NONLINEAR ROLLING OF AN FPSO WITH LARGER-THAN-USUAL BILGE KEELS

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ABSTRACT

The work presents a numerical and experimental investigation on the nonlinear rolling of a Floating Production Storage and Offloading (FPSO) unit to be anchored for operation in the Campos Basin offshore Brazil. The FPSO is to be fitted with special roll damping bilge keels. Free from the usual restrictions imposed by increased resistance to motion ahead, the design of these bilge keels could contemplate larger-than-usual dimensions called here bilge keel *ad hoc* for FPSO[1]. Their effect on the ship's response is the main subject of this study. Roll decay tests with a reduced scale model have been carried out at IPT (São Paulo State Towing Tank) to help determining the best overall arrangement. We also present matching results from a nonlinear time-domain simulation study. However, the current procedure for the assessment of quadratic damping coefficients, based on a local fit of exponential functions between adjacent cycles, has led to a high dispersion of values, which is difficult to interpret. Hence, the work describes an original procedure for nonlinear roll damping estimation. Linear and quadratic damping coefficients estimated through this procedure indicated that roll motion could be significantly suppressed by the use of these bilge keels. Results from irregular waves tests conducted at MARINTEK of a FPSO system are also presented.

INTRODUCTION

The main element of a Floating Production Storage and Offloading (FPSO) unit is often a large converted tanker anchored to the seabed by one of a variety of mooring systems. A common anchoring system is the Spread Mooring System (SMS), in which several anchoring lines are fixed at one end to a point in the vessel and at the other end to an anchor on the seabed. A variant of the SMS is the Differentiated Compliant Anchoring System (DICAS) in which the pre-tensioning of anchoring lines is designed to give the vessel more freedom to align itself with the mean direction of predominant elements. Such schemes are designed primarily to allow the vessel to keep station against the action of waves, currents and wind. In any SMS the configuration of lines is such that the anchored vessel has limited ability to weathervane and therefore the initial alignment of the vessel with respect to predominant directions of incoming waves, current and wind is of paramount importance. Those directions can and do vary with time though, and because the vessel will not be allowed to align itself in the direction of minimum excitation, it is worth investigating the behavior of the system under lateral waves. In addition, even if the vessel were freer to rotate, its *instantaneous* heading would be a result of the combined action of weather elements upon itself (and upon the mooring lines). This means that the position of the vessel could be such that waves, for instance, act laterally.

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[1] PETROBRAS patent pending

In fact, the Brazilian Oil Company – PETROBRAS has reported a case of a moored FPSO unit that exhibits uncomfortable roll motions at sea. A proposed solution to the problem includes the fitting of large bilge keels aimed at damping roll motions to acceptable levels. Because resistance to motion ahead is of minor importance larger-than-usual bilge keels were proposed. The main purpose of this work is to carry out a preliminary investigation of the influence of large bilge keels on the roll response of the vessel as suggested in (Fernandes and Masetti 97).

Experiments with a reduced scale model were conducted at the São Paulo State Institute for Technological Research (IPT). These included roll decay tests to evaluate damping levels, as well as regular beam wave tests for a range of wave periods and amplitudes.

A nonlinear time-domain numerical simulation model was also fine-tuned with results from the experiments and shows good agreement with them. In the course of developing a nonlinear model for the total damping moment, traditional methods based on a local fit of exponential functions between adjacent roll cycles showed a large dispersion of values for damping coefficients. Although this subject is very traditional in the field (Himeno 81), the present work has been able to suggest a new procedure based on examination of a larger number of cycles. When applied to the present problem this new procedure has gotten encouraging results as shown next.

ROLL DECAY TESTS

Roll decay tests were performed at IPT with the purpose of evaluating roll damping levels achieved with different bilge keel designs (IPT 97).

A hull model in 1:70 scale ratio of an existing ship tanker was built in FRP to be used in the model tests. The hull was adjusted in two inertia conditions representing the full load case and a 70% load (ballast condition). The hull model was provided with large fairleads at bow and stern regions to avoid green water.

