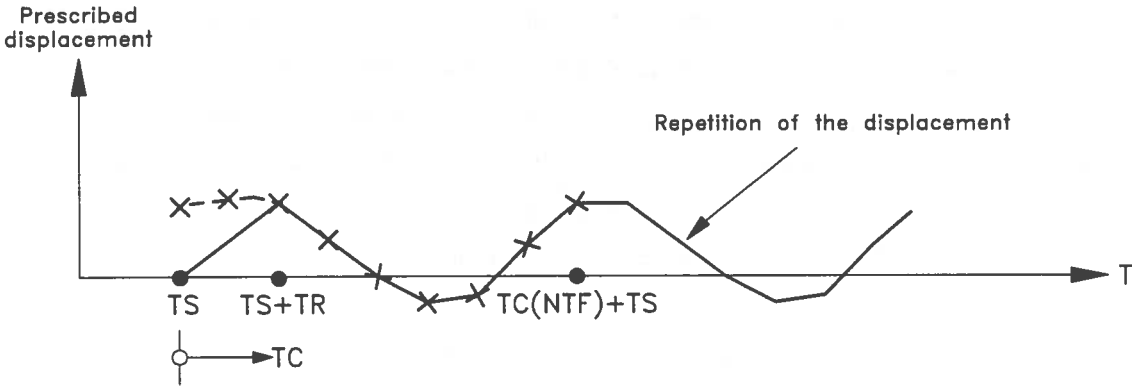


Figure 3.7 A specified displacement created from NTF = 9 number of points. The figure shows two periods of time.

If NDF = 0 and NDP = 0 continue at Data Group No 19.

If IEXCIT > 0 continue at Data Group No 13

Data Group 12 Specification of time points

STRING
TP(I), I = 1, NTF

STRING Explanation of the kind of data or blank line
TP(I) The point of time (s) where force or displacement functions are specified, given in increasing order.

Data Group 13 Scale factor for time

STRING
AMPT

STRING Explanation of the kind of data or blank line
AMPT Scale factor for the point of times given through Data Group No 12 or in external file. All points of time will be scaled to AMPT*TP(I). Use AMPT = 1 if excitatio from external file.

If NDF = 0 continue at Data Group No 16

If IEXCIT > 0 continue at Data Group No 15

Data Group 14 Specification of forces

For J = 1, NDF give:
STRING
F(I,J), I = 1. NTF

STRING Explanation of the kind of data or blank line
F(I,J) The J'th specified force at the time level I. NDF number of force functions are specified. These are identified by the numbers J = 1 to NDF in the order they are given.

Data Group 15 Scale factor of forces

STRING Explanation of the kind of data or blank line
For J= 1, NDF give:
AMPF (J)

STRING Explanation of the kind of data or blank line
AMPF(J) Scale factor of the J'th force F(I,J). The force is scaled to AMPF(J)*F(I,J). Use AMPF = 1 if excitation from external file.

If NDP = 0 continue at Data Group No 18

Data Group 16 Specification of displacements

If IEXCIT > 0 Continue at Data Group No 17

For J = 1, NDP give:
STRING
PS(I,J), I = 1, NTF

STRING Explanation of the kind of data or blank line.
PS(I,J) The J'th specified displacement at the time level I. NDP number of displacements functions are specified. These are identified by the numbers J = 1 to NDP in the order they are given.

Data Group 17 Scale factor for displacements

STRING
For J = 1, NDP give:
AMPP (J)

STRING Explanation of the kind of data or blank line.
AMPP(J) Scale factor for the J'th specified displacement. The displacement is scaled to AMPP(J) * PS(I,J).

If NDP = 0 continue at Data Group No 19

Data Group 18 **Association of specified forces with nodes and directions**

If IEXCIT > 0 continue at Data Group No 20

STRING
For K = 1, NDF give:
I , J , ISF (I, J)

STRING	Explanation of the kind of data or blank line.
I	Node number.
J	Direction J, J = 1, 2 or 3. J = 1, 2, 3 correspond to X, Y, Z-directions.
ISF(I, J) = L	$1 \leq L \leq NDF$. Indicates that the L'th force specified in Data Groups Nos. 14 and 15 shall act in node I direction J. The forces are numbered in the order they are given in data Group No 14.

If NDP + NC = 0 continue at Data Group No 20

Data Group 19 **Association of specified displacements with nodes and directions**

If IEXCIT > 0 continue at Data Group No 20

STRING
For K = 1, NDP + NC give:
I, J, ISP (I, J)

STRING	Explanation of the kind of data or blank line
I	Node number I
J	Direction J = 1, 2 or 3. J = 1, 2, 3 correspond to X, Y, Z directions.

ISP (I, J) =	0	Indicates that the component of the displacement in direction J should be zero for node No I.
=	L	1 < L < NDP. Indicates that in Node No 1 the component of the displacement in direction J should be prescribed with the L'th displacement function specified in Data Group Nos. 16 and 17. The displacement functions are numbered in the order they are given in Data Group No 16.

Data Group 20 Request for plots

STRING
IPLOT

STRING		Explanation of the kind of data or blank line
IPLOT	= 0	No plotting of variables as a function of time.
	= 1	Plotting of variables as a function of time

If IPLOT = 0 continue at Data Group No 29

Data Group 21 Selection of parameters to be plotted

STRING
NAD, NAV, NAA, NAT, NAE, NADT, NADN, NJUMP, TPLOT

STRING	Explanation of the kind of data or blank line
NAD	The number of node displacements that shall be plotted as functions of time. At most 10 displacements.
NAV	The number of node velocities that shall be plotted as functions of time. At most 5 velocities.
NAA	The number of node accelerations that shall be plotted as functions of time. At most 5 accelerations.
NAT	The number of element forces that shall be plotted as functions of time. At most 5 forces.
NAE	The number of element strains that shall be plotted as functions of time. At most 5 strains.
NADT	The number of tangential drag forces acting in the nodes that shall be plotted as functions of time. At most 5 forces.
NADN	The number of transverse drag forces acting in the nodes that should be plotted as functions of time At most 5 forces.
NJUMP	indicates that the variables should be plotted each NJUPM'th time increment. At most 5000 values can be plotted for each variable.
TPLOT	Point of time (s) when the plotting should start. TPLOT ≥ 0.0.

Data Group 22 Displacements

If NAD = 0 continue at Data Group No 23

STRING
For I = 1, NAD give:
IAD (I, 1), IAD (I, 2)

STRING	Explanation of the kind of data or blank line
IAD (I, 1)	Number of the node for which a plot of the displacement is wanted.
IAD (I, 2)	Number indicating the direction of the component i.e. 1, 2 or 3.

Data Group 23 Velocities

If NAV = 0 continue at Data Group No 24

STRING
For I = 1, NAV give:
IAV (I, 1), IAV (I, 2)

STRING	Explanation of the kind of data or blank line
IAV (I, 1)	Number of the node for which a plot of the velocity is wanted.
IAV (I, 2)	Number indicating the direction of the component i.e. 1, 2 or 3.

Data Group 24 Accelerations

If NAA = 0 continue at Data Group No 25

STRING
For I = 1, NAA give:
IAA (I, 1), IAA (I, 2)

STRING	Explanation of the kind of data or blank line
IAA (I, 1)	Number of node for which a plot of the acceleration is wanted.
IAA (I, 2)	Number indicating the direction of the component i.e. 1, 2 or 3.

Data Group 25 Internal force

If NAT = 0 continue at Data Group No 26

STRING
For I = 1, NAT give:
IAT (I)

STRING	Explanation of the kind of data or blank line
IAT(I)	Number of element for which a plot of the internal force is wanted.

Data Group 26 Strains

If NAE = 0 continue at Data Group No 27

STRING
For I = 1, NAE give:
IAE (I)

STRING	Explanation of the kind of data or blank line
IAE(I)	Number of element for which a plot of the strain is wanted.

Data Group 27 Tangential drag force

If NADT = 0 continue at Data Group No 28

STRING
For I = 1, NADT give: IDT (I,1), IDT(I, 2)

STRING	Explanation of the kind of data or blank line
IDT (I, 1)	Number of node for which a plot of the tangential drag force is wanted.
IDT(I, 2)	Number indicating the direction of the tangential drag force component i.e. 1, 2 or 3.

Data Group 28 Normal drag force

If NADN = 0 continue at Data Group No 29

STRING
For I = 1, NADN give:
IDN(I,1), IDN(I,2)

STRING	Explanation of the kind of data or blank line
IDN (I,1)	Number of node for which a plot of the normal drag force is wanted.
IDN(I,2)	Number indicating the direction of the drag force component i.e. 1, 2 or 3.

Data Group 29 Cable positions (Cable envelope)

STRING
NGEM, IGEM (1), IGEM (2)

STRING	Explanation of the kind of data or blank line
NGEM	The number of cable configurations that shall be plotted. At most 20.
IGEM (1)	The first Node number in the chain of nodes that shall be plotted, IGEM(1) > 0.
IGEM (2)	The last Node number in the chain of nodes that shall be plotted IGEM(2) ≤ NE + 1.

IGEM (1) and IGEM (2) indicate which part of the cable that shall be plotted. Several positions can be plotted in the same plot.

If NGEM = 0. End of input.

Data Group 30 Time instants for cable positions

STRING
For I = 1, NGEM give:
TGEM (I)

Through data groups Nos 29 and 30 one can order the plotting of NGEM number of positions that the cable has occupied at different points of time TGEM..

STRING	Explanation of the kind of data or blank line
TGEM (I)	Points of time for which the cable shall be plotted, shall be given in increasing order i. e. TGEM (I+1)>TGEM(I).

End of input.

4 Examples of Calculations

In order to demonstrate MODEX, three examples are accounted for below. The first example concerns a free hanging cable exposed to a current and with displacement excitation in both its ends. By free is understood that the cable is not in contact with the sea bottom. This cable is constituted by two segments with different properties.

In the second example a mooring cable is studied. The displacements are zero in one end (at the anchor). In the other end motions are prescribed which can be thought of as the motions of a fairlead during a storm. In this case the cable is in contact with the sea bottom over a considerable distance.

The third example is the lazy wave riser used as a test case in a comparison between analysis programs of flexible risers by ISSC, 1991 (See also Larsen, 1991). Here the program MODEX is used to perform a preliminary analysis ignoring the bending of the riser. The riser is excited by upper end displacements. The final analyses in ISSC were performed by the program MOBDEX which is developed from MODEX and comprises bending stiffness of the riser and wave kinematics for the relative accelerations and velocities.

4.1 Displacement-Excited Cable in a Current

Assume that a cable is hanging in equilibrium according to Fig. 4.1 at the time t = 0.

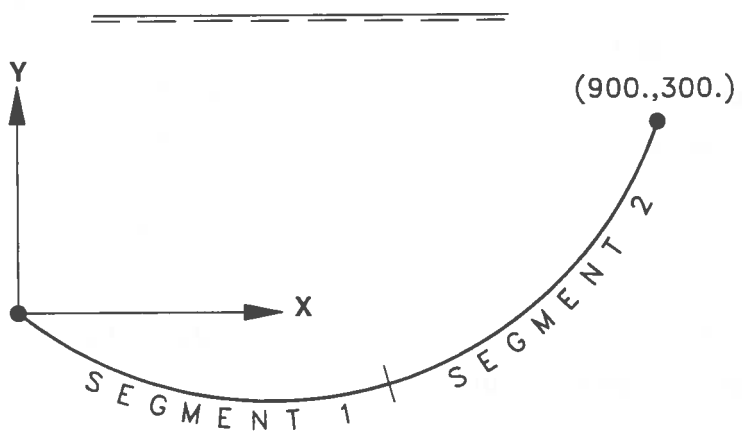


Figure 4.1 The equilibrium and reference configuration of the cable.

