Proceedings of the ASME 2010 29th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2010
June 6-11, 2010, Shanghai, China

OMAE2010-20093

DAMPING COEFFICIENT ANALYSES FOR FLOATING OFFSHORE STRUCTURES

Edgard B. Malta
(edgard@tpn.usp.br)

Rodolfo T. Gonçalves
(rodolfo_tg@tpn.usp.br)

Fabio T. Matsumoto
(fabio_matsumoto@tpn.usp.br)

Felipe R. Pereira
(rateiro@tpn.usp.br)

André L. C. Fujarra
(afujarra@tpn.usp.br)

Kazuo Nishimoto
(knishimo@usp.br)

TPN – Numerical Offshore Tank
Department of Naval Architecture and Ocean Engineering
Escola Politécnica – University of São Paulo
São Paulo, SP, Brazil

ABSTRACT

The damping evaluation of floating offshore systems is based on the viscous effects that are not considered in numerical models using the potential theory. Usually, different techniques for different systems are used to evaluate these hydrodynamic coefficients. The total damping is separated by potential and viscous damping, the first one is evaluated numerically and the second through experiments at reduced scale model. Common techniques considering linear motion equations cannot be applied to all degrees of freedom. Some methods were compared for results of decay test, such as: exponential and quadratic fit. Fourier transform (FT) spectral analysis and Hilbert Huang transform (HHT) can be used to evaluate the signal natural frequency and with HHT this can be done during the time domain. Also, analysis through the Random Decrement Technique (RDT) is presented to demonstrate the damping evaluation for irregular waves. The method to obtain external damping was presented for the different techniques in an ITTC semi-submersible model. The linear method is not sufficient to predict the damping coefficient for all the cases, because in most of them, the viscous damping was better represented by a quadratic fit. The HHT showed to be a good alternative to evaluate damping in non-linear systems.

KEYWORDS

damping coefficient, model test, numerical simulation, floating offshore system.

NOMENCLATURE

A	added mass matrix
B_1	linear component of damping
B_2	quadratic component of the viscous damping matrix
B_{crit}	critical damping
B_{ext}	viscous (external) damping matrix
B_{Pot}	potential damping matrix
C	stiffness matrix
F_{ext}	external forces vector
M	mass matrix
S	power spectrum energy
T_d	damped natural period
x	displacement vector
$\dot{x}$	velocity vector
$\ddot{x}$	acceleration vector
$\bar{x}$	mean displacement
x_0	initial displacement condition
x_k	amplitude of the peak k
δ	logarithmic decrement
ω_d	damped natural frequency
ω_n	natural frequency
ζ	linear damping coefficient (percentage of critical damping)

1. INTRODUCTION

As a rule, damping forces are some of the most important issues to be correctly consider in the motion evaluation on offshore structures. Numerical codes, based on wave potential theory, can accurately estimate the potential forces but not the viscous one, once it does not solve the complete Navier-Stokes equation. Commonly, codes in Computational Fluid Dynamic (CFD) predispose to take into account this viscous component but due to free surface effects they are not so efficient to evaluate it correctly. This reason gives rise to the need of model tests to evaluate the viscous effects and the need to choose the best method to define the damping coefficients.

The common test used by designers to obtain the viscous damping coefficient is a free oscillation test in which the decay signal is analyzed. Depending on the system, the linear or non-linear motion equation can be applied to evaluate the viscous components. Another usual test for floating units is an irregular wave test in which it is possible to evaluate the damping coefficients using the Random Decrement Technique (Yang *et al.*, 1985). Both signals from free oscillation test and irregular wave test can be analyzed using complementary techniques such as the spectral analysis using the Fourier Transform (FT), used to determine the natural period, and the Hilbert-Huang Transform method (HHT) developed by (Huang *et al.*, 1998), which can be used to determine the instantaneous frequency and motion amplitude in time.

In the offshore scenario, the difficulty to consistently determine the contribution of viscous damping component was shown by some authors. (Malta *et al*., 2006) demonstrated the influence of each term of the viscous damping matrix in the coupled motions between the monocolumn platform and the water inside its moonpool. In another work, (Malta *et al.*, 2009) presented results from non-linear damping effects in the design of a FPSO and a TLWP at a small distance.

Finally, (Rateiro *et al.*, 2010) showed the free oscillation and irregular wave tests for ITTC - SR192 scaled model coupled with riser lines, with and without current. Different damping coefficients were used to explain the riser and current influence on the unit motion. Thus, using these tests, the present paper shows different methods to evaluate the damping coefficients.

In the Section 2 the theoretical background for the methods is presented. Section 3 shows examples of decay tests signals and the development of the damping coefficients for each different method. Finally, Section 4 presents the discussion and conclusion about the applied methods.

2. THEORETICAL BACKGROUND

The non-linear motion equation for a floating unit can be written as:

$$(M+A)\ddot{x}+(B_{ext}+B_{Pot})\dot{x}+B_2\dot{x}|\dot{x}|+Cx=F_{ext} \quad (1)$$

where: M is the mass matrix (6x6), A is the added mass matrix, B_{ext} and B_2 are damping coefficients matrix related to viscous damping, B_{Pot} is the potential damping matrix, C is the stiffness matrix and F_{ext} is the vector of external forces. The terms x, $\dot{x}$ and $\ddot{x}$ are displacement, velocity and acceleration vector, respectively, for each degree of freedom.

