

New Ideas about an Old Subject: the Roll Damping Assessment via Model Testing

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Abstract

The methodology to obtain the non-linear roll damping from decay tests is very old. It has been proposed by Froude in the XIX century and used from there on. Behind it there is a quadratic model [\dot{x} times $\text{abs}(x)$] for the damping and a subsequent equivalent linearization. Probably all model basin in the world follows this approach to get assess the damping from a decay test. This is well documented [19] and so is the methods to get the p1-p2 coefficients (see main text). This is very general in the sense that in principle, it could be applied to any kind of hull. However, it has become clear that for hull with a flat bottom such as a VLCC (Very Large Crude Carrier) one, the quadratic and third order approach may lead to confusing results such as negative p2. Faced with this, the work presents a completely new idea. The basic attitude it to avoid the polynomial approximation and, instead, devise two regions from the decaying test response. The first, called the large amplitude response region yields a larger damping, probably due to the large bilge keel vortices that are attracted to the hull flat bottom which provide extra low pressure. The second is the small amplitude response region where the vortices are not attracted to the bottom but travels 45° sidewise. These observations has led to a new approach called the bi-linear approach as discussed in the work after analyzing several (many) model test results.

Keywords: Damping Coefficients, Decay Tests, VLCC, FPSO, Roll.

Introduction

Roll damping of ships is probably one of the most investigated topics of ship hydrodynamics. The influence of the viscous effects on this motion has been known for a long time and several approaches have been proposed (since Froude, who lived in the XIX century!) to assess the clearly nonlinear behavior observed in experiments. The classical approach to the problem consists in consider a restoring drag moment that has a linear component plus another one proportional to the square of roll angular. This is the so-called quadratic model. One of the most important contributions for this approach was made by Ikeda's et al.

publications [1], [2], [3], [4]. A both historical and complete review has been provided by Himeno [5]. Trying to yield a method for calculation by the later approach, the coefficients are related to a linear effect, due to the wave radiation damping and also due to viscous effects. The later are related to four effects (friction, lift associated to the ship service velocity, bilge keel local drag effects and vortex shedding influence over the hull). This prediction method, it is used until nowadays after updates that improved some results. See for instance Ikeda [6].

Some authors like Buča et al. [7] proposed cubic fitting for the damping coefficients, avoiding the even function behavior of the quadratic modeling. Although the later may also be avoided by introducing the discontinuity $\dot{\theta}|\dot{\theta}|$ in the quadratic model.

If the problem seems to be solved for ships in the beginning of the eighties, the same could not be said about barge hulls, which have usually sharp edge corners. In this type of hull sections, as can be observed in Downie et al. article [8], published in the end of eighties, the vortex shedding may become the main damping source in roll response. Reference [8] observes that the damping in barges with sharp edge corners is greater than one with bilge radius. More than that, [8] presents a good visualization of the vortex attracted to the hull bottom. This is reproduced here in Figure 1. It was also observed that the influence of the vortex over the hull bottom changes natural period of the system.

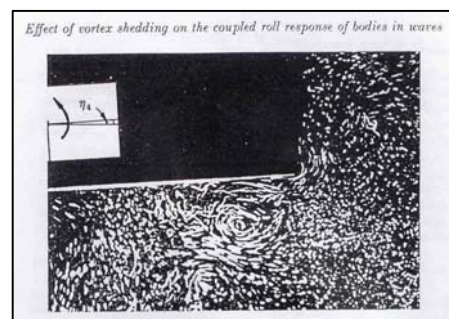


Figure 1 – Flow visualization of vortex shedding, extracted from Downie et al. [8].

In a recent update of his coefficient prediction, Ikeda [6] admits that the prediction method starts to fail while increasing the roll angle of a barge, as can be observed in the Figure 2. The discrepancies, according to [6], “may be because interaction between water surface and shedding vortices from the edge cannot be neglected at larger roll angle”.

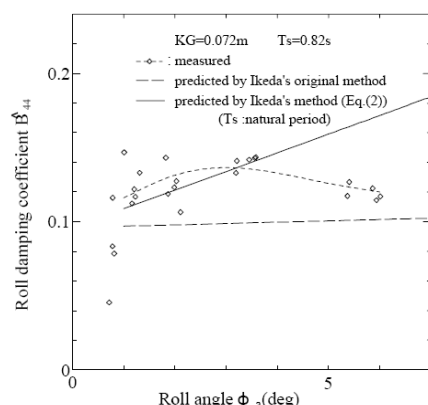


Figure 2 – Comparison between experimental data and prediction method, extracted from Ikeda [6].

The use of old VLCC (Very Large Crude Carrier) ships as Floating Production Storage and Offloading (FPSO) units also introduces questions about roll prediction. Similarly to barges, the VLCCs have flat bottoms. The first conversion designs consider turret mooring system, allowing the units to weathervane with harsh environmental conditions, like a ship that can change the heading to improve its safety. It was expected that the FPSO would align with severe condition directions. However, it was observed that in some locations like the Brazilian coast, swell conditions induces high roll angle as soon it hits the FPSO transversally. The swell itself is non-associated with the local wind, waves and currents in FPSOs. These occurrences motivated studies about extended bilge keels, like the ones by Souza et al. [9], Ferrari et al. [10], Fernandes et al. [11], Pinheiro [12], Oliveira [13] and Oliveira et al. [14]. In a general way, these publications have suggested small correlation obtained while adjusting linear and quadratic coefficients.

