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Mooring Design & Dynamics—a Matlab® package for designing and analyzing oceanographic moorings

Richard K. Dewey *

Centre for Earth and Ocean Research, University of Victoria, Victoria BC, Canada

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Abstract

Mooring Design and Dynamics is a set of Matlab® routines that can be used to assist in the design and configuration of single point oceanographic moorings, the evaluation of mooring tension and shape under the influence of wind and currents, and the simulation of mooring component positions when forced by time dependent currents. The *static* model will predict the tension and tilt at each mooring component, including the anchor, for which the safe mass will be evaluated in terms of the vertical and horizontal tensions. Predictions can be saved to facilitate mooring motion correction. Time dependent currents can be entered to predict the *dynamic* response of the mooring. The package includes a preliminary database of standard mooring components which can be selected from pull down menus. The database can be edited and expanded to include user specific components, frequently used fasteners/wires etc., or unique oceanographic instruments. Once designed and tested, a draft of the mooring components can be plotted and a list of components, including fasteners can be printed.

1. Installation

Version 1.1 (December 1999) of Mooring Design and Dynamics accompanies this document, or you may wish to download the latest version of Mooring Design and Dynamics either as a Unix compressed tar-file mdd.tar.z, or as PC zip archive mdd.zip, or visit the Mooring Design and Dynamics web page for any recent updates

* Fax: +1-250-472-4030.
E-mail address: rdewey@uvic.ca (R.K. Dewey)

1369-9350/99/$ - see front matter
PII: S1369-9350(00)00002-X

and URLs to the latest files. Both archives are approximately 2 Mb in size. Once you have the appropriate archive, extract the tiles into a local toolbox directory, possibly named /*matlab*/*toolbox*/*local*/*mdd* and add this to your Matlab® path. The programs are accessed by typing »moordesign at the Matlab® command prompt. To make this Users Guide accessible from within Matlab®, the contents must be extracted under the Matlab® 'help' directory, in /*matlab*/*help*/*toolbox*/*mdd*/. This Users Guide and model description can then be accessed from within *Matlab*® by typing »mdd at the Matlab® command prompt. It is not necessary to install the Users Guide to use Mooring Design and Dynamics. If your Matlab® path contains blanks, such as 'C:\Program Files\Matlab', then some of the load functions will not work properly. This is because the load command can not have blanks in it. Unfortunately, the easiest workaround is to install Matlab® in a path without blanks (ugh!), i.e. 'C:\Matlab'.

2. Getting started

Mooring Design and Dynamics is a Matlab® application, and requires a pre-installed version of Matlab® to run. The first thing one needs to do, before using MD&D to assist in the design and evaluation of an oceanographic mooring, is get organized. One needs a clear definition of the mooring components, it's desired dimensions, and the environment it will go into. It is suggested the user sketch out the mooring, make a note of all the major components available, what height above the bottom they are to be deployed at, what type of fasteners will be used, and what type/size of mooring wire will be used or is available. All of this information is required before you can complete a mooring design and evaluate it. Then let MD&D do the actual formal designing, evaluation, and plotting/listing of the mooring. Alternately, to earn the basics and functionality of MD&D, one can start the program and get familiar with it's capabilities and what features it has available from it's pull down menus using the example moorings and auxiliary files provided with the program files. Also, despite the authors efforts, it is possible to enter data and design moorings that are incompatible with the present code, and the program(s) and routines can be made to 'crash' if data is entered incorrectly. It is assumed the user will try to design meaningful moorings and follow the suggestions provided here. And as with any development procedure, it is suggested that you '*save early, save often*'.

The main menu (MD&D program) is started by typing at the Matlab® command line prompt. The Main Menu (showing all base options) with active links to each feature is shown below.

2.1. The Main Menu

The Main Menu provides access to all the major functions available in MD&D. Initially however when no mooring or the necessary environmental conditions are loaded into memory, only a sub-set of options will be displayed by the Main Menu. As data is entered and analysis and display options become available, the options displayed on the Main Menu will increase. Shown here is a relatively complete Main Menu showing most functions. You can change the size of the Menu fonts used by MD&D by editing the first executable line of moordesign.m, fs=12; immediately following the global declarations. Fig. 1

Design New Mooring. Initialize mooring design.
Load Existing Mooring. Load a saved mooring.
Save a Mooring. Save the present mooring.
Add/Modify Mooring Elements. Edit present mooring.
Set/Load Environmental Conditions. Set currents.
Display Currents. Display velocity and density values.
Evaluate and Plot 3-D Mooring. Once designed, a mooring can be evaluated under varying environmental conditions.
Display Mooring Elements/Print. Display positions (and tensions of each mooring components and a component summary.
Plot Mooring/Print. Plots mooring components.
Add/Examine Elements in Database. Edit the mooring component database.
Make/Load/Show a Movie. For time varying currents.
Clear All. Clears all MD&D variables/figures.
Whos. Displays list of variables.
Close. Exit MD&D.

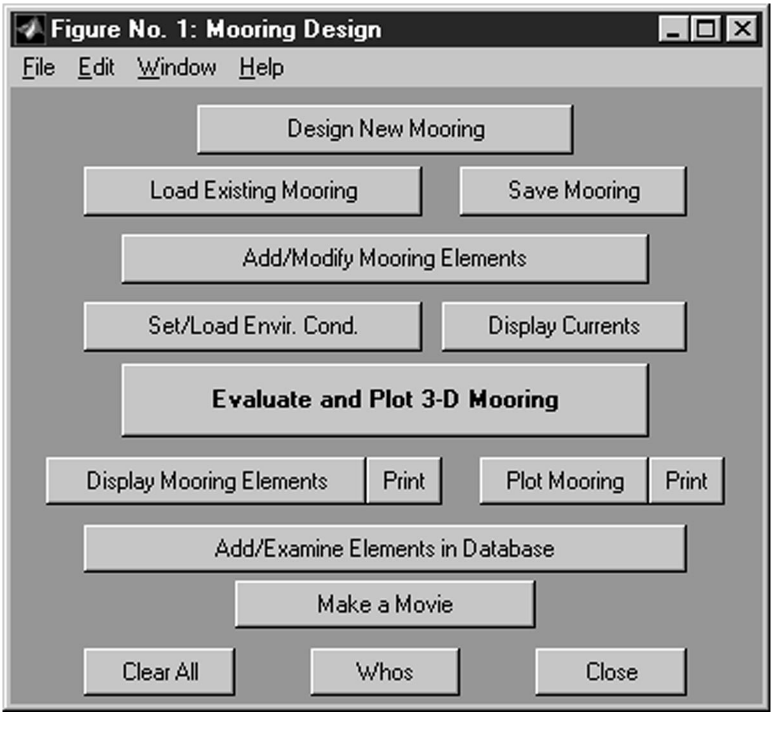


Fig. 1.

2.1.1. Main Menu: Design New Mooring

This function clears the component list, and presents the user with the ‘Modify Mooring Design’ window. This is the primary menu/function from which mooring elements can be added (from the database) or deleted to/from a mooring. By default, mooring elements (components) are added from the top (element one) to the bottom of the mooring. The top element is usually a floatation device, the bottom element usually an anchor. All moorings need to have at least some positive buoyancy elements (floatation) and negative buoyancy elements. Nonsense moorings will likely cause the program to crash. Just as in a real mooring, components should be separated by appropriate fasteners (e.g. shackles), even if the adjacent mooring components are both wire or rope elements. The intent its to have the list of mooring components be as complete and accurate as possible, leaving nothing out which is required for actually building the mooring. Other mooring programs allow you to not specify an anchor, or have adjacent components without fasteners. MD&D requires you to be accurate and complete. This forces one to think about the safe operating loads on each component, as a mooring is only as strong as it’s weakest link. A good mooring should have consistent components (i.e. fasteners) which reflect the anticipated loads and tensions, without wasting oversize components. Sometimes, due to the dimensions of certain devices, shackles of specific size are necessary (i.e. the drop shackle for an Interocean Acoustic Release is a 1 inch anchor shackle). Fitting these specific components with the rest of the mooring may require a series of shackles, and it is recommended that all of these components be included in the mooring design and analysis. MD&D was designed to do exactly this, producing the most accurate analysis and complete list of components. Fig. 2

Element to Add/Insert. This numeric string is editable (click on the number with

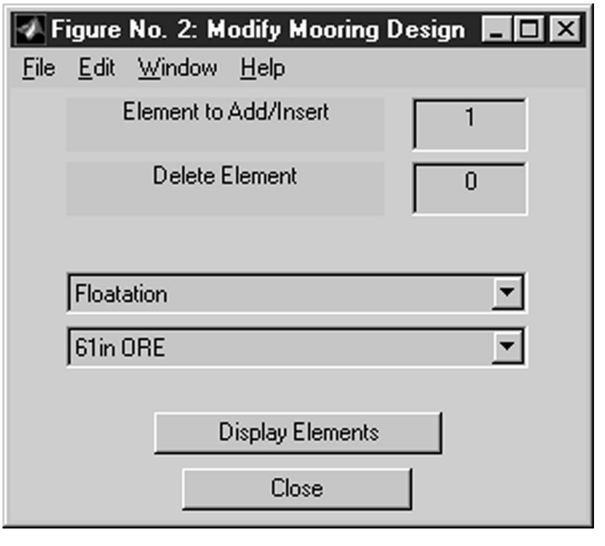


Fig. 2.

the mouse), and must either be the next ‘free’ element (number of present elements plus 1, default) to add, or an existing element number to insert a new element and bump the remaining elements below this.

Delete Element. Editable string, where an existing mooring element number is entered in order to delete this element. You should ‘click’ *Display Elements* both before and after deleting an element to confirm the updated list of mooring elements and their element number.

Floatation (and other mooring component types). This is a pull down menu. Click on the ▼ button to reveal the available list of database component types. They include: *Floatation*, *Wire*, *Chain*, *Current Meter*, *Acoustic Release*, *Anchor*, and *Misc Instrument*. Select a component type by *clicking* on the name of the type. Fasteners (shackles and rings) are listed under *Chain*. 61 in *ORE* (and other available mooring components). A pulldown menu to select the desired mooring component from a list of the available database components for this mooring component type. Click on the ▼ button to reveal the available list of components, then click on the desired component. The mooring element list will automatically be updated and displayed in the Matlab® Command Window.

Display Elements. This button will regenerate an updated list of the present mooring elements and their respective number in the main Matlab® Command Window.

Close. Closes this menu, keeping the present mooring components in memory, and returning to the Main Menu. It would be advisable to *save* a complicated mooring after each major modification.

2.1.2. Main Menu: Load Existing Mooring

Fig. 3

Opens an operating system window, similar to the one shown here, from which the user can select a disk. Directory, and MAT file containing a previously saved mooring or data. This same window is used to load a previously saved movie of a time dependent mooring simulation or environmental data. Some default and test moorings and movies are included with this package (including least the list shown here), with some time dependent current profiles moorings, (*ts.mat). Click on (highlight) the desired file and then click *Open* or double click on the filename (depending on the operating system).

2.1.3. Main Menu: Save a Mooring

Fig. 4

Opens an operating system window, similar to the one shown here, from which the user can select a disk, directory, and MAT filename into which all necessary environmental data is saved. This mat file can then be loaded later to further evaluate, view, modify, or analyze the mooring. Click on an existing filename to overwrite, or enter the filename. This list shows some of my mooring designs from a project in Juan de Fuca in 1997, including three thermistor chain and two ADCP moorings. Time series of current profiles recorded by the ADCPs where then used to ‘simulate’

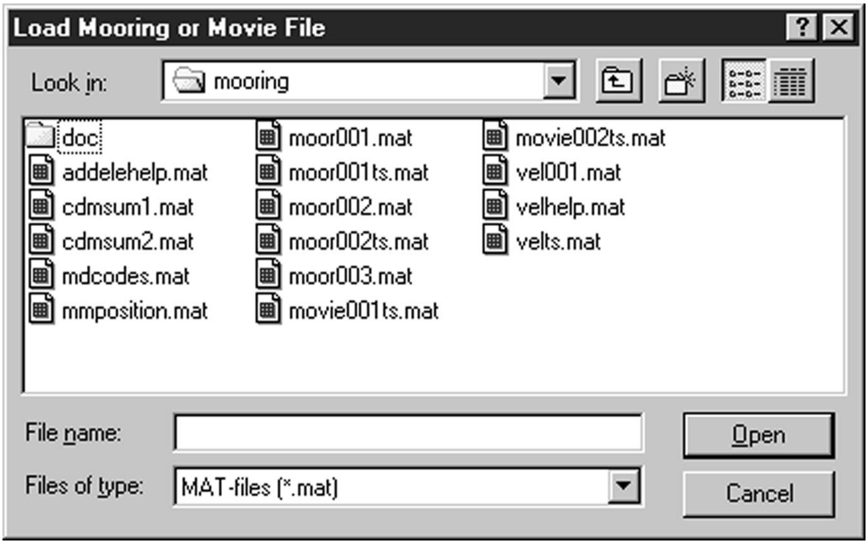


Fig. 3.

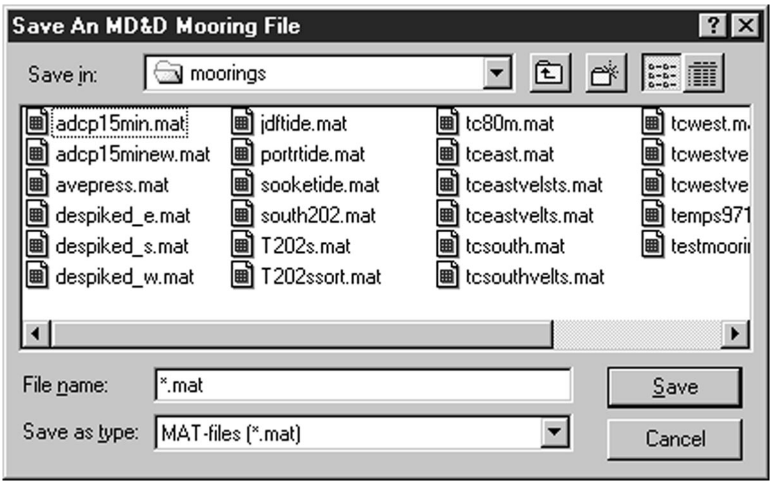


Fig. 4.

mooring motion. The thermistor depths where then corrected. These ‘weakly’ taut moorings had 15 m excursions during peak (1.2 m/s) currents, which where simulated to within 1% of the recorded top and bottom pressure records.

2.1.4. Main Menu: Add/Modify Mooring Elements

As with *Designing a New Mooring*, this is the primary working menu used to modify (add and delete) mooring elements from a mooring.

Element to Add/Insert. This numeric string is editable (click on the number with the mouse), and must either be the next ‘free’ element (number of present elements plus 1, default) to add, or an existing element number to insert a new element and bump the remaining elements below this.
Delete Element. Editable string, where an existing mooring element number is entered in order to delete this element. You should ‘click’ Display Elements both before and after deleting an element to confirm the new list of mooring elements and their element number.
Current Meter (and other mooring component types). This is a pull down menu. Click on the ▼ button to reveal the available list of database component types. They include: *Floatation*, *Wire*, *Chain+Shackles*, *Current Meter*, *Acoustic Release*, *Anchor*, and *Misc Instrument*. Select a component type by *clicking* on the name of the type. Fasteners (i.e. shackles) are listed under *Chain*.
Aanderaa RCM-7 (and other mooring components). A pulldown menu to select the desired mooring component from a list of the available database components for this mooring component type. Click on the ▼ button to reveal the available list of components, then click on the component. The mooring element list will automatically be updated.
Display Elements. This button will generate a list of the present mooring elements and their respective number in the main Matlab® Command Window.
Close. Closes this menu, keeping the present mooring components in memory, and returning to the Main Menu. It would be advisable to *save* a complicated mooring after each major modification.

Fig. 5

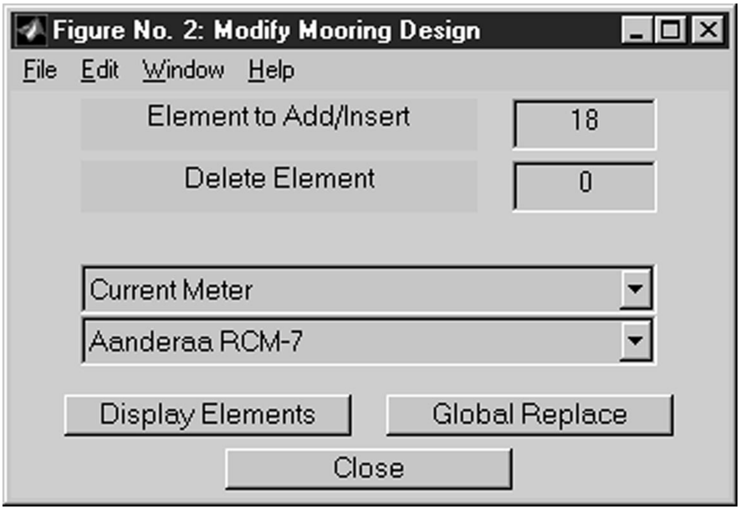


Fig. 5.