The cable is constituted by two segments of chain with data according to the following table.

Segment No 1

Unstretched length of the cable segment	=	500	m
Diameter d_o	=	0.076	m
Stiffness K	=	$5 \cdot 10^8$	N
Internal damping c	=	$5 \cdot 10^6$	Ns
Mass per unit of unstretched length	=	135.35	kg/m
Density	=	7800	kg/m^3
Longitudinal drag coefficient C_{DT}	=	0.5	
Transverse drag coefficient C_{DN}	=	2.5	
Coefficient of added mass C_{MN}	=	3.8	

Segment No 2

Unstretched length of the cable segment	=	600	m
Diameter do	=	0.1	m
Stiffness K	=	$9.1 \cdot 10^8$	N
Internal damping c	=	$9.1 \cdot 10^6$	Ns
Mass per unit of unstretched length	=	233.6	kg/m
Density	=	7800	kg/m^3
Longitudinal drag coefficient C_{DT}	=	0.5	
Transverse drag coefficient C_{DN}	=	2.5	
Coefficient of added mass C_{MN}	=	3.8	

The density of water is set to = 1000 kg/m^3.

At times $t > 0$ the cable is exposed to a uniform current parallel to the X axis and by displacement excitations at both its ends.

The velocity of the current is assumed to grow from zero at the time $t = 0$ to the velocity 4 m/s at the time 2.5 s and is constant equal to 4 m/s for $t > 2.5$ s.

The excitations at the ends of the cable are periodic and are given for a period of T = 10 s. The excitations are assumed to start at t = 10 s and are gradually increased to their prescribed periodic functions during a quarter of a period that is 2.5 s or from t = 10 s to t = 12.5 s.

Segment No 1 is divided into ten elements and Segment No 2 into twelve segments. The length of the elements then becomes 50 m in both segments. Because no forces act transverse to the plane of equilibrium, the calculations are performed as two-dimensional.

In the example we shall study the displacements in the X-direction in Node No 10 and the internal forces in Elements Nos. 10 and 22. These quantities are plotted. The prescribed motions in the cable ends are also plotted as a check of the input.

The calculations are performed during a time of simulation of 100 s with a time increment 0.01 s.

The following input is given to MODEX, and will be created by running the input program.

```
 No sea floor, static analysis and dynamic calculation.
 Data Group 1. Geometry.
 900.0000  300.0000    2    2    2    0    0
 Data Group 2  Segment  1 Properties.
 135.3500 7800.0000    0.50000E+09    0.50000E+07  500.0000   10
   0.0000  0.0000   0.0000   0.0000  0.0000  0.0000  0.00000E+00
 Data Group 2  Segment  2 Properties.
 233.6000 7800.0000    0.91000E+09    0.91000E+07  600.0000   12
   0.0000  0.0000   0.0000   0.0000  0.0000  0.0000  0.00000E+00
 Data Group 3. Dell and Efac.
   0.0200    0.0100
 Data Group 5. Water density
 1000.000
 Data Group 6. Segment  1 Hydr. coeff.,diam
   2.5000    0.5000    3.8000    0.0760    0.0000    0.0000
 Data Group 6. Segment  2 Hydr. coeff.,diam
   2.5000    0.5000    3.8000    0.1000    0.0000    0.0000
 Data Group 7. Current and velocity reduction
   2    2.5000
 Data Group 8. Current level and velocity
-1000.000     4.000
  400.000     4.000
 Data Group 9. Time increment, Time of simulation etc
   0.0100  100.0000   10.0000    2.5000   12.5000    1    1
 Data Group 11. Number of points of time etc.
  21    0    4    0    1
 Data Group 12. Points of time for force or displ.
   0.0000    0.2500    0.5000    0.7500    1.0000    1.2500
   1.5000    1.7500    2.0000    2.2500    2.5000    2.7500
   3.0000    3.2500    3.5000    3.7500    4.0000    4.2500
   4.5000    4.7500    5.0000
 Data Group 13. Scale factor for the points of time
   2.0000
 Data Group 16. Function  1 Displacement
   0.0000    0.6180    1.1756    1.6180    1.9022    2.0000
   1.9022    1.6180    1.1756    0.6180    0.0000   -0.6180
  -1.1756   -1.6180   -1.9022   -2.0000   -1.9022   -1.6180
  -1.1756   -0.6180    0.0000
 Data Group 16. Function  2 Displacement
   2.0000    1.9022    1.6180    1.1756    0.6180    0.0000
  -0.6180   -1.1756   -1.6180   -1.9022   -2.0000   -1.9022
  -1.6180   -1.1756   -0.6180    0.0000    0.6180    1.1756
   1.6180    1.9022    2.0000
 Data Group 16. Function  3 Displacement
   0.0000    0.6180    1.1756    1.6180    1.9022    2.0000
   1.9022    1.6180    1.1756    0.6180    0.0000   -0.6180
  -1.1756   -1.6180   -1.9022   -2.0000   -1.9022   -1.6180
  -1.1756   -0.6180    0.0000
 Data Group 16. Function  4 Displacement
   2.0000    1.9022    1.6180    1.1756    0.6180    0.0000
  -0.6180   -1.1756   -1.6180   -1.9022   -2.0000   -1.9022
  -1.6180   -1.1756   -0.6180    0.0000    0.6180    1.1756
   1.6180    1.9022    2.0000
```

```
Data Group 17. Scale factor for displacement.
  2.0000
  1.5000
  2.0000
  1.5000
Data Group 19. Node, direction, and displ. function.
  1     1     1
  1     2     2
 23     1     3
 23     2     4
Data Group 20. Plotting of variables.
  1
Data Group 21. Number of nodes, elem. for plotting.
  5     0     0     2     0     0     0    20     0.0000
Data Group 22. Num. of the node and dir. for displ.
  1     1
  1     2
 23     1
 23     2
 10     1
Data Group 25. Number of element for internal force.
 22
 10
Data Group 29. Number configuration and interval.
  5     1    23
Data Group 30. Point of time to plot configuration.
 50.0000    55.0000    60.0000    65.0000    78.0000
End of the input file
```

The prescribed displacements at the ends of the cable are shown in Fig. 4.2 - 4.5.

