The Bilinear Behavior for FPSO Rolling Motions

Allan Carré de Oliveira, *PETROBRAS*

Antonio Carlos Fernandes, *COPPE/UFRJ*

ABSTRACT

At least for ships with a practically rectangular section, like a VLCC or barges, it has become clear that the quadratic or even the cubic model to describe the damping of the rolling mode may not match with reduced model decaying tests. This has been shown in the past and is confirmed by several recent model tests. An alternative, named the bilinear approach has been suggested and that has conducted to a very good match between mathematical model and tests. By the bilinear model, the roll damping behavior is divided in two assumed linear regions, and the transition is made around the so-called transition angle. This is clear for sections with wider bilge keels which are presently a trend in the offshore industry. It is shown that despite being non-linear, due to the simplicity of the bilinear model the differential equation for the decaying test has an explicit solution and the matching with experiments is almost exact. How to obtain the transition angle experimentally is discussed in the paper. Several tests are shown and both the quadratic model and the bilinear approaches are applied and compared. It is proposed that typical decaying tests for vessels with this kind of sections, additionally to the usual linear plus quadratic coefficients, the tests should also provide the two linear damping coefficients, the transition angle and also the increase of the added mass due to wider bilge keels. Finally, the physical reason for the behavior is also addressed, and the so-called KC number effect is explicitly discussed**.**

Keywords: *rolling motion, rolling of FLSO, bilinear approach*

1. INTRODUCTION

As discussed by the Ocean Engineering Committee in the ITTC, (2005), the prediction of roll due to the wave is a classical subject in Ship Naval Architecture. A good review contribution that may be cited is Himeno (1981). The prediction of roll generally implies the determination of a roll damping coefficient for inclusion in a seakeeping package used to compute the roll transfer function or extreme values of roll.

The roll damping coefficients have traditionally been generally determined through experiments. It is known that at least for traditional ship forms the response is non-linear and the quadratic model possibly cubic yields adequate results. This leads to good results particularly for the ship in a seaway where the bilge keels that are usually present bring non-negligible lifting restoring moments. The equivalent cycle linearization as presented for instance by Faltinsen (1990) is well known also yielding good results, with the coefficients being obtained via decaying tests.

With the use of platforms with non-ship forms like Semi-submersibles, TLPs, Spars etc, this cited procedure became standard. However, with the trend of stationary ship hull in open seas, that is, without the lifting characteristics, the roll behaviour became an issue again, up to the point that a JIP has been recently proposed, Marin (2002).

Following again ITTC (2005), the roll damping mechanism modelled in conventional, unmodified, potential flow based seakeeping methods is one of wave radiation damping. However, for certain hull forms, if the wave energy in the sea is concentrated at a frequency similar to the vessel's natural frequency, the wave damping can become relatively small, and the system can become dominated by viscous effects.

The principal mechanism involved is one of flow separation from the hull leading to vortex shedding, Downie et al. (1988). This phenomenon is more pronounced for hull forms such as wall sided, flat bottomed barges because stronger vortices are shed from sharp edges than low curvature continuous surfaces. The mechanism is nonlinear because the strength of the vortices also vary with roll amplitude, Oliveira (2003).

When facing decaying tests of FPSO hull with larger than usual bilge keels, Sousa et al (1998) observed that a uniform matching through roll decay time series may be not adequate and has proposed a matching that is different for large roll angles and smaller angles. Later, Fernandes et al. (2000) suggested a bilinear approach. This has led to an investigation shown as in Oliveira (2003) that summarized several model tests results and identified Keulegan-Carpenter effects that are different for the large and small roll angles.

As will be discussed in what follows, for large angles there is a stronger damping due to a strong bilge-keel vortex attracted to the hull bottom. For small angles, the vortices are shed because the smaller amplitude of oscillation (smaller KC number) may not be attracted to the hull, Oliveira (2003).

Predicting rolling for ships and FPSO in Floating Production Unities is a recurrent problem in Ship Design. The present work is under the impression that although the quadratic modeling adjusts well for conventional ship forms, small modifications in the geometry and appends of the hull, can modify the behavior of this one.

