第八讲：系泊系统的设计

数学模型和算法的应用与 MATLAB 实现

周吕文

中国科学院力学研究所

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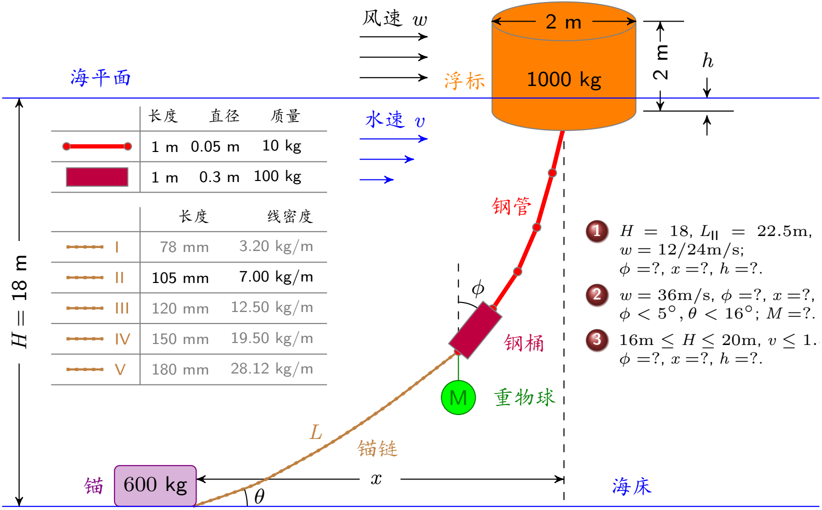
微信公众号：超级数学建模

系泊系统的设计



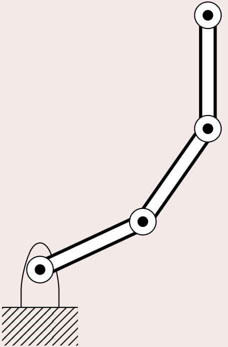
	长度	直径	质量
钢管	1 m	0.05 m	10 kg
钢桶	1 m	0.3 m	100 kg

	长度	线密度
I	78 mm	3.20 kg/m
II	105 mm	7.00 kg/m
III	120 mm	12.50 kg/m
IV	150 mm	19.50 kg/m
V	180 mm	28.12 kg/m

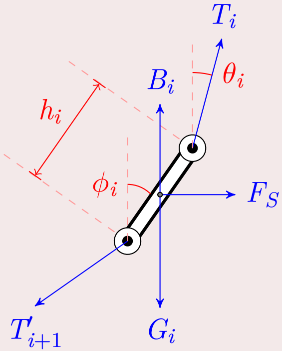
1. $H = 18$, $L_{II} = 22.5$m, $w = 12/24$m/s; $\phi = ?$, $x = ?$, $h = ?$.
2. $w = 36$m/s, $\phi = ?$, $x = ?$, $\phi < 5^\circ$, $\theta < 16^\circ$; $M = ?$.
3. 16m $\leq H \leq$ 20m, $v \leq 1.$ $\phi = ?$, $x = ?$, $h = ?$.

问题分析

简化为杆系结构

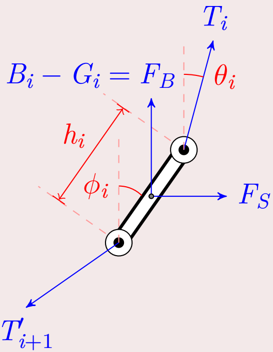


单杆的受力分析



单杆的平衡条件

单杆的受力分析



受力平衡: $F_x = 0,\ F_y = 0$

$$F_x = F_S + T_i \sin\theta_i - T_{i+1}\sin\theta_{i+1}$$

$$F_y = F_B + T_i \cos\theta_i - T_{i+1}\cos\theta_{i+1}$$

力矩平衡: $M_+ = M_-$

$$M_+ = \big(T_i\cos\theta_i + F_B/2\big) h_i \sin\phi_i$$

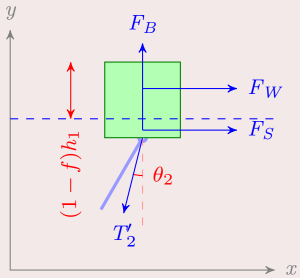
$$M_- = \big(T_i\sin\theta_i + F_S/2\big) h_i \cos\phi_i$$