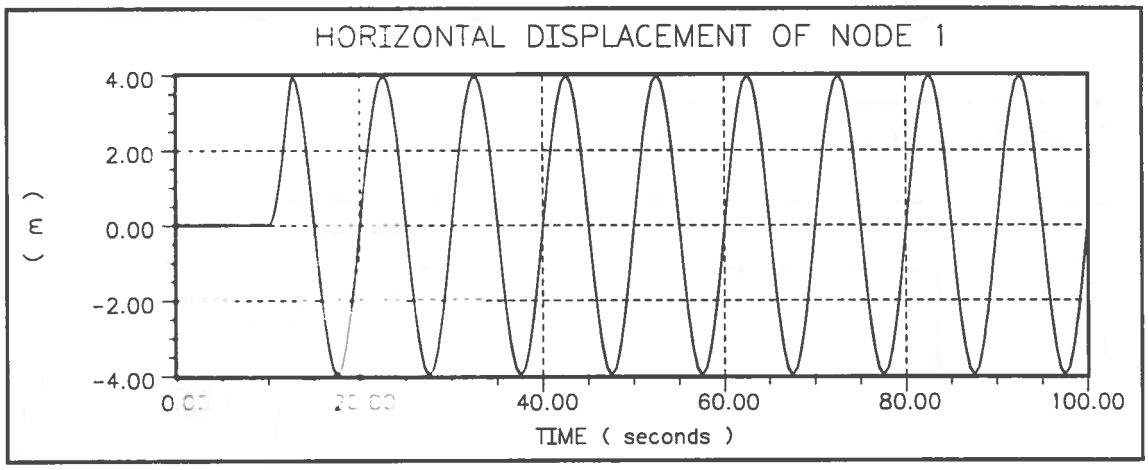


Figure 4.2 Prescribed displacement in Node No 1 direction X

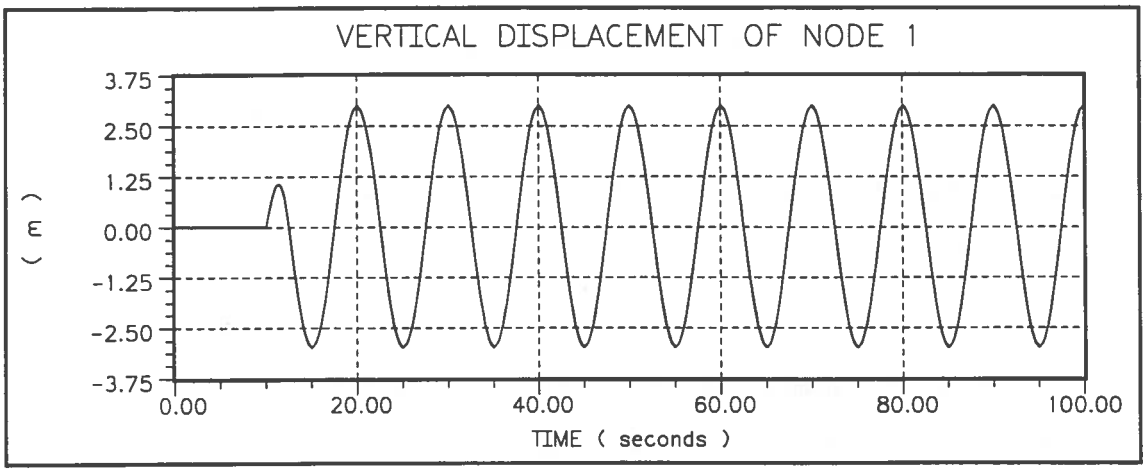


Figure 4.3 Prescribed displacement in Node No 1 direction Y

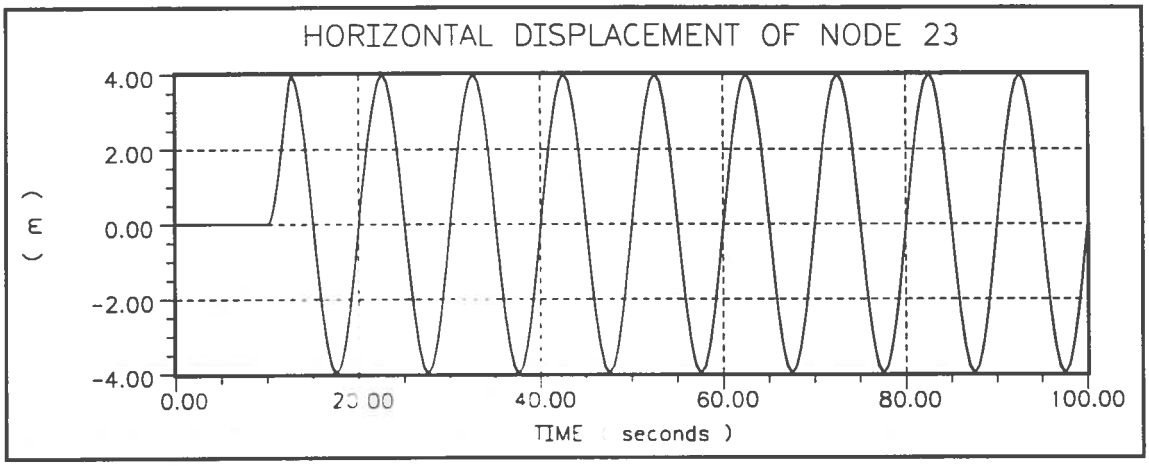


Figure 4.4 Prescribed displacement in Node No 23 direction X

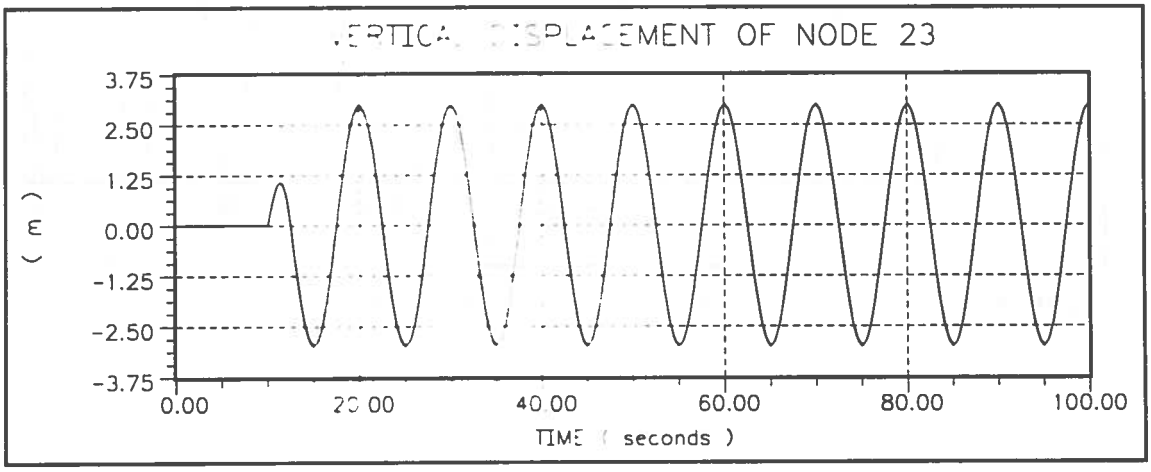


Figure 4.5 Prescribed displacement in Node No 23 direction Y

The calculated displacement in Node No 10 direction X and the calculated forces in Element Nos. 10 and 22 are shown in Fig. 4.6 to 4.8.

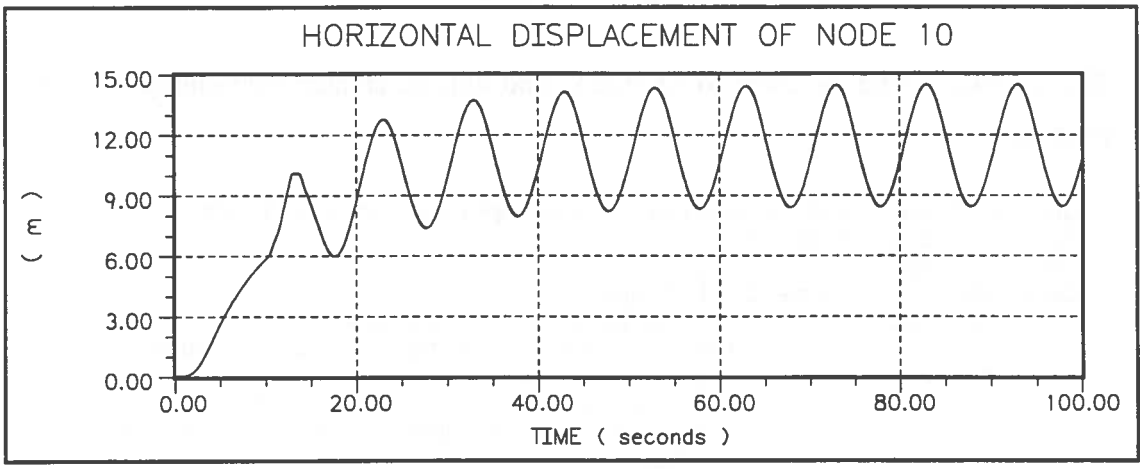


Figure 4.6 The displacement in Node No 10 direction X.

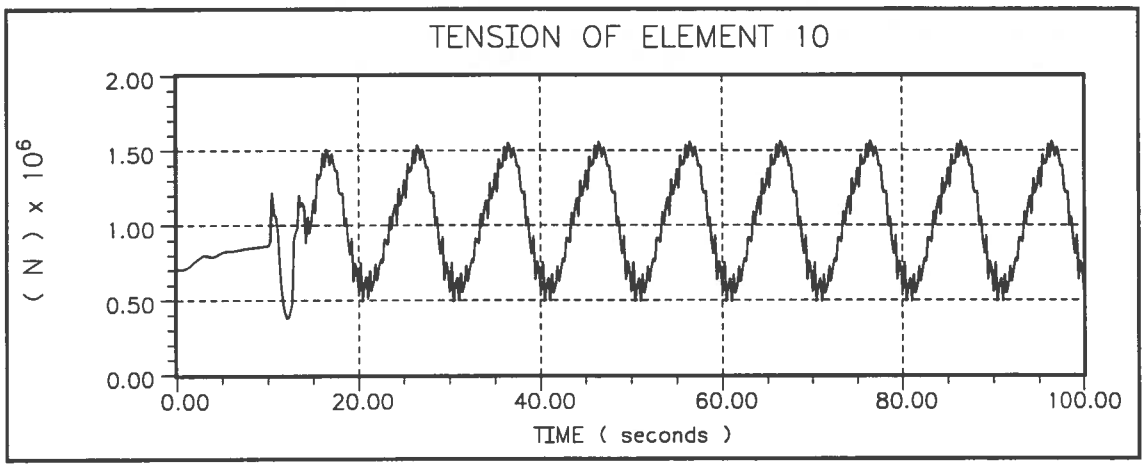


Figure 4.7 The force in Element No 10.

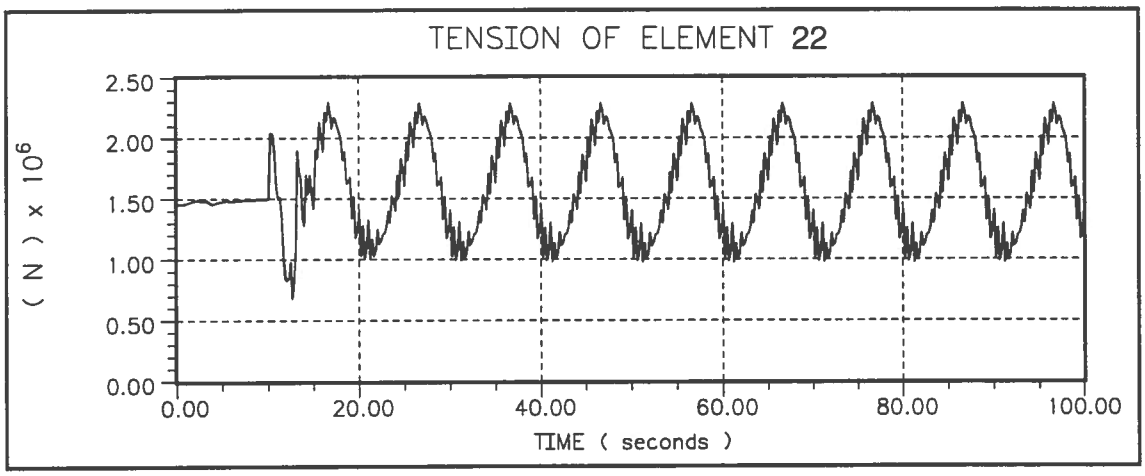


Figure 4.8 The force in Element No 22.

The eigenmodes of the configuration have also been analysed and the first two in the plane of oscillation are shown in Fig 4.9 and 4.10.

The following input is given to MODEX, and will be created by running the input program.

```
No sea floor, static analysis, eigenperiods calculation
Data Group 1. Geometry.
900.0000  300.0000    2    2    1   10    0
Data Group 2  Segment  1 Properties.
135.3500 7800.0000    0.50000E+09    0.50000E+07  500.0000   10
  0.0000  0.0000   0.0000   0.0000  0.0000  0.0000  0.00000E+00
Data Group 2  Segment  2 Properties.
233.6000 7800.0000    0.91000E+09    0.91000E+07  600.0000   12
  0.0000  0.0000   0.0000   0.0000  0.0000  0.0000  0.00000E+00
Data Group 3. Dell and Efac.
  0.0200    0.0100
Data Group 5. Water density
1000.000
Data Group 6. Segment  1 Hydr. coeff.,diam
  2.5000    0.5000    3.8000    0.0760    0.0000    0.0000
Data Group 6. Segment  2 Hydr. coeff.,diam
  2.5000    0.5000    3.8000    0.1000    0.0000    0.0000
```

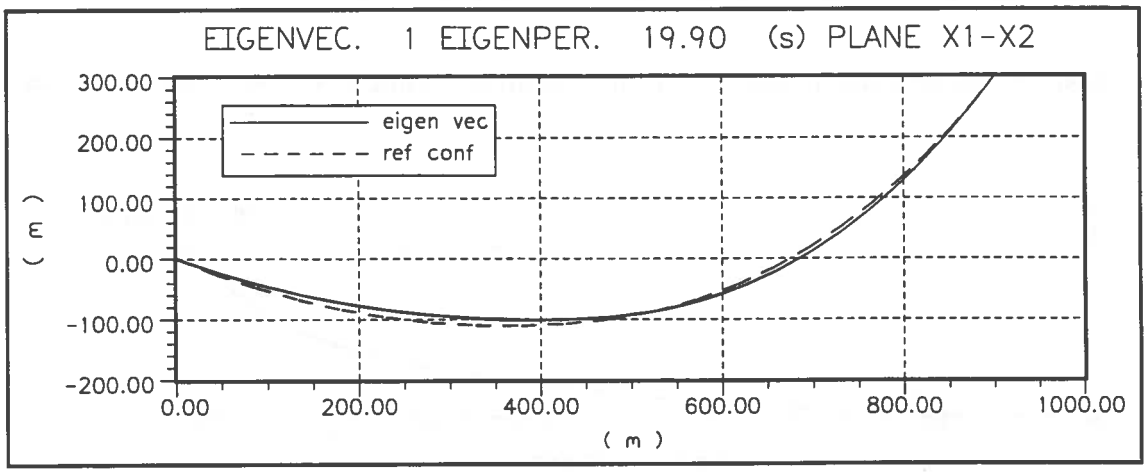


Figure 4.9. Eigenmode No 1 in X-Y Plane.

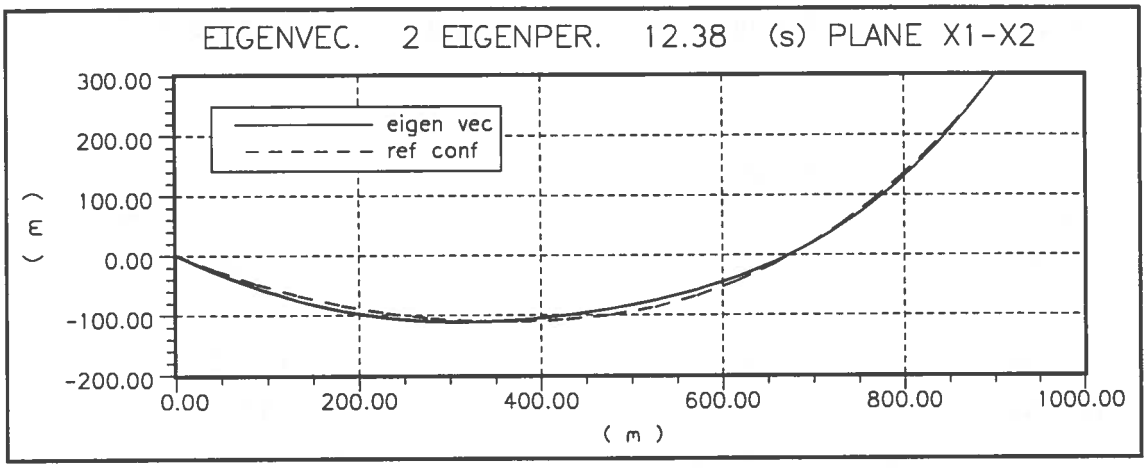


Figure 4.10. Eigenmode No 2 in X-Y Plane.