Three sets of bilge keels were used in the model tests. Design 1 represents a conventional type with 0.45 meter in breadth, Design 2 has a larger breadth (1.00 meter) but is segmented in three parts along the hull, and Design 3 is 1.00 meter in breadth running continuously along 80% of the hull length. The latter design is referred to as the *ad hoc* bilge keel. Table 1 identifies the six roll decay tests used in this work.

Table 1. Identification of roll decay tests.

Bilge Keel Design	Full Load	Ballast Condition
1	F1D8	B1D4
2	F2D4	B2D2
3	F3D4	B3D4

The model motions were measured using an optical position sensor system.

The main dimensions and data for the model and ship tanker are listed in Table 2.

Table 2. Ship and model characteristics; subscript 1 for fully loaded condition; 2 for ballast condition. The co-ordinates are for the ship center of gravity; Rxx is the radius of gyration; GM stands for the metacentric height; L, B, D and T follow ITTC convention.

Characteristics	Model	Ship
L (m)	3.900	273.000
Lpp (m)	3.714	260.000
B (m)	0.636	44.500
D (m)	0.326	22.840
Displacement$_1$ (m^3)	0.443	151,880.400
T_1 (m)	0.231	16,180
x_1 (m)	0.106	7.413
y_1 (m)	0.000	0.000
z_1 (m)	0.189	13.237
Rxx$_1$ (m)	0.209	14.600
GM$_1$ (m)	0.069	4,863
Displacement$_2$ (m^3)	0.304	104,100.500
T_2 (m)	0.162	11.326
x_2 (m)	0.106	7.413
y_2 (m)	0.000	0.000
z_2 (m)	0.135	9.471
Rxx$_2$ (m)	0.229	16.000
GM$_2$ (m)	0.143	9.979

MATHEMATICAL MODELLING

The basic equation to describe the 1-degree-of-freedom free rolling behavior may be written as:

$$I_T(w)\ddot{q} + B(\dot{q}) + C(q) = 0 \qquad (1)$$

where $q, \dot{q}, \ddot{q}$: roll angle, velocity, and acceleration, respectively; w : (natural) frequency of response;

$$I_T(w) = I + I_a(w) \qquad (2)$$

is the vessel's total inertia in roll, with: I: vessel's moment of inertia in air; $I_a(w)$: additional hydrodynamic inertia; $B(\dot{q})$: damping moment; $C(q)$: restoring moment.

Some simplifications are justified in the present application:

1. $$C(q) = \Delta GZ(q)\,; \qquad (3)$$

and:

$$GZ(q) = GMq \qquad (4)$$

That is, the restoring moment may be considered linear up to 20^0 for the ballast condition and more than 30^0 for the fully loaded condition;

2. $I_a(w) \cong I_a = \text{constant}$,

since processing WAMIT (MIT 95), a Diffraction Linear Wave Theory Code, indicated that the added inertia which is about 25% of the total inertia varies less than 4% in the period range (9 to 14 s). (See Figure 1 for a example of panel distribution incorporating the large bilge keel);

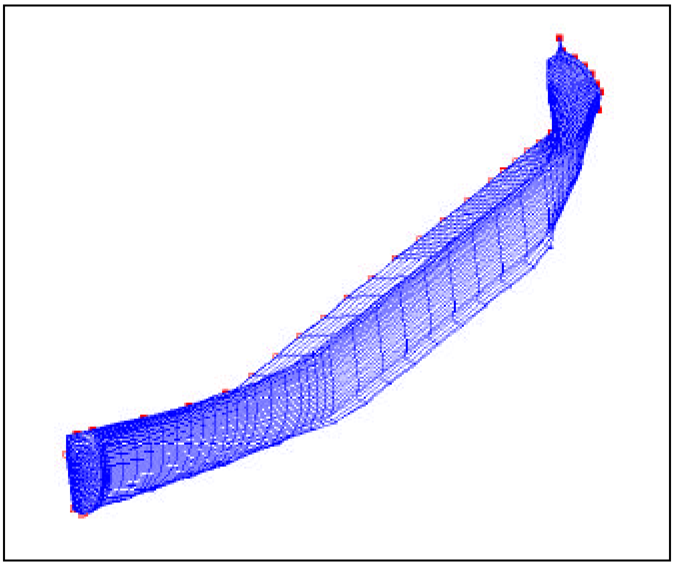


Figure 1. Panel Distribution including the Bilge Keel Ad Hoc for FPSO submitted to the WAMIT code (WAMIT 95).