The offshore industry is converting ships in FPSOs adopting large bilge keels in order to increase the viscous damping, reducing roll motions and increasing the operational performance of the unit, Fernandes (2000). For these cases, the bilinear approach, Souza at al. (1998) and Fernandes at al. (2002) seems to be more useful than the quadratic one. In fact, completing the approach, the present work shows the importance of identifying the transition angle between two regions that corresponds to two physical behaviors.

The present work reviews the so-called bilinear methodology, applying it to several decaying tests, presenting comparisons with the results obtained by the so-called energy cycle quadratic approach.

2. THE BILINEAR APPROACH

The bilinear model for ships roll damping has been proposed by Fernandes et al. (2000) following a preliminary work by Souza et al. (1998) and later developed by Pinheiro (2002) and Oliveira (2003). At first these works have been based on several FPSO rolling model testing for the verification of the adequability of extended bilge keels. These tests have shown a clear evidence of two different behaviors typically shown in Figure 1 and 2, taken from these cited tests. From these figures, two different linear damping coefficients may be easily obtained. The region with initially large roll angles are present has been denominated LARGE (Figure 1) associated to the larger energy dissipation, and the region with small amplitudes has been called SMALL (Figure 2), due to the smaller energy dissipation as discussed below.

From each of these two regions two linear damping coefficients ζ_L and ζ_S may be obtained.

It is important to note for completeness that there is a transition angle such that for roll motion initial amplitudes greater than this angle, the decay test will present the large and the small energy dissipation. For decay tests with small initial angles smaller that the transition angle, only the SMALL behaviour will occur.

For the physical understanding of these observations Oliveira (2003) suggested that in the LARGE region, possibly a huge vortex is generated at the bilge keel following by an attraction to the hull bottom (see also an speculation in Himeno (1981)). On the other hand, in the SMALL region, the vortex attraction does not occurs, since the vortices are shed away in pairs from the bilge keels in a direction around 45 degrees from the hull. Clearly, the occurrence or not of the attraction depends on the amplitude.

The strong vortex attraction may be observed in Figure 3 from Oliveira (2003).

In order to understand the behavior better Oliveira (2003) also proposed a mathematical approach based in potential theory to describe this influence of the vortex and its pressure distribution over the hull. These are shown in Figures 4a and 4b.

3. ESTIMATION OF THE BILINEAR COEFFICIENTS

The bilinear coefficients may be obtained by two different methods. The first one is described in Souza et al (1998), is here called the “r4” method. In this method the following steps may be applied (using the maximum values from temporal series):

1. Compute, for the data, the exponential coefficients and the correlation.

2. Compute, for the data, all the possibilities of bilinear approach, the coefficients and the correlation of each approach (for instance, the first two values for LARGE region and the other values for SMALL region, the first three values in LARGE

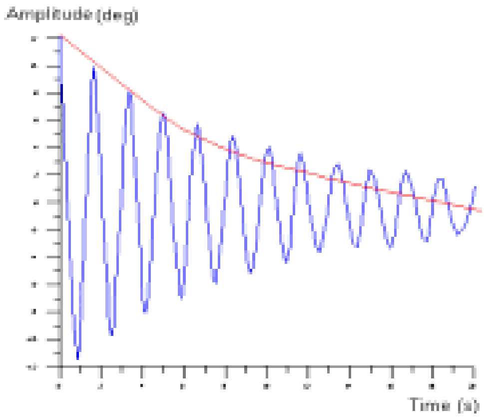

Figure 1 Typical linear behaviour for large angles from rolling decaying tests of FPSO hulls (Souza et al, 1998) and (Fernandes et al, 2000).

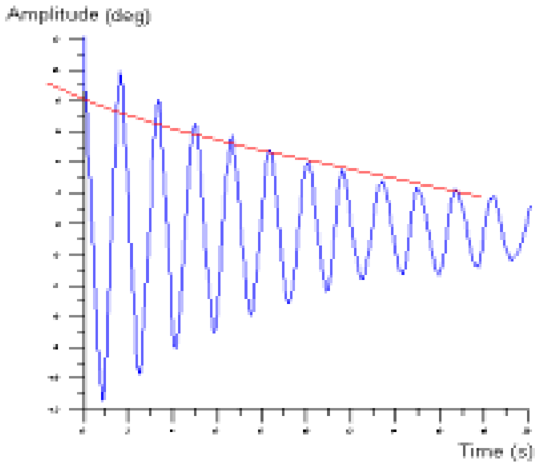

Figure 2. Typical linear behaviour for small angles from rolling decaying tests of FPSO hulls (Souza et al, 1998) and (Fernandes at al, 2000).