2.1.5. Global Change/Replace Mooring Elements

Fig. 6

This menu allows a user to make global or wholesale changes to the mooring componets of an existing mooring.

Display Elements. This button lists in the main Matlab command window all mooring components and a summary or tally of how many of each different type of mooring component is included. For wire and rope components, the total length of material is displayed, even if this is divided into multiple segments in the mooring.

Change All. The mooring summary list is accessable from the Change All pull down menu, from which the user can select a mooring component that has multiple occurances, and then select an alternate component to replace these.

Use the *Type* and *Component* menus to select the new component (e.g. globally replace 1/2″ shackles with 5/8″ shackles).

The change does not occur until the *Change* button is pressed. Be careful, it is possible to remove major components, (e. g. floats) and globally replace them with inappropriate device types (e.g. anchors). The available mooring components displayed are from the default database file (mdcodes.mat).

The *Close* button closes this global change window and sends control back to the Modify Elements Window.

2.1.6. Main Menu: Set/Load Environmental Conditions

Fig. 7

Enter/Edit Velocities Manually. To enter the velocities [$U(z)$ $V(z)$ $W(z)$ and z] using the keyboard.

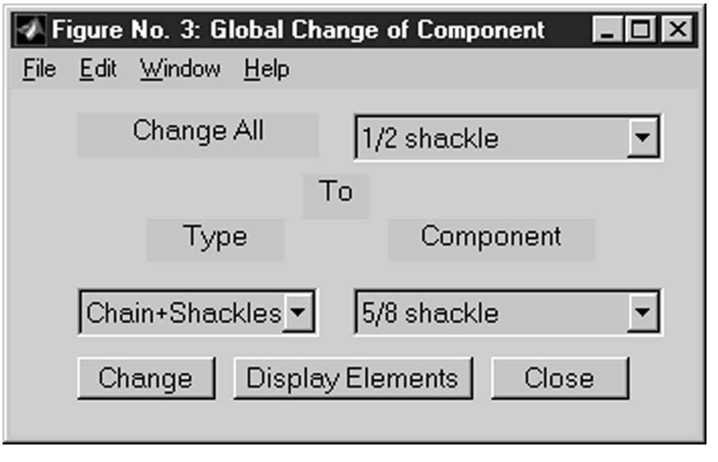


Fig. 6.

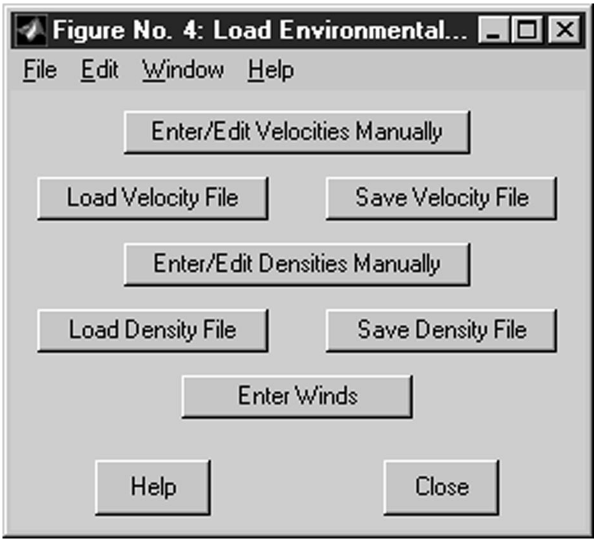


Fig. 7.

Load/Save Velocity File. If velocity profile data has already been entered and/or saved, it can/should be reloaded or saved at this time.
Enter/Edit Densities Manually. Enter or load a density [kg/m^3] profile. The mooring solution depends very weakly on density, but if it is important, one can modify it.
Load/Save Density File. If density profile data has already been entered and/or saved, it can/should be reloaded or saved at this time.
Enter Winds. Allows the user to specify a surface wind, which will apply an extra velocity kick (2% of wind speed) to the upper ocean current speeds.
Help. Brings up a simple text window with a brief description of the types of environmental data which can be entered.

2.1.6.1. Enter/Edit Velocities Manually Fig. 8

The ‘Enter’ buttons bring up (yet) another menu which allows the user the type in a string of delineated (spaces, commas) values for each of the desired profiles [e.g. $U(z)$ and z], each with the exact same number of values, starting from the top (surface) value to the bottom value, which is ALWAYS associated with $z(n)$=0 m, where n is the total number of values making up the velocity profile(s). By default the $V(z)$ and $W(z)$ profiles are set to zeros. The height of the velocity and density profiles determines the water depth which the mooring is in.

Save Velocities. Opens a system window (section 1.3) to save the velocity (environmental) data into a standard Matlab® mat file. This same environmental

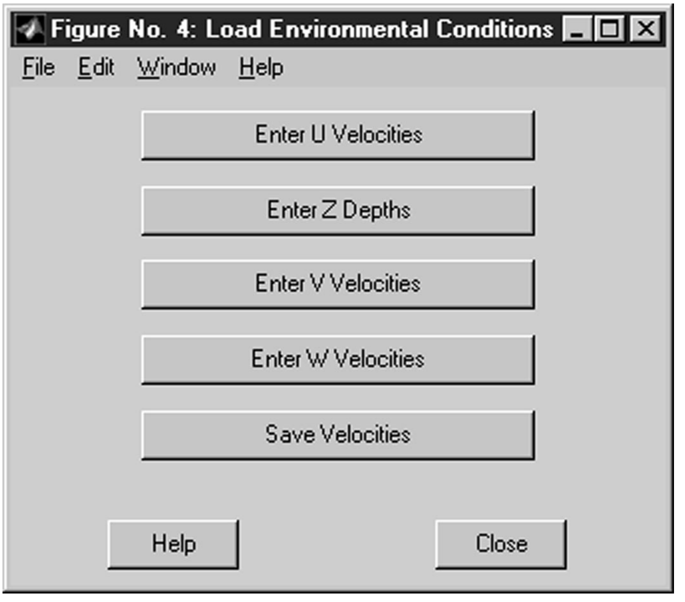


Fig. 8.

data can be re-loaded using the *Load Environmental Conditions* option (section 1.5).
'*Help*' opens a simple text window with simple instructions as to how to enter meaningful velocity profile data as a HI text string (i.e. current values in m/s from top to bottom, where a bottom must be entered at z=0).

2.1.6.2. Enter U Values Fig. 9

Enter the velocity values in m/s H1 by either spaces or commas, as a text string starting with the top (highest) value and ending with the velocity value AT the bottom

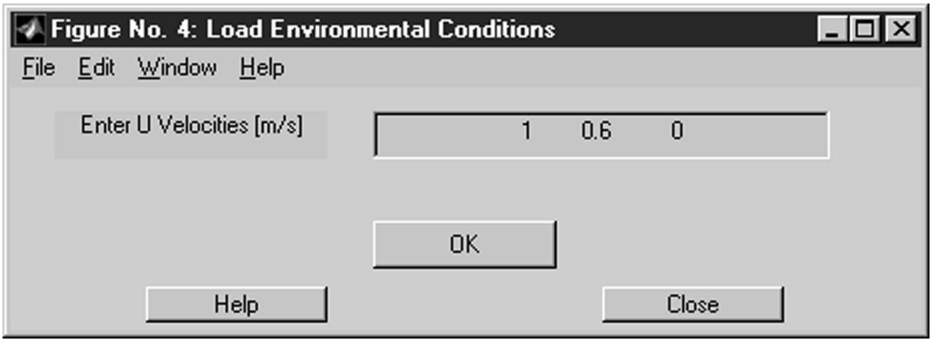


Fig. 9.

(z=0), which in most cases should be 0 m/s. There is no limit to the number of velocity values in a profile. Alternate the provided velocity mat files included with the package to see the data format, and make/load you own velocity data from the keyboard, a model, or measured currents and save these into a mat file. The displayed values make up the default velocity profile with speeds of 1.0, 0.6 and 0 m/s, respectively.

'*OK*' will accept these values and potentially bring up the *Enter Heights* menu.

'*Help*' displays a simple text window of help for entering the velocity profile data.

2.1.6.3. Enter Z Values Fig. 10

Enter the height values in for the associated velocity data, H1 by either spaces or commas, as a text string starting with the top (highest) value and ending at the bottom (z=0). The number of Z values must be the same as the number of velocity values already entered. Alternately the provided velocity mat file (ve1001.mat) included with the package to see the data vector format, and make/load you own velocity and density profile data from the keyboard, a model, or measured values and save these into an appropriately named mat file. The displayed values are the default heights: 120, 10 and 0 m.

'*OK*' will accept these values.

'*Help*' displays a simple text window of help for entering the velocity profile data.

2.1.6.4. Enter/Edit Densities Manually Fig. 11

'*Enter*' either the density values or the height values for the density profile. The solution needs a local density value, so you can enter a specific density structure, or default to a simple stratified ocean [1024 kg/m^3 at surface 1026 at bottom].

Save Density Profile brings up the save Matlab® file menu for saving the density profile data for future retrieval.

'*Help*' brings up a simple text window describing the minimum data entry procedures for entering density profile data as a space or comma procedures text string.

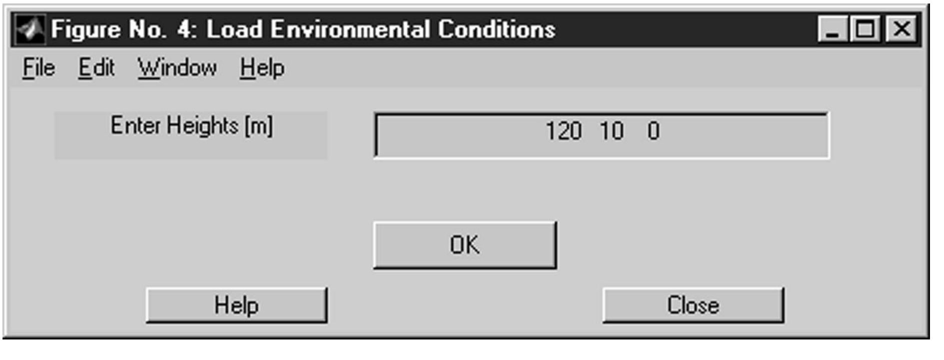


Fig. 10.

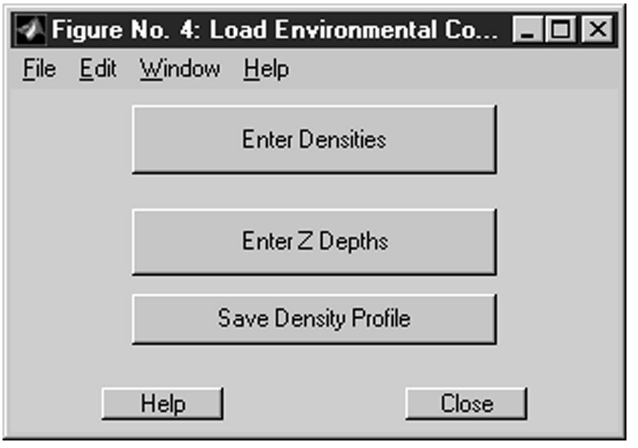


Fig. 11.

2.1.6.5. Enter Density Values Fig. 12

Enter either the density values or the height values for the density profile as text strings procedures by either spaces or commas. The solution needs a local density values (stored in vector rho), so you can enter a specific density structure, or default to a simple linearly stratified ocean [1024 kg/m^3 at surface, 1026 kg/m^3 at bottom].

'*OK*' brings up a similar window to enter or edit the heights for the density values.

'*Help*' brings up a simple text window describing the minimum data entry procedures for entering density profile data as a space or comma procedures text string.

2.1.6.6. Enter Winds Fig. 13

Enter the wind speed [m/s] and direction [degrees from North in meteorological convention, i.e. the direction from which the wind is blowing]. The 2% velocity

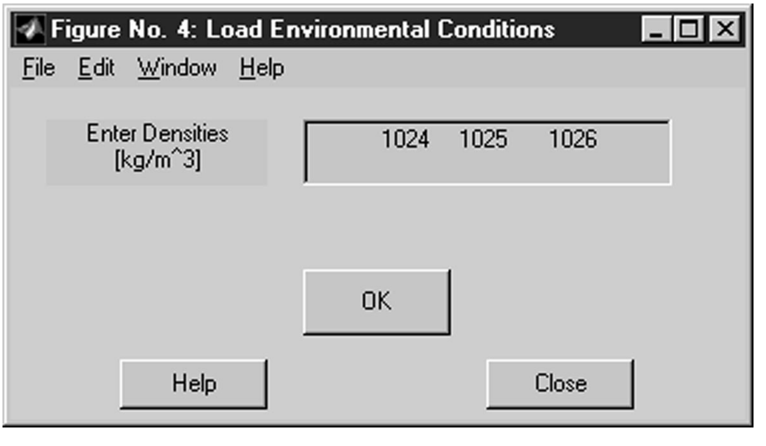


Fig. 12.

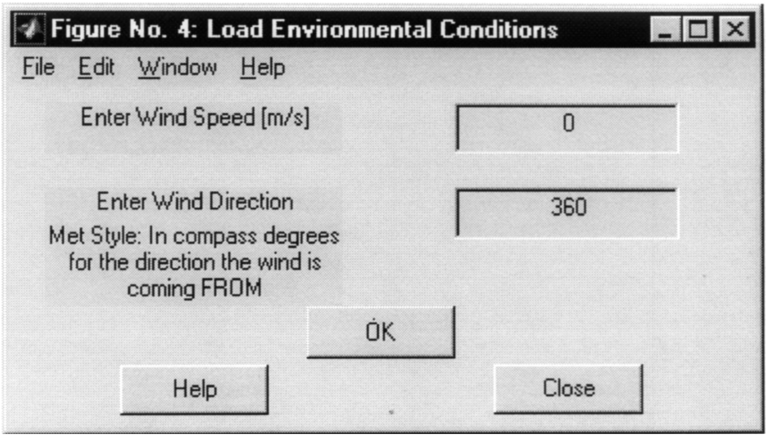


Fig. 13.

'kick' penetrates to depths below the surface at approximately 1 m for every m/s of wind speed (regardless of the density profile), so a 10 m/s wind penetrates an additional linearly decreasing velocity profile down about 10 m in the direction of the wind (no Ekman spiral). The maximum wind penetration is 80% of the water column, assuming that a bottom boundary layer will exist within which wind forcing is negligible/dampened.

'*OK*' returns and stores the surface wind vectors (in East and North components).

'*Help*' brings up a simple text window describing the minimum data entry procedures for entering environmental data.

2.1.7. Main Menu: Display Currents

Pressing this button will display the current velocity and density profile values in the main Matlab® Command Window. To plot these profiles, one can simply enter regular Matlab® plotting commands at the command prompt. I have not included a profile plotting set of routines in this package since there are many ways to present such data, and most oceanographic users will have specific needs and desires with regard to their hydrographic and velocity data. A set of simple plotting commands might look like:

```
»figure
»plot(U(:,l),z,'r',V(:,1),z,'b');
»xlabel('Velocities U=red, V=blue [m/s]');
»ylabel('Height Above Bottom [ml]');
```

2.1.8. Main Menu: evaluate and plot 3-D mooring

Fig. 14

Once a 'complete' mooring has been designed, which includes, from top to bottom, floatation, wires, fasteners and instruments, and an anchor, and appropriate environ-

Fig. 14.

mental conditions have been entered (i.e. current profile(s) have been entered that either exceed the height of the mooring (for sub-surface) or extend to the surface (for shallow or surface moorings), then a ‘solution’ can be sought. If a time series of current profiles (time dependent solution) has been loaded, then the user will have to specify at which time a solution is sought. The ‘Select Time’ window shows the start and end times of the time dependent currents (user specified units). An ‘Edit Time’ option allows the user to edit the approximate (closest) time for which a solution is sought. This exact time will be displayed on the 3-D mooring plot. If a single current profile has been set (not a time dependent solution), then this menu is not displayed. Fig. 15

Initiated from the Main Menu for a time independent solution or by *clicking* ‘OK’ in the ‘Select Time’ window for a time dependent solution, the mathematical solution is evaluated using an iterative approach, repositioning the mooring components in the water column (i.e. velocity and density profiles) according to the wire angle

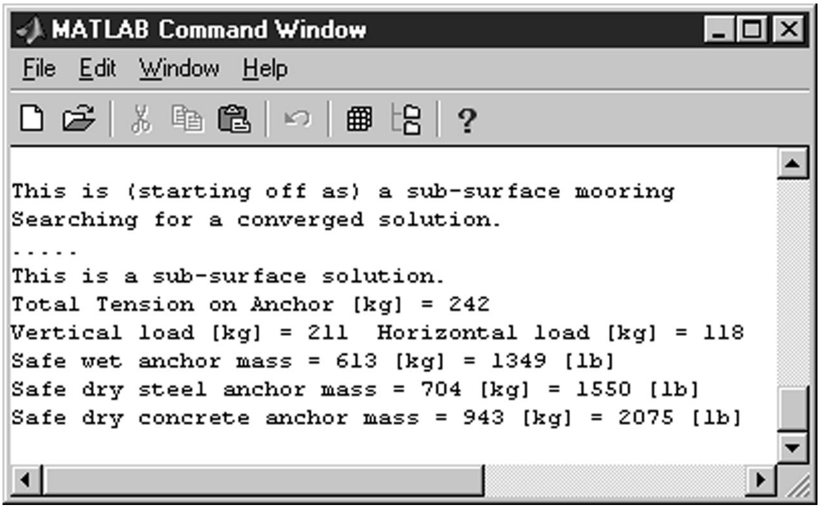


Fig. 15.