2. Following numerous textbooks (e.g. (Faltinsen 90)), the damping component may be split in a linear plus quadratic (but odd) part, that is:

$$B(\dot{q}) = B_1\dot{q} + B_2\dot{q}\left|\dot{q}\right| \qquad (5)$$

where it is important to note that the damping coefficient are dimensionally different, but nevertheless both control energy dissipation as shown above. Another point to be stressed is that, B_1, the linear coefficient is not only due to potential effects but includes a viscous effect as also discussed below.

In summary, for the decay test under consideration, equation (1) may be simplified to:

$$I_T\ddot{q} + B_1\dot{q} + B_2\dot{q}\left|\dot{q}\right| + \Delta GMq = 0 \qquad (6)$$

submitted to the initial condition:

$$q(0) = q_0; \dot{q}(0) = 0 \qquad (7)$$

The canonical form of expression (6) is:

$$\ddot{q} + 2V_1 w_n \dot{q} + 2V_2 w_n \dot{q}\left|\dot{q}\right| + w_n^2 q = 0 \qquad (8)$$

where w_n is the undamped natural frequency and the zeta-coefficients will control the type of decay. Note that V_2, unlike V_1, is not non-dimensional, having the dimension of time.

Whenever treating this equation, it is usual (Faltinsen 90) to make linear the third term of (8) by introducing an equivalent damping (B_e) that produces the same energy dissipation in one (or half) cycle. This condition defines an expression for B_e:

$$B_e = B_2\left|\bar{q}\right| w_d \frac{8}{3p} \qquad (9)$$

or in terms of the zeta coefficients:

$$V_e = V_2\left|\bar{q}\right| w_d \frac{8}{3p} \qquad (10)$$

where:

$$w_d = w_n\sqrt{1 - V^2} \qquad (11)$$

is the damped natural frequency which in ship roll problems can usually be taken as the undamped one since z is very small: $w_d \cong w_n$. In fact with (10), (8) becomes:

$$\ddot{q} + 2(V_1 + V_e)w_n\dot{q} + w_n^2 q = 0 \qquad (12)$$

and z is such that:

$$V = V_1 + V_e \qquad (13)$$

In the decay test taking two time instants separated by $T_d = 2p / w_n$, one may infer the damping coefficient since:

$$\frac{q_1}{q_2} = e^{V w_n T_d} \qquad (14)$$

Combining (10) with (13), the result is:

$$V = V_1 + V_2 \frac{16}{3} \frac{|\bar{q}|}{T_d} \qquad (15)$$

a classical result also shown in (Faltinsen 90).

ESTIMATION OF LINEAR AND QUADRATIC DAMPING COEFFICIENTS FROM DECAY TESTS

Conventional Method (Correlation per cycle)

From here, what is usually made is to get ζ from two consecutive peaks (one or half cycle apart) and also the correspondent $|\bar{q}|$ (average amplitude) and T_d. Then a straight line is fit relating z and $\frac{16}{3}\frac{|\bar{q}|}{T_d}$. This line crosses the coordinate axis at V_1 and its slope yields the V_2 value.

The present work has tried this procedure for the decay tests and an example with the result may be seen in Figure 2 for the test B1D4.