递推关系: $i > 1$

$$\mathbf{T}_{i+1} = \big(F_S + T_i\sin\theta_i, F_B + T_i\cos\theta_i\big),\ \tan\phi_i = \frac{T_i\sin\theta_i + F_S/2}{T_i\cos\theta_i + F_B/2}$$

浮标的平衡条件

受力分析图



受力平衡：$F_x = 0$, $F_y = 0$

$$F_x = -T_2 \sin\theta_2 + F_W + F_D$$
$$F_y = -T_2 \cos\theta_2 + F_B$$

计算力

$$F_B = \rho_{\text{sea}}\, f\pi(d/2)^2 h\, g - mg$$

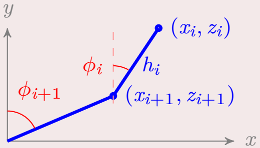
$$F_W = C_W(1-f)hdv^2, \quad F_S = C_S f h d v^2$$

递推首项：$i = 1$

$$\mathbf{T}_2 = \left(F_W + F_S, F_B\right), \quad \tan\phi_1 = \frac{f/2F_S + \left[f + (1-f)/2\right]F_W}{f/2F_B}$$

各杆位置的确定

两杆的相对位置图



相对位置递推关系

$$x_{n+1} = 0, \;\; y_{n+1} = 0$$

$$x_i = x_{i+1} + h_i \sin\theta_i$$

$$y_i = y_{i+1} + h_i \cos\theta_i$$

二分法求解浮标吃水比例 f: $f_{\min} = 0, f_{\max} = 1$

$$f = (f_{\min} + f_{\max}) \Longrightarrow \begin{cases} y_1 - (1-f)h_1 > H & f \to f_{\max} \\ y_1 - (1-f)h_1 < H & f \to f_{\min} \end{cases}$$

计算流程

初始设置 $f_{\min} = 0, f_{\max} = 1$

1. 由浮标吃水比例 $f = (f_{\min} + f_{\max})/2$ 计算浮标所受.
2. 由浮标浮力, 重力, 风力, 拉力四力平衡求得浮标对一号钢管 (第 2 节杆) 的拉力.
3. 迭代递推出出各节杆所受拉力和倾角 ϕ.
4. 根据 ϕ 将各杆长度投影到竖直方向, 求得浮标吃水线距离海床的高度 Z_w.
5. 如果 $Z_w > 18$, 则 $f_{\max} = f$; 否则 $f_{\min} = f$.
6. 如果 $f_{\max} - f_{\min} < E$, 输出结果; 否则回到 1.

主函数

moor

```
function [tilt,elev,xbuoy,f] = moor(Lc,chain,vw,vs,M,depth)
g = 9.81; rho = 1.025e3; rhoFe = 7.9e3; cdwin = 0.625;
[lc, mc, dc] = chainpara(chain); nc = round(Lc/lc);
m = [1000,   10*ones(1,4), 100, mc*ones(1,nc)];
h = [   2,      ones(1,4),   1, lc*ones(1,nc)];
d = [   2, 5e-2*ones(1,4), 0.3, dc*ones(1,nc)];
Fb = pi*(d/2).^2.*h*rho*g - m*g;
phi = zeros(1,length(h)); fmin = 0; fmax = 1;
while fmax-fmin>1e-10
    f = (fmax+fmin)/2;
    Fb(1) = rho * f*pi*(d(1)/2).^2.*h(1) * g - m(1)*g;
    Fw = cdwin * (1-f)*h(1).*d(1) * vw.^2;
    Fs = waterload(vs, h, d, phi, depth, f);
    phi = solvequileq(Fb, Fw, Fs, M, f);
    x = h.*sin(phi); z = h.*cos(phi);
    if sum(z(2:end))+h(1)*f>depth; fmax=f; else; fmin=f; end
end
x = cumsum([0 fliplr(x)]);  z = cumsum([0 fliplr(z)]);
tilt = phi(6)*180/pi;       elev = 90- phi(end)*180/pi;
xsbed = max(x(z<1e-10));    xbuoy = x(end-1);
```

