

The Exact Solutions of Tower-Yoke Mooring Systems

Yonghui (Allen) Liu

SOFEC, Inc.

14741 Yorktown Plaza Dr., Houston, TX 77040, USA

ABSTRACT

Tower-yoke mooring system, which consists of a tower fixed at the seabed and a mooring yoke assembly connecting a platform with the tower and utilizes pendant linkages to hang a heavy weight from top of the vessel, has been utilized for station-keeping applications in extreme shallow water. This paper will derive the exact solutions of the tower-yoke mooring systems. The motions of the tower-yoke mooring system is described based on the three rotational movements of the pendants and yoke. The exact relations between those rotational motions and the vessel motions are derived. The theoretical solutions of the restoring force characteristics of the tower-yoke mooring system can then be calculated. The model tests have been carried-out for the tower-yoke mooring systems. The excellent agreement between the analytical solutions and the measurements has validated and verified the methodology proposed in the paper.

KEY WORDS: Tower yoke mooring system; mooring system; restoring force; station-keeping; shallow water; exact solutions.

INTRODUCTION

In extreme shallow water, the conventional catenary mooring systems are very difficult to hold vessels on position since the water depth limits the effectiveness of the restoring forces generated by the weights of the mooring components. The very shallow water will also induce significant non-linearity to the catenary mooring system.

Tower-yoke mooring system, which consists of a tower fixed at the seabed and a mooring yoke assembly connecting the platform with the tower and utilizes a heavy weight hanging from the top of the vessel, has been utilized for the vessel station-keeping applications in shallow water. The mooring yoke assembly attaches the platform to the turntable on the tower and allows the yoke and platform to weathervane around the tower while allowing transfer of the oil and gas from/to the vessels and electric power to the tower. The yoke contains a two-axis joint that allows the vessel to roll and pitch relative to the tower and heavy ballast to provide restoring forces to moor the vessel. The vessels are attached to the yoke with two pendant linkages, which have

one double-axis joint on upper end (upper U-joint) and one triple-axis joint on lower end (lower U-Joint). The pendants hang over the vessel bow or stern and are attached to the vessel mooring support structure.

The tower yoke mooring systems have been designed to keep the 165,000 DWT new built FPSO vessel secured at CNOOC QHD 32-6 site in the extreme shallow water of 20 meters in Bohai Bay of China, and the 357,000 DWT converted FSO vessel moored on the ESSO Chad site in 35 meters water offshore West Africa. The QHD 32-6 FPSO and ESSO Chad FSO with the tower yoke mooring systems are illustrated in Figs. 1 and 2.



Fig. 1 Tower-yoke mooring system for CNOOC QHD 32-6 FPSO

However, the complexity of the tower-yoke mooring system make the analysis extreme difficult. Special finite element methods have been utilized to analyze the mooring systems. This paper will derive the exact solutions of the tower-yoke mooring systems. The motions of the tower-yoke mooring system is described based on the three rotational movements of the pendants and yoke. The exact relations between those rotational motions and the vessel motions are derived. The

theoretical solutions of the restoring force characteristics of the tower-yoke mooring system can then be calculated. The model tests have been carried-out on the tower-yoke mooring systems. The excellent agreement between the analytical solutions and the measurements has validated and verified the methodology proposed in the paper.



Fig. 2 Tower-yoke mooring system for ESSO Chad FPSO

TOWER YOKE MOORING SYSTEM

The general arrangement of a tower yoke mooring system with a floating LNG receiving platform is shown in Fig. 3a, Liu et al, 2006. A plan view and a elevation view of a typical tower yoke mooring system with a vessel are shown in the Figs. 3b and 3c.