and orientation after each iteration. The Matlab® Command Window, (shown here) displays a 'dot' for each iteration. Once the vertical position of the top most mooring element (usually a floatation device) changes by less than 0.01 m between iterations, it is assumed a solution has been found. Strongly sheared current profiles may make convergence difficult. The type of solution is then displayed (either a surface or sub-surface mooring), and the total, vertical, and horizontal tensions [measured in kg] acting on the anchor are displayed, followed by 'estimates' of the safe anchor mass necessary to hold the mooring in position, based on both the vertical (VWa) and horizontal (HWa) tensions according to 1.5×(VWa+HWa/0.6), which incorporates drag and lift safety factors, and is adopted from the Mooring Group at the Woods Hole Oceanographic Institution. Also displayed are the equivalent dry anchor masses in terms of both steel and concrete. After a solution has been found, the tensions at and positions of all major mooring components and at the ends of each wire segment can be displayed by *clicking* the *Display Mooring Elements* button from the Main Menu. Figs. 16 and 17

After the solution has been found the three-dimensional mooring shape is plotted, and a *Modify Plot* menu is displayed that will allow you to modify the plot (i.e. plot title, orientation, view, etc.). The view angles are standard three-dimensional controls, explained by the help available for the 'plot3' and 'view' commands. Alternately, the view of the mooring can be modified by clicking the *Rotate3D* button, and then using the mouse to click-and-drag on the figure axes to rotate the view, (The help for the Matlab® command 'rotate3d' is automatically displayed in the Matlab® Command Window when this button is clicked.) The *U* and *V* velocity

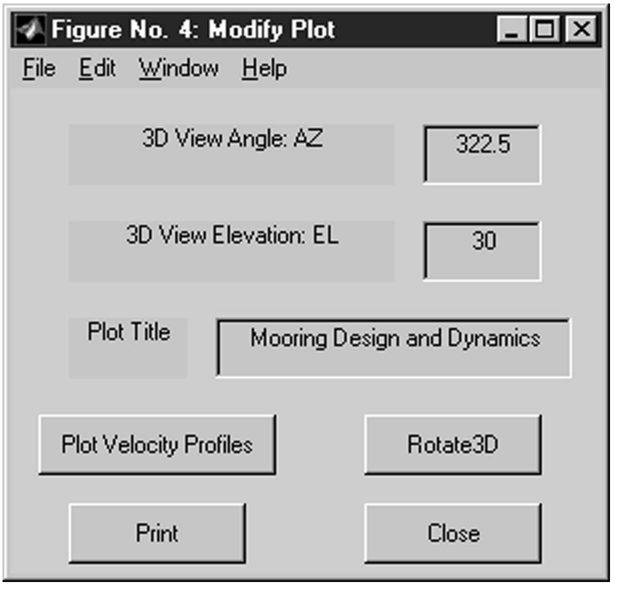


Fig. 16.

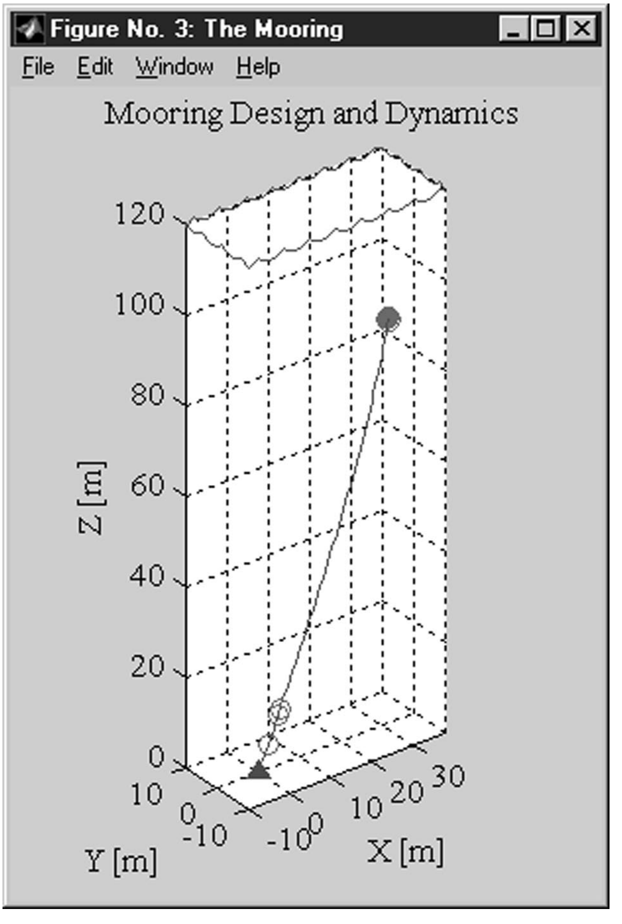


Fig. 17.

profiles can be plotted against the *Y* and *X* faces of the plot, respectively, normalized to the scale of the axes by *clicking* on the 'Plot Velocity Profiles' button. Fig. 18

When the water depth (as defined by the height of the velocity profile) is near or at the top of the mooring (i.e. in the case of a surface mooring, then a blue wave field is plotted. Additional plot controls can be entered manually from the Matlab® Command Window. For example, axis format and titles can be modified using the Matlab® commands for 'axis' and 'xlabel'/'ylabel'. Similarly, additional text or information can be added to the plot using standard Matlab® commands. The plot can be printed by *clicking* the 'Print' button in the *Modify Plot* Menu, sending the displayed figure to the 'default' printer. If you do not have a default printer that Matlab® can print to, **DO NOT** click on the 'Print' button. Alternately, the plot (and for that matter any of the displayed 'figures') can be printed to a file using the 'print -d *device* filename' option of the Matlab® 'print' command.

If the mooring is anticipated to be a SURFACE mooring (i.e. the mooring height

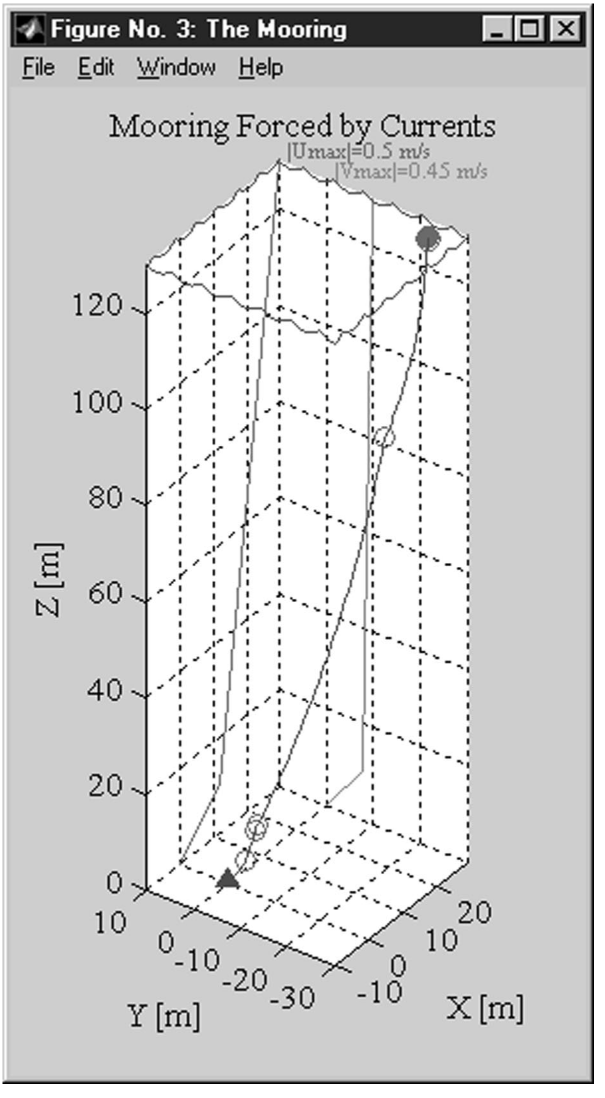


Fig. 18.

is expected to exceed the water depth and the top floatation device will float at the ocean surface), then one can expect a much higher number of iterations before a converged solution is found. This is because the solution does not know a priori how much of the buoyancy of the top floatation component(s) to use to keep the mooring 'up'. In fact, **if** the model estimates that the top floatation components provide virtually no lifting buoyancy to the remainder of the mooring (i.e. as in the case of example mooring moor002.mat (shown to the left) when the current speeds are reduced), especially for S-mooring configurations, then the solution may **NOT** converge (i.e. tensions are near zero), then the unnecessary floatation/wire components of the mooring are **removed** and a subsequent solution is sought. If the model does strip off the upper components, a warning to this effect is displayed in the a href='http://www.mathworks.com/'>Matlab® Command Window. An example of a mooring which poses grave convergence problems for the solution algorithm is a simple Polypropylene mooring with multiple small float/Polypropylene segments, far exceeding the water depth. The small tensions and large changes in the drag to buoyancy ratio with only tiny adjustments to the surface float buoyancy prevent a 'stable' solution, even though we know the mooring can exist. Trailing a line and floats on the surface tends to have horizontal tensions only, and the vertical position and vertical tensions are naturally unstable. If you need to know the position of such a mooring, then simply add the known length of the trailing segments to the part of the mooring which has only a float and submerged components.

2.2. Surface solution output

Fig. 19

For surface solutions, the approximate percentage (%) of the top floatation device (i.e. the amount of buoyancy) used to 'hold' the mooring in position is displayed in the Matlab® Command Window (see below). In this way, both the required anchor mass and surface floatation can be evaluated to maintain a specific mooring configuration.

The user should be aware that certain wire types do stretch under tension. In particular, nylon is used as a 'bungy' wire in deep surface moorings to maintain tension along the mooring wire, but not 'pull' the top buoy under the surface. See for example the mooring 'cdmsum2.mat', which is a mooring designed by Berteaux (1976) as part of his Cable Dynamics and Mooring Systems package, which is available commercially. MD&D provides an identical solution: and shows how the nylon is stretched to +120% in order to keep the mooring taut and at the surface.

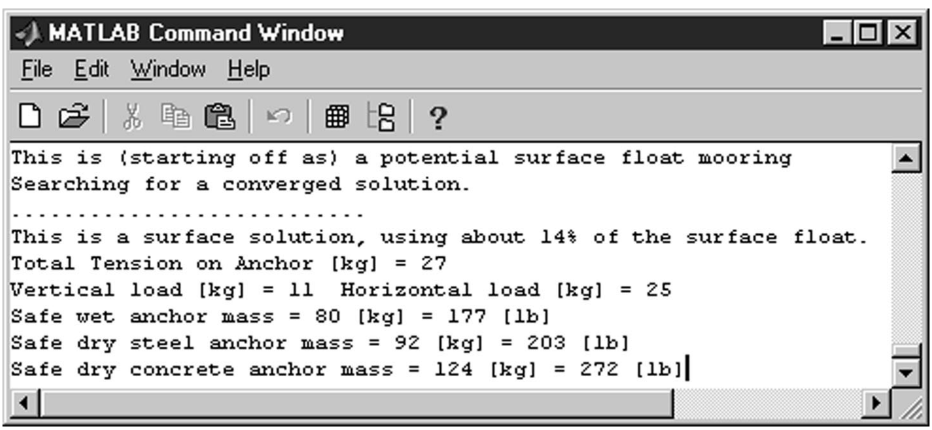
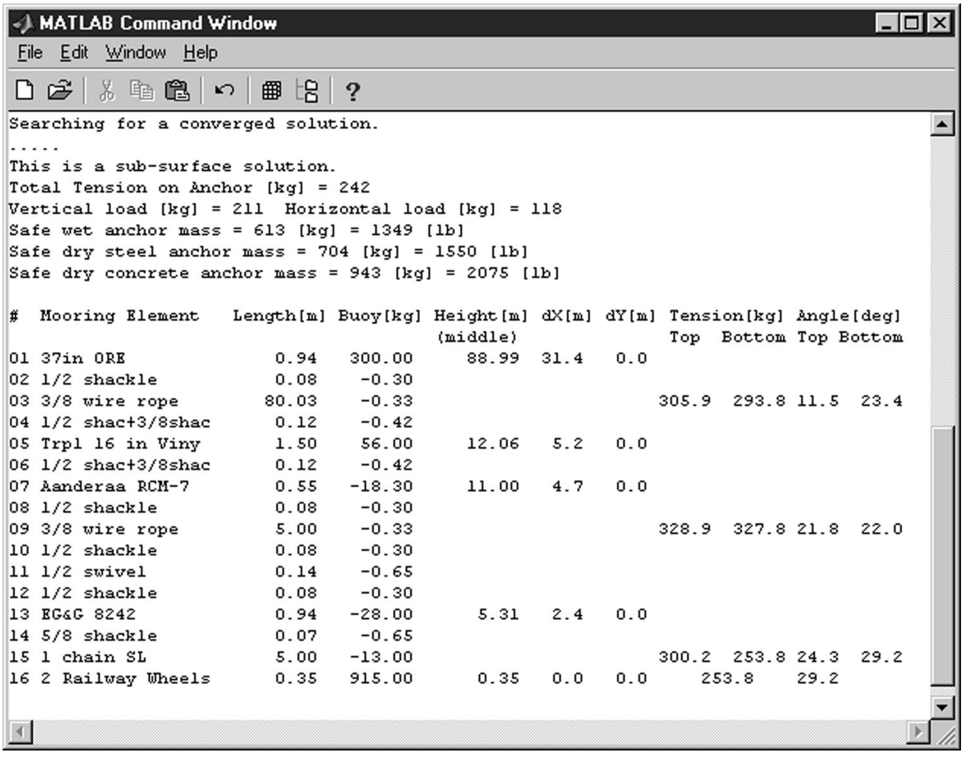


Fig. 19.

2.2.1. Main Menu: Display Mooring Elements/Print

Once a mooring has been designed and/or evaluated (i.e. a solution has been found and plotted by executing the *Evaluate and Plot* function), then mooring elements can be listed, or alternately the specific tensions, positions, and alignment of each mooring component can be displayed in the Matlab® Command Window (as shown below) by clicking the *Display Mooring Elements* button located on the Main Menu. A summary of the number of each component type and total wire/rope lengths is also displayed. This list can also be printed to the default printer by *clicking* the *Print* button next to the *Display Mooring Elements* button. A full page can display a mooring with 80 components. Printing this list will temporarily open a new figure window within which the mooring components are listed. This temporary window should close automatically once the list has been sent to the printer. Fig. 20

Shown in the above list of mooring elements is the component number and name, the physical length of the component, it's buoyancy in kg (positive upwards), the height of the top of the component when forced by the specified currents, the North (X) and East (Y) displacements from a vertical line above the center of the anchor, the tension in kg at the top and bottom of each wire segment, and the total angle in degrees from the vertical at the top and bottom of each wire segment. The horizontal




```
Searching for a converged solution.
.....
This is a sub-surface solution.
Total Tension on Anchor [kg] = 242
Vertical load [kg] = 211  Horizontal load [kg] = 118
Safe wet anchor mass = 613 [kg] = 1349 [lb]
Safe dry steel anchor mass = 704 [kg] = 1550 [lb]
Safe dry concrete anchor mass = 943 [kg] = 2075 [lb]

#  Mooring Element    Length[m]  Buoy[kg]  Height[m] dX[m]  dY[m]  Tension[kg] Angle[deg]
                                            (middle)                Top  Bottom Top Bottom
01 37in ORE               0.94    300.00     88.99  31.4    0.0
02 1/2 shackle            0.08     -0.30
03 3/8 wire rope         80.03     -0.33                          305.9  293.8 11.5  23.4
04 1/2 shac+3/8shac       0.12     -0.42
05 Trpl 16 in Viny        1.50     56.00     12.06   5.2    0.0
06 1/2 shac+3/8shac       0.12     -0.42
07 Aanderaa RCM-7         0.55    -18.30     11.00   4.7    0.0
08 1/2 shackle            0.08     -0.30
09 3/8 wire rope          5.00     -0.33                          328.9  327.8 21.8  22.0
10 1/2 shackle            0.08     -0.30
11 1/2 swivel             0.14     -0.65
12 1/2 shackle            0.08     -0.30
13 EG&G 8242              0.94    -28.00      5.31   2.4    0.0
14 5/8 shackle            0.07     -0.65
15 1 chain SL             5.00    -13.00                          300.2  253.8 24.3  29.2
16 2 Railway Wheels       0.35    915.00      0.35   0.0    0.0       253.8    29.2
```

Fig. 20.

displacements *X* and *Y* are associated with the current components *U* and *V*, respectively, which are typically associated with currents in the (positive) North and East directions, respectively. If entered: vertical velocities (*W*) are positive upwards.