Some time ago as reported in Souza et al. [9] it has been recognized the need of a new approach. Subsequently this new approach has been called bi-linear in Fernandes et al. [11] where the polynomial modeling has been considered not essential. The name bi-linear is a way to stress the dual behavior in the rolling behavior as discussed below. By fitting two linear coefficients to describe the phenomenon (see below) the time series was recovered completely as shown later by Oliveira [13]. In fact, Pinheiro [12] and Oliveira [13] have also noticed that the roll damping of ships using large bilge keels are mainly affected by the vortex shedding effect on ship bottom. The extended bilge keel can generate a huge amount of vortices that affects the pressure on the bottom of ship, increasing the damping effect pretty much. Experimentally this has been reported

by Oliveira [13] and Pinheiro [12] and pictures from these are reproduced here for the first time; the picture from first stages (larger angles region) is shown in Figure 3 and another one for later stages (smaller angles region) is shown in Figure 4. Both are from the same decaying test.



Figure 3 – Visualization of the bilge keel vortex formed by a VLCC mid-ship section box rolling is a decay test; first stages (larger region angles) from Pinheiro [12] and Oliveira [13].



Figure 4 – Visualization of the bilge keel vortex formed by a VLCC mid-ship section box rolling is a decay test; later stages (smaller region angles) from Pinheiro [12] and Oliveira [13]; the vortices form a sidewise 45° street - see Figure 6.

The use of CFD tools (Wanderley et al. [15]) for modeling roll problem seems to confirm this proposal, as can be observed in Figure 5 where the behavior for large angles are shown (the vortex is attracted to the flat bottom). See also Kinna [16].

On the other hand, also from [15], the decaying test result for smaller angles is clearly different (much smaller intensity and not attracted to the bottom, but forming a transversal street) as shown in Figure 6.

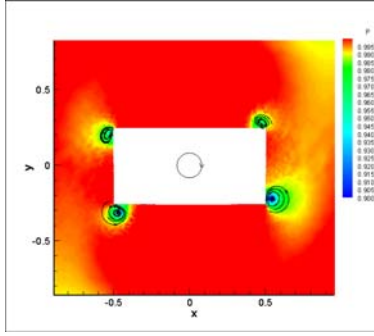


Figure 5 – Pressure distribution for box rolling in a decay test; first stages (larger region angles) from Wanderley et al [15].

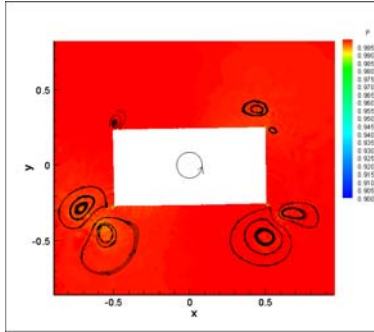


Figure 6 – Pressure distribution for box rolling in a decay test; later stages (smaller region angles) from Wanderley et al [15]; the vortices form a sideways 45° street.

At least one may say that there are many aspects in FPSO roll problem that deserve deeper investigations. Some of them will be covered along this text, but the understanding of vortex shedding mechanism is essential to increase the quality of numerical model. It is quite clear that the vortex effects rule in the damping composition. Also, depending on the rolling amplitude the vortices will be attracted or will form a sideways about 45° street.

Modeling Options

Polynomial Methods

In a more general way, the equation of rolling motions in free decaying for one degree of freedom may be written as

$$\ddot{\theta} + P(\dot{\theta}) + \omega^2 \cdot \theta = 0 \quad (1)$$

Where P is a non-linear function of $\dot{\theta}$.

$$P(\dot{\theta}) = p_1 \cdot \dot{\theta} + p_2 \cdot \dot{\theta} \cdot |\dot{\theta}| + p_3 \cdot \dot{\theta}^3 + \dots \quad (2)$$

A polynomial expansion is just one way to express it since it is ready for linearization. The linearization is

usually the first step to analyze non-linear system. However, the polynomial is by no means the best physical correlation.

Assuming that the variation of the angle during the decay test cycle is slow, the solution in a cycle can be approximated by a harmonic solution:

$$\theta(t) = \theta_m \cdot \cos(\omega \cdot t) \quad (3)$$

The energy dissipated in a half cycle can be obtained by the integration of the motion equation multiplied by the velocity, as shown below:

$$E_D = \int_0^{\frac{T}{2}} (p_1 \cdot \dot{\theta} + p_2 \cdot \dot{\theta} \cdot |\dot{\theta}| + p_3 \cdot \dot{\theta}^3 + \dots) \cdot \dot{\theta} \cdot dt \quad (4)$$

$$E_D = \left(\frac{1}{2} \pi p_1 \omega \theta_m + \frac{4}{3} p_2 \omega^2 \theta_m^2 + \frac{3\pi}{8} p_3 \omega^3 \theta_m^3 + \dots \right) \cdot \theta_m \quad (5)$$

The energy from stiffness moment can be obtained by the expression:

$$E_R = \int_{\theta_i}^{\theta_{i+1}} \omega^2 \cdot \theta \cdot d\theta = -\frac{\omega^2}{2} \cdot (\theta_i^2 - \theta_{i+1}^2) = -\frac{\omega^2}{2} \cdot (\theta_i + \theta_{i+1}) \cdot (\theta_i - \theta_{i+1}) \quad (6)$$

$$E_R = -\omega^2 \cdot \theta_m \cdot \partial \theta \quad (7)$$

Once assumed that **the angle variation is small**, it can be assumed that the energy during a cycle is the same. The consequence is then:

$$E_D \mid E_R = 0 \Rightarrow \partial \theta = \frac{\pi p_1}{2\omega} \cdot \theta_m \mid \frac{4p_2}{3} \cdot \theta_m^2 \mid \frac{3\pi p_3 \omega}{8} \cdot \theta_m^3 \mid \dots \quad (8)$$

This corresponds to the Froude proposal as reviewed by Neves [17] proposal. The approach is called quadratic when the third order terms and High Order Terms (HOT) are ignored. One could also consider adjusting cubic terms, quartic terms and so on. Several combinations of those terms are tested as mentioned before, but the quadratic approach is the most used in ship industry.