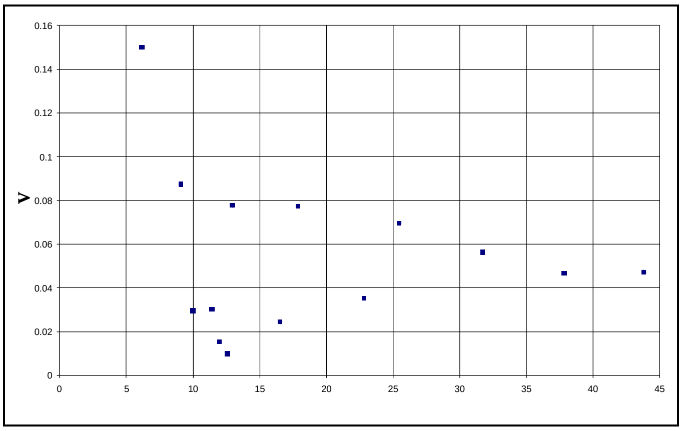


Figure 2. Decay Test B1D4 analysis using the conventional method with $\frac{16}{3}\frac{|\bar{q}|}{T_d}$ in the abscissa axis.

Observing results like that where a lot of dispersion is present one may realize the following assertion from (Faltinsen 90), page 252:

> *"It is difficult and in some cases impossible to determine this straight line from the experimental results."*

In the next subsection, a new method is suggested.

Present Method (Correlation per n-cycles)

If the system were linear, the dispersion illustrated before would not occur and a flat line parallel to the abscissa axis would result. On the other hand, the correlation using n cycles (taking peaks n cycles apart) would yield the same result. However, this is not the case for a non-linear system.

What the present method recognizes is that the energy dissipation must depend on the path due to the non-linearity. Hence, it is essential to have an approach that takes into account the history of the dissipation. This is naturally made considering the correlation for n cycles (or 2n half-cycles) and also the following characteristics:

- The non-linearity is much stronger at the beginning of the decay test (first cycles), where large roll angles are present;
- The damping at the last cycles is very small, leading to a very small decay;
- Due to the non-linearity, the damping in one cycle must depend on the former cycles and their amplitudes.

These have lead to the following procedure based on considering always n-cycles (or 2n half-cycles). Initially one considers separately the first cycles and the last cycles.

Concretely, the linear component (V_1) is estimated by the small amplitude damping from the last cycles (V_S) that is:

$$V_1 = V_S \qquad (16)$$

On the other hand, using the notation of expression (15), the large amplitude damping from the first n-cycles (V_L) is taken such that:

$$V = V_L \qquad (17)$$

Finally using expression (15):

$$V_2 = \frac{3}{16} \frac{T_d}{|\bar{q}|} (V_L - V_S) \qquad (18)$$

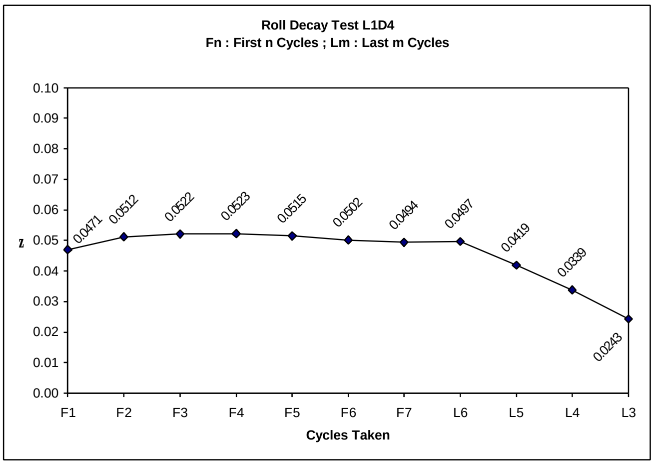
The choice of a suitable number of large- and small-amplitude roll cycles can be made after inspection of the behavior of V for different selections of cycles. As an example, Figure 3 is here presented. Each graph displays values of V obtained by taking the first n cycles (with n varying from 1 to the total number of cycles in the decay test), as well as the values obtained taking the last m cycles (with m varying from 3 to the total number of cycles in the decay test). Estimates taken from less than three small-amplitude cycles showed large numerical error and were discarded. For this study we calculated V_L (respectively, V_S) for all roll decay tests taking the first (respectively, last) three roll cycles. Results are summarized in Table 3.

Table 3. Estimated damping coefficients, proposed method (model scale).