2.2.2. Main Menu: Plot Mooring/Print

Fig. 21

Once a mooring has been designed, it's components can be plotted by *clicking* the *Plot Mooring* button from the Main Menu, or the plot can be printed to the

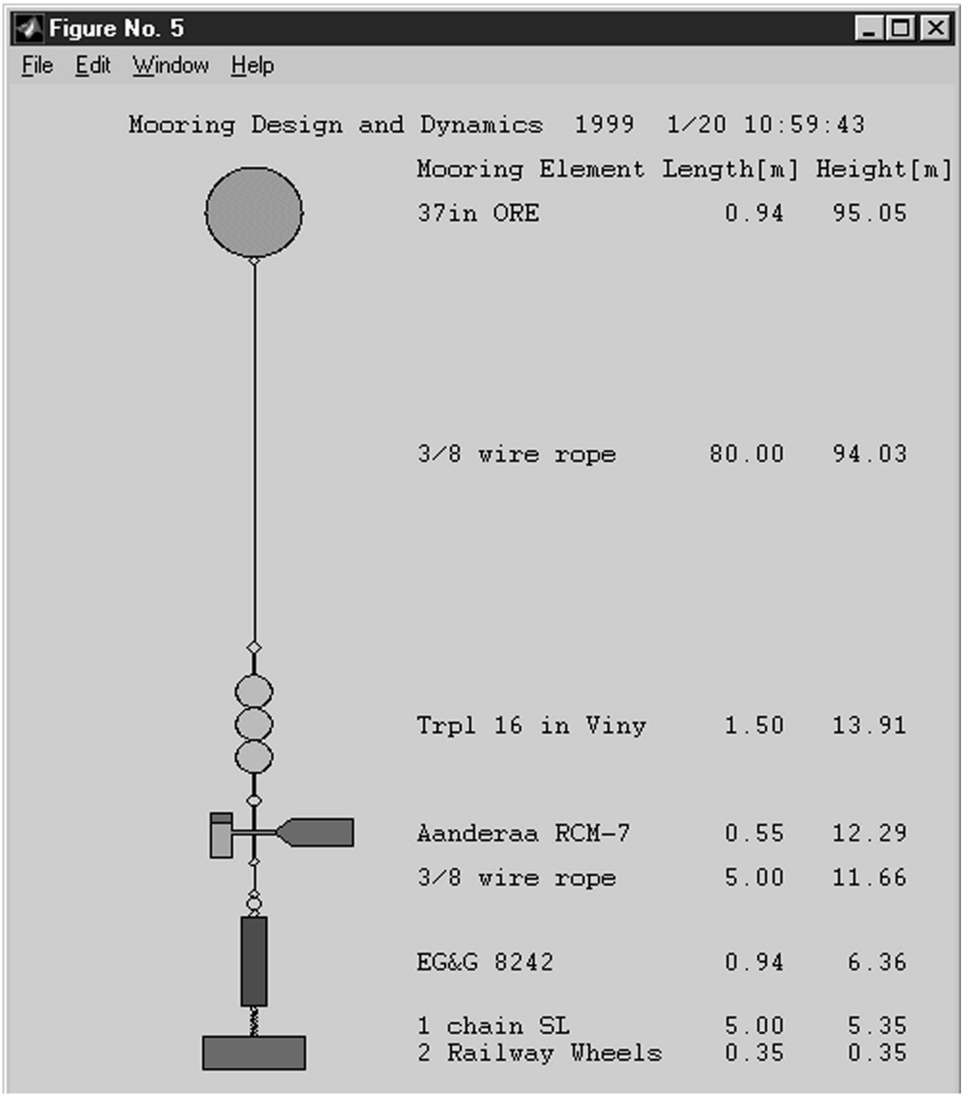


Fig. 21.

default printer by *clicking* the *Print* button next to the *Plot Mooring* button. If a solution has been found, then the length of each mooring component and the height above the bottom of each major component is displayed alongside the graphic plot of the mooring elements. User specific components will not be drawn accurately, but the user can develop a routine (e.g. *pltMYdevice.m*) to plot specific components and associate these routines with the component name in *plot_elements.m*, the routine that generates the mooring plot.

The plot can be saved into a file using the Matlab® Command Window and the Matlab® *print* command. For example, a color postscript file containing the mooring plot with a new title could be generated by typing:
»title('A Simple Mooring');
»print -f5 -dpsc2 moor01.ps
Note that the mooring is **NOT** drawn to scale. In particular, the wire segments are displayed as a fraction of their actual length. True deep water moorings have a large vertical to horizontal aspect ratio, as the ocean does, and the mooring devices would only show up as small dots. Note also that connecting devices (shackles, chain: etc.) are not draw in detail, or listed on the plot. For a complete 'component' list, *click* the *Display Mooring Elements* button on the Main Menu.

2.2.3. Main Menu: Add/Examine Elements in Database

Fig. 22

The usefulness of Mooring Design and Dynamics is greatly enhanced by maintaining an accessible database of frequently used mooring components. In particular, it is anticipated that you will have access to a wide and varied, and possible unique selection of mooring hardware, fasteners, and instruments. To this end MD&D has the capability of editing, adding and deleting components to/from the database. The

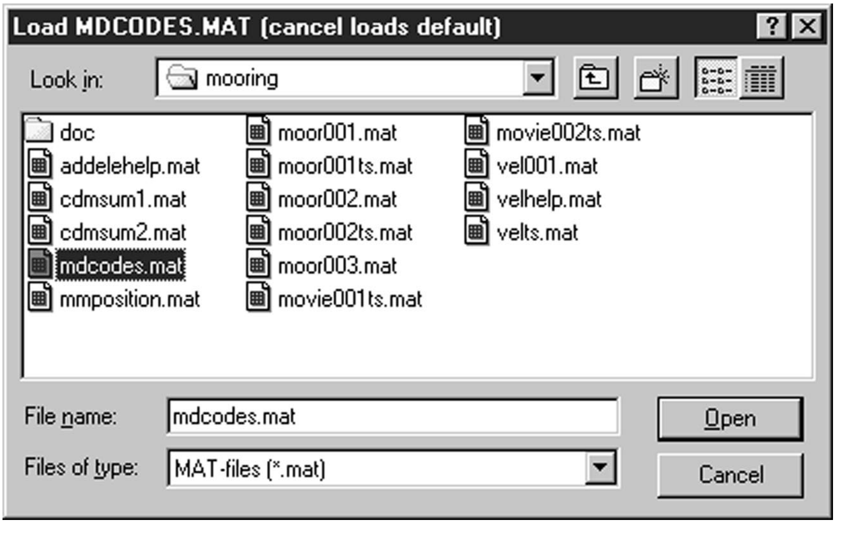


Fig. 22.

original database included with MD&D was built from Clark Darnall's (APL, Seattle) MOORDSGN program and has sufficient material to build a significant variety of moorings. An original database can always be restored from disk, a backup copy, or retrieved via ftp from the Internet. It would be wise to backup the original database (file *mdcodes.mat*) before making edits.

Clicking the *Add/Examine Elements in Database* button for the first time from the Main Menu opens a system window displaying the *.mat files available in the MD& D directory. By default, the original database file *mdcodes.mat* is opened, but if a user has developed their own database, or renamed the default file, then select the appropriate file for editing/viewing.

Unfortunately, the whole world (North America) has not gone metric. As a result, many mooring 'hardware' components are still referenced in terms of imperial measurements (i.e. 1/2 inch chain, 5/8 inch shackle, 3/8 inch wire). However, the formulae in MD&D use metric units (i.e. kg and m). Just to further confuse the issue, I have set the units for mooring component dimensions to centimeters [1 cm=1/100 m], which is a more natural unit for measuring oceanographic devices. Consequently, component names often refer to the 'manufacturers' unit (i.e. inches), the buoyancy is in kilograms [kg], while component dimensions are in centimeters [cm]. Until manufacturers (in North America) sell chain in metric units I'll maintain this 'mix' of units.

Once 'opened', the Add/Delete Element menu is displayed (see graphic below). Pull down menu items ▼ identify preset lists that cannot be edited or modified. Editable menu items and element characteristics are displayed as menu items with a description on the left, and an edit window on the right.

2.2.3.1. Add/Delete/Modify Elements in Database Fig. 23

Element Type. (*Floatation*, *Wire*, *Chain* (including fasteners), *Current Meter*, *Acoustic Release*, *Anchor*, *Misc Instrument*) Select the type of mooring element.
Selected Element. (i.e. 61 in ORE) The name of the selected element.
Add/Delete/Modify Element. Select to either add, delete, or modify an element.
Element Name. Enter the elements name (max 16 char).
Buoyancy. Enter the submerged buoyancy in kg (+ upwards).
Dimensions. Enter three dimensions in cm (height, width, diameter).
Drag Coefficient. Enter the drag coefficient.
Material. Select the approximate material type, used primarily For determining the modulus of elasticity for 'stretching' under tension calculations.
Add/Delete/Modify. Add, Delete, or Modify the elements in the database.
Help. Display some simple help.
Save. Save the new database.
Close. Close this window and return to the Main Menu.

2.2.3.2. Element Type The top option in the Add/Examine Database function allows the user to select the category or general mooring hardware type. The avail-

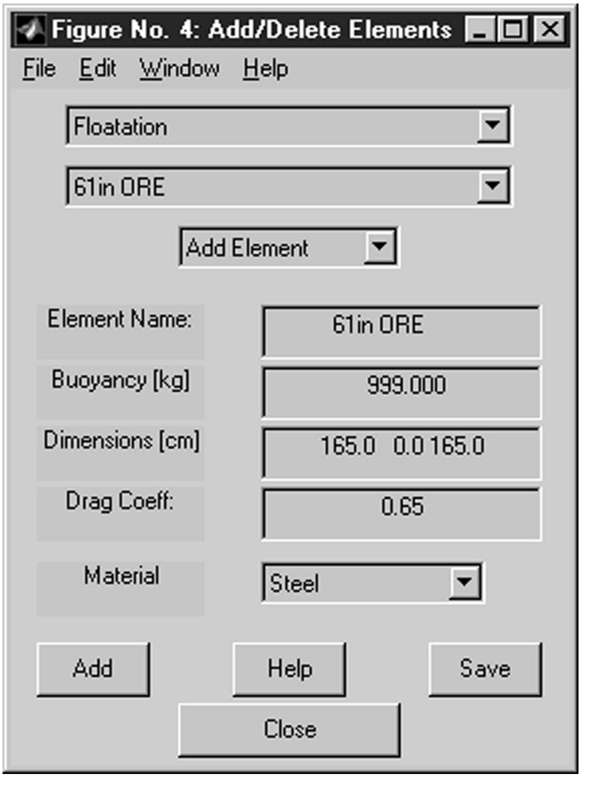


Fig. 23.

able mooring component types are: *Floatation*, *Wire*, *Chain* and *Shackles* (*including special fasteners such as swivels*), *Current Meter*, *Acoustic Release*, *Anchor*, or *Misc Instruments*. Most of these categories are self explanatory. *Floatation* devices primarily includes positive buoyancy spheres. Strings of commonly used combinations of floatation (i.e. a string of three 16 inch Viny floats) can be added to the database for frequent retrieval. The buoyancy for such 'combined' elements should include the *net* buoyancy. The *Wire* type includes steel and non-steel ropes.

The category *Chains* also includes fasteners such as *shackles*. Due to the important role played by chain and shackles in designing a good mooring, I have included a separate document with typical/available chain and shackle specifications. Images included with this package are scanned pages of chain and shackle specifications from Myers, Holm and McAllister (1969). These images are best printed when they are loaded separately into a browser or image view software. The information is provided to assist in determining the size, weight, and strength characteristics of various steel chains, shackles and joiners. One inch is equal to 2.54 cm. The conversion from lb (pounds) to kg is 1 kg=2.2046 lb. Steel retains approximately 87% of it's weight (buoyancy) in seawater. Therefore a 20 lb length of chain weighs 20[1b]/2.2046[lb/kg]=9.072 [kg] in air, and 9.072[kg]×0.87=7.91 [kg] in seawater.

Since it is heavier than seawater, we would assign it a negative buoyancy of −7.91 kg. MD&D requires weight/length of chain and wire to be entered as the buoyancy per unit meter of length. For example, in the table (buoychain.gif) for buoy chain, the weights are given in pounds (lb) per 15 fathoms of length, which equals approximately 27 432 m (6 ft=1 fathom=1.8288 m). So for 1/2 inch buoy chain, with a weight of 210 lb per 15 fathoms, the buoyancy per unit metre is: -210[lb/fathom] / 27.432[m/fathom] = -7.6553[lb/m] / 2.2046[lb/kg] = -3.4734[kg/m] $\times$ 0.87 = -3.021 [kg/m]. Further, working load limits are most often given in 'tons' (short ton) which is 2000 [lb], or 907.3 [kg].

2.2.3.3. Select Element Once the type of mooring element has been selected, then the database list of available elements for this type is loaded into the menu, and the user can pull down/view the list by *clicking* the ▼ button. Use the mouse to highlight or select an element. By default the first item in the list is selected. Once an element has been selected, it's name, buoyancy, dimensions, drag coefficient and material are displayed in the appropriate windows.

2.2.3.4. Add/Delete/Modify Element This option specifies whether the existing element is to be deleted or modified, or that a new element will be added. Once one of these options has been selected, the 'action' button in the lower left of the menu should show the present option selected (either Add, Delete, or Modify). This is an internal consistency check to reduce the likelihood that a mistake will not be made and elements will not be modified or deleted until the correct 'action' button is actually pushed. During the Add option, the five element characteristic menu item can be changed. In particular, the *Name* of the element must be changed, as the database cannot store identical named elements with different characteristics. Be aware however, that the name may include spaces, and very similar names will be accepted, even if the elements are intended to be the same. When Modifying an element, the name should remain the same, but the remaining four element characteristics (buoyancy, dimensions, drag coefficient, and material) can be changed. Once the characteristics have been entered correctly, the action button (Add or Modify) will update that elements characteristics in the 'loaded' database. If the element is to be Deleted, than do not edit the element characteristics (why bother), just characteristics the appropriate element, and click the Delete action button. Once the action button has been pushed, the entire routine re-initializes. The user should confirm that the desired changes have been integrated into the resident database. These changes are **NOT YET STORED** in a database file. To save these database changes, the user **MUST** *click* the *Save* button (lower right). This subsequently brings up a system window where the user can specify the new/updated database filename. By default the *MD&D* program selects and loads the database file named: *mdcodes.mat*. Therefore, it is recommended that you make a backup of the original mdcodes.mat file, and save subsequent modifications into the default file, mdcodes.mat.

2.2.3.5. Element Name This is an editable menu item, within which one can type the NEW element name to Add to the database. There is no need to edit this item during either a Delete or Modify action. The element name is limited to 16 ASCII characters, including spaces. The name should identify the element, and should be sufficiently descriptive as to remind the user of the specific decodes of the element (i.e. size, manufacturer, etc.).

2.2.3.6. Buoyancy (kg) The buoyancy of the element is given in kilograms [kg], where positive buoyancy represents objects that have an upward buoyancy force when submerged under water, and negative buoyancy represents a downward force. To determine buoyancy, one needs to know the mass and displacement (volume) of the object. The net buoyancy (value require here) is the mass of seawater displaced (volume [m^3]×1025 [kg m^{-3}]) minus the mass [kg] of the device. If the device floats, then the mass of seawater displaced by the volume of the object will be more than the mass of the object, and the buoyancy will be positive. If the device sinks, then the mass of seawater displaced will be less than the mass of the device and the buoyancy will be negative.

2.2.3.7. Dimensions (cm) At the moment, all devices are treated as either cylinders or spheres. Perhaps surprisingly, with the appropriate selection of a drag coefficient, this approximation provides sufficient accuracy for most oceanographic instruments. It does not, however, accommodate very complex devices that may hinge, flex, or change shape when submerged or under tension. Nor is cable motion and strumming considered in this model, which may be an issue for devices with more complex shapes. But even for such devices, a reasonable approximation to the effective drag and shape of the device can be approximated using appropriate orientation and adjustments to the drag coefficient.

Three dimensions are required to define the type and shape to the device, and the effective surface area over which the fluid drag will 'work'. The first dimension is the device's vertical height (these dimensions are given in cm). For a vertical mooring, this is the amount of length added to the mooring height by the inclusion of this device in the mooring. The second dimension is for cylinders, and specifies the diameter (width) of the cylinder. If the device is a sphere (or is better approximated by a sphere), then set the second dimension to zero (0). The third dimension is for spheres, and specifies the diameter (D=2×radius) of the sphere. For cylinders, set the third dimension to zero (0). For cylinder devices, the 'un-tilted' surface area is simply the height multiplied by the diameter. The effective surface area for drag calculations will take into account the tilting of the device when the 'solution' is sought. For spheres, the surface area is $\pi\times(D/2)^2=\pi\times r^2$, and does not change with tilting. The setting of a devices effective dimensions, not necessarily the true dimensions, for drag calculations may involve detailed knowledge of how the device will 'hang', what the effective drag coefficient will be, and the devices 'preferred' orientation in a flow. If the device is streamlined and will orient itself in a flow, then the dimensions should be set to represent the effective surface area looking head-on to the object down the direction of the flow. For devices that can orient themselves in the flow, the mooring should include swivels, preferably sein bearing style which can support approximately one ton (2000 lb). The combination of a sphere (set the third dimension to the effective diameter for the exposed surface area) and the appropriate chose of drag coefficient can represent most objects, even very complex ‘caged’ instruments which may bear no resemblance to a true sphere. Hydrodynamically, all we need to do is calculate the drag forces. Imagine holding a rope attached to some device, with ones eyes closed. There is tension, and we really don’t care what shape the device is that is providing that tension. Following Galileo, a similar analogy is to try and determine an objects material and shape, given only it’s weight. Two objects can provide identical drag forces, even though they may look and be quite different in size and shape. However, complex instruments may provide torque, twist a mooring, and have hydrodynamic lift. None of these characteristics are considered here.