Still using the quadratic approximation, another approach is described in Faltinsen [18]. It also consists of finding an equivalent linear damping but using the p_1 and p_2 terms based on the following expression:

$$\int_0^{\frac{T}{2}} (P_e \cdot \dot{\theta}) \cdot \dot{\theta} \cdot dt = \int_0^{\frac{T}{2}} (p_1 \cdot \dot{\theta} + p_2 \cdot \dot{\theta} \cdot |\dot{\theta}| + p_3 \cdot \dot{\theta}^3 + \dots) \cdot \dot{\theta} \cdot dt \quad (9)$$

That leads to the following result [18]:

$$P_e = \frac{2 \cdot \ln\left(\frac{\theta_i}{\theta_{i+1}}\right)}{T} = p_1 + \frac{8}{3\pi} \cdot \omega \cdot \theta_m \cdot p_2 \quad (10)$$

It is shown in [18] that it possible to built a figure with $\frac{8}{3\pi} \omega \theta_m$ in the abscissas. If the model really is quadratic, by using expression (10), the experimental data will then be aligned as a straight line. This line will then cross the coordinate axis at p_1 , while p_2 may be obtained by the inclination of such a straight line.

It could be expected that applying those two approaches to the same test would lead to similar values of p_1 and p_2 coefficients. However, Oliveira et al. [14] has shown that this is a false expectation. Several tests have been analyzed (the tests codes are listed in Table 1) and completely different results are obtained from FPSO decaying tests. This can be observed in the Figure 7. This gives and compares the values of p_1 and p_2 for the 22 decaying tests listed in Table 1.

Table 1 – Test Matrix extracted from Oliveira et al. [14]; the basin where the decay test was performed are in the third column; the ships are all tankers.

	Code	Basin	Ship
1	a2d51	IPT	1
2	a2d52	IPT	1
3	a6d61	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

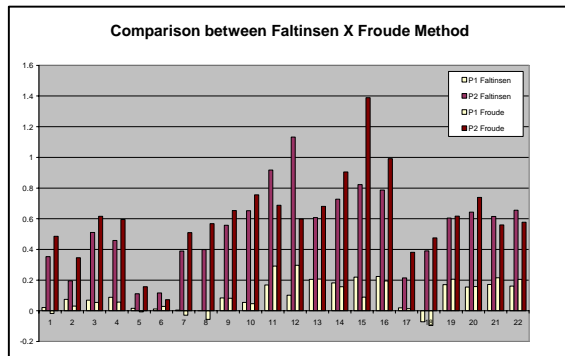


Figure 7 – Comparison between Faltinsen and Froude decay test analysis approach, extracted from Oliveira et al. [14]. Yellowish bars represent p_1 coefficients and red bars represent p_2 coefficients.

As shown next, the approaches considered cannot lead to the same solution for p_1 and p_2 coefficients. Considering the quadratic approach in the Froude proposal and editing the

equation (10), it can be found a very familiar expression in the right side of the equation (11):

$$\frac{\partial \theta \cdot 2\omega}{\pi \cdot \theta_m} = p_1 + \frac{8}{3\pi} \cdot \omega \cdot \theta_m \cdot p_2 \quad (11)$$

Now using (10) again and assuming the same solution as possible it is possible to get the following relation:

$$\frac{2 \cdot \ln\left(\frac{\theta_i}{\theta_{i+1}}\right)}{T} = \frac{\partial \theta \cdot 2\omega}{\pi \cdot \theta_m} \rightarrow \ln\left(\frac{\theta_i}{\theta_{i+1}}\right) = 4 \cdot \frac{\theta_i - \theta_{i+1}}{\theta_i + \theta_{i+1}} \quad (12)$$

This relation can be verified only if $\theta_i = \theta_{i+1}$, that is, only when there is no decay during the test. In practical terms, as can be verified further in this paper, Faltinsen approach works for a very slow variation of decay angle during the test, smaller than the range covered by Froude original proposal. It does not means that the methods should be condemned. The following Figures 7 and 8 show examples of well succeed application of those methods to a decaying test (Santos [21]). The comparison is in Table 2.

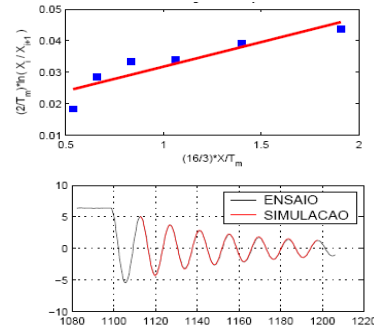


Figure 8 – Faltinsen method applied a FPSO decay test. It can be observed a perfect match between test (gray line) and simulation (red line). Angle unit in decay test graph is degrees.