The yoke head contains a two-axis joint that allows the vessel to roll and pitch relative to the tower and is attached to the turntable on the tower allowing the yoke and vessel to weathervane around the tower. A heavy liquid ballast on the yoke is utilized to provide restoring forces to moor the vessel. With the vessel drifting away from the equilibrium position, the potential energy of the heavy ballast will pull the vessel back to the origin. The vessels are attached to the yoke with two pendant linkages, which have one double-axis joint on upper end (upper U-joint) and one triple-axis joint on lower end (lower U-Joint). The height from the seabed to the yoke attachment at the turntable on the tower is defined as h , whereas the height from the seabed to upper U-Joint at the vessel mooring support structure is denoted as H . The length from the yoke pivot point at the tower attachment to the lower U-Joints of the pendant linkages on the yoke is defined as the yoke length L and the pendant length is l . The ballast tank of the yoke hung under the lower U-Joints is filled with liquid or other weights to provide the restoring forces for the station-keeping. Based on the detail design of the yoke and the total weight of the yoke structure and ballast, the equivalent weight W underneath the lower U-Joints can be estimated. The breadth between the pendant linkages is defined as b . All the dimensions are illustrated in Fig. 4.

COORDINATE SYSTEMS

For analysis, the global Cartesian coordinate $oxyz$ with the oxy -plane parallel to the quiescent free surface and z positive upward is utilized. Its origin is set at the yoke pivot attachment point to the turntable. The vessel fixed coordinates are denoted by $O_vX_vY_vZ_v$. The third coordinate system $o'x'y'z'$ is fixed on the yoke and rotated with the yoke. The tower yoke coordinate systems are shown in Fig. 4.

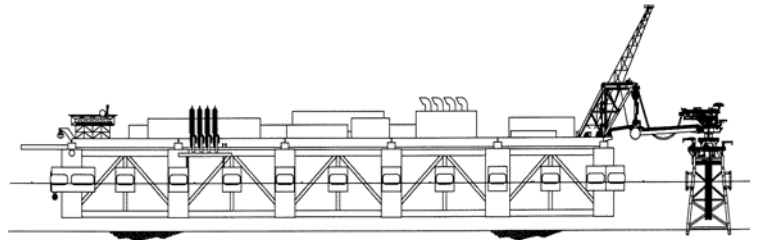


Fig. 3a General arrangement of tower yoke mooring system for LNG receiving platform in shallow water

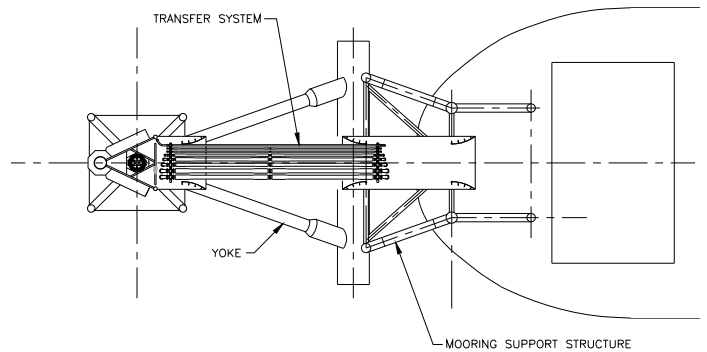


Fig. 3b Plan view of tower yoke system general arrangement

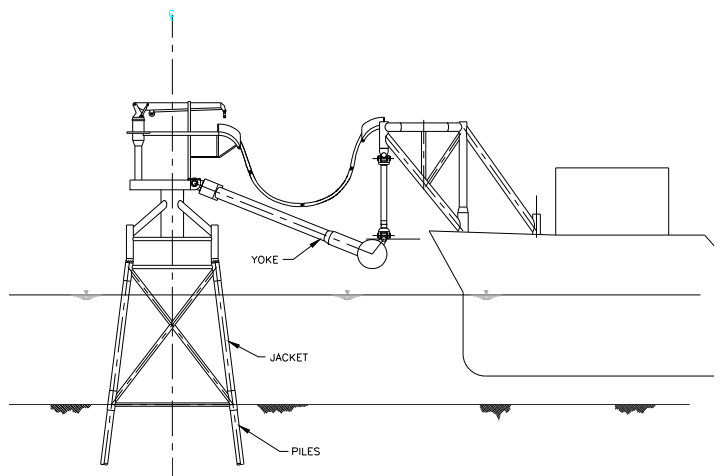


Fig. 3c Elevation of tower yoke system general arrangement

$$\begin{cases} \cos \gamma_x = (x_v - x)/l \\ \cos \gamma_y = (y_v - y)/l \\ \cos \gamma_z = (z_v - z)/l \end{cases} \quad (2)$$