All device dimensions must be entered in centimeters [cm] and within the range 0–9999 cm (99.99 m).

2.2.3.8. Drag Coefficient Fig. 24

There is much literature on the effective fluid drag on objects (i.e. Schlichting, 1968). However, apart from spheres, with which drag and fluid viscosity are effectively defined, there are few formulae to calculate a direct fluid drag coefficient according to a simple set of body dimensions. Most fluid drag data is empirical and obtained by direct measurement of different objects and orientations in flows of varying speed. Additional factors such as surface roughness and any flanges also play critical roles in determining the effective fluid drag and the resulting forces acting on submerged objects. For our purposes, it will be assumed that the Reynolds Number (Ud/ν) of the flow past the object is relatively large, and verging on either the transition from laminar to turbulent flow (Reynolds Number>100), or turbulent flow (i.e. Reynolds Number>=1000). Streamlined objects can have relatively low

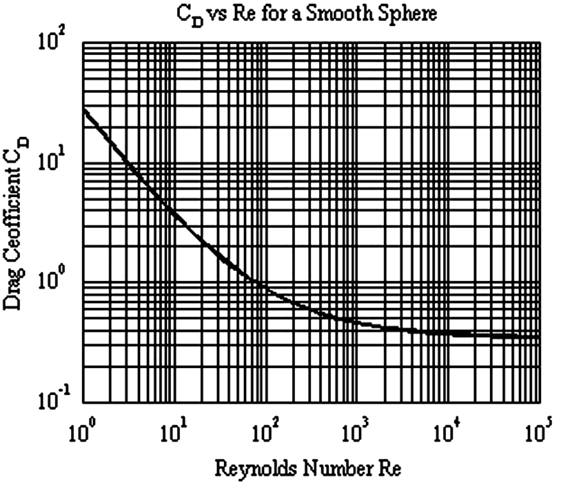


Fig. 24.

drag coefficients (0.1), while blunt objects that introduce considerable wake may have a drag coefficient as high as 3–4.

The user can enter the known drag coefficient, with a range limited between 0 and 9.99. A typical drag coefficient for a ‘painted’ large (100 cm diameter) sphere is 0.65, while a small sphere (20 cm) may have a drag coefficient as high as 1.0. A cylinder will have a drag coefficient in the range 1.0–1.3, with larger cylinders have slightly lower drag than small. If your device has specific surface roughness or shape designed to reduce the net drag, then these approximate drag coefficients should be reduced slightly.

For extremely accurate simulations it will be necessary to have accurate device information and/or data. The data may be of the form of an actual drag (force) measurement on an object in a flow, or pressure/position data from a previous mooring deployment. For example, if you have the capability to do a test deployment with a device, then place the device on a simple mooring in a current stream similar to that which might be experienced in the final deployment scenario. Pressure/position sensors will need to be mounted near the top and bottom of the mooring, or at least immediately above the device for which a drag coefficient is desired. The test mooring should be as simple as possible (i.e. a float, wire, pressure gauge, the device, wire, acoustic release and anchor). Record the pressure record at the device for a variety of flow conditions (i.e. weak and strong flows). Ideally, the flow/velocity profile should be measured, with perhaps an Acoustic Doppler Current Profiler. With MD&D, design a similar test mooring and simulate the exact current conditions from the test deployment using the measured currents. By adjusting the drag coefficient for the device, one should be able to ‘match’ the observed pressure records to within a few percent. Using simple spheres and the ‘text’ book drag coefficients, I have data and simulations that are within 1%.

2.2.3.9. Material In order to predict accurate mooring positions, it is necessary to consider the stretching of mooring components while under tension. Elongation is determined as a percentage increase in a components height when under tension. For most mooring instruments (e.g. current meters), the net increase in mooring height is negligible because the component takes up a relatively small fraction of the mooring height. However, for wire and rope, this is not the case. In particular, nylon is often used because it stretches without significant lose of tensile strength, and therefore provides a source of elasticity in keeping the mooring wire taut. The present set of materials available within MN&D includes: steel, aluminum, nylon, Dacron, polypropylene, polyethylene and Kevlar.

The percentage of elongation is determined according to the material’s Young’s Modulus of Elasticity. Once under tension, the ‘stretched’ length of a wire/rope segment L_i is calculated according to,

$$L_i=H_i\left(1+\frac{T_i}{\pi R_i^2 M_i}\right) \tag{1}$$

where H_i is the unstretched height of the element or wire segment, T_i is the tension in Newtons on the element, R_i is the radius of the element, and M_i is the Young’s modulus of elasticity for the material. Specifically, the fractional increase is proportional to the tension and inversely proportional to the cross sectional area.

2.2.3.10. Add/Delete/Modify Once the desired element has been selected, and appropriate information has been entered or edited in the displayed fields, then the desired action is actually executed by clicking the appropriately labeled button in the lower left of the window. The label and action are set by the pull down list near the top of the window. This action actually only updates the data presently loaded in memory, and the actual database file is not updated until you click the *Save* button.

2.2.3.11. Save Once the mooring component database information has been updated and checked by viewing and expecting the new/modified elements, then the user should save the database to file. This action will bring up a system save window. The user will be required to select an existing file (default database filename is *mdcodes.mat*), or enter a new filename. It is always a good idea to save or rename the old database file before you overwrite it. If for some reason the numbers didn't get entered properly, or the database was corrupted during the edits, then it will be an easy operation to recover the original (and working) database, and re-enter the edits.

2.2.4. Main Menu: Make/Load/Save a Movie: time dependant solutions

Fig. 25

When time dependent current data is available, one can *Make a Movie* or a *Time Dependant* set of solutions of the mooring component positions. This may be done purely for visualization or one may wish to compile a detailed time history of the vertical position of a set of sensors so that mooring motion can actually be corrected for in the data. In order to make a time series of mooring shapes it is necessary to have a time series of current profiles. Ideally, such a time series will represent the currents at the mooring location, either from a local Acoustic Doppler Current Profiler (ADCP) mooring, ship board ADCP, current meters on the mooring, or even from a tidal or hydrodynamic model. The accuracy of the simulation (mooring shape) will only be as good as the current time series represents the currents acting on the mooring. Even small changes in current shear (the vertical structure of the current) can have a dramatic impact on the mooring shape. Note, that each solution is a static solution, assuming that the mooring has had time to reach a stable position. Shown here are two times series of sensor height as measured by a pressure sensor located near the top of a thermistor chain mooring deployed in Juan de Fuca Strait in July 1997 and the simulated height of the sensor modeled using MD&D. The actual mooring was forced by strong tides (+/−1.5 m/s) and experienced a tilting in excess of 15 m. An ADCP was deployed near (approximately 400 m away) the thermistor chain mooring, and a 15 min time series extracted from the ADCP data was used to simulate mooring motion using MD&D. The agreement is very good (within a few percent), especially considering that there was considerable shear and spatial variability in the velocity data. For this data, the height of all the thermistors was then corrected for mooring motion and the 'true' internal wave characteristics of the environment are being studied.

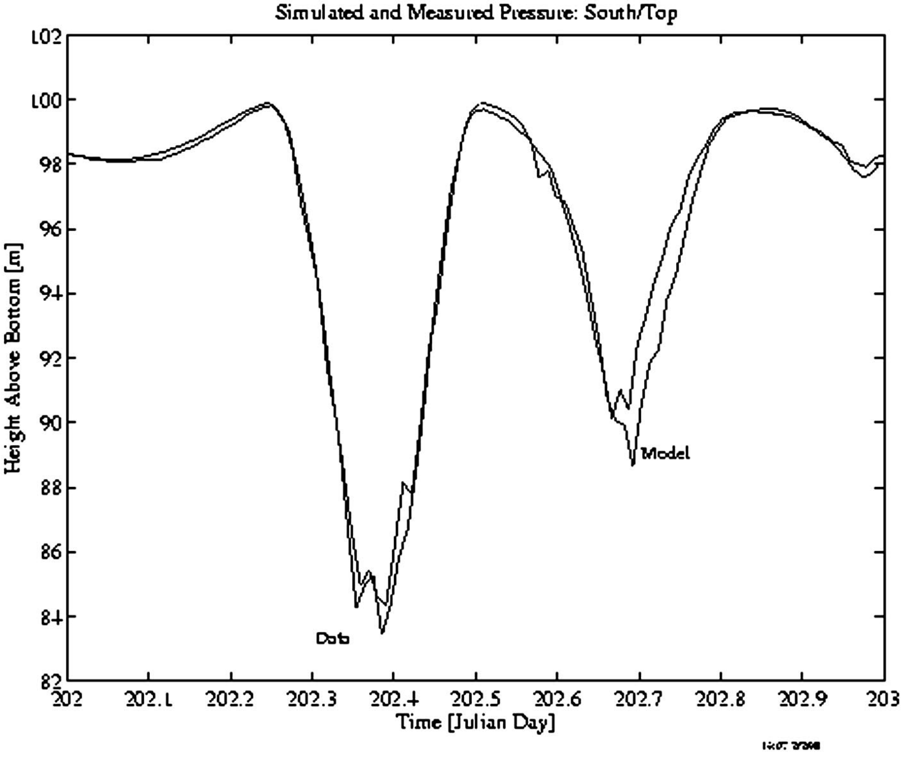


Fig. 25.

MD&D allows the user to make and save movies, or load and re-display previously made movies of moorings forced by time dependent currents. When moordesign is started, the Main Menu displays the option to '*Load a Movie*'. This button brings up a system window from which the user can click or select a mat file of a previously saved movie. Two example movie mat files (*movie001ts.mat and movie002ts.mat*) are included with the MD&D) package. Once a movie is loaded, the Main Menu displays both the '*Load a Movie*' and '*Show Movie*' options. The Show Movie button will bring up a menu that allows the user to select the number of times to cycle through the movie, the frame rate, a figure scale factor and a '*Play*' button.

To Make a movie or produce a time dependent set of mooring component positions, it is necessary to both load or design a mooring, and then load a time dependent set of current profiles. An example mat file with a simple time dependent set of current profiles in included with MD&D in the file *velt.mat*. Five matrices are required: $U(i,j)$, $V(i,j)$, $W(i,j)$, $z(i)$, time(j), where U,V,W are the north, east and vertical velocity profile matrices with $z(i)$ heights as the rows, including the surface and bottom ($z(i)$=0) and time(j) as the time base for the columns (user defined units [i.e. seconds, hours, days], although I find Julian day the most useful). In addition, one can include time dependent density profiles by specifying $\rho(i,j)$ values, otherwise ρ

is a single and constant profile. Due to the advanced nature of this option. I have not included a menu to 'edit' time dependent currents, and the user will need to generate the necessary matrices in the Matlab® Command Window, either manually, or synthetically (i.e. sine and cosine waves), or from user supplied data. When a mooring and a time dependent set of environmental profiles have been loaded they can be saved together in a mooring mat file. An example time dependent mooring mat file *moor002ts.mat* is included in the MD&D package. When the necessary time dependent data has been loaded, the Main Menu will display the option to *'Make a Time Series'*.

2.2.4.1. Make a Time Series Fig. 26

Once the necessary time dependent data has been loaded, a movie or time dependent set of mooring positions can be sought by clicking the '*Make Movie*' button from the Main Menu. This brings up menu to select the time interval to work with (shown here on the right). Since the program will calculate a 'static' mooring solution for each time step in the time dependent data, it may be desirable to select a subset of the time interval. This menu shows the full time base stored in the vector time(j). The user can edit the displayed time interval to any values within or including the end time values. The default time window is the entire time base. The program will select the 'closest' start and end time marks within the values entered. Then click the '*Generate Time Series*' button to initiate the process of finding a mooring solution for each time step within the selected time interval. It may be necessary to click the button twice in order to register the edited values. The Matlab® Command Window will then display the progress of finding the time dependent solutions, showing the percent completed and the 'solution found' dialogue for each time step (i.e. either a surface or subsurface solution with the estimated anchor tensions for that time period). Once completed, the time dependent solution data is in memory, and the user can either save this information, or proceed to *Make a Movie*. If the time dependent solutions have already been found, and the user has returned to the Main Menu, then the '*Make Movie*' option is displayed on both the 'Main' and the 'Make a Time Series' menus.

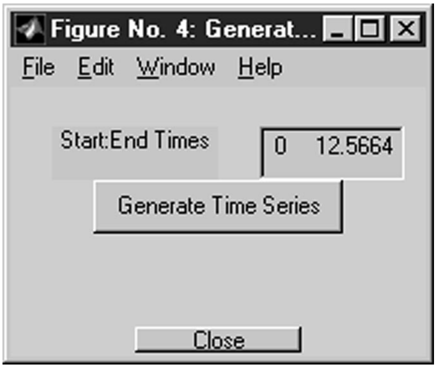


Fig. 26.

2.2.4.2. Make a Movie Fig. 27

Once the time dependent solutions of mooring positions and and tensions are in memory, the user can make an animation or movie of the time dependent mooring shape. When the ‘Make Movie’ button has been clicked, a menu is displayed to set the figure characteristics for the movie frame. Matlab® produces movies rather inefficiently. The routine compresses the 2-D screen (pixel) image into a vector of values, and stores the time dependent vectors in a matrix. There is no attempt to save just the ‘changed’ pixels (i.e. as in mpeg), so that every frame takes up an equal amount of reducing the amount of memory and disk space required, MD&D gives the user an option to reduce the size of the figure by setting the ‘*Figure Scale Factor*’. One can increase the figure window size by setting the ‘*Figure Scale Factor*’ to a number greater than 1, but a maximum factor of 1.6 is assumed (full screen). In addition, the user can set the view angles (azimuth and elevation), the figure title, the time interval (which can be a sub-set of the time dependent solutions times), and the axis scale (in m, allowing a uniform view if multiple moorings are to be compared). When one or more of these editable items is changed, it may be necessary to click the window or ‘*Make a Movie*’ button more than once (allowing the program to stored the changed values). A new figure(*j*) is then displayed and the mooring solution at each time step is plotted and saved into a movie matrix. Once the entire time series has been saved into a movie matrix, the *Show Movie* option is available from the Main Menu. It is also recommended that the movie be saved in it’s own mat tile using the ‘*Save Movie*’ option from the Main Menu. Note that there is a Matlab® mex routine ‘mpgwrite.mex’ which, when compiled, will take a Matlab® movie matrix and turn it into an MPEG file.

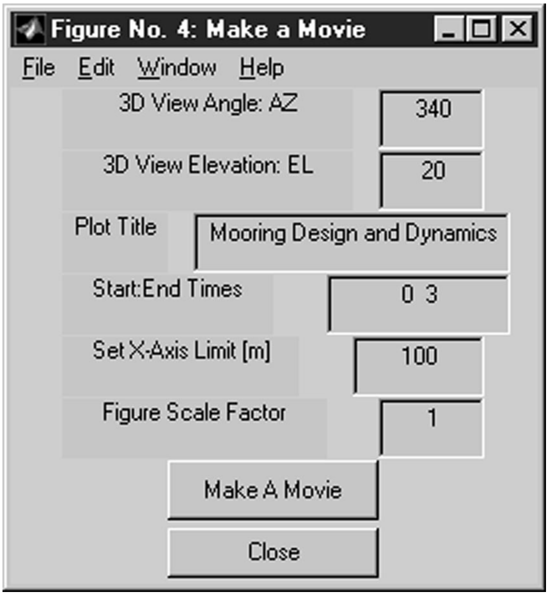


Fig. 27.

NOTE: Matlab® versions 5.0, 5.1 and 5.2 have a known bug when trying to make a movie with the computer hardware set to display 24-bit (true color) color resolution. Matlab® still (even though it now can store higher dimension matrices) stores a movie as a 2-D matrix, with one component representing time and the other a set of numbers, each representing an entire column of pixel values. To do this, the routine must compress the pixel values for an entire column into a single number. Previous versions of Matlab® used 8-bit color maps for 'movie'. Matlab® version 5.3 has fixed the problem. If you are using Matlab® 5.0–5.2, and have 24-bit color, then the movie will be gabbled on playback. You will have to physically reduce the color depth (i.e. for Windows, right click the desktop, select Properties, Settings, Color Palette) to 16-bit (<=65536 colors) prior to making the movie.