Matrix A and B_{Pot} so that F_{ext} can be provided by a numerical code based on the potential theory. Matrix C is composed by hydrostatic and line restoring forces. To completly evalute equation (1), the external damping, B_{ext} and B_2 still need to be evaluated. These parameters, in general, are obtained from model tests and different methods to estimate the viscous damping are explained below.

Linear Damping

The most common way to determine the viscous damping is through free decay tests. The equation of motions for the free decay tests, considering only the linear damping and no external forces, is a simplification of Equation (1) as:

$$(M+A)\ddot{x}+B_1\dot{x}+Cx=0 \quad (2)$$

where the sum between B_{ext} and B_{Pot} can be written as B_1. This equation is linear and can be written in non-dimensional form as:

$$\ddot{x}+2\zeta\omega_n\dot{x}+{\omega_n}^2x=0 \quad (3)$$

where ζ is a percentage of critical damping B_{crit} (ζ=B_1/B_{crit}) and ω_n is the natural frequency of the motion ($\omega_n=\sqrt{C/(M+A)}$). Equation (2) is linear and its solution can be written as:

$$x=x_0e^{-\zeta\omega_nt}\cos\sqrt{1-\zeta^2}\omega_nt \quad (4)$$

where x_0 is the initial condition of motion. A exponential fitted curve can be adjusted through the amplitude peaks x_k, the parameters *a* and *b* from exponential fit can be found as:

$$x=x_0e^{-\zeta\omega_dt}=ae^{-bt} \quad (5)$$

where ω_d is the damped natural frequency obtained from the oscillations of free decay tests. Thus, the natural frequency ω_n can be written as:

$$\omega_n=\omega_d/\sqrt{1-\zeta^2} \quad (6)$$

Linear Damping for Different Amplitudes

The damping level can vary for different amplitudes, i.e. $B_1(x)$. This fact can occur because the viscous damping has a quadratic behavior (or non-linear) or even in cases of non-linear stiffness of the system. The equation below should be used to represent these situations, in which the damping coefficient is defined in terms of the amplitude motion x.

$$(M + A)\ddot{x} + B_1(x)\dot{x} + Cx = 0 \tag{7}$$

or in the non-dimensional form as:

$$\ddot{x} + 2\zeta(x)\omega_n\dot{x} + {\omega_n}^2 x = 0 \tag{8}$$

The relation between the logarithmic decrement δ and the damping coefficient can be demonstrated below.

$$\bar{x} = \frac{x_k + x_{k+1}}{2} \tag{9}$$

$$\delta = \ln x_k - \ln x_{k+1} \tag{10}$$

$$\cos\omega_d t = 1 \rightarrow t = \omega_d T_d k \tag{11}$$

$$\delta = \ln\left(\bar{x}e^{-\zeta\omega_d T_d k}\right) - \ln\left(\bar{x}e^{-\zeta\omega_d T_d (k+1)}\right) \tag{12}$$

$$\delta = \ln\left(\bar{x}e^{-\zeta 2\pi k} / \bar{x}e^{-\zeta 2\pi (k+1)}\right) \tag{13}$$

$$\delta = \zeta(\bar{x})2\pi \tag{14}$$

$$\zeta(\bar{x}) = \delta/2\pi \tag{15}$$

where T_d is the damped natural oscillation period (note in this case the damped natural period is kept constant).

Quadratic Damping

The floating unit dynamic can present a non-linear behavior due to the damping forces. Studies have shown that the quadratic equation (16) is more appropriated to represent the viscous damping forces.

$$(M + A)\ddot{x} + B_1\dot{x} + B_2\dot{x}|\dot{x}| + Cx = 0 \tag{16}$$

or in other form as:

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \frac{B_2}{M + A}\dot{x}|\dot{x}| + {\omega_n}^2 x = 0 \tag{17}$$

For evaluating the term B_2, first the linearization of the term $\dot{x}|\dot{x}|$ is performed as follows:

$$\dot{x}|\dot{x}| = \frac{8}{3\pi}\omega_n\dot{x}_k\dot{x}_k \tag{18}$$

The linearization in equation (18) allows writing:

$$\frac{1}{2\pi}\ln\frac{x_{k-1}}{x_{k+1}} = \zeta + \frac{4}{3\pi}\frac{B_2}{(M + A)}x_k \tag{19}$$

Equation (19) can be used to determine the values of ζ and B_2. Details about this procedure can be found in (Chakrabarti, 1994).

Spectral Analysis

Another way to determine the damping coefficients and natural periods is based on the power spectrum of the signal obtained from the decay test. The value of the power spectrum in natural frequency determines the damping coefficient as the following equations:

$$S(\omega_1) = S(\omega_2) = \frac{\sqrt{2}}{2}S(\omega_n) \tag{20}$$

$$\zeta = \frac{1}{2}\left(\frac{\omega_2 - \omega_1}{\omega_n}\right) \tag{21}$$

where $S(\omega_n)$ represents the energy level of the power spectrum in the natural frequency (the maximum energy level for assumption occurs in the natural frequency in signals of linear systems obtained from decay tests), ω_1 and ω_2 represent the frequencies at which the energy level is $\sqrt{2}/2$ of the energy in ω_n. This procedure is reasonable only for narrow band signals, but it is very simple to be applied.