Here, the superscriptions of p and s are ignored for simplicity.

The original yaw pitch angle in calm water is defined as:

$$\beta_0 = \arcsin\left(\frac{l+h-H}{L}\right)$$

The yoke and pendant angles as well as the pendant tensions are illustrated in Figure 5. Taking moments at the yoke pivot point o, we can derive the relations for the tensions and rotational angles in the equations as below:

$$\begin{aligned} T^p (y^p \cos \gamma_z^p - z^p \cos \gamma_y^p) + T^s (y^s \cos \gamma_z^s - z^s \cos \gamma_y^s) \\ - W \frac{(y^p + y^s)}{2} = 0 \end{aligned} \quad (3)$$

$$\begin{aligned} T^p (z^p \cos \gamma_x^p - x^p \cos \gamma_z^p) + T^s (z^s \cos \gamma_x^s - x^s \cos \gamma_z^s) \\ + W \frac{(x^p + x^s)}{2} = 0 \end{aligned} \quad (4)$$

$$\begin{aligned} T^p (x^p \cos \gamma_y^p - y^p \cos \gamma_x^p) + \\ T^s (x^s \cos \gamma_y^s - y^s \cos \gamma_x^s) = 0 \end{aligned} \quad (5)$$

where W is the equivalent weight of the ballast and yoke structure.

With the assumption that the pendant linkages are the un-stretchable rigid bodies, the following formulae can be derived:

$$(x_v^p - x^p)^2 + (y_v^p - y^p)^2 + (z_v^p - z^p)^2 = l^2 \quad (6)$$

$$(x_v^s - x^s)^2 + (y_v^s - y^s)^2 + (z_v^s - z^s)^2 = l^2 \quad (7)$$

where l is the length of the pendant linkages.

Therefore, the five unknowns, the yoke rotation angles α, β, γ , and pendant tensions T^p and T^s , can be completely solved from the above five Eqs., (3) through (7), with assistance of the Eqs. (1) and (2).

Once the exact yoke rotations and pendant tensions are determined, the restoring forces and yaw moments on the vessel in the oxyz coordinates can then be evaluated by the formulae below:

$$\begin{cases} F_x^v = -T^p \cos \gamma_x^p - T^s \cos \gamma_x^s \\ F_y^v = -T^p \cos \gamma_y^p - T^s \cos \gamma_y^s \\ F_z^v = -T^p \cos \gamma_z^p - T^s \cos \gamma_z^s \\ M_z^v = \frac{b}{2} (-T^p \cos \gamma_x^p + T^s \cos \gamma_x^s) \end{cases} \quad (8)$$