2.2.4.3. Show a Movie Figs. 28 and 29

Once a movie has been generated and/or loaded, it be displayed. At this time the user can select the number of times the movie is to be cycled through. It may appear that the movie is always played at least twice. This is because Matlab® loads the frames first, and then plays the movie the desired number of times, at the selected fps (frames per second). Versions of Matlab® prior to 5.3 may not play the exact fps, but this does provide relative speed control. In addition, the actual frame rate

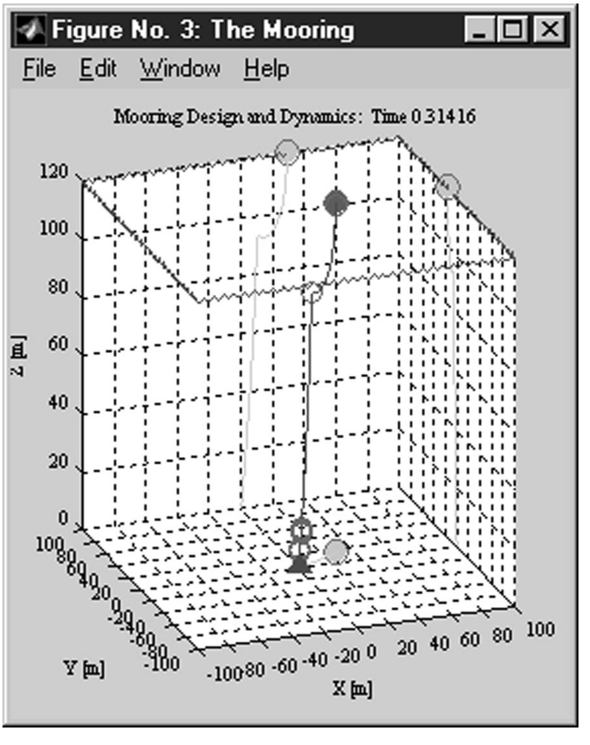


Fig. 28.

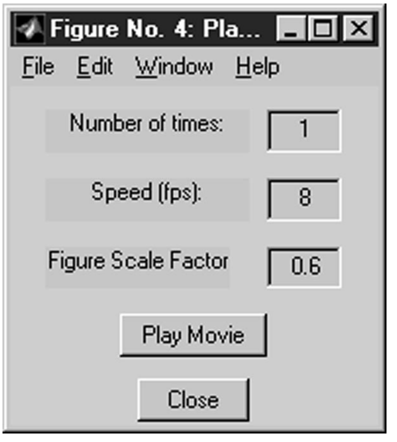


Fig. 29.

realized may depend on the memory and speed of the computer used to display the movie. The '*Figure Scale Factor*' is also displayed, although there should be no reason to change this value at show time, as it was set when the movie matrix was created. Re-setting the '*Figure Scale Factor*' here will set the figure window size, but not the size of the axes stored in the movie matrix. Note that the projection of the mooring wire/rope is plotted on all three planes. This allows one to see the extent of the displacement in the *X*, *Y* and *Z* directions. Clicking '*Play Movie*' will do exactly that.

2.2.4.4. Using the time dependant solution When a movie is saved, the time dependent solutions (tensions and component positions) are saved. When solving for a solution, the algorithm breaks the wire/rope components into small segments, so that many points along the mooring are solved for and the mooring shape is realistic. However, the positions of the main mooring components (i.e. sensors) are most likely of interest. The primary time dependent matrices include: *M* (the movie), Tits(i,j) the tensions between the 'segments' (components) of the mooring, *X*ts(i,j), *Y*ts(i,j) and *Z*ts(i,j) the horizontal and height positions of the mooring components relative to the anchor, iobjts(m,j) are the indices into these (i,j) matrices for the 'main' mooring components (e.g. floatation, current meters, acoustic releases, anchor, and misc, excluding fasteners, wire/chain, etc.), psits(i,j) are the ψ angles from vertical for each mooring segment, and ts(j) are the times. Note that typically iobjts(i,1)=iobjts(i,2)=iobjts(i,3)=…, since for most time dependent moorings the component position in the mooring is constant. However, it is possible that during a time dependent solution, an ill-posed surface solution arises, at which time the top part of the mooring may be removed, changing the location of the remaining devices. This is rare, and should not be an issue for most users. If a current meter is the third device on a mooring, then the time series of the first 100 vertical positions of the current meter can be plotted by typing:

```
»plot(ts(1:100),Zts(iobjts(3,l),1:100))
```

Similarly, the tensions, angles, or horizontal positions of any mooring section can be plotted or analyzed. In this way, the time history of the position for any mooring component (i.e. sensor) can be estimated. If an instrument's performance depends on it's vertical angle (i.e. a rotor current meter), then a measure of the performance is generated by the time dependent solution.

2.2.5. Main Menu: Clear All

This button simply executes the Matlab® command 'clear all', and is forced to include 'clear global', so that both local and global variables are cleared. Once all variables are cleared, the Main Menu is started, effectively reinitializing the program. This is use if mistakes are made, or if a user wishes to start afresh. Note: all changes and loaded information is lost.

2.2.6. Main Menu: Whos

This button simply executes the Matlab® command 'whos', and displays a list of the program variables in the main Matlab® command window that are presently loaded into memory, including all global variables. Since MD&D involves a tremendous amount of switching between windows and routines, many of the common variables are defined and passed between routines as 'global' variables. Such variables are not typically listed with the 'whos' command, unless one adds the global qualifier ('whos global').

2.2.7. Main Menu: Close

This button clears all variables and closes all MD&D windows and menus. NOTE: All variables and system information is lost when you 'close' the Main Menu. Also, there is no prompt or warning to inform the user of unsaved variables or mooring configurations. Save early, save often.

3. The mathematical solution

The 'model' part of MD&D (moordyn.m) solves for the positions of each mooring element using an iterative process, until the component positions converge (within 1 cm between successive iterations). This may only take three iterations for a simple sub-surface configuration. In a strongly sheared current and for surface moorings, however, as many as 100 iterations may be required. Mooring element positions are solved to within 1 cm in the vertical.

The effective water depth is set by the current profile. For subsurface moorings, it is assumed that the velocity data is sufficient to describe the currents throughout the water column, from the bottom (z=0) to a height that exceeds the vertical height of the mooring. For surface moorings, the top (highest) velocity value defines the water depth. A density profile, and even a time dependent density profile may be entered, as the drag depends on the water density. A constant wind can be set that produces an additional 2% surface current in the direction of the wind (modify the wind direction if you want to simulate Ekman veering), which decreases linearly to a depth that increases with wind speed. The model will predict if the surface float gets ‘dragged’ under the surface by the currents.

The first iteration (solution) starts with the mooring standing vertically in the water column. Once the first estimate of the ‘tilted’ mooring has been made, new solutions are sought with the updated positions of each element in the sheared current used to re-calculate the local drag, considering ‘tilted’ elements and appropriate exposed surface area. Also, now that the wire/rope are under tension, there may be stretching. The database assumes six different rope materials may be used (i.e. steel, aluminum, nylon, Dacron, polypropylene, polyethylene, and Kevlar), for which appropriate moduli of elasticity are used. If the position of the top element (usually a float, or at least a positively buoyant instrument) moves less than 1 cm between successive iterations, then it is assumed the solution has converged and the position of the mooring has been found.

Inertia is not considered, nor is vibration or snap loading. The solutions, even for time dependent simulations, are all assumed to be (locally) ‘static’. In strongly sheared currents, where small differences in element depth may result in significant changes in the drag, or for surface float moorings, where the exact percentage of the required surface floatation keeping the mooring afloat needs to be determined, many (100) iterations may be necessary. On a Pentium 133 MHz PC, this may take tens of seconds. Once the solution has converged, the 3-dimensional mooring is plotted, and the final element positions, wire tensions, lengths and angles can be displayed or printed. Future versions may include wave and more truely dynamic forcing of mooring strings.

The final solution assumes that each mooring element has a static vector force balance (in the x, y, and z directions), and that between time dependent solutions the mooring has time to adjust. The forces acting in the vertical direction are: (1) buoyancy (mass [kg]$\times\boldsymbol{g}$ [acceleration due to gravity]) positive upwards (i.e. floatation), negative downwards (i.e. an anchor), (2) tension from above Newtons], (3) tension from below, and (4) drag from any vertical current. The model does not calculate ‘lift’ for an aerodynamic device. In each horizontal direction, the balance of forces is: (1) angled tension from above, (2) angled tension from below, and (3) drag from the horizontal velocity. Buoyancy is determined by the mass and displacement of the device and is assumed to be a constant (no compression effects and a constant sea water density). The buoyancy is entered in kg (kg, positive upwards), and converted into a force within the program. The drag is determined for each element according to the shape, the exposed surface area of the element to the appropriate velocity component, and a drag coefficient. Only cylinders and spherical shapes are assumed. More complicated shapes can accurately be approximated by either a cylinder or a sphere with an appropriate (adjusted) surface area and drag coefficient. Spheres characterize devices whose surface area is isotropic, while cylinders are anisotropic with respect to vertical and horizontal directions. Vained devices are ‘modelled’ as cylinders with appropriate (user determined) surface areas and drag coefficients.

For each element there are three equations and six unknowns: tension from above, tension from below, and the two spherical coordinate angles each tension makes from the vertical (z) axis (ψ) and the x–y plane (θ). However, the top floatation device has no tension from above and therefore, three unknowns and three equations. The tension and associated tension angles between any two elements is equal and acts in opposite directions, so that the tension from above for the lower element is equal and opposite to the tension and angles from below for the upper element. The method of solution is to estimate the lower tension and angles for the top element (floatation), and then subsequently estimate the tension and angles below each subsequent element. The resulting set of angles [$\psi(z)$ and $\theta(z)$] and element lengths determines the exact (X, Y, Z) position of each mooring element relative to the anchor. Also, once the top of the anchor is reached, one has a direct estimate of the necessary tension required to effectively 'anchor' the mooring. The program assumes that the anchor is stationary with respect to the ground, regardless of it's mass. The tension acting on the anchor can be inverted into an estimate of the required anchor weight. Safety factors for both horizontal and vertical load are used to estimate a safe, realistic anchor weight. The suggested submerged and dry anchor weights are displayed in the main Matlab® window.

Specifically, the solution is obtained as follows. First the velocity (current) and density profiles and wire/chain sections are interpolated to approximately one metre vertical resolution using linear interpolation. The drag Q in each direction acting on each mooring element is calculated according to,

$$Q_j = \frac{1}{2}\rho_w C_{Di} A_j \mathbf{U} U_j \tag{2}$$

where Q_j is the drag in [N] on element 'i' in water of density ρ_w in the direction 'j' (x, y, or z), U_j is the velocity component at the present depth of the mooring element which has a drag coefficient C_{Di} appropriate for the shape of the element, with surface area A_j perpendicular to the direction j. $\mathbf{U}$ is the total vector magnitude of the velocity,

$$\mathbf{U} = \sqrt{U^2 + V^2 + W^2} \tag{3}$$

at the depth of the element. The drag in all three directions [j=1(x), 2(y) and 3(z)] is estimated, including the vertical component, which in most flows is likely to be very small and negligible.

Once the drag for each mooring element and each interpolated segment of mooring wire and chain have been calculated, then the tension and the vertical angles necessary to hold that element in place (in the current) can be estimated. The three [x,y,z] component equations to be solved at each element are:

$$\begin{aligned} Q_{xi} + T_i \cos\theta_i \sin\psi_i &= T_{i+1} \cos\theta_{i+1} \sin\psi_{i+1} \\ Q_{yi} + T_i \sin\theta_i \sin\psi_i &= T_{i+1} \sin\theta_{i+1} \sin\psi_{i+1} \\ B_i \boldsymbol{g} + Q_{zi} + T_i \cos\psi_i &= T_{i+1} \cos\psi_{i+1} \end{aligned} \tag{4}$$

where T_i is the magnitude of the wire tension from above, making spherical angles

ψ_j and θ_i from the vertical and in the x and y plane, respectively, B_i is the buoyancy of the present element, $\boldsymbol{g}$ is the acceleration due to gravity (=9.81 ms^{-2}), and Q_{xi}, Q_{yi} and Q_{zi} are the respective drag forces. The tension below this element is T_{i+1}, with spherical coordinate angles ψ_{i+1} and θ_{i+1}. Thus each element act dynamically as a 'hinge' in the mooring, although it may be 'rigid' in reality. Fig. 30

The diagram shows the orientation of the tension vectors, the angles, and 'hinge' characteristics for an element E_i suspended in the middle of a mooring. Each device and each interpolated segment of wire or chain is considered an element. In this way, the mooring is flexible and can adjust to any necessary catenary or spiral shape according to the sheared current profile and associated drag on each mooring element. The convention of X=East, Y=North and Z=Up is used, with associated current components U=Eastward, V=Northward and W=Upward.

Once all of the tensions and angles have been calculated, the position of each element relative to the anchor can be determined using the length of each element L_i and summing from bottom to top, namely:

$$\begin{aligned} X_i &= X_{i+1} + L_i \cos\theta_i \sin\psi_i \\ Y_i &= Y_{i+1} + L_i \sin\theta_i \sin\psi_i \\ Z_i &= Z_{i+1} + L_i \cos\psi_i \end{aligned} \tag{5}$$

When displayed, the position of each major mooring device is listed, while the tensions and appropriate angles at the top and bottom of each mooring wire/chain length are listed. The tilt and position of each mooring element is stored and can be saved or retrieved within the main Matlab® command window.

The tilt of each element is taken into account when estimating the drag and surface area (2). In particular, the drag on a spheres require no direct modification except

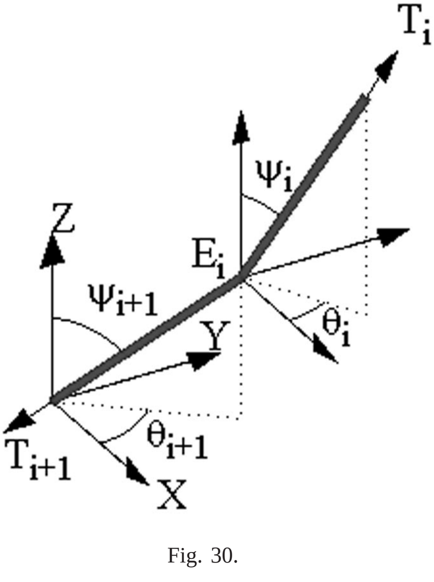


Fig. 30.

that the actual velocity acting on it corresponds to the velocity at the depth of the 'tilted' mooring. For cylinder elements, once the mooring is tilting over, several modifications occur. First, the exposed area in the horizontal and vertical directions change. Also, the drag is broken into tangential and normal components for each current direction acting on the element. This holds for wire/rope/chain as well (which are treated as cylinder segments), with tilted wire having both a reduced area and drag coefficient to a horizontal current, but increased exposure and drag in the vertical.

4. Examples

There are three primary mooring examples included with the MD&D package [Example 1 (MOOR001.MAT), Example 2 (MOOR002.MAT), and Example 3 (MOOR003.MAT)], that can be loaded and evaluated to see the strengths and features of MD&D. MOOR002.MAT and MOOR003.MAT are similar, differing only in materials and water depth (130 and 120 m respectively). Additionally, two mooring files (MOOR001TS.MAT and MOOR002TS.MAT) have been saved with time dependent current vectors, so that movies or time dependent solutions can be sought and movies generated. Finally, I have included two examples, one sub-surface and another a surface mooring, directly entered from Berteaux's (Cable Dynamics and Mooring Systems) software analysis package so that solutions obtained by MD&D can be compared against CDMS's SFMOOR.EXE (Surface Mooring) and SSMOOR.EXE (Sub-Surface Mooring).

4.1. Example one

Fig. 31

MOOR001.MAT is a simple, sub-surface, Aanderaa current meter mooring. It consists of I6 total elements, including a 37 inch ORE (Ocean Research Equipment Inc.) buoy, 80 m of 3/8 inch wire rope, a triple set of 16 inch Viny floats, an Aanderaa RCM-7 current meter (at a height of 12.3 m off the bottom), 5 m of 3/8 inch wire rope, an EG&G S242 acoustic release, 5 m of 1 inch stud-link chain, a double railway wheel anchor, and miscellaneous shackles (fasteners) and a swivel. Due to the crowding of labels, the fasteners and joiners are not listed when a mooring is plotted (as in the figure to the right), but are listed when the mooring elements are displayed in the command window. The initial (no current) height of the buoy (mooring) above the bottom is 95 m. This can be displayed by requesting *Display Mooring Elements* from the Main Menu prior to requesting a solution. The displayed information includes a list of the mooring element number (from top to bottom), and mooring element names, their vertical 'length', their buoyancy (kg), and their height above the bottom. Not displayed are the horizontal (X and Y) displacements or wire tensions and angles, since no formal calculations have been performed yet. Fig. 32

When MOOR001.MAT is loaded, a preset current profile (environmental condition) is loaded, specifying a water column 120 m deep, with surface current

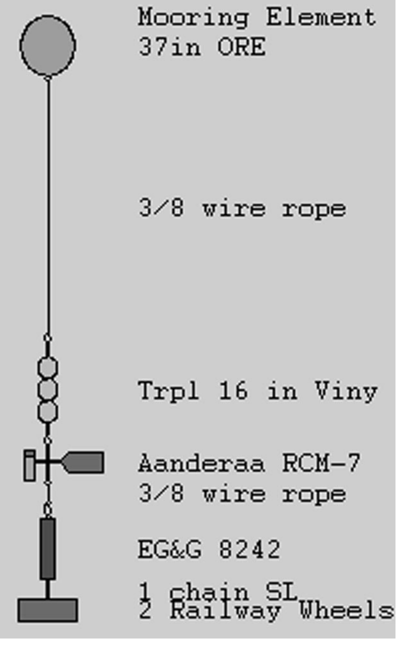


Fig. 31.

of 2 ms^{-1}. When evaluated, this strong current causes the mooring to lay over considerably. Shown above is the plot of the mooring forced with a single component current of 2 ms^{-1}. The major mooring components (i.e. floats, current meters, acoustic releases,… are plotted as special symbols on the mooring wire. Shown below is the information displayed in the command window subsequent to the evaluation and after requesting the updated display.