4.2 Displacement-Excited Mooring Cable

Assume that the cable is hanging in equilibrium according to Fig. 4.11 at the time t=0

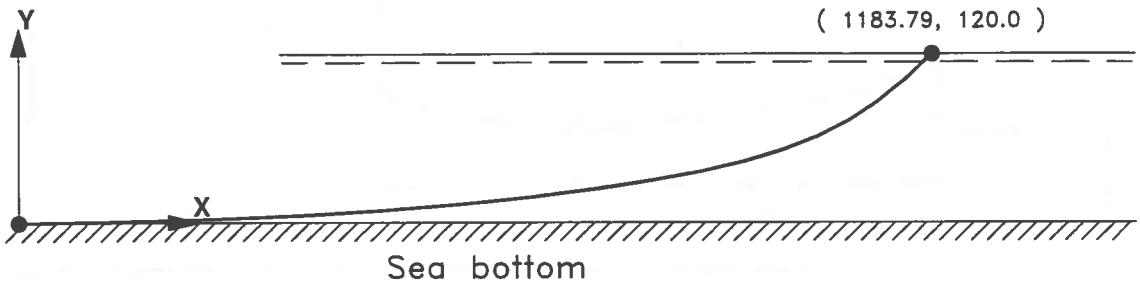


Figure 4.11 The equilibrium and reference configuration of the cable.

The cable is constituted by one segment of chain with data according to the following :

Unstretched length of the cable segment	=	1200	m
Diameter d_o	=	0.076	m
Stiffness K	=	$5 \cdot 10^8$	N
Internal damping c	=	0.0	Ns
Mass per unit of unstretched length	=	135.35	kg / m
Density	=	7800	kg / m^3
Longitudinal drag coefficient C_{DT}	=	0.5	
Transverse drag coefficient C_{DN}	=	2.5	
Coefficient of added mass C_{MN}	=	3.8	
Coefficient of friction between the cable and the sea floor	=	1.0	
Tolerance in the model of friction	=	0.3	m / s
The density of water	=	1000	kg / m^3

At times t > 0 periodically varying displacements are prescribed for the upper end of the cable with a period of T = 15 s. The displacements are assumed to start at t = 0 and are gradually increased to their prescribed periodic functions at t = 3.75 s. The cable is divided into 20 elements. The calculations are two-dimensional.

In this case we wish to plot the internal forces in Element No 1 and 20, and the vertical displacement in Node No 13. The prescribed displacements in the upper end of the cable are also plotted as a check on the input. We also wish to study the cable configurations in the vertical plane at the points of time t = 46, 49, 52, 55 and 58 s.

The following input is given to MODEX and will be created by running the input program.

```
With sea floor, static analysis and dynamic calculation.
Data Group 1. Geometry.
1183.790   120.000    2    1    4    0    0
Data Group 2  Segment  1 Properties.
135.3500 7800.0000    0.50000E+09    0.00000E+00 1200.0000   20
  0.0000  0.0000  0.0000  0.0000  0.0000  0.0000    0.00000E+00
Data Group 3. Dell and Efac.
  0.0100    0.0100
Data Group 4. Sinking of the cable.
  0.1000
Data Group 5. Water density
1000.000
Data Group 6. Segment  1 Hydr. coeff.,diam
  2.5000    0.5000    3.8000    0.0760    0.0000    0.0000
Data Group 7. Current and velocity reduction
  0    0.0000
Data Group 9. Time increment, Time of simulation etc
  0.0150  100.0000    0.0000    3.7500   10.0000    1    1
Data Group 10. Friction with sea floor and Tolerance
  1.0000    0.3000
Data Group 11. Number of points of time etc.
 21    0    2    2    1
Data Group 12. Points of time for force or displ.
  0.0000    0.2500    0.5000    0.7500    1.0000    1.2500
  1.5000    1.7500    2.0000    2.2500    2.5000    2.7500
  3.0000    3.2500    3.5000    3.7500    4.0000    4.2500
  4.5000    4.7500    5.0000
Data Group 13. Scale factor for the points of time
  3.0000
Data Group 16. Function  1 Displacement
  0.0000    0.6180    1.1756    1.6180    1.9022    2.0000
  1.9022    1.6180    1.1756    0.6180    0.0000   -0.6180
 -1.1756   -1.6180   -1.9022   -2.0000   -1.9022   -1.6180
 -1.1756   -1.6180    0.0000
Data Group 16. Function  2 Displacement
  2.0000    1.9022    1.6180    1.1756    0.6180    0.0000
 -0.6180   -1.1756   -1.6180   -1.9022   -2.0000   -1.9022
 -1.6180   -1.1756   -1.6180    0.0000    0.6180    1.1756
  1.6180    1.9022    2.0000
Data Group 17. Scale factor for displacement.
  5.0800
  4.2500
Data Group 19. Node, direction, and displ. function.
  1    1    0
  1    2    0
 21    1    1
 21    2    2
```

```
Data Group 20. Plotting of variables.
  1
Data Group 21. Number of nodes, elem. for plotting.
  3    0    0    2    0    0    0   20    0.0000
Data Group 22. Num. of the node and dir. for displ.
 21    1
 21    2
 13    2
Data Group 25. Number of element for internal force.
  1
 20
Data Group 29. Number of configurations and interval.
  5    1   21
Data Group 30. Point of time to plot configuration.
 46.0000   49.0000   52.0000   55.0000   58.0000
End of the input file
```

The prescribed displacement at the upper end of the cable is shown in Fig. 4.12 - 4.13.

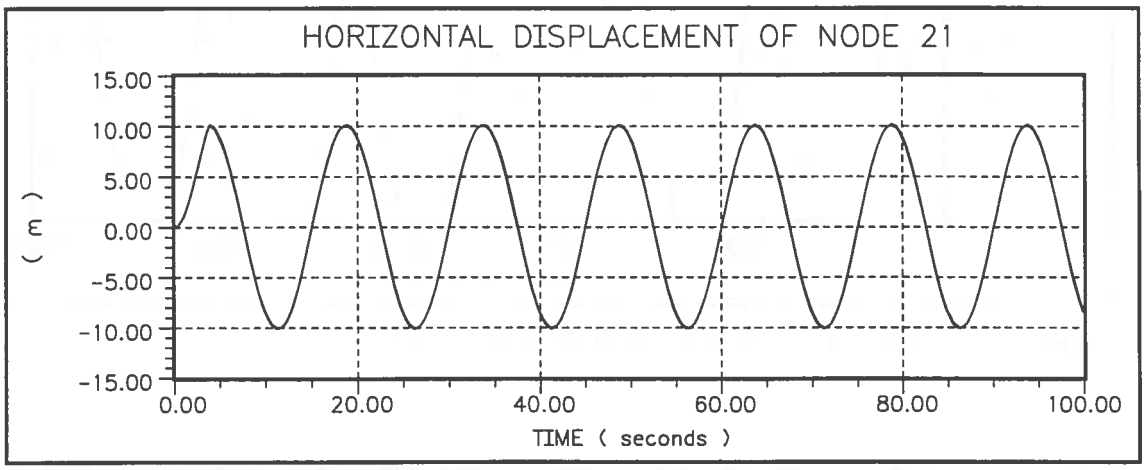


Figure 4.12 Prescribed displacement in Node No 21 direction X.

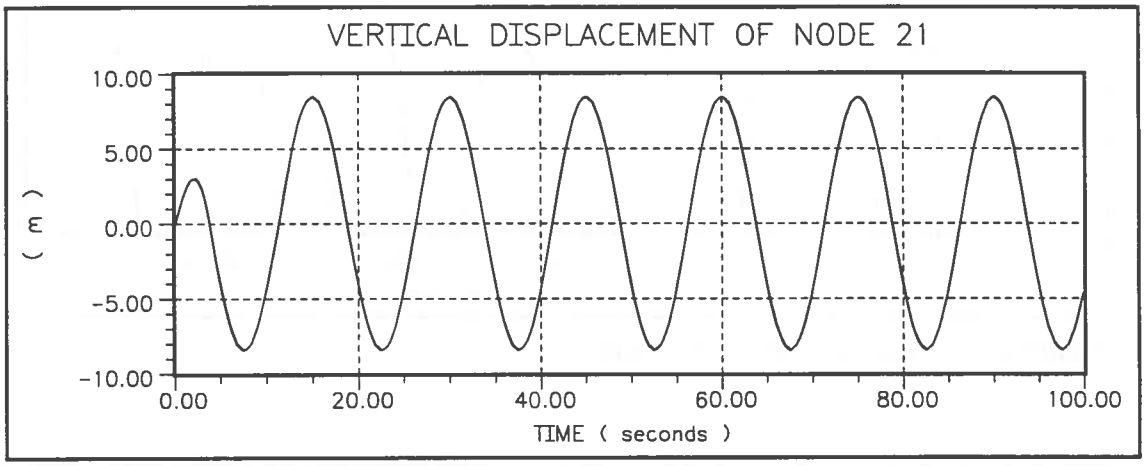


Figure 4.13 Prescribed displacement in Node No 21 direction Y.

The vertical displacement in Node No 13 and the forces in Element Nos. 1 and 20 are shown in Fig. 4.14 to 4.16. Note that the cable is staved (compressive force) at times. We have in this case chosen to null (NSS = 1) the force in an element if the cable is compressed in this element.

In Fig. 4.17 the cable positions at different time instants in the vertical plane are shown. It is obvious how the cable is "buckled" due to the compressive internal force. Dynamically unstable conditions have occurred. The maximum force is, however, reliable and close to the one which is obtained with retained negative forces (NSS = 0) in the cable, as in a steel rope.

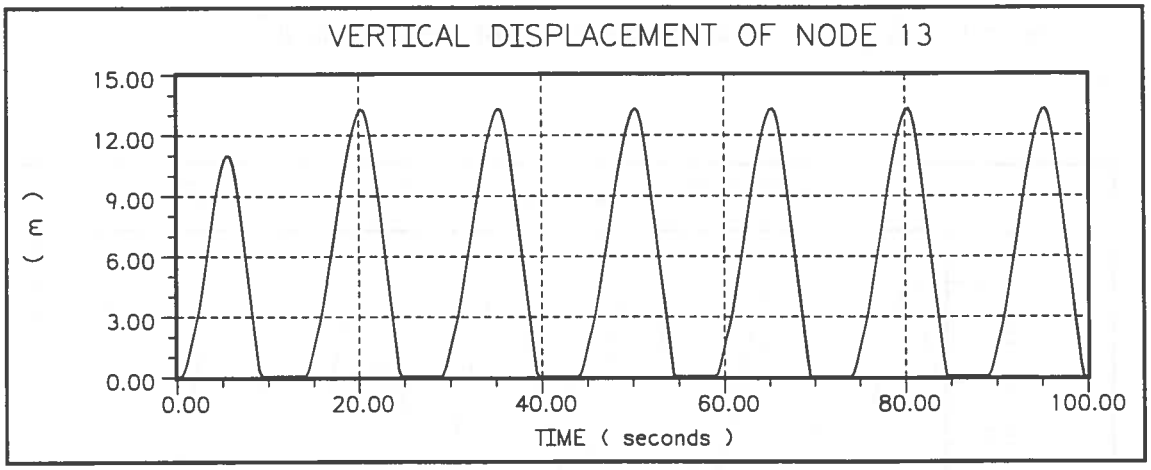


Figure 4.14 The vertical displacement of Node No 13..