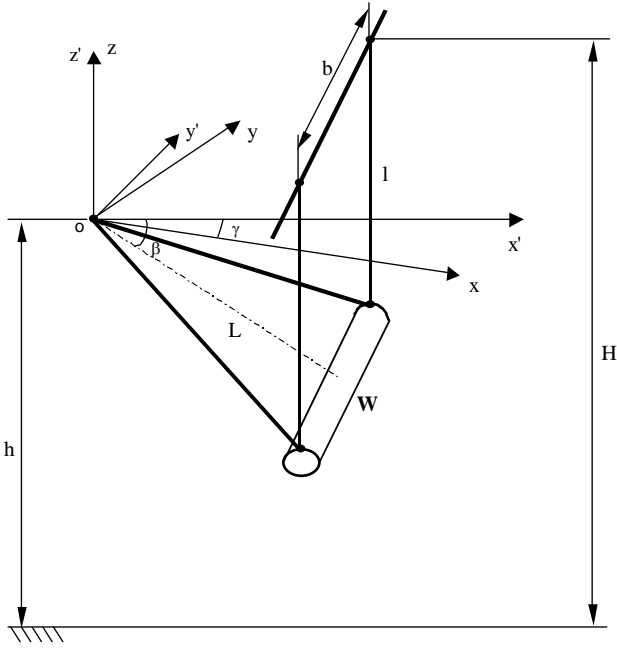


Fig. 4 Coordinate systems

ANALYSIS OF TOWER YOKE MOORING SYSTEM

For the station-keeping analysis of the tower yoke mooring system, we have to derive the mooring system restoring forces and motion behavior with the tower, yoke, ballast and pendants. Physical tower yoke characteristics, including geometric dimensions, ballast weight and hydrodynamic properties of each element, shall be specified.

First, it is assumed that the yoke is rotated about the pivot point at the attachment point to the turntable and the small distance between the yoke weathering axis, i.e. yaw axis, and pitch/roll axis is ignored. The weights of the pendant linkages are much smaller than the weight of the ballast and are negligible. The yoke and pendant linkages are assumed to be the un-stretchable rigid bodies

We consider the yoke will rotate about its pivot point o by the following sequence: rotation about its z-axis, γ , rotation about its y-axis, β , and rotation about its x-axis, α . Thus, the positions of the lower U-Joints in the oxyz coordinates can be described as:

$$\begin{cases} x^{s,p} = L \cos \beta \cos \gamma \mp \frac{b}{2} \cos \alpha \sin \gamma \\ y^{s,p} = L \cos \beta \sin \gamma \pm \frac{b}{2} \cos \alpha \cos \gamma \\ z^{s,p} = -L \cos \beta \pm \frac{b}{2} \sin \alpha \end{cases} \quad (1)$$

where, the superscriptions of p and s denote the components on port and starboard side of the vessel. The positions of the upper U-joint can be described by the vessel motions, such as (x_v, y_v, z_v) . Thus the pendant angles in the oxyz coordinates are expressed as:

where $\mathbf{F}^v = (F_x^v, F_y^v, F_z^v)$ are the longitudinal, transverse and vertical force components on the vessel and M_z^v is the yaw moment on the vessel.

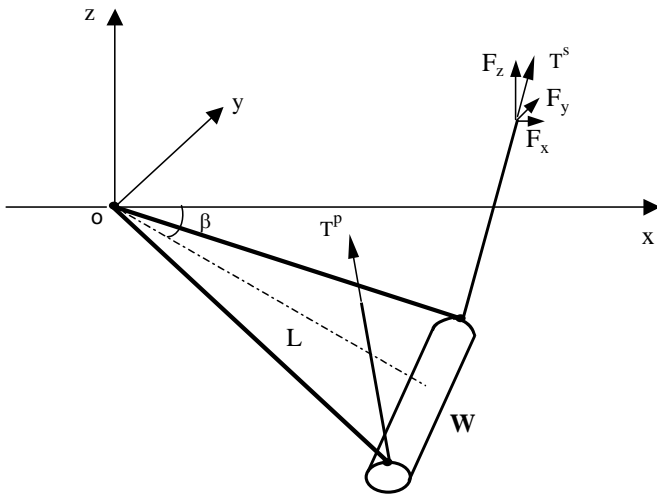


Fig. 5 Forces on yoke

The forces on the tower can be calculated by the following equations:

$$\begin{cases} F_x^t = T^p \cos \gamma_x^p + T^s \cos \gamma_x^s \\ F_y^t = T^p \cos \gamma_y^p + T^s \cos \gamma_y^s \\ F_z^t = T^p \cos \gamma_z^p + T^s \cos \gamma_z^s - w - W \end{cases} \quad (9)$$

where $\mathbf{F}^t = (F_x^t, F_y^t, F_z^t)$ denote the corresponding force components on the tower and w is the equivalent weight at the tower.