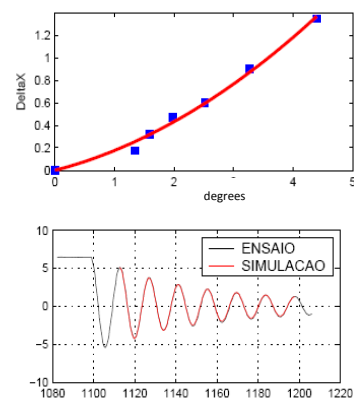


Figure 9 – Froude method applied a FPSO decay test. It can be observed a perfect match between test (gray line) and simulation (red line). Angle unit in decay test graph is in degrees. DeltaX means $\Delta \theta$ and on the abscissas θ_m is shown in degees.

Table 2 – Results obtained for a decay test (Santos, /21/).

Property	Value
Natural Period	14.17 sec.
P1 – Faltinsen Approach	0.0162
P1 – Froude Approach	0.0193
P2 – Faltinsen Approach	0.0156
P2 – Froude Approach	0.0149

Observing the values obtained for coefficients, the difference between the approaches can be considered acceptable in this case. Unfortunately, large discrepancies between methods are common, as can be observed in Figure 9. Small correlation factor brings doubts about the coefficients estimate.

The Faltinsen approach usually presents a larger dispersion results. Both methodologies can present negative values for both p_1 and p_2 coefficients that have non-physical sense. In general it is the authors' opinion that the polynomial methods presents inconsistent results for highly damped ships as FPSOs with large bilge keels or barges with sharp corners, as will be demonstrated below.

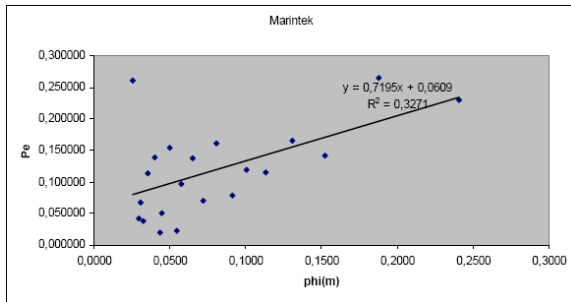


Figure 9 – Example of a Faltinsen approach applied to a Marintek decay test using Equation (10).

Bilinear Method

A breakdown about the roll modeling occurs when it has been noticed that no one is obliged to follow the old polynomial expansion. It has been noticed by the researches reported by Souza et al. [9], Fernandes et al. [11], Pinheiro [12], Oliveira [13] and Oliveira et al. [14] that there are at least two regions according to the angular amplitude. A dual behavior has become clear, then. Thinking about what would be the best way, the first idea has been to propose a bilinear model because of its simplicity. The model still non-linear but it is linear at each region. The bilinear model was proposed by Fernandes et al. [11], based on the evidence of two different behaviors found in decaying tests of VLCC hulls with bilge keels. Results like the ones in Figures 10 and 11, extracted from Oliveira [13], seem to support the new proposition. The first region, with larger roll amplitudes, is called LARGE

region. The second one is called SMALL region. The frontier between LARGE and SMALL regions is characterized by the TRANSITION ANGLE.

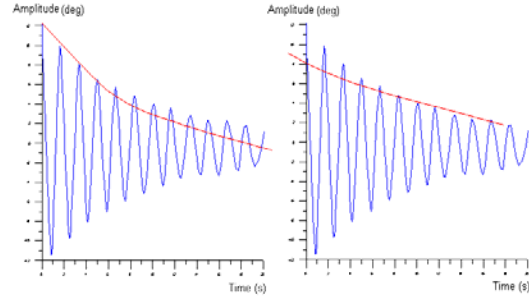


Figure 10 – Evidence of bilinear behavior in a decay test. The linear fit considering large angles that cannot fit linearly the small amplitudes, the linear fit considering small angles either cannot fit linearly the larger ones.

The equation of motion proposed for the bilinear model can be defined as follow:

$$\ddot{\theta} + 2 \cdot \zeta_{bi}(\theta) \cdot \omega_n \cdot \dot{\theta} + \omega_n^2 \cdot \theta = 0 \quad (13)$$

Where:

$$\zeta_{bi}(\theta) = \begin{cases} \zeta_L, & \theta \leq \theta_T \\ \zeta_S, & \theta \geq \theta_T \end{cases} \quad (14)$$

and θ_T is the TRANSITION ANGLE.

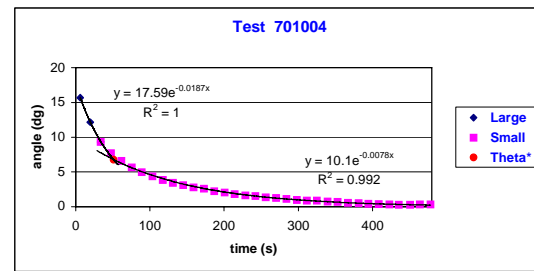


Figure 11 – Bilinear method applied to a model test; extracted from Oliveira /14/.

The methodology to obtain the coefficients was used in Pinheiro [12] and Oliveira [13]. The idea is compute all possibilities of bilinear approach for a test. The most adherent solution is the pair of solutions (LARGE and SMALL) that presents the minimum square error among all possibilities. The error comparison in the bilinear method can be done multiplying the correlation factors of LARGE region and SMALL region, in a process called R4 in Figure 10. Another possibility is to evaluate the sum of the square error between experimental peaks and simulated peaks for each possibility and chooses the minimum error solution. This is the ER process. These two error analysis processes

have been presented in Oliveira et al. [14] and the results are summarized in Figure 12.