锚链参数和近海风荷载

chainpara

```
function [lc, mc, dc] = chainpara(typeid)
rhoFe = 7.9e3;                           % kg/m^3
rho= [3.2 7.0 12.5 19.5 28.12];          % kg/m
lc = [ 78 105  120  150   180]*1e-3;     % m
mc = rho.*lc;                            % kg
lc = lc(typeid); mc = mc(typeid);
dc = 2*sqrt(rho(typeid)/rhoFe/pi);
```

waterload

```
function Fs = waterload(vs, h, d, phi, depth, f)
cd = 374;
z = h.*cos(phi);
zi = fliplr(cumsum(fliplr(z))) - z/2;
zi(1) = depth - f*h(1)/2;
vsi = vs./sqrt(depth)*sqrt(zi);
Fs = cd * h.*d.*cos(phi) .* vsi.^2;
Fs(1) = Fs(1)*f;
```

解平衡方程求倾斜角度

solvequileq

```
function phi = solvequileq(Fb, Fw, Fs, M, f)
g = 9.81; N = length(Fb);
rho = 1.025e3; rhoFe = 7.9e3
[theta, phi, Ft] = deal(zeros(1,N));
for i = 1:N-1
    fx = Ft(i)*sin(theta(i)) + Fs(i);
    if i==1; fx = fx + Fw; end
    fz = Fb(i) + Ft(i)*cos(theta(i));
    if i==6; fz = fz -M*g + rho*(M/rhoFe)*g; end
    Ft(i+1) = sqrt(fx^2+fz^2);
    theta(i+1) = acos(fz/Ft(i+1));
    if theta(i+1)>pi/2; theta(i+1) = pi/2; end
end
phi =atan2( Ft.*sin(theta)+Fs/2, Ft.*cos(theta)+Fb/2);
phi(phi>pi/2) = pi/2;
phi(1) = atan2( Fs(1)*f/2+Fw(1)*(f+(1-f)/2), Fb(1)*f/2 );
```

主程序

问题一

```
Lc = 22.05;chain = 2; M = 1200; depth = 18; vs = 0;
[tilt,elev,xbuoy,f] = moor(Lc, chain, 12, vs, M, depth);
[tilt,elev,xbuoy,f] = moor(Lc, chain, 24, vs, M, depth);
```

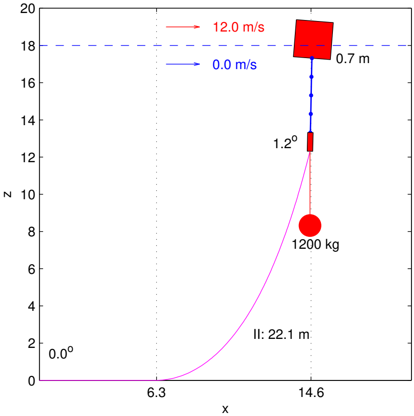
问题二

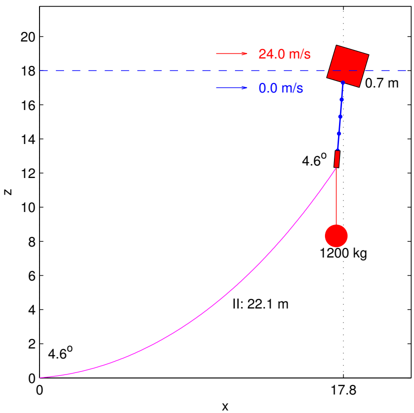
```
Mi = 1200:10:4000; tilti = []; elevi = [];
for mi = Mi
     [tilt,elev,xbuoy,f] = moor(Lc,chain,36,0,mi,depth);
     tilti = [tilti,tilt]; elevi = [elevi,elev];
end
plot(Mi, tilti,'r', Mi, elevi, 'b');
```

问题三：一个符合条件的算例

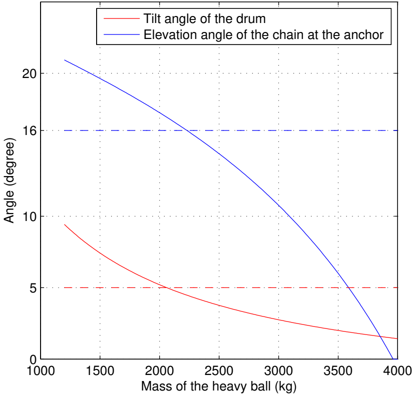
```
Lc = 20.88;chain = 5; M = 4000; depth = 20; vw = 36;vs = 1.5;
[tilt,elev,xbuoy,f] = moor(Lc,chain,vw,vs,M,depth);
```