Figure 3. Strong vortex attracted to the hull bottom in the LARGE region (Oliveira, 2003).

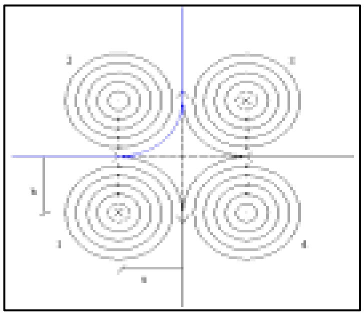

Figure 4a. Potential flow model with four vortices simulating a FPSO hull corner (Oliveira, 2003).

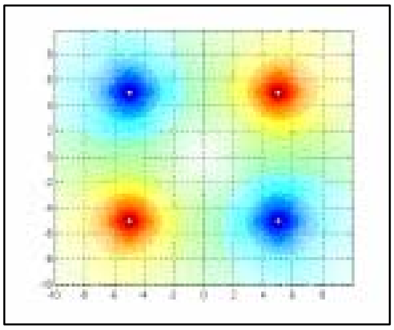

Figure 4b. Streamlines for the potential flow model with four vortices of Figure 4a simulating a FPSO hull corner (Oliveira, 2003).

region and the others in SMALL region, until it covers all possibilities). The correlation can be calculated multiplying the correlation of region LARGE for correlation of region SMALL. An example of bilinear approach can be viewed in Figure 5.

3. The correlation obtained in 1 should be compared with the maximum value of the correlation obtained in 2. If the value obtained in 1 is greater, only SMALL region must be considered, the start angle of the temporal series is less than the transition angle. If the result obtained in 2 is greater, both LARGE and SMALL regions will exist, and the transition angle can be obtained by the intersection of LARGE and SMALL curves.

This method “r4” can be easily implemented in a worksheet, or in a specific code. It works well for tests using large roll start angles and without unexpected behaviors.

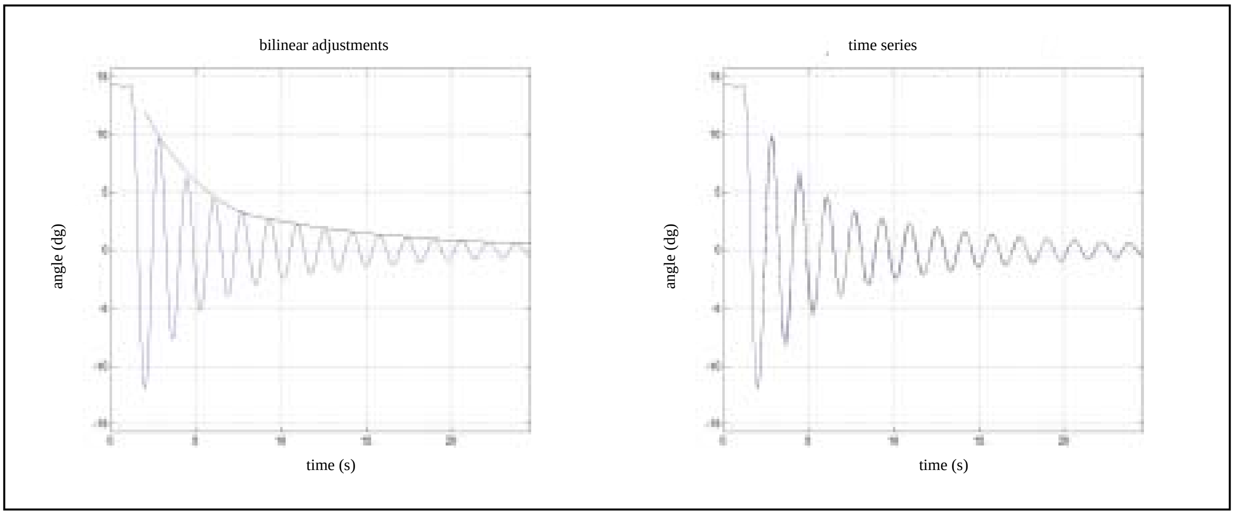

Figure 5. Typical results for the bilinear analysis.