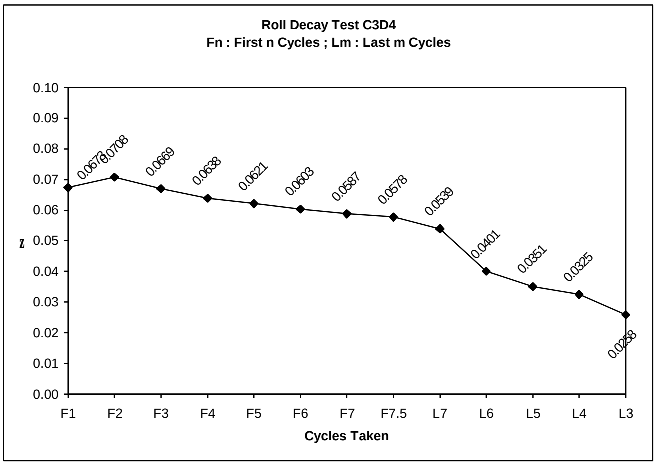
Roll Decay Test	$V_1 = V_S$	V_L	V_2 (s)
F1D8	0.0136	0.0306	0.0323
F2D2	0.0301	0.0485	0.0401
F3D4	0.0258	0.0669	0.0982
B1D4	0.0243	0.0522	0.0485
B2D2	0.0497	0.0612	0.0202
B3D4	0.0484	0.0722	0.0447

The six roll decay tests described in section 2 were simulated in computer using expression (6). As seen in section 2 these tests cover three bilge keels designs in both ballast and

full displacement conditions. Initial results showed slight discrepancies in natural roll period, which were eliminated by adjust of initial hydrostatic righting arms. Results are shown in Figure 4.

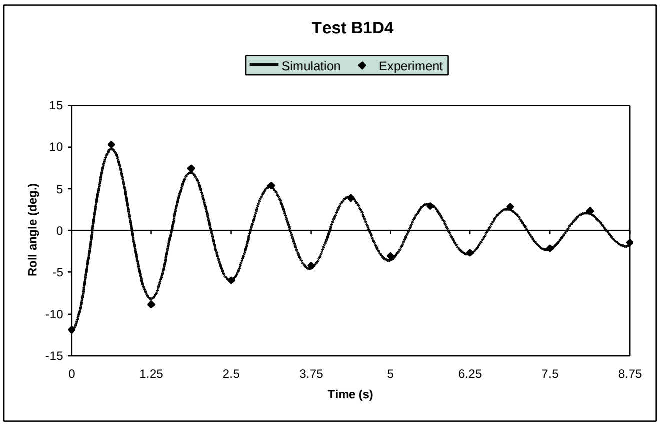


(a)

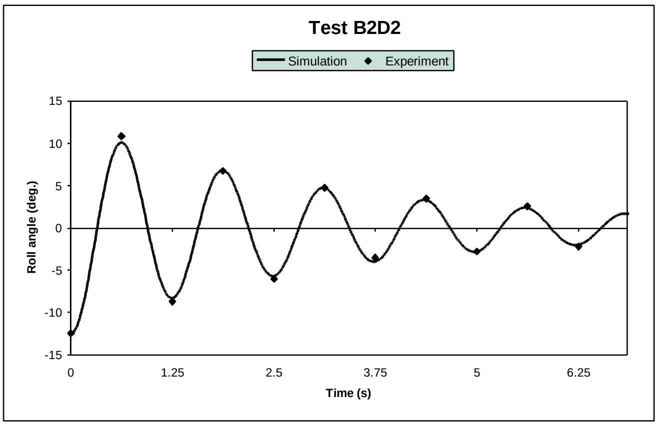


(b)

Figure 3 (a)-(b). Behavior of equivalent linear damping coefficients for various selections of roll cycles.