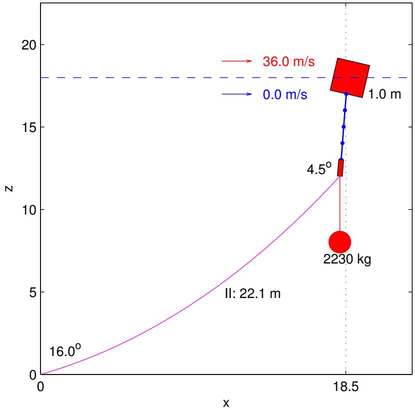
问题一


20
18
16
14
12
10
8
6
4
2
0
z
x
6.3
14.6
12.0 m/s
0.0 m/s
0.7 m
1.2°
1200 kg
ll: 22.1 m
0.0°

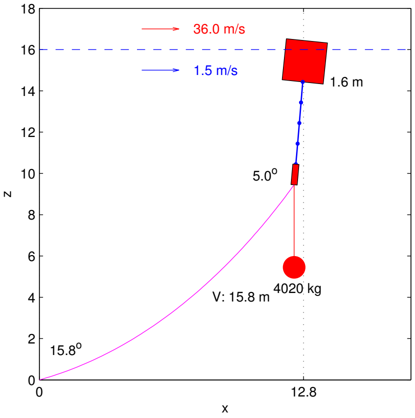

20
18
16
14
12
10
8
6
4
2
0
z
x
0
17.8
24.0 m/s
0.0 m/s
0.7 m
4.6°
1200 kg
ll: 22.1 m
4.6°

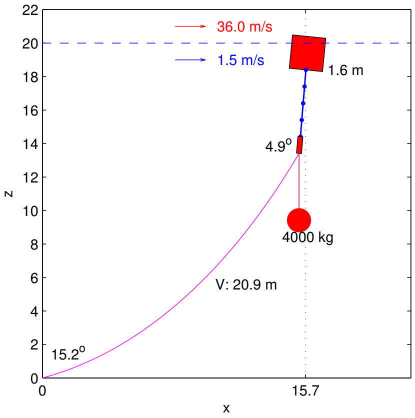
问题二


Tilt angle of the drum
Elevation angle of the chain at the anchor
Angle (degree)
Mass of the heavy ball (kg)
0
5
10
16
20
1000
1500
2000
2500
3000
3500
4000


36.0 m/s
0.0 m/s
1.0 m
4.5°
2230 kg
ll: 22.1 m
16.0°
z
x
0
5
10
15
20
0
18.5

问题三


18
16
14
12
10
8
6
4
2
0
z
0
12.8
x
36.0 m/s
1.5 m/s
1.6 m
5.0°
4020 kg
V: 15.8 m
15.8°


22
20
18
16
14
12
10
8
6
4
2
0
z
0
15.7
x
36.0 m/s
1.5 m/s
1.6 m
4.9°
4000 kg
V: 20.9 m
15.2°

评审要点

- 本问题要求学生分析浮标, 钢管, 钢桶, 重物球和锚链的受力情况, 建立计算锚链形状, 钢桶和钢管的倾斜角度, 浮标的吃水深度和游动区域的数学模型.
- 在此基础上, 确定锚链的型号, 长度和重物球的质量, 给出不同情况下锚链形状, 锚链与海床的夹角, 钢桶和钢管的倾斜角度, 浮标的吃水深度和游动区域的表达式和具体数值.
- 评阅应该以模型为主, 数值结果为辅.

评审要点

问题 1

- 要求学生对给定的锚链型号, 长度和重物球的质量, 分别计算出当海面风力为 12m/s 和 24m/s 的情况时锚链的形状, 在锚点锚链与海床的夹角, 钢桶和钢管的倾斜角度, 浮标的吃水深度和游动区域.
- 当海面风力为 12m/s 时, 有 6.2m 左右的锚链拖地, 钢桶的倾斜角度 1.2 度左右, 浮标的吃水深度 0.7m 左右, 游动区域的半径 14.7m 左右;
- 在海面风力为 24m/s 时, 锚链与海床在锚点的夹角 4.5 度左右, 钢桶的倾斜角度 4.6 度左右, 浮标的吃水深度 0.7m 左右, 游动区域的半径 17.8m 左右

评审要点

问题 2

- 对题目中给定的锚链型号，长度和重物球的质量，当海面风力为 36m/s 时，钢桶的倾斜角度，锚链在锚点与海床的夹角都不满足要求.
- 需要对重物球的质量进行调整，论文中要给出调整后重物球的质量，在这个质量下锚链与海床的夹角，钢桶的倾斜角度.
- 满足要求的重物球的质量不会小于 2160kg.