The bilinear model, as can be observed in Oliveira et al. [14], shows very small deviation considering the two methods of obtaining the coefficients. It can be said that the R4 and the ER have no significant differences, although ER method have more robustness in the coefficients computation. These results support the consistency of the bilinear method.

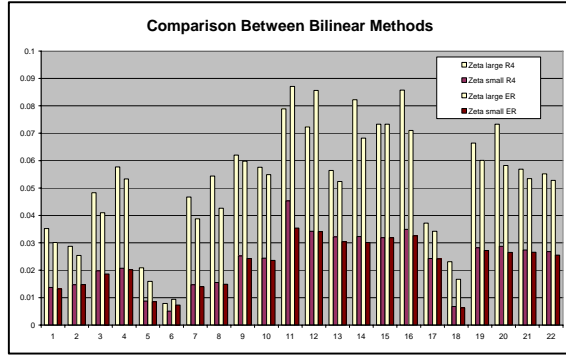


Figure 12 – Comparison between R4 and ER decay test analysis coefficients as shown by Oliveira et al. [14]. Yellow bars represents zeta LARGE coefficients and red bars represent zeta SMALL ones.

With the bilinear idea it is easy /13/ to show that the solution for (13) for a decaying test initial conditions ($\theta(0) = 0$ and $\dot{\theta}(0) = \theta_0$) is such that

$$\theta(t) = Ae^{-\zeta_L \omega_n t} \cos(\omega_n t + \varphi), t_T > t > 0 \quad (15)$$

$$\theta(t) = A_1 e^{-\zeta_s \omega_n (t-t_T)} \cos(\omega_n t + \varphi_1), t > t_T \quad (16)$$

$$\text{Where } A = \frac{\theta_0}{\cos \varphi} \quad (17)$$

$$\varphi = \arctg(-\zeta_L) \quad (18)$$

$$t_T = \frac{1}{\zeta_L \omega_n} \ln \frac{\theta_0}{\theta_T \cos \varphi} \quad (19)$$

$$A_1 = \frac{\theta_T}{\cos(\varphi)} \quad (20)$$

$$\varphi_1 = \arctg \left[-\frac{\theta_T \omega_n (-\tg \varphi - \zeta_L)}{\omega_n \theta_T} - \zeta_s \right] \quad (21)$$

Results like the one shown in Figure 13 have been reported [13]

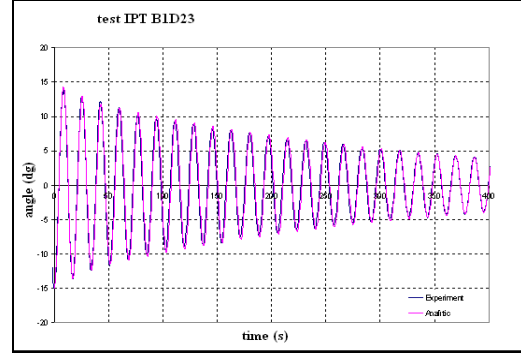


Figure 13 – Recovering a decaying test result with the bilinear analytical solution (Equations (15)-(21)).

The physical behavior behind bilinear modeling has been proposed in Oliveira [13]. Based on the experimental observations already mentioned (Figure (3) and (4)) and incipient CFD results (Figure (5) and (6)). It has becoming clear that in the LARGE region the role of a huge vortex, generated at the bilge keel and attracted to the flat bottom, is almost predominant to define the damping intensity.

For the LARGE region, Oliveira [13] also studied the pressure distribution on the hull with a potential theory four-vortices modeling such that

$$\phi = \phi_1 + \phi_2 + \phi_3 + \phi_4 \quad (22)$$

$$\text{Where } \phi_1 = -k \cdot \arctg \left(\frac{y+b}{x+a} \right) \quad (23)$$

$$\phi_2 = k \cdot \arctg \left(\frac{y-b}{x+a} \right) \quad (24)$$

$$\phi_3 = -k \cdot \arctg \left(\frac{y-b}{x-a} \right) \quad (25)$$

$$\phi_4 = k \cdot \arctg \left(\frac{y+b}{x-a} \right) \quad (26)$$

This leads to Figure 14 shown that the existence of the vortex near the flat bottom affects the pressure on the ship hull significantly.

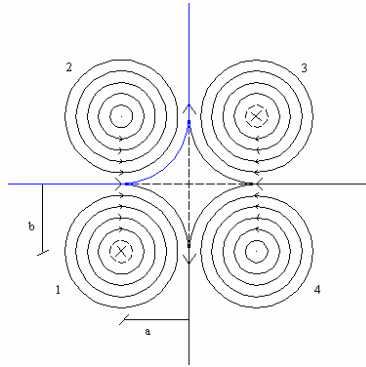


Figure 14 – Four-vortices model has been proposed to show the effect of the vortex on the hull flat bottom pressure; extracted from Oliveira [13]; note that vortex number 2, 3 and 4 are implemented in model only to assure the hull boundary conditions

On the other hand, the SMALL region consists of a vortex dissipation sent away from the hull. In this region the amplitude is so small that the vortex generation is due to the changing of direction of the hull and the vortex in never attracted to the flat hull bottom. As already mentioned they indeed form a 45° with the reverse vortices as shown proposed in Figure 15. The damping is this case is much smaller than in the LARGE region.