VALIDATION AND VALIDATION WITH MODEL TESTS

Two model tests have been carried-out for tower-yoke mooring systems in the extreme shallow water. The numerical results from the aforementioned formulae were evaluated and compared with the model test measurements in order to verify and validate the theoretical model derived in the paper. The model test set-up is illustrated in Fig. 6.

The first example is the tower yoke mooring system applied to the vessel in the extreme shallow water of 20 meters. The detail dimensions of the tower yoke mooring system are listed in Table 1. The vessel draft is 14.5 meters. Both surge and sway force deflection tests have been conducted. The results are summarized in Figures 7 and 8 and compared with the numerical calculations based on the above theory. Excellent agreement between the model test results and numerical data can be observed.

The second tower yoke mooring system was designed to secure the vessel in the water of 33 meters. The vessel draft is 22.8. The detail dimensions of the tower yoke system are summarized in Table 1 as well. As shown in Figures 9 and 10, the excellent agreement between the calculated numerical results and the model test measured data are

evidently for both surge and sway force-deflection characteristics of the mooring system.

Table 1. Principle particulars of tower yoke mooring systems

Tower Yoke Mooring		1	2	
Yoke Length	L	35	40	(m)
Yoke Height	h	40	60.3	(m)
Yoke Breadth	b	28	28	(m)
Ballast Weight	W	1172	1460	(MT)
Pendant Length	l	15	18	(m)
Pendant Height	H	45	65.7	(m)



Fig. 6 Model test of a tower yoke mooring system

CONCLUSIONS

This paper presented the analytical solutions of the tower yoke mooring system for station keeping in very shallow water. The theoretical solutions have been verified and validated through the comparisons with the results of the model tests. The excellent agreement has verified the theoretical methodologies proposed in the paper for solving the tower yoke mooring system. The mathematical model proposed in the paper has been successfully implemented in the design and analysis of the several tower yoke mooring systems. This model can be easily incorporated with time-domain and frequency-domain methods for global performance analysis of a vessel station-keeping with a tower yoke mooring system.

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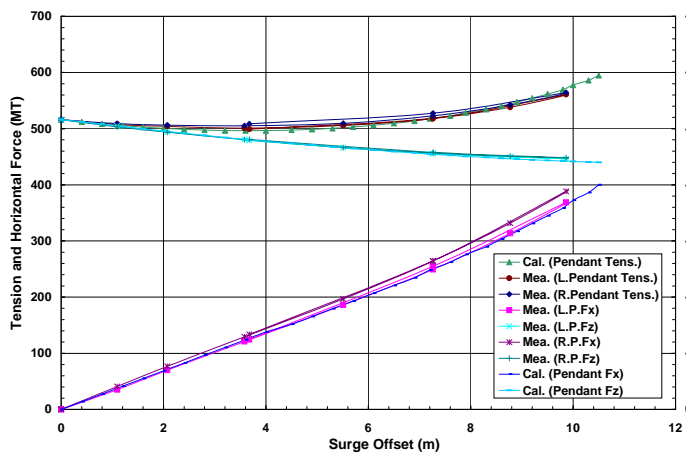