Another possibility using bilinear methods for decaying tests is using a new approach called Error Reduction, based in the minimum square method. In Error Reduction, or “ER” Method, the following steps should be applied:

1. Compute, for the data, all the possibilities of bilinear approach, the coefficients of each approach (for instance, the first two values for LARGE region and the other values for SMALL region, the first three values in LARGE region and the others in SMALL region, until it covers all possibilities, very similar “r4” method). New temporal series are generated using

these coefficients.

2. For each temporal series, the maximum values are obtained and compared with the maximum from the decay original series. The sum of the squares of the differences between these maxima compounds an error function for each possibility of approach.

3. The configuration with the minimum value of the error function defines the best coefficients for the LARGE and SMALL regions. If these coefficients are very close, it means that only the SMALL solution exists.

The “ER” method request more computational requirements, since this method solves the differential equation for each possible solution. On the other hand, this method can solve all types of decaying tests, treating better unexpected behaviors of the original time series. See Figure 6.

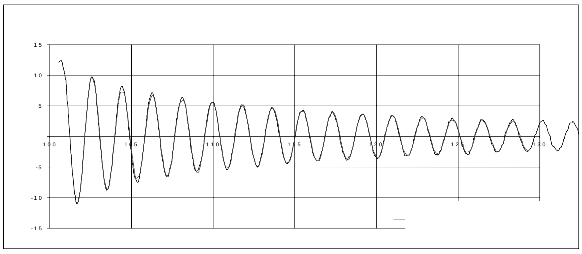

Figure 6. Time series for the “ER” method. comparing bilinear theory with experimental result (b2d42).

4. SEVERAL DECAYING MODEL TESTS

For some model decay tests, bilinear parameters ζ_L and ζ_S and the transition angle were calculated using “r4” and “ER” method. The temporal series of these methods were compared with the original time series in order to compare solutions that agree with the model test. Quadratic modeling was also applied for the same tests, using Faltinsen (1990) and the energy conservation approach, Neves (2004). For each model test, the deviation between bilinear parameters could be compared with the deviation between quadratic parameters p1 and p2. See Faltinsen (1990) for definitions.

There were used model tests from 3 different basins, 4 different ship models, and for a specific model, 3 different drafts were tested with different bilge keels, in a total of 22 tests. Table 1 presents a summary of these tests.

Table 1 Decaying tests performed in several basins, Fernandes et al (2002), LabOceano (2004)

	Code	Basin	Ship
1	a2d51	IPT	1
2	a2d61	IPT	1
3	a6d31	IPT	1
4	a6d41	IPT	1
5	b1d24as	IPT	1
6	b1d22as	IPT	1
7	b2d52	IPT	1
8	b2d51	IPT	1
9	b6d12	IPT	1
10	b6d22	IPT	1
11	b5d11	IPT	1
12	b5d22	IPT	1
13	c2d11	IPT	1
14	c2d22	IPT	1
15	c3d11	IPT	1
16	c3d22	IPT	1
17	Marin-1 *	MARIN	2
18	tatau-12 *	IPT	3
19	pt002-101	LabOceano	4
20	pt002-102	LabOceano	4
21	pt002-103	LabOceano	4
22	pt002-104	LabOceano	4

A computer code was generated in MATLAB® to perform the analysis. This code treats the original time series due to remove a small offset present in the time series and select a desired number of periods desired to perform the analysis. After this first step, the code allows the user to choose the desired approach (quadratic or bilinear) and the desired method to estimate the parameters (Faltinsen 1990 and energy conservation for quadratic approach and “r4” and “ER” for bilinear approach).