As part of the 'solution', information with regard to the tensions and recommended anchor mass is displayed. Total tension on the anchor, as well as the vertical and horizontal components of tension are displayed. The height of the buoy is now 88.99 m, with a horizontal displacement in the *X* direction (associated with a *U* [eastward] current) or 31.4 m. The 37 inch ORE buoy provides a buoyant force equivalent to 300 kg, but due to the drag on the buoy, the tension in the wire just below the buoy is 305.9 kg. Since the 3/S inch wire has negative buoyancy (sinks), at the bottom of the 80 m length of wire, the tension is reduced to 293.5 kg. The angle from vertical for the first section of wire changes from 11.5° just below the buoy to 23.4° just above the triple Viny floats. The Viny floats are now at a height of 12.06 m, down from the no-current case of 13.9 m. The height of the Aanderaa current meter is 11.0 m and the acoustic release is at 5.31 m above the bottom. The inclusion or mid-mooring flotation increases the tension for elements below the Viny floats. The 1 inch chain is heavy (buoyancy of -13 kg/m) and significantly reduces the tension at the anchor (242.6 kg).

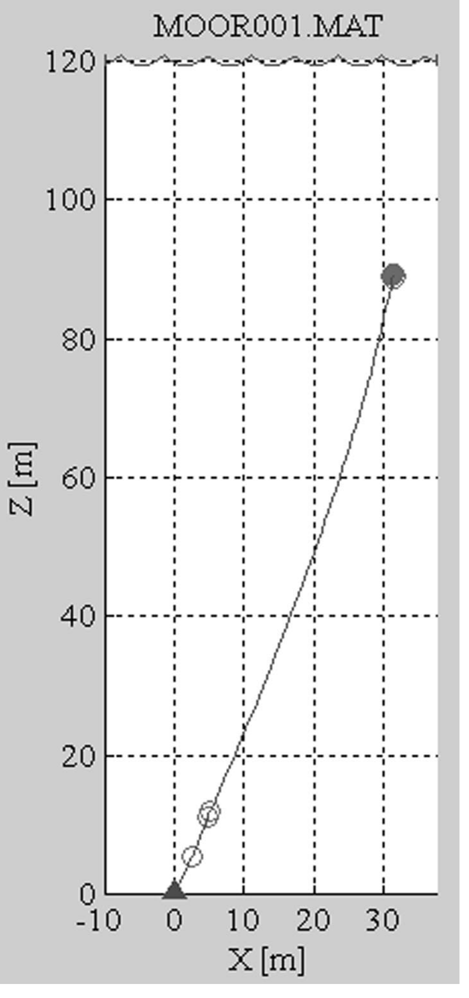


Fig. 32.

Below is the solution for moor001.mat as displayed in the Matlab® command window (Table 1).

4.2. Example two

Fig. 33

MOOR002.MAT (shown on the right) is another simple mooring, now configured to represent an S-shaped surface mooring. It consists of 19 components, with a single Aanderaa current meter near the bottom, and three sets of floatation separated by 3/8 inch wire rope. The mooring height (without currents) is 136.63 m. The water depth is set in the prescribed current profile to 130 m. Example 3 is a similar moor-

Table 1

This is sub-surface solution
This Total Tension on Anchor [kg]=242
Vertical load [kg]=211 Horizontal load [kg]=118
Safe wet anchor mass=613 [kg]=1349 [lb]
Safe dry steel anchor mass=704 [kg]=1550 [lb]
Safe dry concrete anchor mass=943 [kg]=2075 [lb]

#	Mooring Element	Length [m]	Buoy [kg]	Height [m] (middle)	dX [m]	dY [m]	Tension [kg]		Angle [deg]	
							Top	Bottom	Top	Bottom
01	37in ORE	0.94	300.00	88.99	31.4	0.0				
02	1/2 shakle	0.08	−0.30							
03	2/8 wire rope	80.03	−0.33				305.9	293.4	11.5	23.5
04	1/2 shac+2/8 shac	0.12	−0.42							
05	Trpl 16 in Viny	1.50	56.00	12.06	5.2	0.0				
06	1/2 shac+3/8shac	0.12	−0.42							
07	Aanderaa RCM-7	0.55	−18.30	11.00	4.7	0.0				
08	1/2 shackle	0.08	−0.30							
09	3/8 wire rope	5.00	−0.33				328.9	327.6	21.8	22.0
10	1/2 shackle	0.08	−0.30							
11	1/2 swivel	0.14	−0.65							
12	1/2 shackle	0.08	−0.30							
13	EC&G 8242	0.94	−28.00	5.31	2.4	0.0				
14	5/8 shackle	0.07	−0.65							
15	1 chain SL	5.00	−13.00				300.2	242.6	24.3	29.2
16	2 Railway Wheels	0.35	915.00	0.35	0.0	0.0		242.6	29.2	

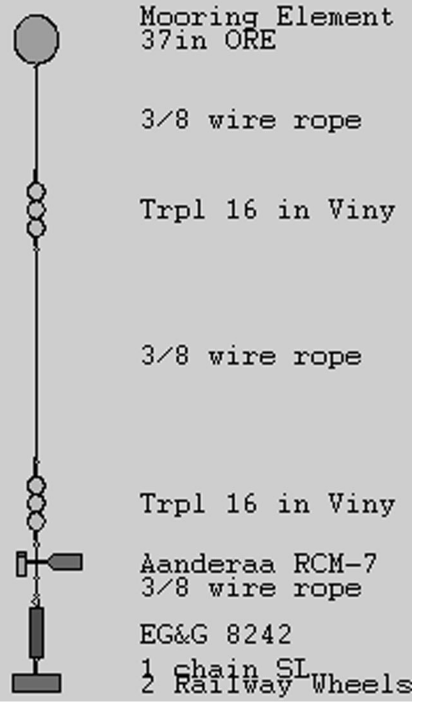


Fig. 33.

ing, but the upper section of 3/8 wire has been replaced with polypropylene rope, and the water depth has been reduced to 120 m. The ‘S’ shape is derived from the fact that during weak current conditions, the upper ‘wire’ will hang down, with the lower portion of the mooring being supported by the second set of floats, and the uppermost floatation device will then only support the weight of the top section of wire.

When a solution is sought for moor002.mat, since the height of the initial mooring exceeds the water depth, the command window indicates the program knows it may be searching for a ‘surface’ solution (see displayed solution below). The default current profile in moor002.mat includes both U and V, with peak current speeds at the surface of 0.5 and 0.45 m/s, respectively. In searching for a converged ‘surface’ solution, the algorithm must determine the exact amount of buoyancy required to support the mooring under the tensions introduced by the submerged weight of the mooring components and the drag on the submerged components. By definition, a ‘surface’ solution will not ‘use’ all of the buoyancy of the top floatation device, leaving a portion of the floatation above water. This reduces both the effective (used) buoyancy of the top floatation device, and the drag of the float, proportional to the portion in the water. Consequently, a ‘surface’ solution may take many more iterations to converge. For the case of moor002.mat, 28 iterations are needed before a converged surface solution is reached (a dot is displayed for each iteration). Fig. 34

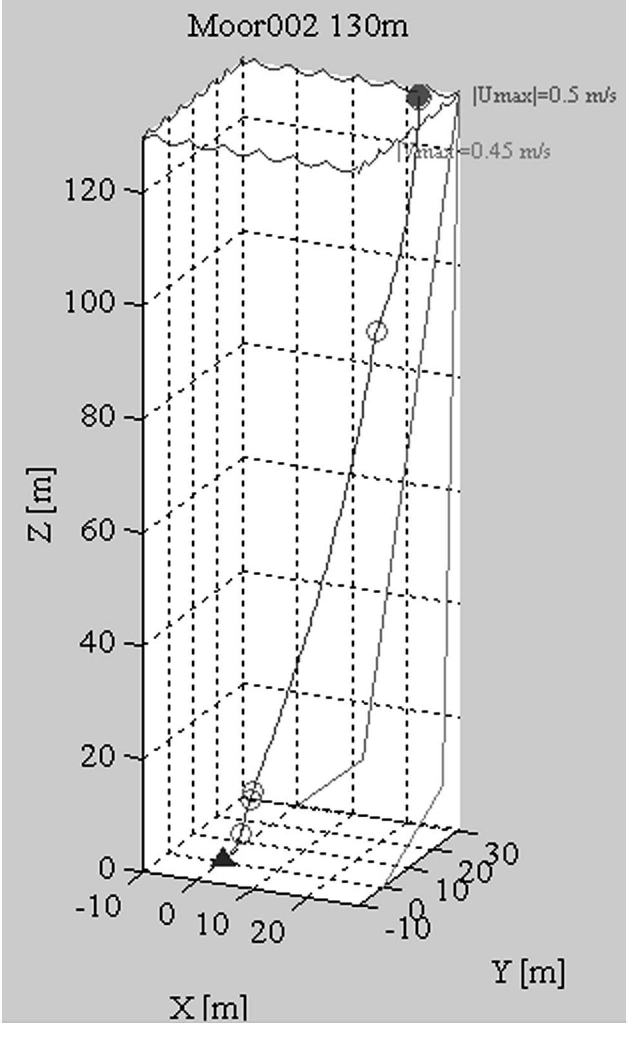


Fig. 34.

Shown here is the plot of the solution for moor002.mat. The normalized current profiles are plotted, normalized in such a way as to give full scale to the maximum speed for each component (*U* and *V*), with this maximum speed plotted at the top of the velocity profile. We can see the lifting of the mooring by the upper two floatation devices and the displacement of the mooring in both the *X* and *Y* directions. Below is the text display of the solution, showing the fact that it is a surface solution, using only 14% of the surface float to support the top section of wire.

Two very important 'features' of MD&D can be demonstrated with the mooring stored in MOOR002.MAT. First, if the current profiles are modified such that the depth of the water [height of the first current estimate $z(1)$] is reduced to 95 m, and a solution is then requested, we find that the second set of floats is now on the surface, and the uppermost floatation and wire will nearly hang downstream of this second set of floats and provide no vertical tension, only horizontal drag. This type of solution is extremely tricky to get to converge, and so the upper portions of the mooring (above the second set of floats), where there are no instruments, is ‘removed’ in order to find a solution. A message stating that several components of the mooring have been removed is displayed in the command window, and the remaining portion of the mooring is then used to find a solution. This limitation means that an ‘S-shaped’ mooring where the second set of floatation device(s) can fully support the mooring as a surface solution can **NOT** be evaluated (with out removing the ‘S’ portion of the string). Another ‘feature’ can be tested by taking the original MOOR002.MAT mooring and increasing the upper most (surface) current speed. If one sets $U(1)$ to 1.5 m/s at $z(1)$=130 (using *Set/Load Environmental Conditions*), then while the solution is sought, the model will find that 100% of the uppermost float is required to support the mooring, and the solution becomes a sub-surface solution. Note for this modified example, the large double railway wheel anchor is only just sufficient. When such a mooring is forced by time varying currents (i.e. MOOR002TS.mat), one can determine when a surface mooring will become a sub-surface mooring. This is particularly important as the original anchor mass maybe sufficient for a surface solution, but inadequate for a sub-surface solution.

4.2.1. Solution for MOOR002.MAT

Table 2

4.3. Example three

Fig. 35

The mooring example found in tile MOOR003.MAT is virtually identical to that of MOOR002.MAT, except that the top section of 3/8 inch steel wire has been replaced with 40 m of 3/4 inch Polypropylene, and the water depth (current profiles) has been reduced to 120 m. Since Polypropylene is positively buoyant (floats), the ‘S’ characteristics of the mooring change somewhat. For weak current conditions and water depths shallower than the full mooring height, a portion of the Polypropylene rope will lie on the surface, with the surface float streaming off down current of the mooring (see solution plot to the left). The top float is only supporting itself and providing slight horizontal drag (proportional to the fraction of the float that is submerged). Since there is no wave action in this model, the top float sits passively on the surface. In rough seas, one may expect the float to ‘bob’ and have an increased (albeit periodic) net drag. If one modifies the current profile data loaded from MOOROOJ.MAT, and increases the surface current speed, then the mooring (MOOR003.MAT) will gradually stretch out and begin to use the top float for buoyancy. Alternately, one can test a time dependent solution by loading the time dependent currents found in file VELTS.MAT, and follow the steps to *Make a Movie*. The time dependent solution will have periods of slack water with a surface float and slack Polypropylene, extended surface ‘S’ solutions, and submerged solutions, as the currents go through a simple four quadrant ‘tidal’ oscillation.

Table 2

This is (starting off as) a potential surface float mooring
Searching for a converged solition.
....
This is a surface solution, using about 14% of the surface float.
Total Tension on Anchor [kg]=27
Vertical load [lg]-11 Horizontal load [kg]=25
Safe wet anchor mass=80 [kg]=177 [lb]
Safe dry steel anchor mass=92 [kg]=204 [lb]
Safe dry concrete anchor mass=124 [kg]=273 [lb]

#	Mooring Element	Length [m]	Buoy [kg]	Height [m] (middle)	dX [m]	dY [m]	Tension [kg]		Angle [deg]	
							Top	Bottom	Top	Bottom
01	37in ORE	0.94	300.00	130.34	24.5	25.1				
02	1/2 shakle	0.08	−0.30							
03	3/8 wire rope	40.00	−0.33				43.1	31.9	2.1	20.0
04	Trpl 16 in Viny	1.50	56.00	89.89	19.1	20.0				
05	1/2 shackle	0.08	−0.30							
06	3/8 wire rope	80.01	−0.33				86.8	64.1	9.2	22.9
07	1/2 shac+3/8shac	0.12	−0.42							
08	Trpl 16 in Viny	1.50	56.00	11.48	3.5	4.0				
09	1/2 shackle/3/8shac	0.12	−0.42							
10	Aandreaa RCM-7	0.55	−18.30	10.41	3.3	3.7				
11	1/2 swivel	0.08	−0.30							
12	3/8 wire rope	5.00	−0.33				99.3	97.8	15.9	16.3
13	1/2 shackle	0.08	−0.30							
14	1/2 swivel	0.14	−0.65							
15	1/2 shackle	0.08	−0.30							
16	EC&G 8242	0.94	−28.00	4.52	2.2	2.5				
17	5/8 shackle	0.07	−0.65							
18	1 chain SL	5.00	−13.00				69.8	28.0	23.5	66.8
19	2 Railway Wheels	0.35	915.00	0.35	0.0	0.0		28.0	66.8	

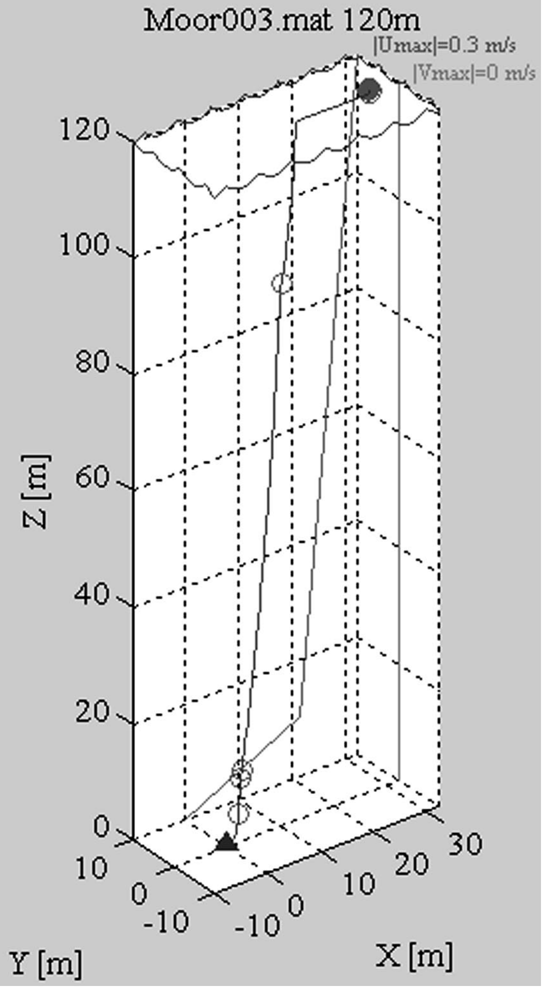


Fig. 35.