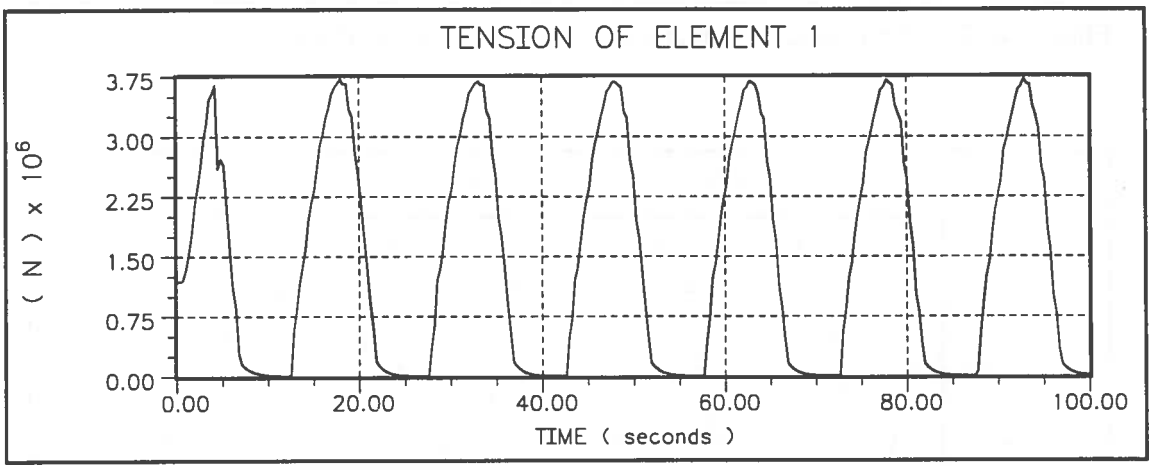


Figure 4.15 Internal force in Element No 1

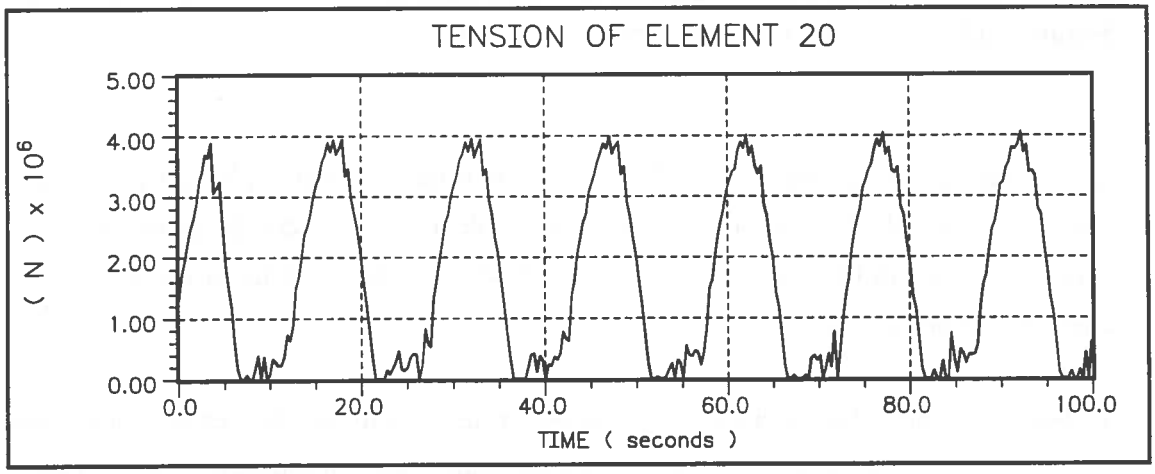


Figure 4.16 Internal force in Element No 20

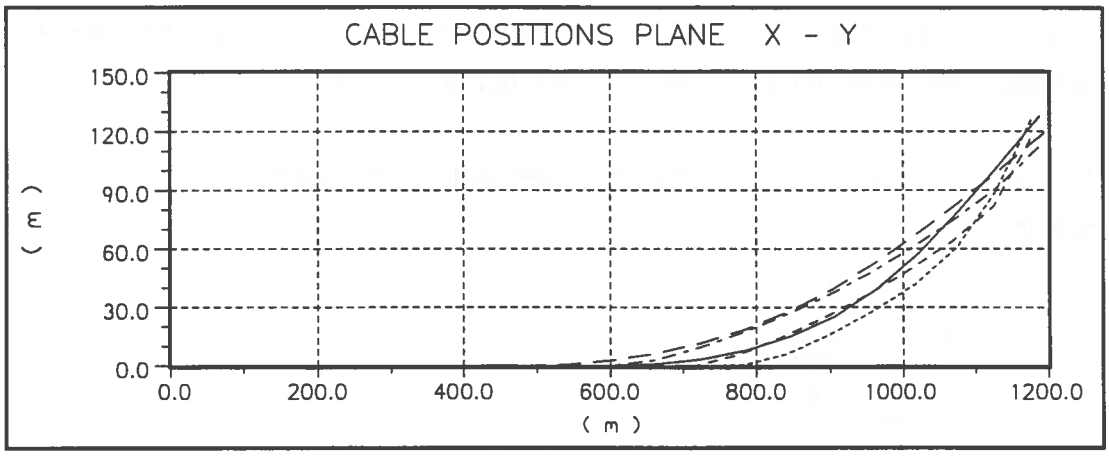


Figure 4.17 Cable positions in the vertical plane.

The eigenmodes of the configuration have also been analysed and the first and the third one in the plane of oscillation are shown in Fig. 4.18 and 4.19.

The following input is given to MODEX, and will be created by running the input program.

```
  With sea floor, static analysis, eigenperiods calculation.
  Data Group 1. Geometry.
  1183.790   120.000    2    1    3   10    0
  Data Group 2  Segment  1 Properties.
  135.3500 7800.0000    0.50000E+09    0.00000E+00 1200.0000   20
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 3. Dell and Efac.
    0.0100    0.0100
  Data Group 4. Sinking of the cable.
    0.1000
  Data Group 5. Water density
  1000.000
  Data Group 6. Segment  1 Hydr. coeff.,diam
    2.5000    0.5000    3.8000    0.0760    0.0000    0.0000
  End of the input file
```

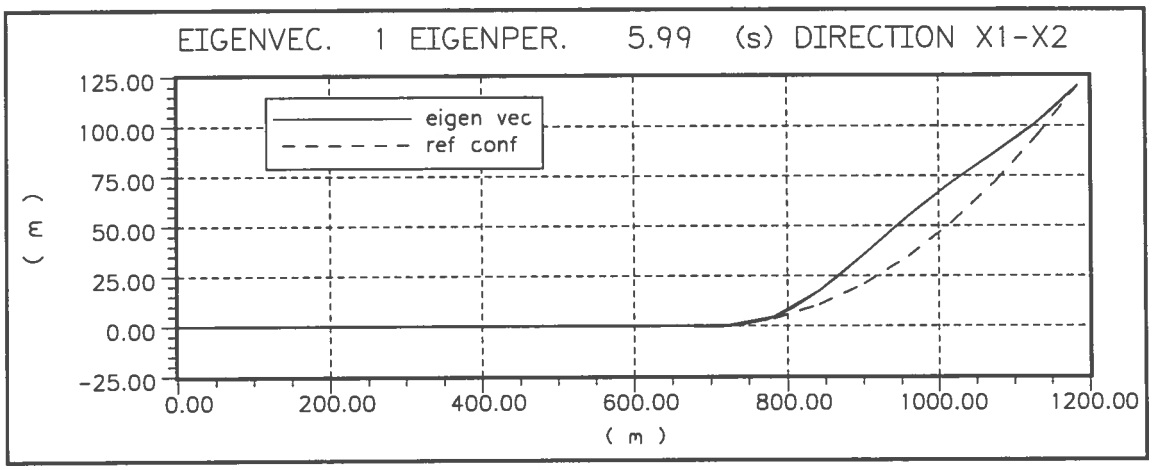


Figure 4.18. Eigenmode No 1 in X-Y Plane.

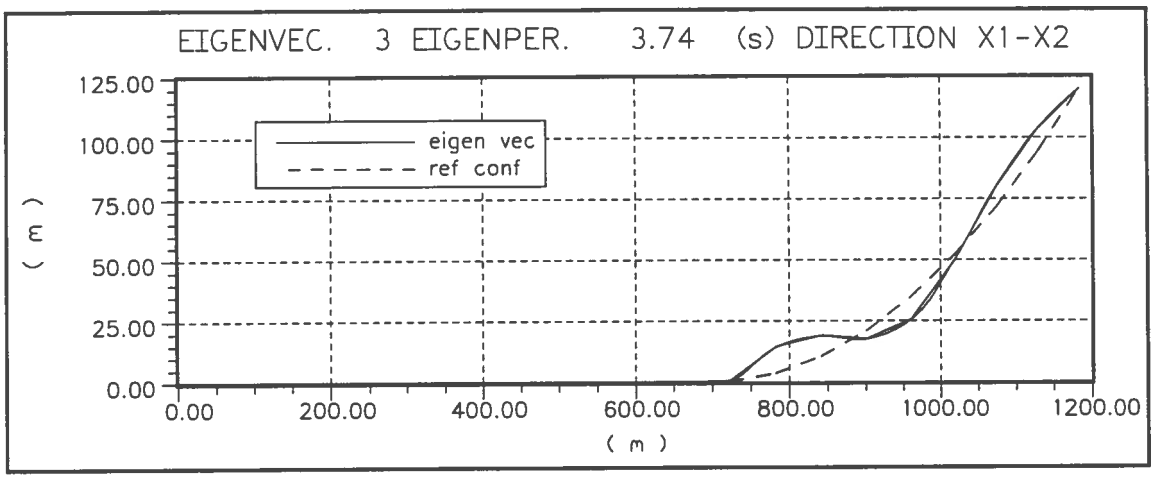


Figure 4.19. Eigenmode No 3 in X-Y Plane.

4.3 Displacement-Excited Flexible Riser.

Assume that a riser is hanging in equilibrium according to Fig. 4.20 at the time t=0.

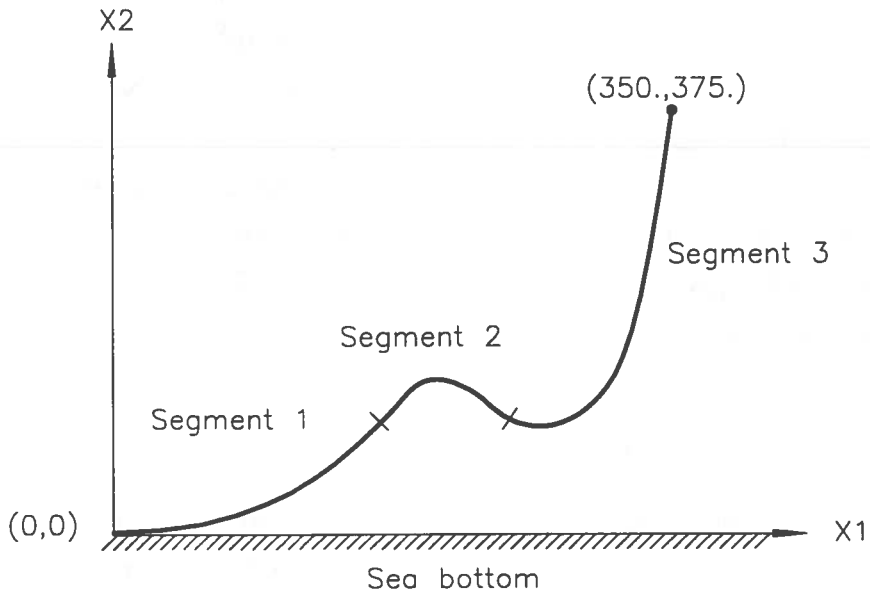


Figure 4.20 The equilibrium and reference configuration of the cable.