Table 2 Results for decaying tests performed in several basins (Fernandes et al 2002) and LabOceano (2004)

Case	ZL_r4	Zs_r4	ZL_er	ZS_er
1	0.0352	0.0137	0.0301	0.0132
2	0.0287	0.0147	0.0254	0.0148
3	0.0483	0.0198	0.041	0.0186
4	0.0577	0.0207	0.0533	0.0202
5	0.0209	0.0088	0.0159	0.0085
6	0.0079	0.0051	0.0094	0.0073
7	0.0467	0.0147	0.0388	0.014
8	0.0544	0.0155	0.0426	0.0149
9	0.062	0.0252	0.0598	0.0243
10	0.0576	0.0244	0.0549	0.0236
11	0.0789	0.0453	0.0871	0.0354
12	0.0723	0.0342	0.0856	0.0341
13	0.0564	0.0322	0.0524	0.0304
14	0.0822	0.0323	0.0682	0.0301
15	0.0733	0.0319	0.0733	0.0319
16	0.0857	0.0349	0.071	0.0326
17	0.0372	0.0243	0.0342	0.0242
18	0.0231	0.0068	0.0167	0.0063
19	0.0664	0.0282	0.0601	0.0272
20	0.0733	0.0287	0.0582	0.0265
21	0.0569	0.0274	0.0534	0.0266
22	0.0552	0.0268	0.0528	0.0255

Table 3 Results of decaying tests performed in several basins, Fernandes et al (2002) and LabOceano (2004)

Case	P1m	P2m	P1ce	P2ce
1	0.0211	0.3531	-0.0177	0.4853
2	0.075	0.1954	0.0304	0.3456
3	0.0696	0.5109	0.0543	0.6157
4	0.0874	0.4581	0.0565	0.5952
5	0.016	0.1103	-0.0067	0.156
6	0.0115	0.1166	0.028	0.0726
7	0.0039	0.3896	-0.0294	0.5091
8	2.87E-04	0.3987	-0.0556	0.5682
9	0.0839	0.5572	0.0812	0.6531
10	0.0541	0.6529	0.0457	0.7551
11	0.1676	0.9171	0.2909	0.6877
12	0.1015	1.1329	0.2963	0.5982
13	0.205	0.6081	0.2072	0.6806
14	0.1825	0.7276	0.1566	0.9051
15	0.2193	0.8224	0.0892	1.3893
16	0.2234	0.7869	0.194	0.9915
17	0.0188	0.2137	0.0138	0.3814
18	-0.0717	0.3901	-0.0955	0.4747
19	0.1699	0.6042	0.206	0.6169
20	0.155	0.6432	0.1582	0.7388
21	0.1712	0.615	0.2147	0.5588
22	0.1607	0.6556	0.2048	0.5772

5. RESULTS

The good agreement between the coefficient values for “r4” and “ER” methods shows that, for a gives series, there is an optimum value of each coefficient that adjust the series, and the methods described here can get a result very close to this optimum value. The same analysis using quadratic approach show some larger deviations and negative linear damping (that not agree with the theory proposed in Himeno (1981). For two different quadratic approaches, the large deviation does not permit to conclude if an optimum set of coefficients exists, because the time series have good agreement with the original series. Because of that, it can be concluded that Faltinsen (1990) method or energy conservation method leads to a good solution, but not a unique solution.

These results also tend to confirm the bilinear theory. For tests with the same physic characteristics (same ship, same bilge keel and same draft), the bilinear approach have presented small coefficient deviations (mainly for SMALL region). This behavior agrees with the theory described in (Oliveira 2003), since the behavior of the LARGE region depends on the vortex shedding and the way this vortex modify the pressure distribution. For SMALL region, the damping is not affected by this effect, and the result tends to be independent of small initial conditions modifications. For quadratic approach, linear damping coefficients have shown large deviations and negative coefficient damping, which is not expected by the theory. For the cases analyzed in this study, bilinear approach seems to have a better agreement with the physics of the problem