4.4. Example CSMS-1 SSMOOR

The next example (file *cdmsum1.mat*) was taken directly from the Cable Dynamics and Mooring Systems™ (CDMS) Users Manual for the program SSMoor.exe (subsurface mooring). and was used for model verification. The mooring, Fig. 36 consists of a large (1.2 m) diameter spherical floatation device located 483 m above an anchor (SSMoor.exe and SFMoor.exe do not include the anchor in their list of mooring hardware). Three 'vanilla' current meters, coded into the database as 'CDMS CM', are strung between wire and kevlar segments. A set of 10 17 inch Benthos glass floats are strung at the bottom, along with an acoustic release ('CDMS AR') and some 3/8 inch chain above the anchor. Strings of 10 paired 17 inch benthos

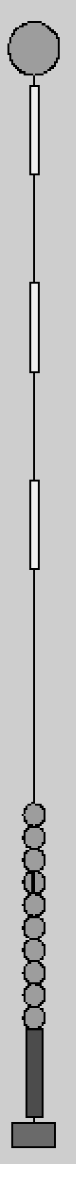


Fig. 36.

glass floats are commonly used by the mooring Group at the Woods Hole Oceanographic Institute. The example described in the CDMS Users Manual is for a single component current profile (which is all that is allowed in SSMoor.exe), with a water depth of 525 m and a surface current of 1.5 m/s. The solution is plotted Fig. 37, showing the effective height of 432 m and a horizontal displacement of 75 m. The

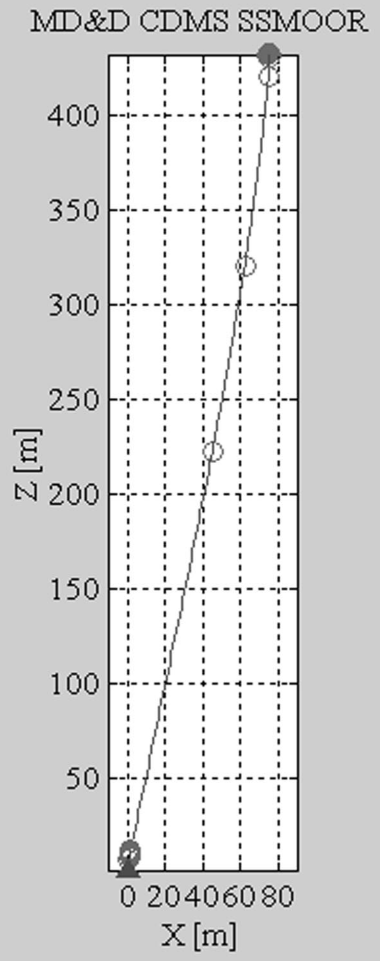


Fig. 37.

total tension at the anchor is 827 kg, with 816 kg of vertical lift and 131 kg of horizontal drag. This agrees very well with the numbers generated by SSMoor.exe. Shown below is the Matlab® command window data, displaying the current and density profiles used, and the solution, including the suggested anchor requirements and the segment by segment tensions and positions. This is followed by the solution generated using SSMoor.exe. The agreement is good (to get heights: water depth−component depth, e.g. 525−92.6=432.4), but there are subtle differences. These differences are attributed to the formulae used to calculate drag, SSMoor using U_i*U_i, while MD&D uses $|U|*U_i$, where the subscript 'i' refers the the component of the current in the direction of the drag force, with MD&D forces always being slightly higher.

4.4.1. MD&D solution for CDMS-1 (cdmsum1.mat)

Height [m]	U [m/s]	V [m/s]	W [m/s]	Density [kg/m–3]
525.00	1.50	0.00	0.00	1024.00
325.00	0.60	0.00	0.00	1025.00
0.00	0.10	0.00	0.00	1026.00

4.4.1.1. SSMoor solution for CDMS-1

SSMoor CDMS-1|

Element	Depth	X-Disp	Angle	Tension	U (cm/s)	Name
1	92.6	71.0	2.93	0	108.3	BUOY
2	93.8	71.0	3.02	682.9	107.8	3/16 WR
6	101.8	70.5	3.38	681.9	104.2	3/16 WR
7	103.8	70.4	4.57	681.8	103.3	CM#1
8	105.8	70.2	5.96	681.8	102.4	1/4 KEV
27	198.3	58.4	8.26	660.9	60.8	1/4 KEV
28	203.1	57.7	8.76	660.8	59.5	CM#2
29	205.1	57.4	8.83	641.1	59.2	1/4 KEV
48	297.1	42.3	9.79	640.2	45.1	1/4 KEV
49	302.0	41.5	10.15	640.1	44.3	CM#3
50	303.9	41.1	10.2	620.4	44.0	1/4 KEV
79	501.8	3.9	10.92	618.5	13.6	1/4 KEV
80	508.6	2.6	9.3	618.4	12.5	10 GB
81	518.5	1.2	9.41	842.4	11.0	AC REL
82	520.5	0.8	9.47	822.6	10.7	3/8 CHAIN
83	523.0	0.4	9.53	817.7	10.3	3/8 CHAIN
84	525.0	0.0	9.53	812.8	10.0	ANCHOR

The above tables show how similar the solutions are. Compare for example the tension in the wire underneath the float. Due to differences in how the hydrodynamic drag is calculated, the tension above the anchor is predicted to be slightly (2%) higher by MIX&I) than by SSMoor. When the zero current solutions are sought, the positions and tensions are identical. Fortunately, the difference in solutions with currents errs (if MD&D is in error, although I believe it is not) on the side of requesting a larger anchor mass and slightly higher in-line tensions. Similarly, the component positions are in good agreement. SSMoor.exe displays the depth of the devices, while I have chosen to display the height above the bottom. To get height above the bottom, subtract the SSMoor.exe’s component depth from the water depth (535 m).

4.4.2. Example CDMS-2 SFMOOR

Fig. 38

The last example (file *cdmsum2.mat*) is the surface float mooring example presented in the CDMS Users Manual for the Surface Mooring program SFMoor.exe. This mooring is similar to that of *CDMS-1*, but includes a long segment of nylon rope, which has good stretch and strength characteristics. The total length of the

Table 3

This is (starting off as a sub-surface mooring
Searching for a converged solution
....
This is a sub-surface solution.
Total Tension on Anchor [kg]=827
Vertical load [kg]=816 Horizontal load [kg]=131
Safe wet anchor mass=1553 [kg]=3417 [lb]
Safe dry steel anchor mass=1785 [kg]=3928 [lb]
Safe dry concrete anchor mass=2390 [kg]=5258 [lb]

#	Mooring Element	Length [m]	Buoy [kg]	Height [m] (middle)	dX [m]	dY [m]	Tension [kg]		Angle [deg]	
							Top	Bottom	Top	Bottom
01	CDMS 1.2m sphere	1.20	682.00	432.07	75.5	0.0				
02	3/16 wire rope	10.01	−0.12				682.9	682.1	2.9	3.3
03	CDMS CM	2.00	−20.00	420.47	74.9	0.0				
04	1/4 Kevlar	98.24	−0.01				664.8	667.8	5.7	8.3
05	CDMS CM	2.00	−20.00	321.03	62.4	0.0				
06	1/4 Kevlar	98.24	−0.01				649.4	650.5	9.3	10.4
07	CDMS CM	2.00	−20.00	222.28	45.2	0.0				
08	1/4 Kevlar	213.40	−0.01				631.7	631.3	11.1	11.9
09	Benthos 17in	0.51	−23.00	12.0	31.9	0.0				
10	Benthos 17in	0.51	−23.00	11.5	31.8	0.0				
11	Benthos 17in	0.51	−23.00	11.0	31.7	0.0				
12	Benthos 17in	0.51	−23.00	10.5	31.6	0.0				
13	Benthos 17in	0.51	−23.00	10.0	31.5	0.0				
14	Benthos 17in	0.51	−23.00	9.5	31.4	0.0				
15	Benthos 17in	0.51	−23.00	9.0	31.4	0.0				
16	Benthos 17in	0.51	−23.00	8.5	31.3	0.0				
17	Benthos 17in	0.51	−23.00	8.0	21.2	0.0				
18	Benthos 17in	0.51	−23.00	7.5	21.1	0.0				
19	CDMS AR	2.00	−20.00	6.2	80.9	0.0				
20	3/8 chain SL	4.80	−2.33				828.2	827.2	9.0	9.1
21	3 Railway Wheels	0.55	1350.00	0.55	0.0	0.0		827.2	9.1	

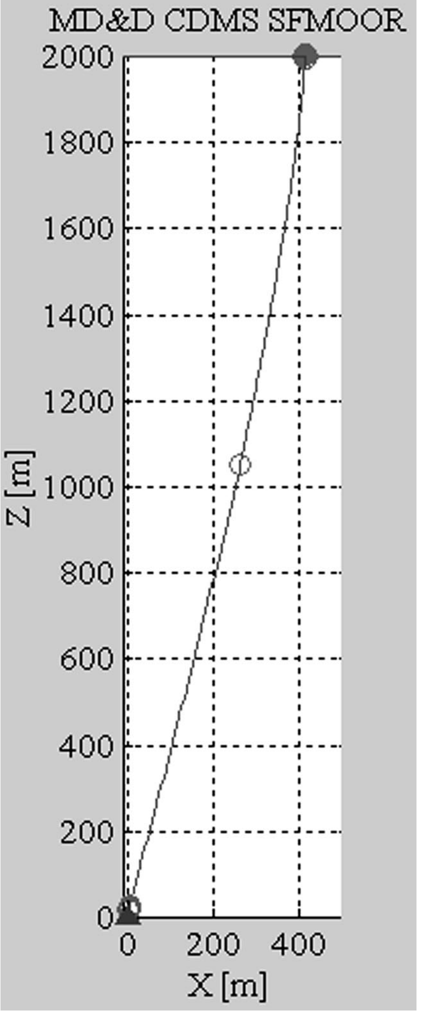


Fig. 38.

mooring components is 1950 m, and the mooring is deployed in 2000 m of water. A 3D current structure is imposed, with all *U*, *V* and *W* specified. The surface bloat is a 2 m diameter sphere, and current meters are located at the surface and at a depth of 950 m. The Nylon rope stretches under the tension, so that 52% of the float is used to support the surface mooring. For demonstration purposes, the mooring configured in the MD&D file *cdmsum2.mat*, has only a single railway wheel as the anchor, clearly insufficient for a large, current forced surface mooring. When the solution is sought, the tension on the anchor is estimated, and a warning is posted to indicate that the selected anchor is most likely insufficient for this mooring. A six railway wheel anchor would work (Table 4).

Table 4

This is (starting off as) a sub-surface mooring
Searching for a converged solution.
....
This is a surface solution, using about 52% of the surface float.
Total Tension on Anchor [kg]=1442
Vertical load [kg]=1417 Horizontal load [kg]=263
Safe wet anchor mass=2784 [kg]=6126 [lb]
Safe dry steek anchor mass=3201 [kg]=7042 [kg]
Safe dry concrete anchor mass=4284 [kg]=9426 [lb]
||*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|
||*|* Warning. Anchor is likely TOO light! *|*|*|*
||*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*|*

Height [m]	U [m/s]	V [m/s]	W [m/s]	Density [kg/m–3]
2000.00	1.00	0.20	0.00	1024.00
1900.00	0.80	0.10	0.10	1024.15
1800.00	0.50	0.05	0.10	1024.30
1000.00	0.25	0.05	0.15	1025.25
0.00	0.15	0.00	0.00	1026.00

A comparison of the wires tensions and component positions as predicted by MD&D and SFMoor.exe are shown below.

4.4.2.1. MD&D solution for CDMS-2 (cdmsum2.mat) Table 5

4.4.2.2. SFMoor Solution for CDMS-2 Table 5

Element	−Y	X	Depth	Angle	Tension	Name
0	−28.9	458.1	0.95	0.0	1262.2	″BUOY″
1	−28.9	458.1	3.57	1.7	1253.5	″1/2 CHAIN″
2	−28.9	458.0	6.19	2.0	1244.8	″1/2 CHAIN″
3	−28.9	457.9	8.19	2.3	1225.1	″CM#1″
4	−28.9	457.0	30.79	3.5	1219.1	″3/8WR″
23	−25.3	399.2	456.51	10.5	1105.6	″3/8WR″
24	−25.1	395.6	476.31	10.7	1102.0	″5/16WR″
48	−18.8	294.0	948.58	13.6	1015.0	″5/16WR″
49	−18.8	293.5	950.52	13.7	995.66	″CM#2″
50	−18.4	288.0	973.19	14.1	994.65	″3/4NYL″
94	−.6	10.1	1960.43	17.0	950.19	″3/4NYL″
95	−.2	3.7	1981.45	17.1	1435.3	″22GB″
96	−.2	3.1	1983.41	11.3	1405.9	″C REL″
97	−.1	2.0	1988.88	11.5	1405.7	″1 NYL″
98	−0.06	1.0	1994.35	11.5	1405.5	″1 NYL″
99	−0.03	0.5	1996.93	11.5	1369.9	″1/2 CHAIN″
100	0.00	0.0	2000.0	11.6	1388.3	″ANCHOR″

Table 5

#	Mooring Element	Length [m]	Buoy [kg]	Height [m] (middle)	dX [m]	dY [m]	Tension [kg]		Angle [deg]	
							Top	Bottom	Top	Bottom
01	CDMS 2m shpere	2.00	2470.00	1999.95	413.4	67.8				
02	1/2 chain SL	5.00	−4.12				1285.5	1265.6	2.0	2.5
03	CDMS CM	2.00	−20.00	1992.96	413.1	67.8				
04	3/8 wire rope	450.59	−0.33				1247.7	1113.9	3.7	9.6
05	1/2 shackle	0.08	−0.30							
06	5/16 wire rope	500.76	−0.19				1113.7	1026.4	9.6	12.3
07	CDMS CM	2.00	−20.00	1052.61	262.2	42.8				
08	3/4 Nylon	1054.76	−0.03				1007.2	988.1	12.6	15.3
09	BENTHOS 17in	0.51	23.00	29.10	5.6	0.9				
10	BENTHOS 17in	0.51	23.00	28.60	5.5	0.9				
11	BENTHOS 17in	0.51	23.00	28.11	5.4	0.9				
12	BENTHOS 17in	0.51	23.00	27.62	5.3	0.8				
13	BENTHOS 17in	0.51	23.00	27.12	5.1	0.8				
14	BENTHOS 17in	0.51	23.00	26.63	5.0	0.8				
15	BENTHOS 17in	0.51	23.00	26.13	4.9	0.8				
16	BENTHOS 17in	0.51	23.00	25.64	4.8	0.8				
17	BENTHOS 17in	0.51	23.00	25.14	4.7	0.7				
18	BENTHOS 17in	0.51	23.00	24.64	4.6	0.7				
19	BENTHOS 17in	0.51	23.00	24.14	4.4	0.7				
20	BENTHOS 17in	0.51	23.00	23.65	4.3	0.7				
21	BENTHOS 17in	0.51	23.00	23.15	4.2	0.7				
22	BENTHOS 17in	0.51	23.00	22.65	4.1	0.7				
23	BENTHOS 17in	0.51	23.00	22.15	4.0	0.6				
24	BENTHOS 17in	0.51	23.00	21.65	3.9	0.6				

(continued on next page)

Table 5 (*continued*)

#	Mooring Element	Length [m]	Buoy [kg]	Height [m] (middle)	dX [m]	dY [m]	Tension [kg]		Angle [deg]	
							Top	Bottom	Top	Bottom
25	BENTHOS 17in	0.51	23.00	21.15	3.8	0.6				
26	BENTHOS 17in	0.51	23.00	20.65	3.7	0.6				
27	BENTHOS 17in	0.51	23.00	20.15	3.6	0.6				
28	BENTHOS 17in	0.51	23.00	19.65	3.5	0.6				
29	BENTHOS 17in	0.51	23.00	19.15	3.4	0.6				
30	BENTHOS 17in	0.51	23.00	18.64	3.3	0.5				
31	CDMS AR	2.00	−20.00	17.41	3.1	0.5				
32	3/4 Nylon	11.47	−0.03				1463.0	1462.7	10.4	10.4
33	1/2 shackle	0.08	−0.30							
34	1/2 chain SL	5.00	−4.12				1462.5	1442.2	10.4	10.5
35	1 Railway Wheel	0.15	454.55	0.15	0.0	0.0		1442.2	10.5	

These tables show how similar the solutions are, in both wire tension and angle, and component position. Slight differences are attributable to how MD&D correctly calculates hydrodynamic drag. When the zero current solutions are sought, the positions and tensions are identical.

5. Disclaimer

The user of this package takes full responsibility for designing and building a safe and reliable mooring that will allow safe and easy deployment, and safe and easy recovery. This set of programs is only an aide in evaluating different mooring designs and configurations forced by varying 3D currents. It does not attempt to estimate the forces and tensions during deployment or recovery, which may be significantly higher than the 'in-water/static' tensions, as components hanging out of water will have significantly more weight and 'falling' moorings will experience significant velocities and drag. The author does not provide sources for instruments or mooring components (i.e. wire), nor endorse the manufacturers specified strength and tension limits. If in doubt, add a safety factor of 1.5, or larger.

This package can be used to predict wire tensions, anchor weights, and sensor heights, potentially for backing out the actual depth/height of a mooring sensor in a current and correcting for mooring motion. My intent is to maintain this package as a free research tool. However, the potential uses are varied, including commercial applications. If you use this package and find it helpful, appropriate reference to this article or the Mooring Design and Dynamics web page is appreciated.

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