(a)



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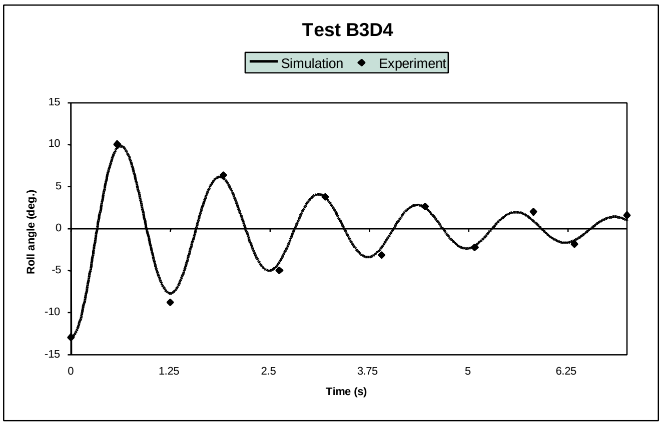
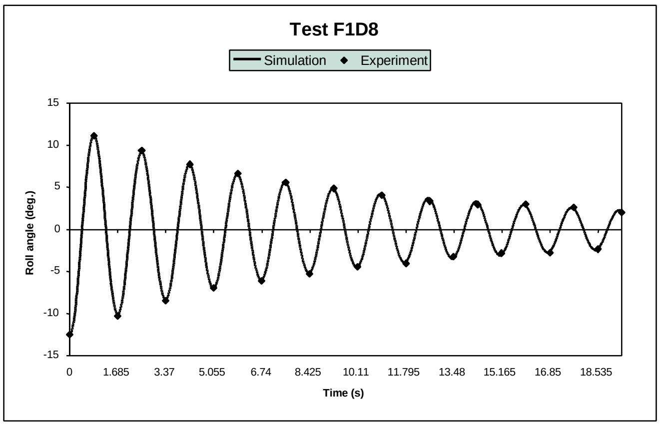


(c)



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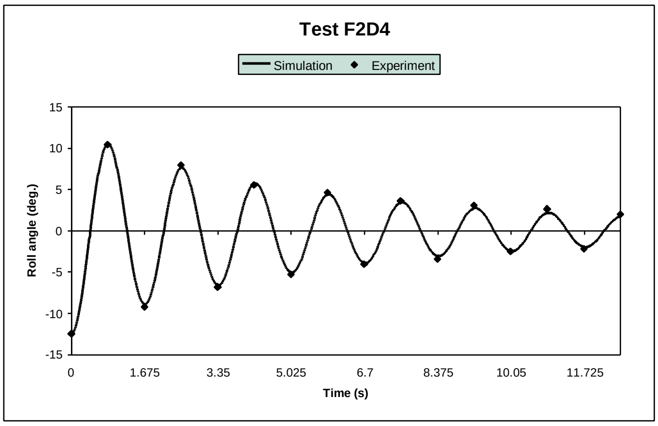
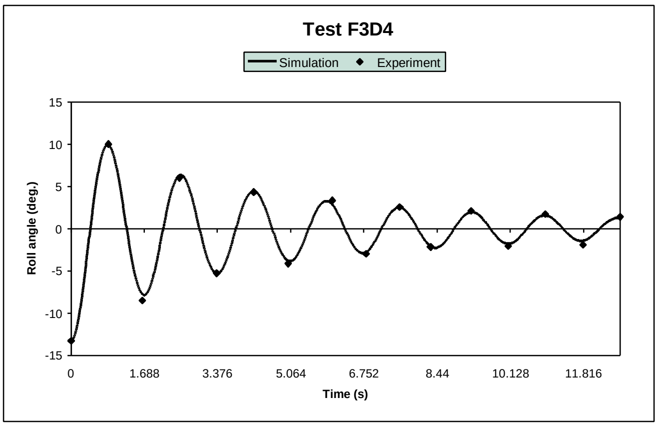


(e)



(f)

Figure 4 (a)-(f). Simulated and experimental roll decay tests (model scale).

EFFECTIVENESS OF THE BILGE KEEL *AD HOC* FOR FPSO

Inspection of the linear and quadratic damping coefficients presented in Table 3 suggests a significant increase in the damping level with use of the larger, *ad hoc* bilge keels. In fact to compare the overall effect, considering both the linear and the quadratic effects, it is essential to use the equivalent damping concept defined by expression (10). These results are shown in Table 4 and it is important to recall that they may be extrapolated to full scale since they are non-dimensional.