评审要点

问题 3

- 要求学生根据模型在最大风速可达 36m/s，海水最大速度可达 1.5m/s，海水深度在 16m 到 20m 之间变化的情况下给出锚链的型号，长度，重物球的质量，使得在不同情况下锚链与海床的夹角不大于 16 度，钢桶的倾斜角度不超过 5 度，且浮标的吃水深度和游动区域较小．
- 并基于该设计，给出一些典型情况下钢管的倾角，钢桶的倾角，在锚点锚链与海床的夹角，浮标的吃水深度和游动区域．

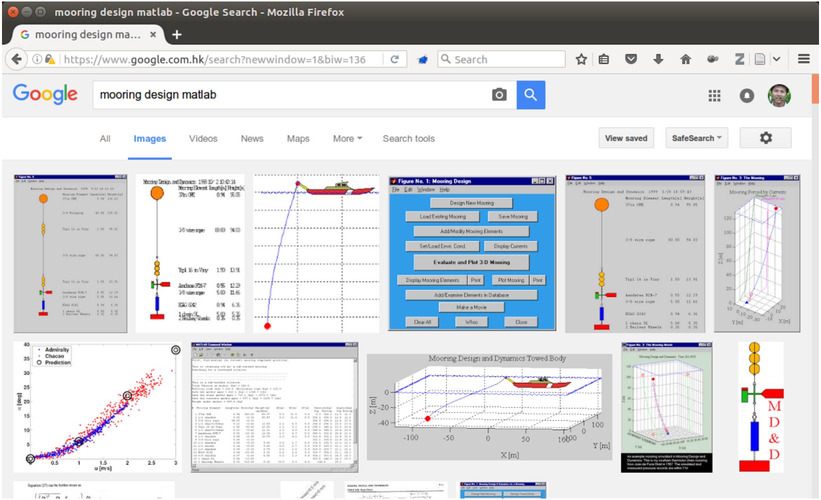
2014 年国赛 B 题：创意平板折叠桌

圆形桌面，桌腿随铰链可摊成平板．桌腿由两组木条组成，每组由一根钢筋连接，钢筋两端固定于最外侧的两根木条上，沿木条有空槽以保证可滑动．

- 给定平板 120cm×50cm×3cm，木条宽 2.5cm，钢筋固定在最外侧木条中心，折叠后桌高 53cm．描述折叠过程，给出设计加工参数．
- 对于给定桌高和桌面直径，讨论矩形板材料和折叠桌的最优（稳固，方便加工，用材最少）设计加工参数．
- 根据指定桌高度，桌面边缘线的形状大小和桌脚边缘线的大致形状，给出平板形状尺寸和最优加工参数．

- 参考解题程序：https://github.com/CUMCM/2014-B

快速检索 I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Search
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Images
Videos
News
Maps
More
Search tools
View saved
SafeSearch
Figure No. 1: Mooring Design
Design New Mooring
Load Existing Mooring
Save Mooring
Add/Modify Mooring Elements
Set/Load Envir. Cond.
Display Currents
Evaluate and Plot 3-D Mooring
Display Mooring Elements
Print
Plot Mooring
Add/Examine Elements in Database
Make a Movie
Clear All
Whos
Close
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Chacao
Prediction
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Y [m]
Z [m]
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&
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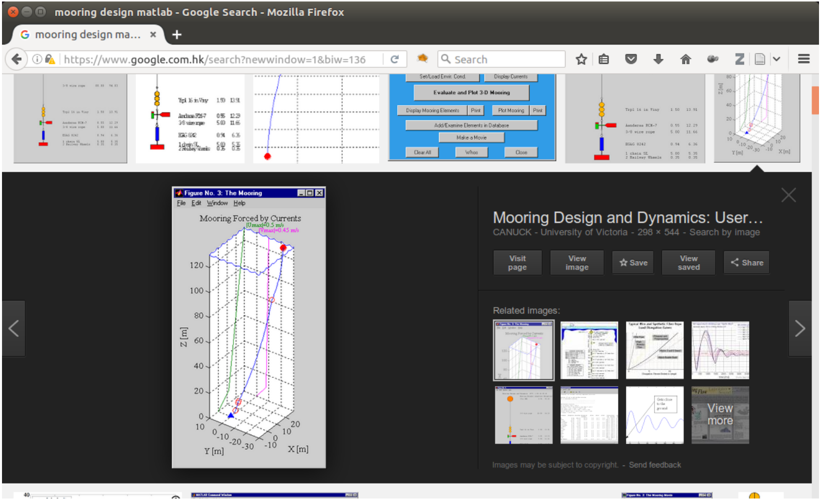
快速检索 I