The riser is constituted by three segments with segments Nos. 1 and 3 of the same properties. The uppermost part of segment No 3 is above the mean water surface which is neglected in this calculation.

<u>Segment No 1</u>

Unstretched length of the cable segment	=	200	m
Diameter d_0	=	0.2154	m
Stiffness K	=	$10 \cdot 10^6$	N
Internal damping c	=	0.0	Ns
Mass per unit of unstretched length	=	89	kg/m
Density	=	2442.36	kg/m^3
Longitudinal drag coefficient C_{DT}	=	0.16	
Transverse drag coefficient C_{DN}	=	1.0	
Coefficient of added mass C_{MN}	=	1.0	

Segment No 2

Unstretched length of the cable segment	=	91	m
Diameter d_o	=	0.5290	m
Stiffness K	=	$5 \cdot 10^8$	N
Internal damping c	=	0.0	Ns
Mass per unit of unstretched length	=	178	kg/m
Density	=	813.2	kg/m^3
Longitudinal drag coefficient C_{DT}	=	0.16	
Transverse drag coefficient C_{DN}	=	0.82	
Coefficient of added mass C_{MN}	=	1.0	

Segment No 3

Unstretched length of the cable segment	=	360	m
Diameter d_o	=	0.2154	m
Stiffness K	=	$10 \cdot 10^6$	N
Internal damping c	=	0.0	Ns
Mass per unit of unstretched length	=	89	kg/m
Density	=	2442.36	kg/m^3
Longitudinal drag coefficient C_{DT}	=	0.16	
Transverse drag coefficient C_{DN}	=	1.0	
Coefficient of added mass C_{MN}	=	1.0	

Coefficient of friction between the cable and the sea floor	=	1.0	
Tolerance in the model of friction	=	0.3	m/s
The density of water	=	1025	kg/m^3

The following input is given to MODEX and will be created by running the input program.

```
  With sea floor, buoys, or clumpweights, static and dynamic
analysis.
  Data Group 1. Geometri.
   350.000   375.000    3    3    6    0    0
  Data Group 2  Segment  1 Properties.
   89.0000 2442.3600    0.10000E+08    0.00000E+00  200.0000   12
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 2  Segment  2 Properties.
  178.0000  813.2000    0.10000E+08    0.00000E+00   91.0000    8
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 2  Segment  3 Properties.
   89.0000 2442.3600    0.10000E+08    0.00000E+00  360.0000   22
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 3. Dell and Efac.
    0.0100    0.0400
  Data Group 4. Sinking of the cable.
    0.1000
  Data Group 5. Water density
  1025.000
  Data Group 6. Segment  1 Hydr. coeff.,diam
    1.0000    0.1600    1.0000    0.2154    0.0000    0.0000
  Data Group 6. Segment  2 Hydr. coeff.,diam
    0.8200    0.1600    1.0000    0.5290    0.0000    0.0000
  Data Group 6. Segment  3 Hydr. coeff.,diam
    1.0000    0.1600    1.0000    0.2154    0.0000    0.0000
  Data Group 7. Current and velocity reduction
    0    0.0000
  Data Group 9. Time increment, Time of simulation etc
    0.0150  100.0000    0.0000    3.7500   10.0000    1    1
  Data Group 10. Friction with sea floor and Tolerance
    1.0000    0.3000
  Data Group 11. Number of points of time etc.
   21    0    2    2    1
  Data Group 12. Points of time for force or displ.
    0.0000    0.2500    0.5000    0.7500    1.0000    1.2500
    1.5000    1.7500    2.0000    2.2500    2.5000    2.7500
    3.0000    3.2500    3.5000    3.7500    4.0000    4.2500
    4.5000    4.7500    5.0000
  Data Group 13. Scale factor for the points of time
    3.0000
  Data Group 16. Function  1 Displacement
    0.0000    0.6180    1.1756    1.6180    1.9022    2.0000
    1.9022    1.6180    1.1756    0.6180    0.0000   -0.6180
   -1.1756   -1.6180   -1.9022   -2.0000   -1.9022   -1.6180
   -1.1756   -0.6180    0.0000
  Data Group 16. Function  2 Displacement
    2.0000    1.9022    1.6180    1.1756    0.6180    0.0000
   -0.6180   -1.1756   -1.6180   -1.9022   -2.0000   -1.9022
   -1.6180   -1.1756   -0.6180    0.0000    0.6180    1.1756
    1.6180    1.9022    2.0000
  Data Group 17. Scale factor for displacement.
    5.0800
    4.2500
```

```
  Data Group 19. Node, direction, and displ. function.
    1    1    0
    1    2    0
   41    1    1
   41    2    2
  Data Group 20. Plotting of variables.
    1
Data Group 21. Number of nodes, elem. for plotting.
   10    5    5    5    5    5    5   20    0.0000
  Data Group 22. Num. of the node and dir. for displ.
   41    1
   41    2
   21    1
   21    2
   17    1
   17    2
   13    1
   13    2
    7    1
    7    2
  Data Group 23. Num. of the node and dir. for veloc.
   41    1
   41    2
   21    1
   21    2
    7    2
  Data Group 24. Num. of the node and dir. for accel.
   41    1
   41    2
   21    1
   21    2
    7    2
  Data Group 25. Number of element for internal force.
    1
    7
   13
   21
   40
  Data Group 26. Number of element for strain.
    1
    7
   13
   20
   40
  Data Group 27. Num. of the node and dir. tang force.
   41    1
   41    2
   13    1
   13    2
    7    2
  Data Group 28. Num. of the node and dir. tran force.
   41    1
   41    2
   13    1
   13    2
    7    2
  Data Group 29. Number configuration and interval.
    5    1   41
  Data Group 30. Point of time to plot configuration.
   46.0000   49.0000   52.0000   55.0000   78.0000
  End of the input file
```

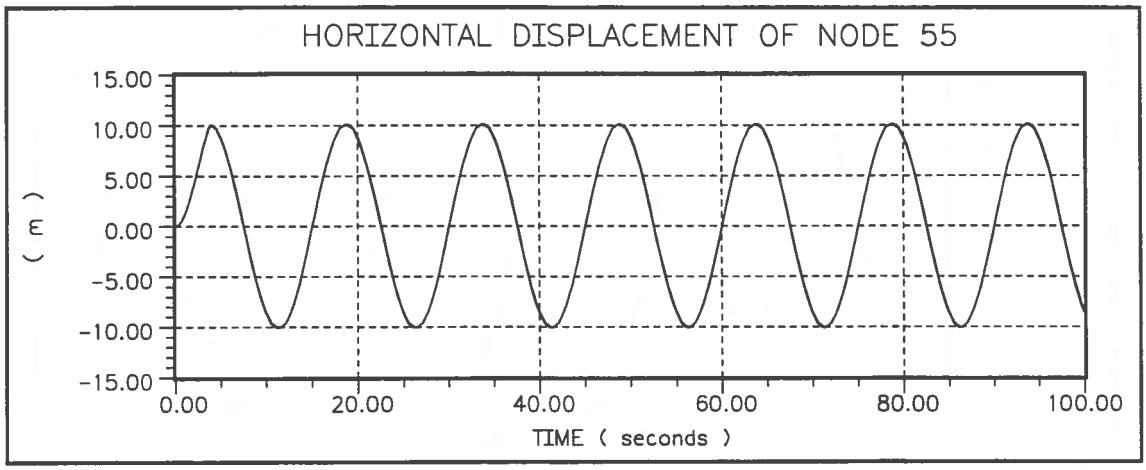


Figure 4.21 Prescribed displacement in Node No 55, direction X.

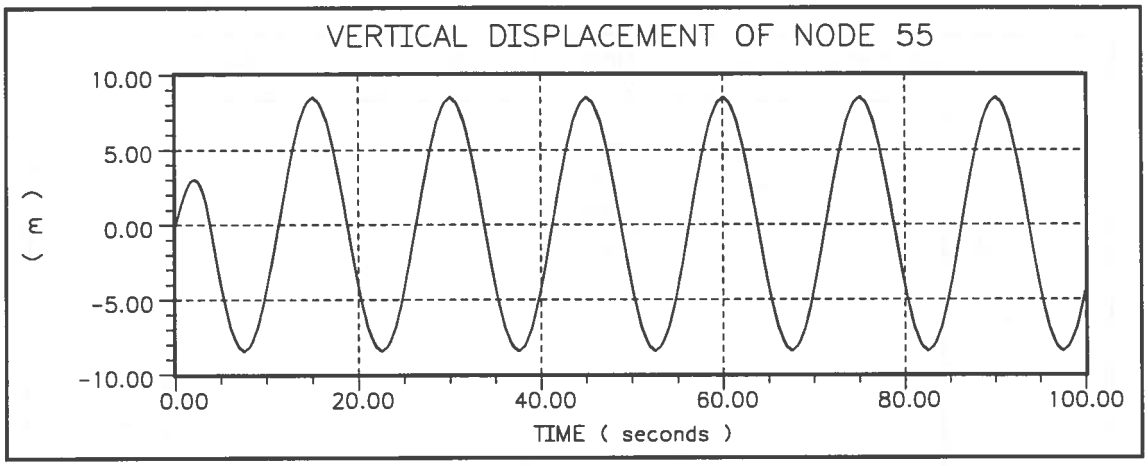


Figure 4.22. Prescribed displacement in Node No 55, direction Y.

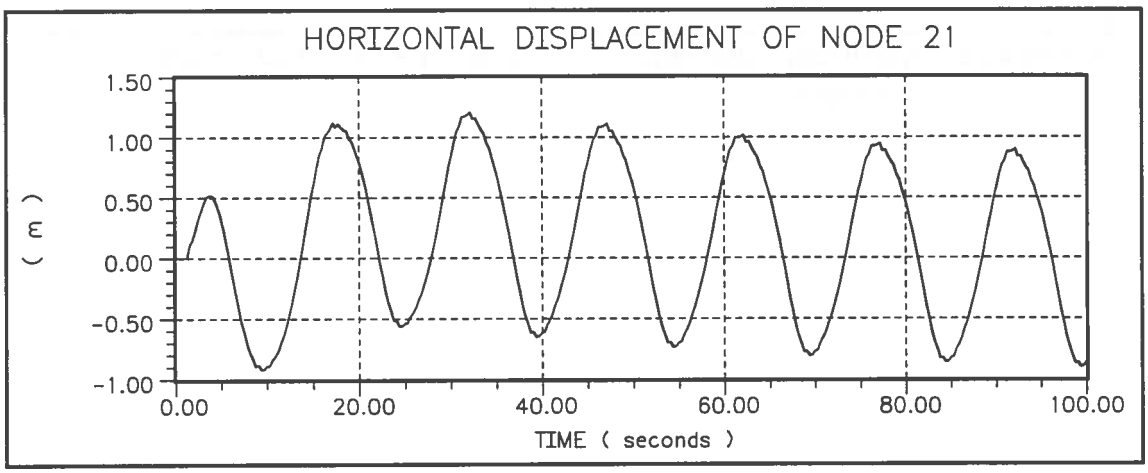


Figure 4.23. The horizontal displacement of Node No 21.