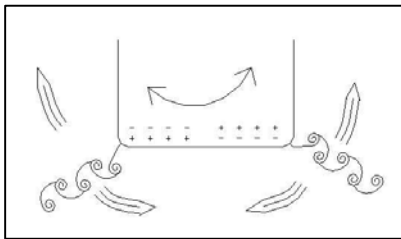


Figure 15 – Scheme of the vortex street generated during ship oscillations.

Large Damping in Large Amplitudes

As mentioned before, the use of VLCC as FPSOs introduces the problem of controlling the large rolling. One of the proposed solutions is enlarge the bilge keels, mainly the breadth of those ones. Studies of damping using large bilge keels seem to conclude that there is a limit of bilge keel efficiency. This has been observed by Pinheiro [12], Ferrari et al [10] and recently by Thiagarajan et al. [19].

This perception complements the non-linear idea that for large angles the damping increases with the roll angle increase.

In fact something interesting can be observed when the initial angle on a decay test. In Figure 16 some results from a FPSO study is shown. This study with low roll motions combined large bilge keels and large natural period of rolling. It is clear from Figure 16 that the poor match of experimental results with the quadratic model simulation when using large initial angles (but in the linear range of GZ curve). This difficulty also can be observed when the tests were repeated without bilge keels in large angles. For small angles, there is a good agreement between experimental and simulation data. See Figure 17.

A reason for quadratic modeling failure in the large angle decay tests is the assumption of small variation of angle during a cycle which is required by the polynomial model. In other words, increasing the polynomial degree will not solve the discrepancies found in experiments as also observed in Oliveira [13]. An approach developed by Matos [20] for grouping several tests for quadratic modeling has been used to exhibit the behavior of damping. This allows the determination of the range of validity.

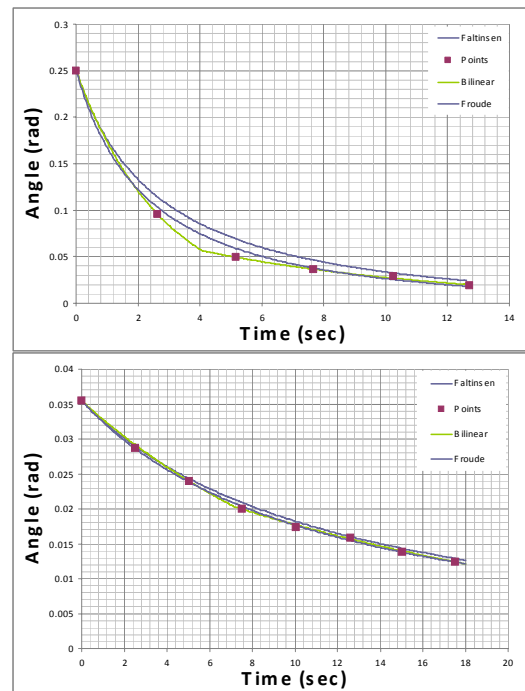


Figure 16 – Comparison among experimental data and simulations for FPSO with large bilge keels. For small angles, it can be observed that all models can reproduce correctly the experimental. For large angles, some difficulties can be observed in simulations using quadratic modeling.

On the other hand, although bilinear modeling seems to provide a better adjustment (and have no dependence about angle variation during the decay test), a deeper observation shows that the bilinear model as proposed in Oliveira [13] cannot explain a phenomena observed in FPSO decay tests.

Considering several tests, varying the initial test angle, it was observed that while the SMALL coefficient has presented small variance with the initial angle (that was expected in bilinear theory), the LARGE coefficient had presented significant variation, as shown in Figure 18.

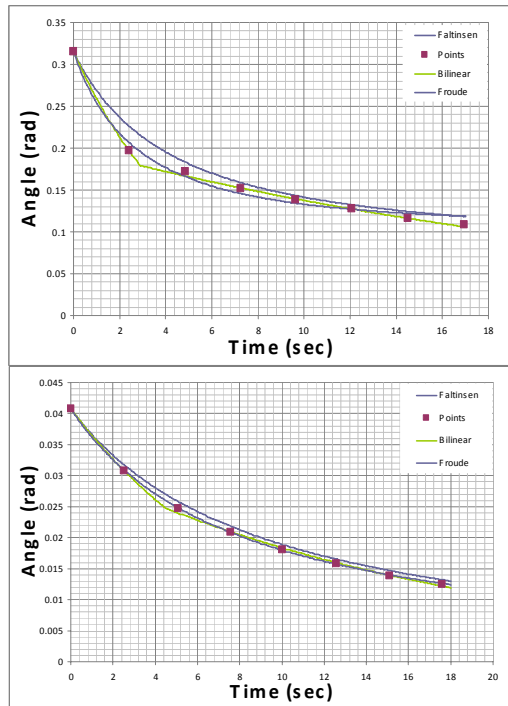


Figure 17 – Comparison among experimental data and simulations for FPSO with no bilge keels. For small angles, it can be observed that all models can reproduce correctly the experimental. For large angles, some difficulties can be observed in simulations using quadratic modeling.

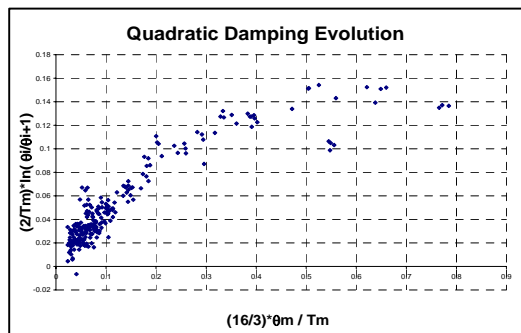


Figure 18 – Compilation of quadratic (Faltinsen) approach applied to 19 FPSO with extended bilge keel tests; positive and negative peaks were considered; it can be noted that the prediction based in small angles overestimates the damping in large angles; it is also possible determining the validation range of coefficients for polynomial modeling.