mooring design matlab - Google Search - Mozilla Firefox
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https://www.google.com.hk/search?newwindow=1&biw=136
Search
Figure No. 3: The Mooring
File Edit Window Help
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Y [m]
X [m]
Mooring Design and Dynamics: User...
CANUCK - University of Victoria - 298 × 544 - Search by image
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View saved
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View more
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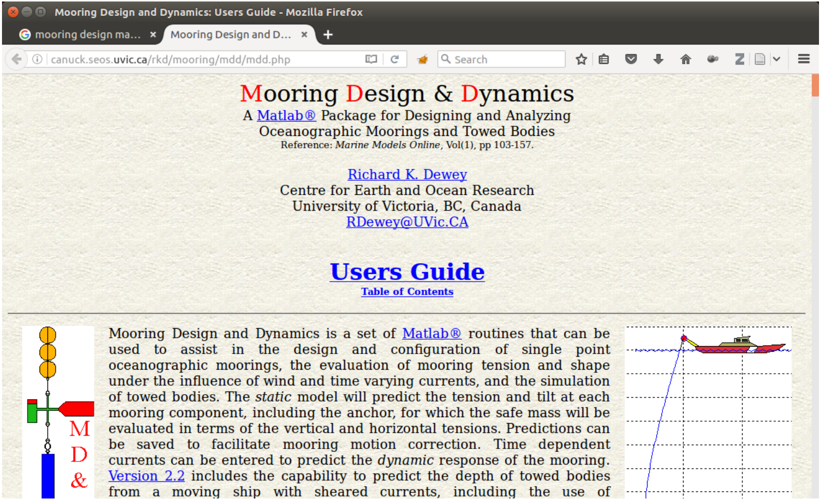

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canuck.seos.uvic.ca/rkd/mooring/mdd/mdd.php

Mooring Design & Dynamics

A Matlab® Package for Designing and Analyzing
Oceanographic Moorings and Towed Bodies
Reference: *Marine Models Online*, Vol(1), pp 103-157.

Richard K. Dewey
Centre for Earth and Ocean Research
University of Victoria, BC, Canada
RDewey@UVic.CA

Users Guide

Table of Contents

M D &

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 time varying currents, and the simulation of towed bodies. 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. Version 2.2 includes the capability to predict the depth of towed bodies from a moving ship with sheared currents, including the use of

快速检索

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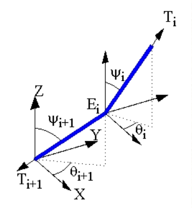
Search

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:

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

where T_i is the magnitude of the wire tension from above, making spherical angles Ψ_i and θ_i from the vertical and in the x and y plane, respectively, B_i is the buoyancy of the present element, 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 acts dynamically as a "hinge" in the mooring, although it may be "rigid" in reality.



The diagram to the right 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,

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

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.