Fig. 7a System surge force-deflection characteristics

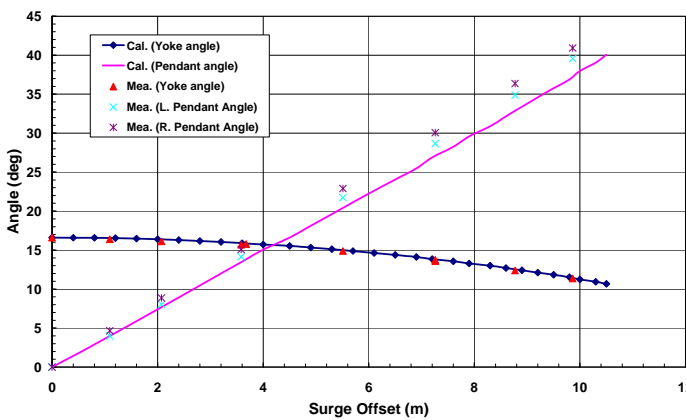


Fig. 7b System surge motion characteristics

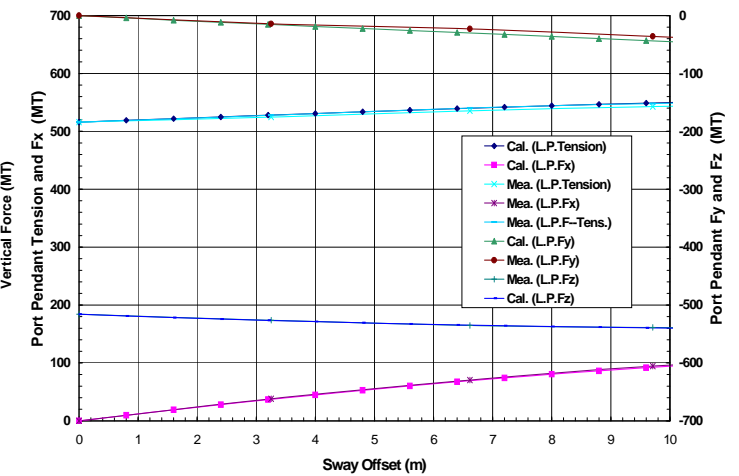


Fig. 8b System sway and port pendent tension characteristics

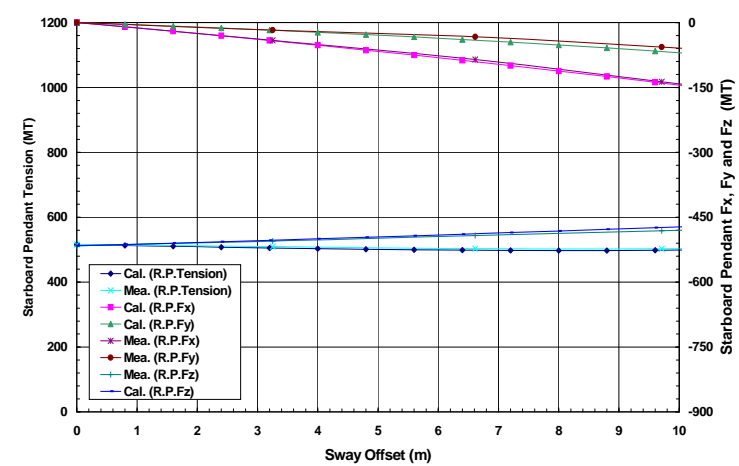


Fig. 8c Sway and starboard pendent tension characteristics

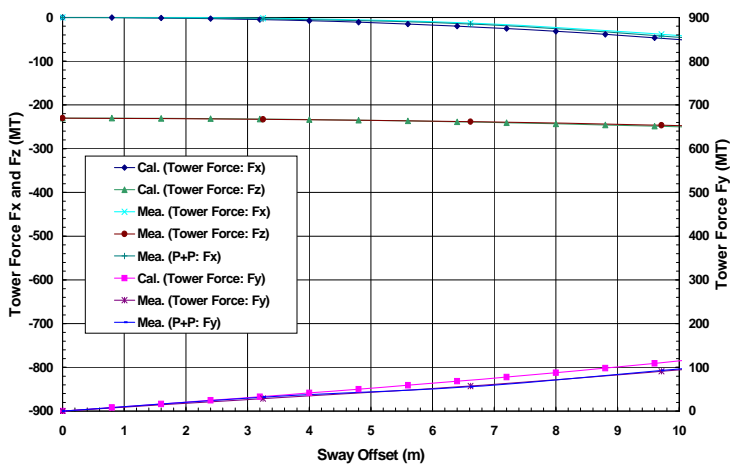