The variation verified in Figure 18 leads to a conclusion that instead of using one sharp transition angle proposed before, it is more sensible to allow the possibility for a transition range. In this the system changes its behavior from a lighter damping to a higher damping more smoothly. On the other hand, it should be noticed that the information obtained from a single decay test is not sufficient to observe the presence of transition range. Several tests are recommended since the larger damping reduces the number of peaks in the LARGE region. The small number of peaks in the LARGE region allows a small deviation when calculating the LARGE coefficient and consequently, when simulating the series using the bilinear model. This is shown in Figure 19.

The main conclusion is that the non-linear phenomenon depends on the initial conditions as expected. How to deal with this is discussed next.

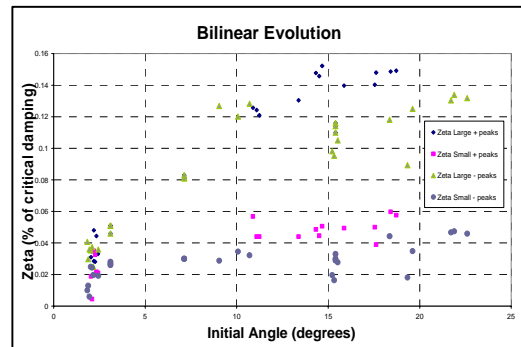


Figure 19 – Bilinear analysis for several decay tests of a FPSO; for the same test, analyses were done considering positive and negative peaks of the time series; it can be noted the variation of Zeta LARGE coefficient with the initial test angle is significant; the Zeta SMALL coefficient, however, have small variation with test angle.

Improving Bilinear Model

As originally proposed, the bilinear theory can predict the FPSO behavior while oscillating in large angles or in small angles, since the LARGE and small coefficients have been obtained from a large initial angle decay test. It covers some of engineering purposes, like maxima prediction or fatigue loads. Since it was identified the presence of transition range, a model considering SMALL and LARGE regions and a transition from one to another is proposed here. It was assumed that the transition occurs continuously.

One advantage is that least square method can be used easily for continuous functions. Based on a continuous model premise, a hyperbolic tangent model was assumed as a first attempt to model the damping behavior through the transition range. The hyperbolic tangent function characteristics allow the simulation of two levels of damping with a continuous transition between them. The rate of change of this transition can be controlled by introducing of

a new parameter α which multiplies the function argument to control the curve slope, as shown below in Figure 20.

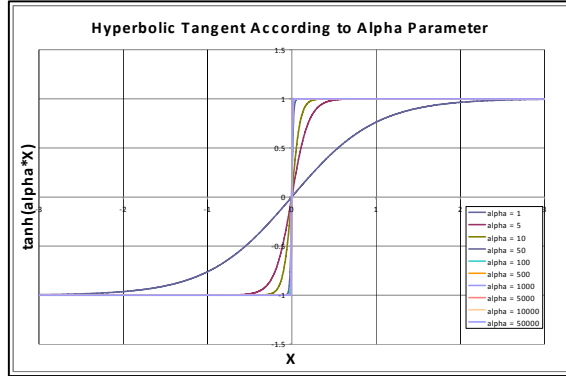


Figure 20 - Hyperbolic tangent evolution according to alpha parameter; it introduces to control the transition phase in damping model.

The control function has to allow a variation from the SMALL region observed to the LARGE one as observed. It is convenient that the expression to be used in the argument is squared, due to the roll characteristics (the same damping behavior is expected for a positive or negative rotation). Two possibilities for the argument are presented in this paper, one considers the roll velocity of the hull and the other considers roll displacement and velocity of the FPSO hull. Considering now the non-dimensional roll equation (27),

$$\ddot{\theta} + 2 \cdot \zeta_{21}(\theta, \dot{\theta}) \cdot \omega_n \cdot \dot{\theta} + \omega_n^2 \cdot \theta = 0 \quad (26)$$

the first attempt is to define the zeta function can be defined as in (27):

$$\zeta_{21}(\theta, \dot{\theta}) = \frac{(\zeta_s + \zeta_b)}{2} + \left(\frac{\zeta_s - \zeta_b}{2} \right) \cdot \tanh \left(\alpha \cdot \left[(\dot{\theta})^2 - (\omega_n \cdot \theta)^2 \right] \right), \theta_i \approx \frac{2}{\alpha} + \theta_T \quad (27)$$

It can be observed that the introduction of the new parameter α and the θ_i which corresponds to the inflection point of the hyperbolic tangent function. In this new formulation, the transition angle limits the region where the transition starts, instead of the point where transition occurs. Both α and θ_i define the width of the transition range (considering the relation in the equation above, just alpha is sufficient to define it). It can be noted that, for $\alpha \rightarrow \infty$ the damping tends to be equal to the classical bilinear approach, like a step function.