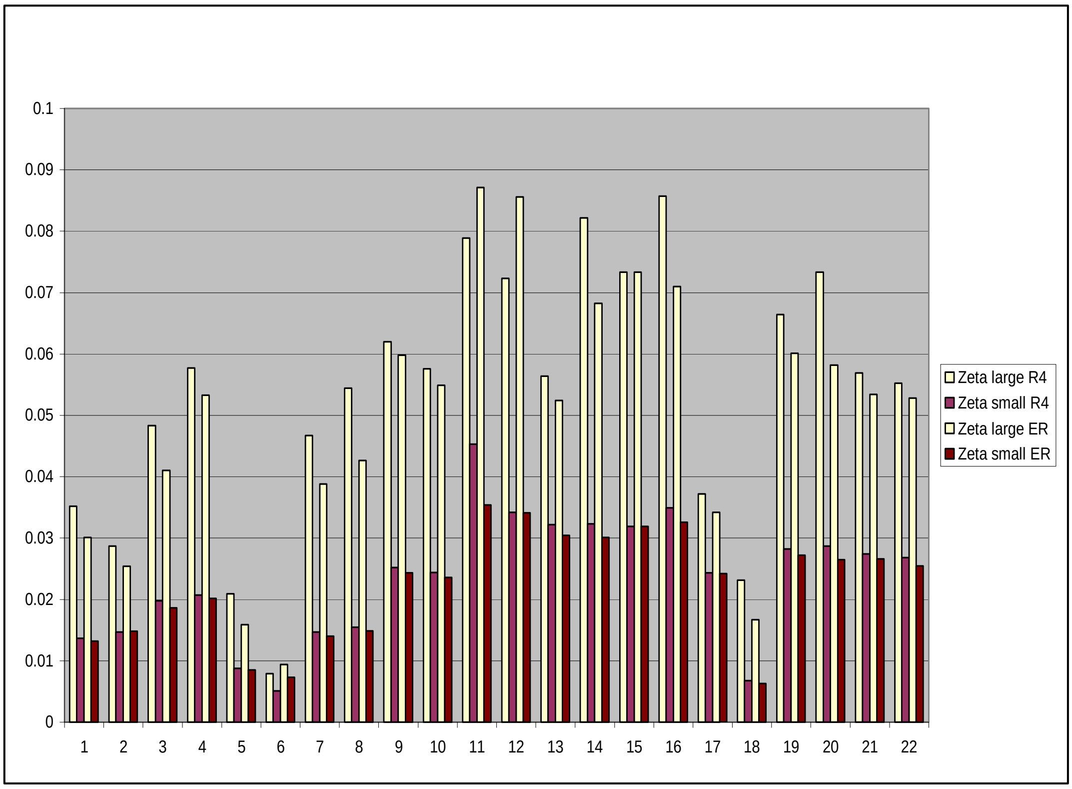

Figure 7. Comparison r4 X ER

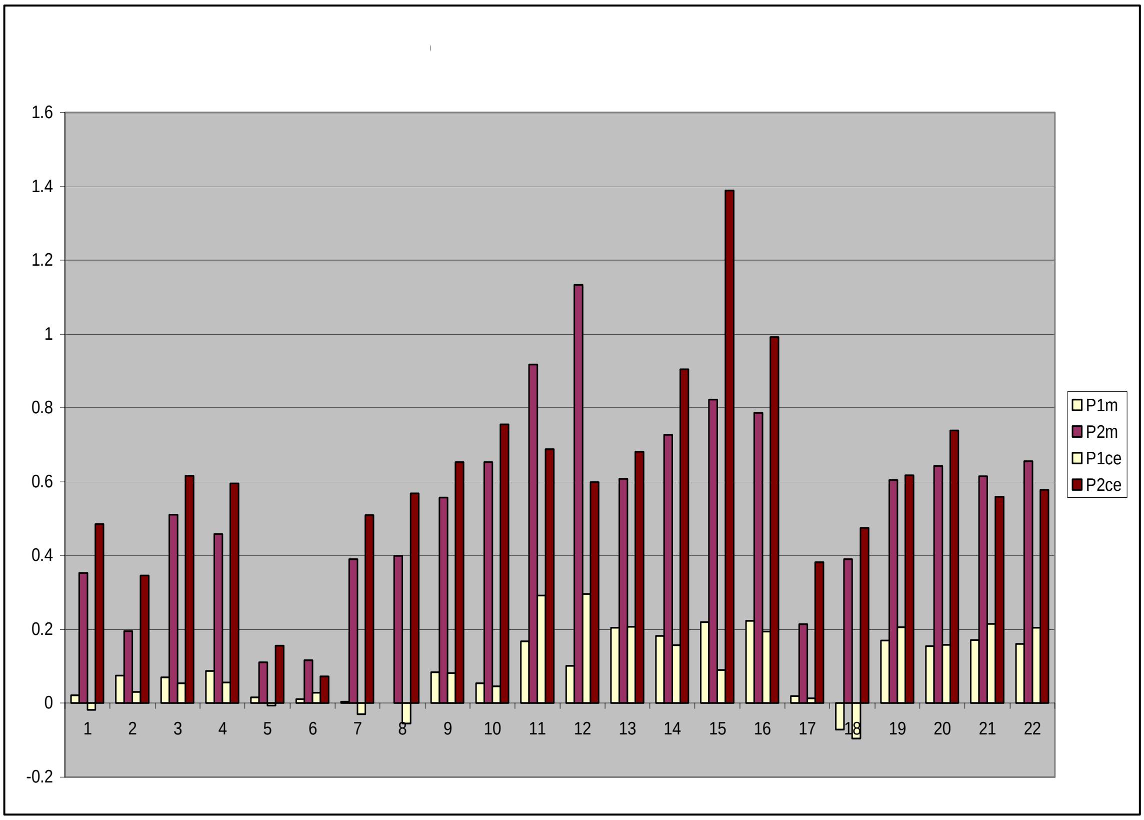

Figure 8 Comparison Faltinsen (1990) X Energy Conservation

The main reason is that the two regions identified by the bilinear approach correspond to two different behaviour characterized by two different KC regime. In the LARGE region a strong vortex has time to be generated and it is attracted to the hull bottom. In the other regime the vortex is shed by the change of the flow direction and is necessarily weak and it is not generated to the bottom by instead it matched with a contrary spinning vortex following a 45 degrees (almost parallel to the ship section diagonal) street.

6. CONCLUSIONS

The work has compared basically two theories, one that is quadratic in nature and another that allows for dual behaviour (bilinear) during the rolling of a FPSO in a decaying test. Besides the better matching with the experiments the work has the impression that the bilinear theory correspond better to the observed physics. It has been possible to identify a LARGER amplitude region with a strong vortex shed and subsequently attracted to the hull bottom and another SMALL region where the vortex travels sidewise (diagonally) in pairs. Clearly this behaviour will never be explained by the quadratic approach that does not identify the transition angle between the two regions.

7. ACKNOWLEDMENTS

The authors thanks CNPq, the Brazilian National Research Council for the support and PETROBRAS for the support and data.

8. REFERENCES

Downie, M.J., Bearman, P.W. and Graham, J.M.R., 1988, "The Effect of Vortex Shedding on the Coupled Roll Response of Bodies in Waves", Journal of Fluid Mechanics, vol. 189, pp. 243-264.