Fig. 8a System sway force-deflection characteristics

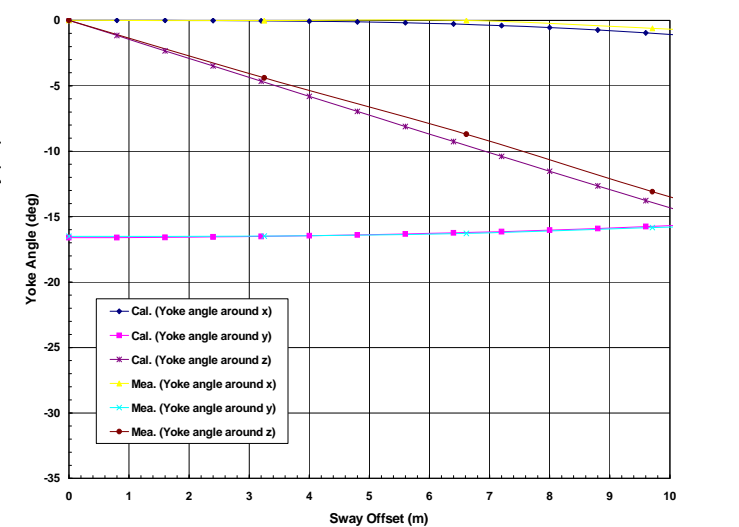


Fig. 8d Sway and yoke rotations characteristics

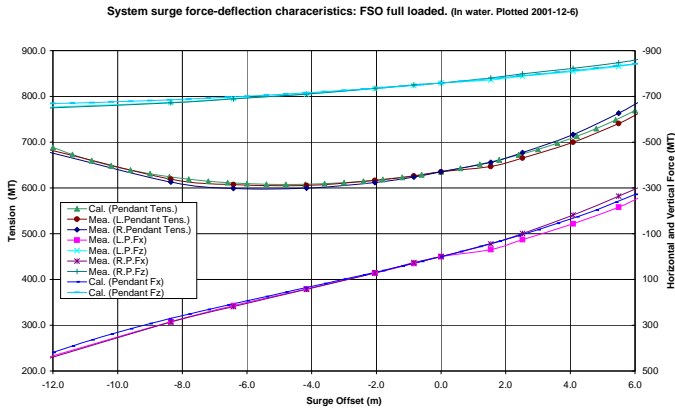


Fig. 9a System surge force-deflection characteristics

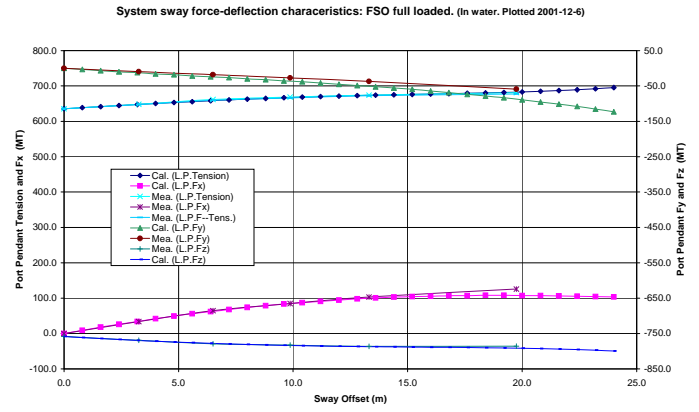


Fig. 10b Sway and port pendent tension characteristics