Other possibility for the argument of hyperbolic tangent function is one considering displacement and velocity in zeta function, as described below:

$$\zeta_{21}(\theta, \dot{\theta}) = \frac{(\zeta_s + \zeta_b)}{2} + \left(\frac{\zeta_s - \zeta_b}{2} \right) \cdot \tanh \left(\alpha \cdot \left[\left(\frac{\dot{\theta}}{\omega_n} \right)^2 - (\theta_i)^2 \right] \right), \theta_i \approx \frac{2}{\alpha} + \theta_T \quad (28)$$

A reason for the formulation (28) is the way of obtain the experimental data. The measurement of the instantaneous loss of energy during a cycle in a decay test, for instance, is unpractical. An inference can be done if a damping model is assumed, but the difference between peaks in a decay test is easily measured, so it is easy to quantify the energy loss per cycle in the decay problem. The “instantaneous energy” of the system can be normalized and compared to the inflection angle in the same basis.

Some tests considering both methods (27) and (28) were carried out considering decay tests and regular wave tests. To obtain the parameters for both models some decay tests were used and a visual procedure for error minimization was done. The parameters found for the analysis are shown in Table 3.

Table 3 – Parameters obtained for the two approaches.

Property	Velocity	Energy
Alpha	2100 (1/s) ²	274
Inflection Angle	4.09 deg	4.13 deg
Zeta Small	0.02	0.025
Zeta Large	0.14	0.14

The visual method has been chosen to fit the curve adjusting the coefficients to verify the quality of the result obtained. It is possible to use numerical algorithms to determine precisely the correct values for the coefficients, since the function used is continuous and have the first derivate also continuous. In this phase, the major concern is to know whether the hyperbolic modeling can lead to good results.

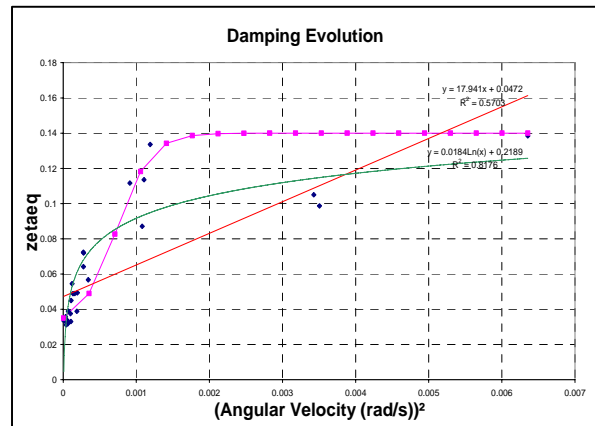


Figure 21 – Example of visual fitting of the hyperbolic model, compared to other kind of fittings.

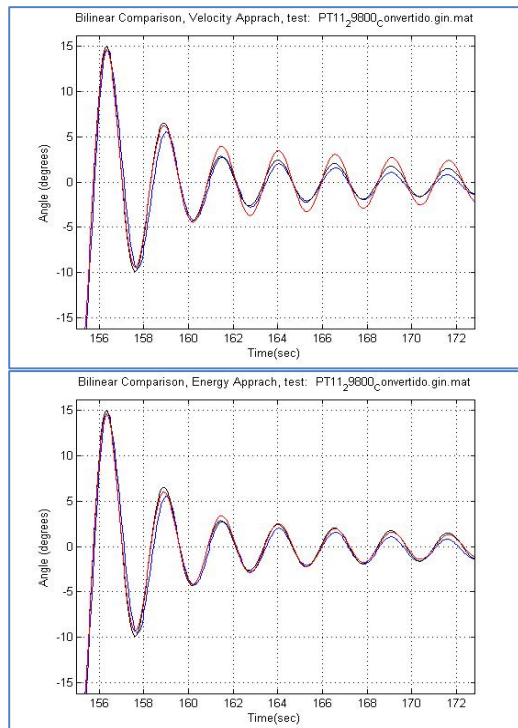


Figure 22– Example of Comparison between the two hyperbolic approaches, the blue line is the experimental, the black one is the simulation considering traditional bilinear approach and the red one is the simulation using the hyperbolic model considering some decay tests.

Conclusions

Fascinating since the 19th century, the roll problem of a ship still have aspects that are not completely understood. The use of FPSOs ship shape with falt bottom, large bilge keels and large natural periods of rolling have forced the community to review the traditional theory. Undoubtedly more research is necessary in this area. In this paper, some questions have been discussed. The main topics are:

- Large damping is a vortex induced phenomena. Even for hulls or structures without edges, bilge keels in high oscillation angles, where large damping were achieved, vortex shedding is observed. When it not occurs as for the case of V shape hulls the traditional theory works well.
- Large damping behavior is not quite well described by polynomial techniques. There is a trend of maximum level of damping that the polynomial techniques can not achieve. The reason seems to be that a large degree polynomial (certainly more than three) is necessary to describe the discontinuous large amplitude rolling.
- A single decay test cannot yield all information necessary about the damping behavior, the idea

of multiple testing provide a better understanding of the problem.

- The bilinear theory may be improved to consider the transition region.
- The use of a continuous function to represent the damping behavior is desirable, allowing the possibility of using numerical techniques to obtain the function parameters by error minimization.
- The hyperbolic approach (the first continuous model tested) seems to be capable to provide good results even for regular wave ship behavior, although is in the beginning of the test phase.

Acknowledgements

The Authors would like to thanks the PETROBRAS R&D Center Basic Engineering Design Deapartment for the support, as well as Mr. Paulo Mauricio Videiro, Mr. Luis Augusto Petrus Levy and Mr. Vinicius Leal Ferreira Matos who made available some tests/analyses presented in the work.. CNPq is also greatly acknowledged.

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