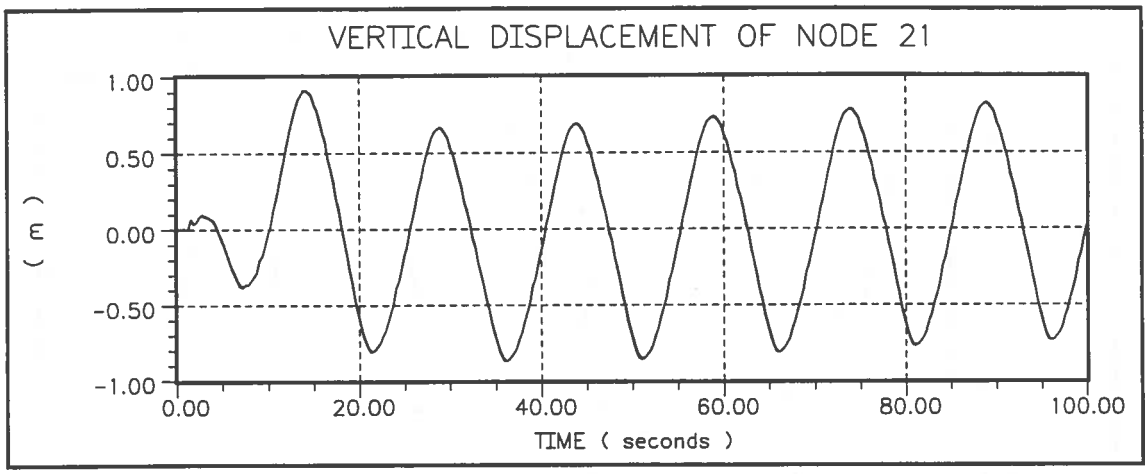


Figure 4.24. The vertical displacement of Node No 21.

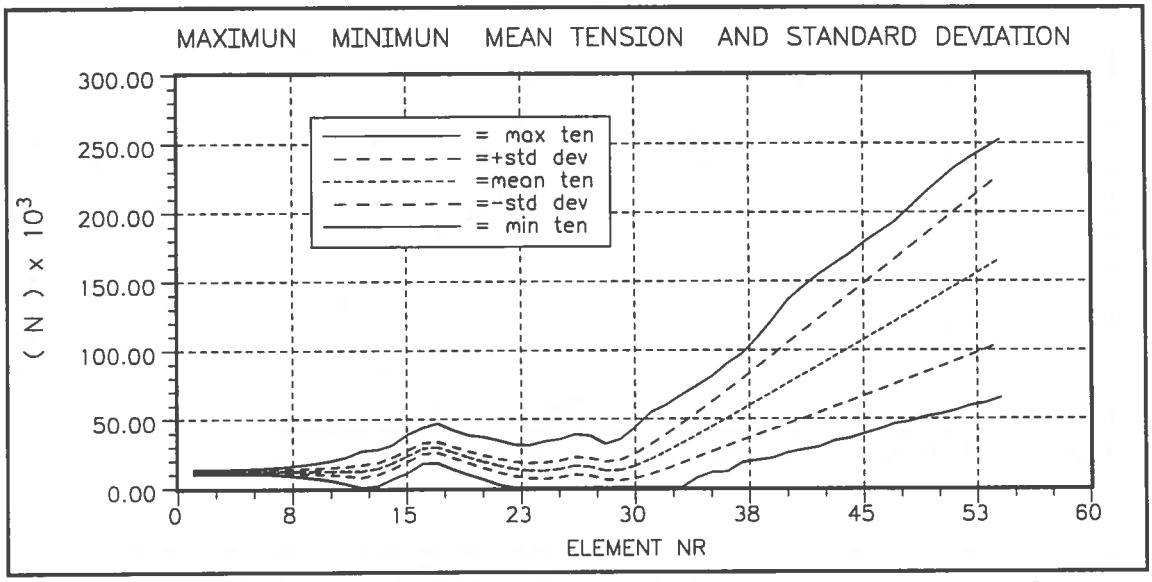


Figure 4.25. Maximum, minimum, mean, and mean +/- standard deviations of cable tensions.

The three-dimensional eigenmodes of the configuration have also been analysed and the first two are shown in Fig 4.26 and 4.27.

The following input is given to MODEX and will be created by running the input program.

```
  With sea floor, buoys, or clumpweights, static analysis,eigen
periods.
  Data Group 1. Geometri.
   350.000   375.000    3    3    5    3    0
  Data Group 2  Segment  1 Properties.
   89.0000 2442.3600    0.10000E+08    0.00000E+00  200.0000   12
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 2  Segment  2 Properties.
  178.0000  813.2000    0.10000E+08    0.00000E+00   91.0000    8
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 2  Segment  3 Properties.
   89.0000 2442.3600    0.10000E+08    0.00000E+00  360.0000   22
    0.0000    0.0000    0.0000    0.0000    0.0000    0.0000
0.00000E+00
  Data Group 3. Dell and Efac.
    0.0100    0.0400
  Data Group 4. Sinking of the cable.
    0.1000
  Data Group 5. Water density
  1025.000
  Data Group 6. Segment  1 Hydr. coeff.,diam
    1.0000    0.1600    1.0000    0.2154    0.0000    0.0000
  Data Group 6. Segment  2 Hydr. coeff.,diam
    0.8200    0.1600    1.0000    0.5290    0.0000    0.0000
  Data Group 6. Segment  3 Hydr. coeff.,diam
    1.0000    0.1600    1.0000    0.2154    0.0000    0.0000
  End of the input file
```

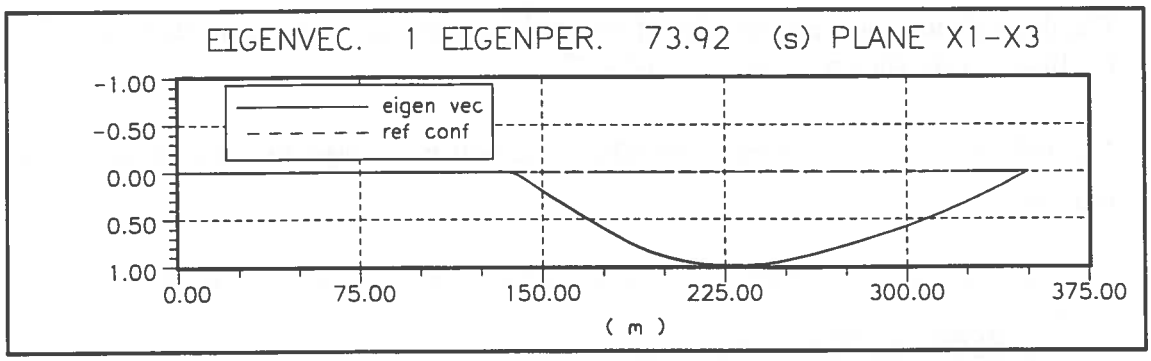


Figure 4.26 Eigenmode No 1, transverse eigenmode, projected on X-Z Plane.

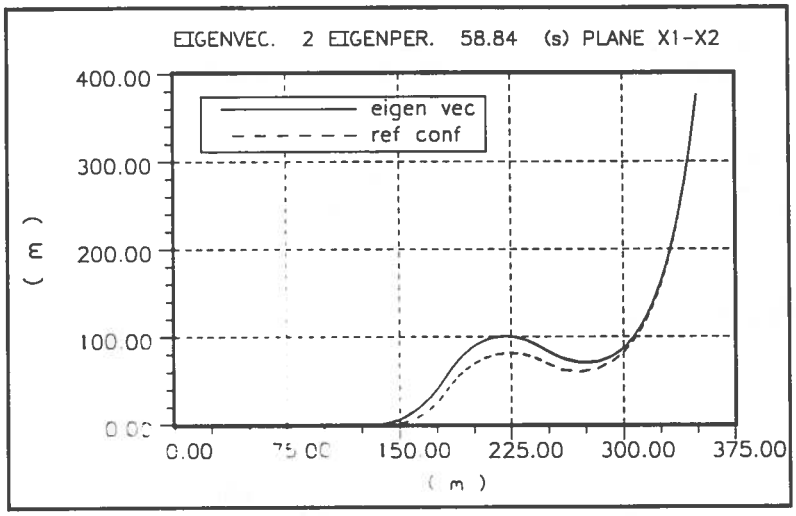


Figure 4.27 Eigenmode No 2, in-plane eigenmode, projected on X-Y Plane.

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APPENDIX A

A.1 Flow Chart

The main program for the explicit time integration is MODEX. In this appendix a flow chart for the program is shown. Short descriptions of the subroutines are given in A.2.

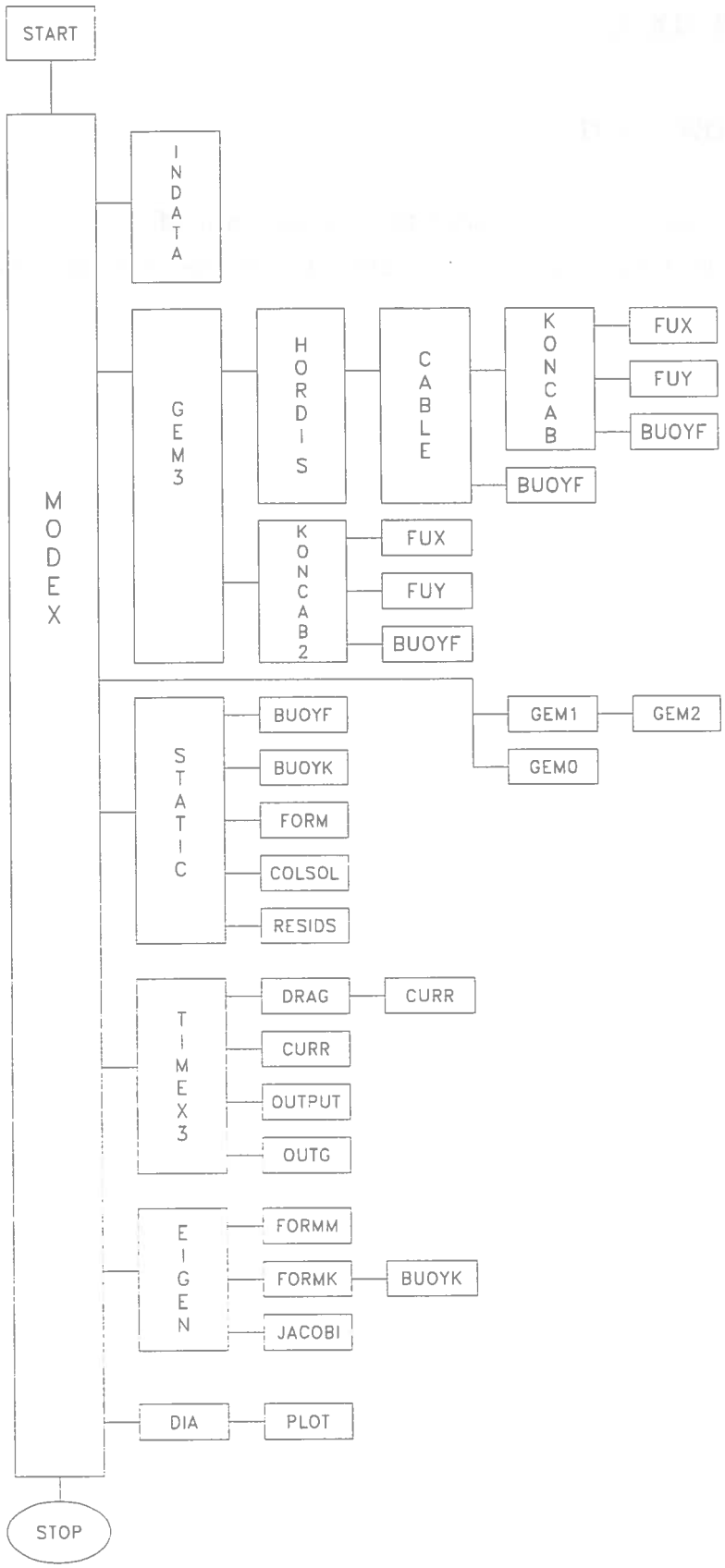

Figure A.1 Flow chart for MODEX.

A2. Description of Main Program and Subroutines.

MODEX — Is a main program. It reads and writes input data and governs the calculations. With this main, static equilibrium, dynamic simulations and eigenmodes can be calculated.