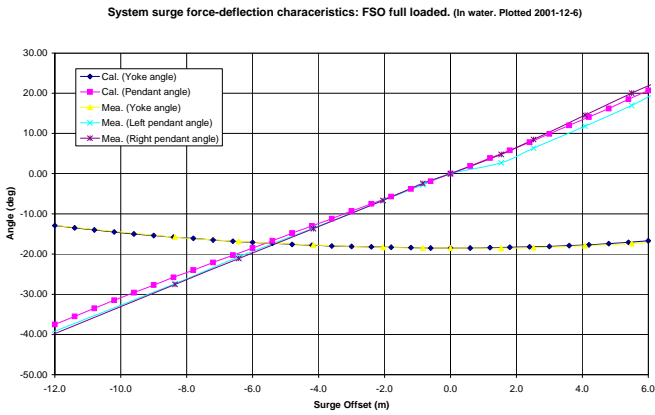


Fig. 9b System surge motion characteristics

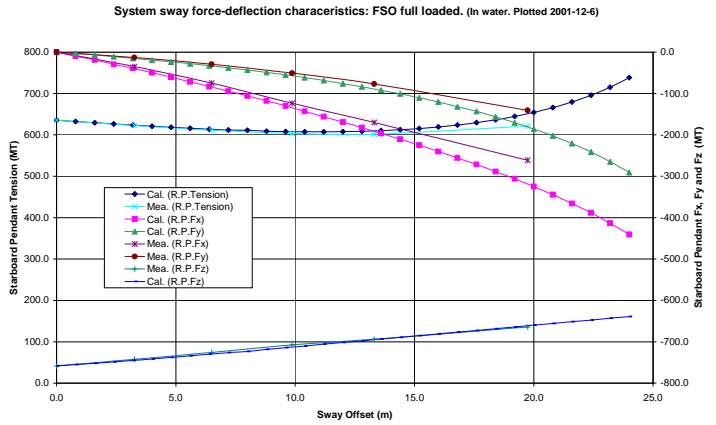


Fig. 10c Sway and starboard pendent tension characteristics

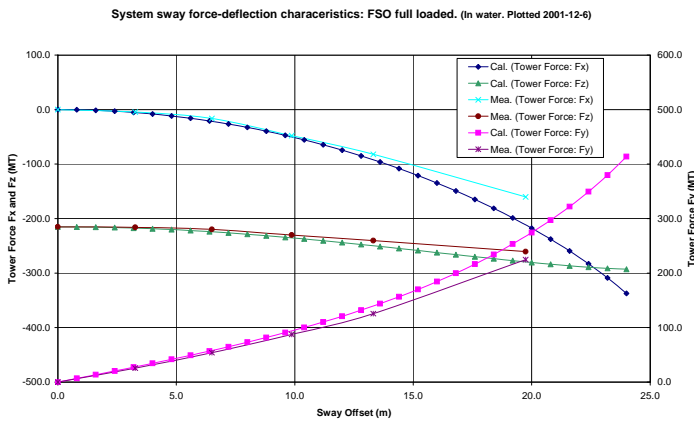


Fig. 10a System sway force-deflection characteristics

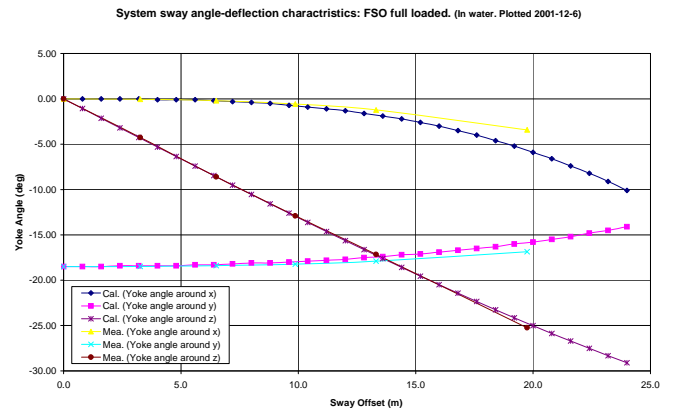


Fig. 10d Sway and yoke rotations characteristics