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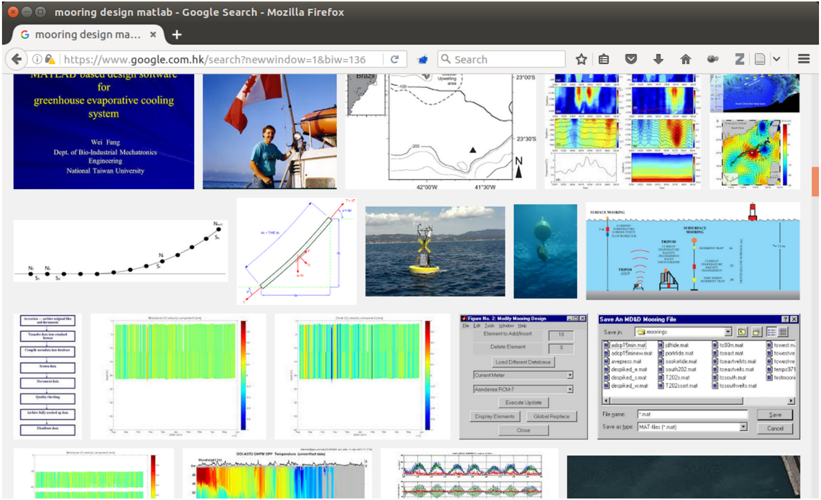
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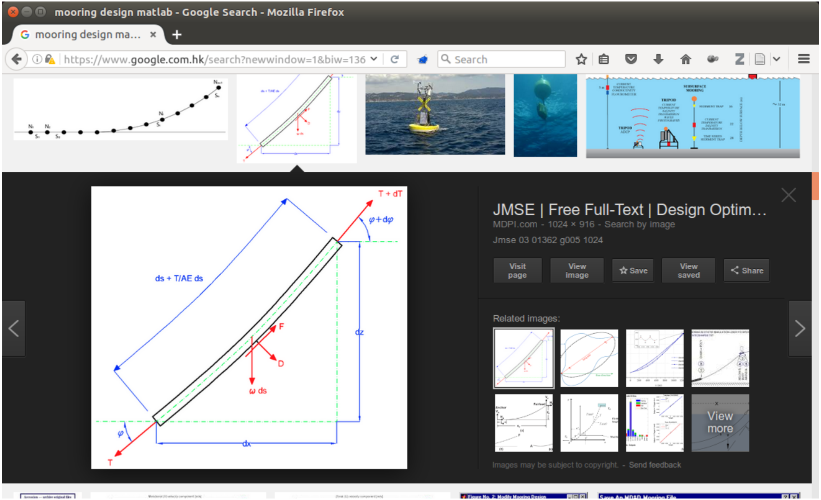
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Design Optimization for a Truncated Catenary Mooring System for Scale Model Test

Climent Molins [1,*], Pau Trubat [1], Xavi Gironella [2] and Alexis Campos [1]

[1] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya—BarcelonaTech, Jordi Girona 1-3, Campus Nord C1-206, 08018 Barcelona, Spain
[2] Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya—BarcelonaTech, Jordi Girona 1-3, Campus Nord D1- 111A, 08018 Barcelona, Spain

* Author to whom correspondence should be addressed; Tel.: +34-934-011-053.

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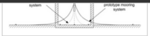

Figure 4. Prototype *vs.* truncated mooring system.

4. Static Mooring Lines Forces

The static catenary line can be described by the equations deduced from applying equilibrium on the whole forces acting on a line segment. As is shown in Figure 5, a catenary segment is subjected to the inner line tensions (T), the gravity forces accounted by the weight per unit length of the line (ω) and the hydrodynamic forces, which are the transversal drag forces per unit length (F) and the normal drag forces per unit length (D).

The static equilibrium of the line segment leads to the following equations:

$$dT = \left[\omega \sin(\phi) - \mathrm{F}\left(1 + \frac{T}{EA}\right)\right] ds \tag{1}$$

$$T \cdot d\phi = \left[\omega \cos(\phi) + D\left(1 + \frac{T}{EA}\right)\right] ds \tag{2}$$

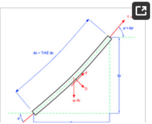

Figure 5. Segment line forces scheme.

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应对策略

特点

- 前几问为封闭性问题，后几问为开放性的优化问题.
- 问题所要求解的是多个刚体间的空间位置关系.

策略

- 将问题转化为由多个类似元件构成的空间几何运动问题.
- 根据运动分析和力学分析，找出各元件之间的相互关系.
- 从某个或某几个元件入手，找出求解所依赖的初始条件.

结果

- 给出一套解决问题的通用方法. 输入参数就能给出结果.
- 根据给定参数，给出封闭性问题的准确答案.
- 通过调整输入参数，对开放性的问题进行优化.

Thank You!!!