Table 4. Effectiveness of the Bilge keel ad hoc for FPSO, comparing the equivalent damping coefficients from the decay tests.

Roll Decay Test	z_1	z_e	$z = z_1 + z_e$	% increase
F1D8	0.0136	0.017	0.0306	
F2D2	0.0301	0.0184	0.0485	58
F3D4	0.0258	0.0411	0.0669	119
B1D4	0.0243	0.0279	0.0522	
B2D2	0.0497	0.0115	0.0612	17
B3D4	0.0484	0.0238	0.0722	38

It may be observed that more that 100% increase has been observed when using the *ad hoc* bilge keels for the fully loaded condition. For the ballasted condition the increase has been less but nevertheless significant.

The effect of this increased damping on the roll response of the vessel may be verified by other experiments such as the regular wave tests which is under way and also in irregular waves, simulating the overall FPSO system. The latter has been performed at MARINTEK. In its deep water ocean tank, several model tests in scale 1:100 for different headings of irregular waves (centenary conditions: significant wave high = 7.8m; mean period = 11.5 s) were performed in 1997 using the *ad hoc* bilge keels. As expected, the largest roll motion occurred for incidence angles between 90 and 135 degrees, see Figure 5. The mean relative angle between the wave direction and the FPSO longitudinal axis is, in this case, very close to 90 degrees. Note that, as predicted in Table 4, for the ballasted conditions, the *ad hoc* bilge keel tends to be less effective at resonance but not for other frequency ranges.

Even if the roll period is close to the wave periods, roll maximum peak-to-peak value above 14.2 degrees was not recorded for the tanker 100% loaded. The main reason for this small peak-to-peak angular motion is the large relative roll damping of 10 to 15% of the critical roll motion, due to the large bilge keels, "*ad hoc* bilge keel", and also probably due to some small contribution from mooring line damping.

It is convenient to emphasize that half of the maximum recorded peak-to-peak value is less than the maximum single amplitude roll angle estimated of 9.9 degrees.

The scale effects on wave frequency motions are usually only important for the roll motion, but, in this particular case, they can be neglected since the tanker models are equipped with large bilge keels.

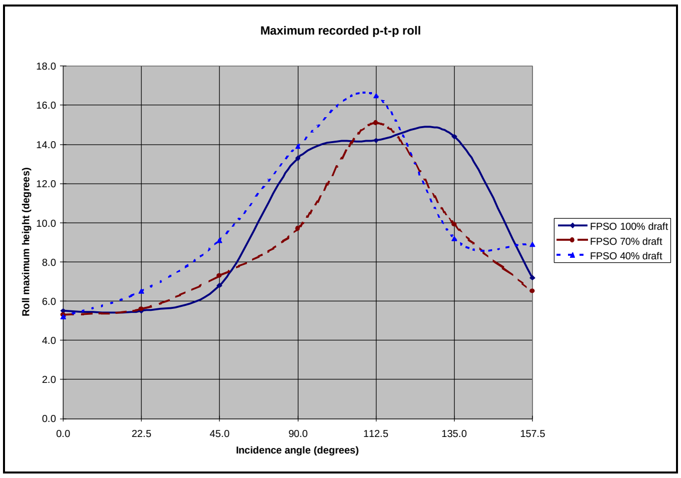


Figure 5. Roll response of FPSO in irregular wave model tests with ad hoc bilge keels (p-t-p: peak to peak response) from (MARINTEK 97).

CONCLUSIONS

In this work, the effectiveness of larger-than-usual bilge keels to suppress roll motion of an FPSO under lateral waves has been assessed. Procedures conventionally employed to calculate linear and quadratic roll damping coefficients based on a local fit of exponential functions between adjacent cycles from roll decay tests produced poor results for this highly nonlinear problem. An original procedure, based on an averaging of results over a larger number of cycles was applied to experimental roll decay tests. Using this procedure, computer simulations showed that a linear plus quadratic damping model could be used to reproduce accurately roll decay tests. The effectiveness of these bilge keels, was confirmed by inspection of roll damping coefficients which is summarized in Table4.

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