Faltinsen, O. 1990, "Sea Loads on Ships and Offshore Structures", Cambridge Un. Press, UK.

Fernandes, A.C. and Kroft, S.A.B., 2000, "Bi-Linear Modeling Of Wider, Longer and Continuous Bilge-Keels for FPSOs Roll Motion Control", Proceedings 19th International Conference on Offshore Mechanics and Arctic Engineering (ETCE/OMAE2000 Joint Conference), New Orleans, USA, February, 14-17.

Himeno, Y., 1981, "Prediction of Ship Roll Damping: State-of-the Art", Ann Arbor, Un. of Michigan, 75pp, (College of Eng., Dept of Naval Architecture and Marine Eng.), 239.

Marin, 2002, FPSO Roll JIP, www.marin.nl (current projects/ joint industry projects)

Neves, M.A.S., 2004, “Analysis of Roll Decay Tests”, Technical Report, LabOceano, COPPE/UFRJ, June, (In Portuguese).

Oliveira, A. C. 2003, "Investigation on the Bilinear Theory for the Analysis of FPSOs Rolling Motions", Ocean Engineering Program, COPPE/ UFRJ, Federal University of Rio de Janeiro, (in Portuguese).

Ocean Engineering Committee, ITTC, International Towing Tank Conference, 2005, Edinburgh, UK,

Pinheiro, K. A. G., 2003, “Control of Roll Motions of FPSOs”, Final Project, Naval Architecture and Marine Engineering Course, Department of Naval Architecture, Marine Engineering and Offshore Engineering, Federal University of Rio de Janeiro (UFRJ), Rio de Janeiro, (in Portuguese).

Souza, J.R., Fernandes, A.C., Masetti, I.Q., da Silva, S. and Kroft, S.A.B., 1998, "Nonlinear Rolling of an FPSO with

Larger-than-usual Bilge Keels", Proceedings 17th International Conference on Offshore Mechanics and Arctic Engineering (OMAE'98), Lisbon, Portugal, July 5-9.