The dynamic simulations can be two- or three-dimensional and are performed by explicit time integration.

STATIC — Subroutine for the calculation of the static equilibrium. Calculates loads in the nodes of the cable and governs the static calculation by iterations and check of convergence of the solution. Gives output from the static calculation.

GEM0 — Calculates a first reference configuration for STATIC, when $\sqrt{XL1^2 + XL2^2} \geq$ the unstretched length of the cable. The first reference configuration in this case is a straight line.

GEM1 — Calculates a first reference configuration for STATIC, when $\sqrt{XL1^2 + XL2^2} <$ the unstretched length of the cable, if the cable is not affected by the sea floor. The first reference configuration is then given by the inelastic catenary.

GEM2 — Calculates a first reference configuration for STATIC when $\sqrt{XL1^2 + XL2^2} <$ the unstretched length of the cable and the cable is partly resting on the sea floor. The first reference configuration is given by the inelastic catenary and a straight line along the sea floor.

GEM3 — A more complete subroutine for the preliminary reference configuration. This subroutine can handle cables (risers) with submerged buoys and clump weights and with densities lower than that of the water. An elastic catenary is used. (Oppenheim and Wilson, 1982)

FORM — Forms the stiffness matrix of the static calculation in STATIC.

COLSOL — Subroutine for the solution of a banded matrix. Taken from Bathe and Wilson (1976).

RESIDS	Calculates the unbalanced forces during the iterations in STATIC.
EIGEN	Subroutine that calculates the eigenperiods and eigenmodes.
FORMK	Forms the stiffness matrix for the calculations in EIGEN.
FORMM	Forms the mass matrix for the calculations in EIGEN.
JACOBI	Solves the eigenvalue problem with Jacobi iterations. Taken from Bathe and Wilson (1976).
TIMEX3	Subroutine for dynamic calculation by explicit integration. Governs the numerical integration, calculates forces, mass matrices etc. as functions of time.
DRAG	Calculates drag forces in the nodes of the cable for TIMEX3 when IPOL = 2, 3, 4 and 5.
DRAGI	Calculates drag forces in the nodes of the cable for IPOL=1.
OUTPUT	Gives output of data computed by TIMEX3 to the file " *.OUT" Stores fields for plotting of time dependent variables.
OUTG	Stores fields for the plotting of the cable configuration at different points of time.
HORDIS	Iterates the horizontal upper end co-ordinate of the cable by varying the horizontal force
KONCAB	Calculates the cable tension in the ends of each segment from the elastic catenary.
KONCAB2	Calculates the cable tension in the ends of each element from the elastic catenary.
CABLE	Calculates the horizontal upper end co-ordinate of the cable for given horizontal force and vertical co-ordinate.

FUX	Calculation of relative X-position of right hand side of segment or element.
FUY	Calculation of relative Y-position of right hand side of segment or element.
BUOYF	Calculation of buoyancy force of the surface buoy.
BUOYK	Calculation of total stiffness of buoy with pendant line for addition to FORMK in EIGEN.
INDATA	Pre-processor to edit and generate input to the program.
DIA	Subroutine module that handles the monitoring of the graphs.
PLOT	Subroutine module that generates the plot files.

APPENDIX B

Internal Damping of the Cable in MODEX

Lindahl and Sjöberg (1983) defined the reaction force T of the cable in its longitudinal direction as

$$T = K\tilde{\varepsilon}(1+\varepsilon) \cong K\varepsilon \qquad (\varepsilon << 1)$$
$$\tilde{\varepsilon} = \frac{1}{2}\left(\left(\frac{\partial s}{\partial s_0}\right)^2 - 1\right) \qquad \text{...(B 1)}$$
$$\varepsilon = \frac{\partial s}{\partial s_0} - 1$$

Where ε and $\tilde{\varepsilon}$ are measures of the strain of the cable in its longitudinal direction and where K is the stiffness of the cable (cross sectional area times elasticity). When strained, elastic energy is stored in the cable, and this can be lost through drag forces, but not through internal damping in the cable itself, and this is a deficiency of the model of Eq. (B1). such a purely elastic material model can sometimes give rise to superposed longitudinal waves of artificial amplitude, which especially can be noticed after an occasion with slack in the cable, when the cable is stretched again. In order to get a more realistic model for the reaction forces a damping force T_c has been introduced in MODEX.

$$T_c = c\dot{\varepsilon} \qquad \text{...(B 2)}$$

where T_c is parallel to T and c (Ns) is a constant depending on the internal damping of the cable and $\dot{\varepsilon}$ (s^{-1}) is the rate of strain of the cable. If Eq. (B1) and (B 2) are added the total reaction force T_t is :

$$T_t = K\tilde{\varepsilon}(1+\varepsilon) + c\dot{\varepsilon} \qquad \text{...(B 3)}$$

With Eq. (B 3) as the material model one can show that the internal forces of the cable give the following contribution to the loads in the nodes :

$$\underline{F} = \sum_{j=1}^{n_c} \underline{\underline{C}}_j^T \int_0^1 \left(\frac{K\tilde{\varepsilon}_j}{l_j} + \frac{c\dot{\tilde{\varepsilon}}_j}{(1+2\tilde{\varepsilon}_j)l_j}\right) \underline{\underline{G}}\ \underline{r}_j\ dx_j \qquad \text{...(B 4)}$$

Eq. (B 4) should be compare to Eq. (3.20) in Lindahl, Sjöberg (1983) . The rate of strain of the element becomes

$$\dot{\tilde{\varepsilon}} = \underline{r}_j^T \, \underline{\underline{G}} \, \dot{\underline{p}}_j \qquad ...(B\ 5)$$

Kawashima and Kimura (1952) (as cited by Johansson 1976) report values on the internal friction of wire cables per unit cross sectional area to be about $c_c = 1.5 \cdot 10^7$ Ns/m² and the constant c of Eq. (B 2) to (B 5) would then be

$$c = c_c \cdot A_o \qquad ...(B\ 6)$$

where A_o is the nominal cross sectional area of the wire cable. Lindahl (1984) uses the value $c = 5 \cdot 10^6$ Ns for a chain with the diameter $d_o = 0.076$ m. In this case the internal friction per unit cross sectional area would be
$c_c = 2c / \pi d_o^2 = 5.5 * 10^8$ Ns/m²

(The information in Appendix B is taken from Lindahl (1984) with small changes.)

APPENDIX C

Friction Between the Cable and the Sea Floor in MODEX

By reasons similar to those in Appendix B the explicit model described by Lindahl and Sjöberg (1983) has been modified with respect to friction between the cable and the sea floor. At the tightening up after an occasion with slack a longitudinal transient with artificially high elastic waves is calculated if damping is not introduced in the longitudinal direction of the cable. The friction model described by Lindahl and Sjöberg (1983) was used only transverse to the cable, which is sufficient in many cases, but the now implemented model is better.

Assume that a node, k, is moving along the sea floor $r_2^{(k)} \cong 0$ with the velocity $\dot{p}_1^{(k)}$ in the X-direction and $\dot{p}_3^{(k)}$ in the Z-direction. Introduce a friction force $\underline{F}_f = (F_{f1}, F_{f3})^T$ with is parallel to the velocity vector but with the opposite direction. F_{f1} = the X-component of the frictional force and F_{f3} the Z-component.

The frictional force $\underline{F}_f$ is assumed to be linearly viscous for velocities $\dot{p}_a < c_v$ but constant and equal to $\mu | R_k^{(1)} |$ for $\dot{p}_a > c_v$.

$$\dot{p}_a = \sqrt{(\dot{p}_1^{(k)})^2 + (\dot{p}_3^{(k)})^2} \qquad \text{...(C 1)}$$

$R_k^{(1)}$ = resultant of weight and buoyancy in node No k.

μ = coefficient of friction between the cable and the sea floor.

c_v = Velocity along the seabed when full friction is developed, given in order to avoid numerical problems when the model of friction is used in time-domain dynamic analyses. Equal to CVTOL in Data Group 10.

The model becomes as follows:

$$F_{f1} = -\frac{\dot{p}_1^{(k)}}{\dot{p}_a} \mu | \underline{R}_k | \qquad \text{...(C 2)}$$

$$F_{f3} = -\frac{\dot{p}_3^{(k)}}{\dot{p}_a} \mu | \underline{R}_{(k)}^{(1)} | \qquad \text{...(C 3)}$$

if

$\dot{p}_a > c_v$

or

$$F_{f1} = -\frac{\dot{p}_1^{(k)}}{c_v} \mu \left| \underline{R}_{(k)}^{(1)} \right| \qquad ...(C4)$$

$$F_{f3} = -\frac{\dot{p}_3^{(k)}}{c_v} \mu \left| \underline{R}_{(k)}^{(1)} \right| \qquad ...(C5)$$

if

$$\dot{p}_a < c_v \qquad ...(C6)$$

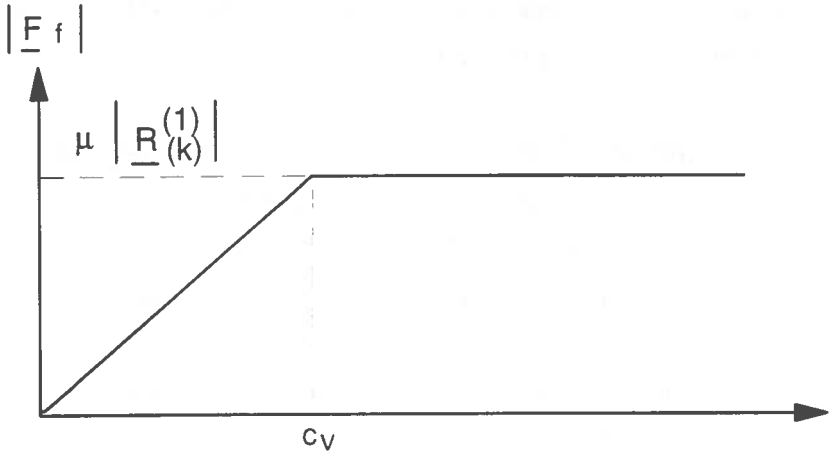

Figure C1. The frictional force as a function of node velocity

The frictional force $\underline{F}_f$ is added to the forces $P_1^{(k)}$ and $P_3^{(k)}$ which are the resultant forces received at contact with the sea floor under the condition $r_2^{(k)} \cong 0$ and $\dot{p}_2^{(k)} = 0$

The total forces in the node are

$$P_1^{*(k)} = P_1^{(k)} + F_f \qquad ...(C7)$$

$$P_3^{*(k)} = P_3^{(k)} + F_f \qquad ...(C8)$$

The Eq. (3.26) in Lindahl, Sjöberg (1983) is transformed into

$$\begin{bmatrix} \ddot{p}_1^{(k)} \\ 0 \\ \ddot{p}_3^{(k)} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} & P_1^{*(k)} \\ c_{21} & c_{22} & c_{23} & P_2^{*(k)} \\ c_{31} & c_{32} & c_{33} & P_3^{*(k)} \end{bmatrix} \qquad ...(C9)$$

from which $P_2^{*(k)}$ can be solved:

$$P_2^{*(k)} = -\frac{1}{c_{22}}(c_{12}P_1^{*(k)} + c_{23}P_3^{*(k)}) \qquad \text{...(C 10)}$$

The effect of the frictional forces are seen clearly if Fig. 4.15 and Fig. 4.16 in paragraph 4.2 are compared. The former figure shows the force close to the anchor and the latter figure the force at the upper end of the cable. The former contains almost no oscillations of high frequency. In the example the internal damping was set to zero.

The value 0.3 m/s has been used in most simulations and has recently proven to give results agreeing with frequency-domain analyses. (Liu and Bergdahl, 1997)

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