Another kind of spectral analysis uses the Hilbert transform as presented in (Huang *et al.*, 1998). The method is called Empirical Mode Decomposition (EMD) and through the decomposition of the signal in some functions, called Intrinsic Mode Functions (IMF), the Hilbert-Huang spectrum is obtained with information about the amplitude and frequency during time. The information given by HHT can be used by the methods explained before providing better results.

Random Decrement Technique

This technique considers that the response of the floating units is linear and it is subjected to a random excitation, as occurs in an irregular wave. Assuming the external force is zero-mean, stationary and a Gaussian random process, the response will also have these characteristics.

The technique computes the average of the response segments with the same length. The segments are chosen with a constant value and with the slope alternating from positive to negative.

The choice of the constant value is a percentage of the root-mean-square value and the signal that remains after the averages is a decayed oscillation that should be analyzed with the methods described above. Details about this method can be found in (Yang, *et al.*, 1985).

3. METHOD COMPARISONS

This chapter presents the different methods to evaluate the damping coefficient for floating units. A comparison is made using some tests carried out at the IPT towing tank with ITTC-RS192 scaled model presented in (Rateiro *et al.*, 2010). The model was moored in the towing car by “quasi” horizontal mooring lines. The lines did not provide a significant restoring force for vertical motions (heave, roll and pitch) and negligible damping forces. On the other hand, a group of risers was located on board of the model in order to represent its influence on the damping and restoring forces. Also, the current influence on the dynamic behavior was verified by tests with and without current. Figure 1 presents the test setup overview.

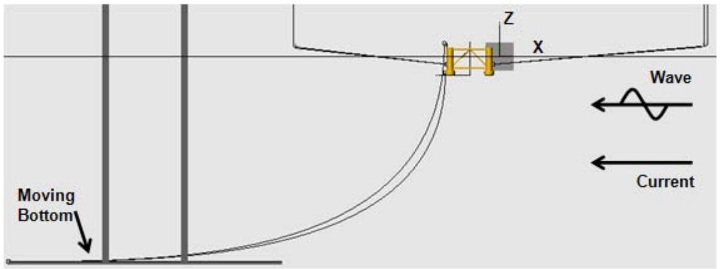

Figure 1 –Model test overview [(Rateiro *et al.*, 2010)].

Table 1 presents the main ITTC dimensional properties in the real and model scale.

Table 1 – ITTC RS-192 main properties

Main Dimensions		
	real scale	model scale
Total lenght	115 m	109.52 cm
Beam	75 m	71.43 cm
Draft	27 m	25.71 cm
Height	43 m	40.95 cm
Displecement	37413 ton	32.32 kg

Mainly, the roll decay tests were chosen for comparison because this motion was more affected by external agents: current and risers. Next, each method is applied to different test conditions, and the advantages and disadvantages for each technique are presented.

The analyses were performed for three conditions:

- Condition 1: Without risers and no current;
- Condition 2: With risers and no current;
- Condition 3: With risers and current.

Exponential, Linear and Quadratic Fit

The exponential fit is a method commonly used to determine the damping coefficient used on the linear motion presented in equation (2).

Figure 2 presents the sway decay test for the ITTC model (dashed line) and a numerical simulation represented by linear simulation using exponential fit (solid line). The comparison of the motions showed a good agreement between the decay test signal and the numerical simulation. It is possible to note that the exponential fit undergoes almost all extreme points. This fact is explained due to the linear behavior of the sway motion for this platform, which confirms the coherence of using the damping in linear form for this case.

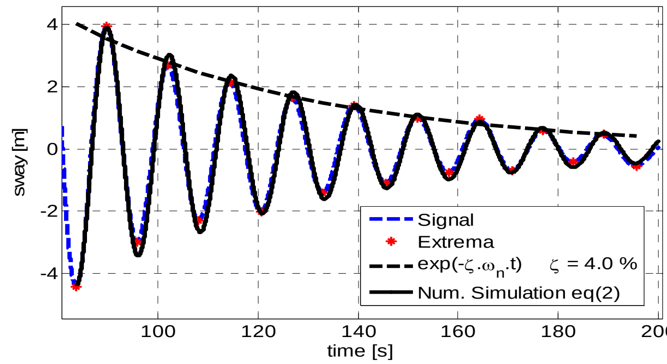

Figure 2 - ITTC sway decay test vs Exponential fit for condition 1

However, if the system has a non-linear behavior, this method generally underestimates the viscous damping effects and the simulation decays more slowly than in the effective decay test signal.

In Figure 3, the differences between a linear simulation and the roll decay test are presented. It is possible to see that the simulation results (solid line) are larger than the decay test ones (dashed line), this fact can be explained by the non-linear behavior of this motion that implies a non-linear damping behavior.

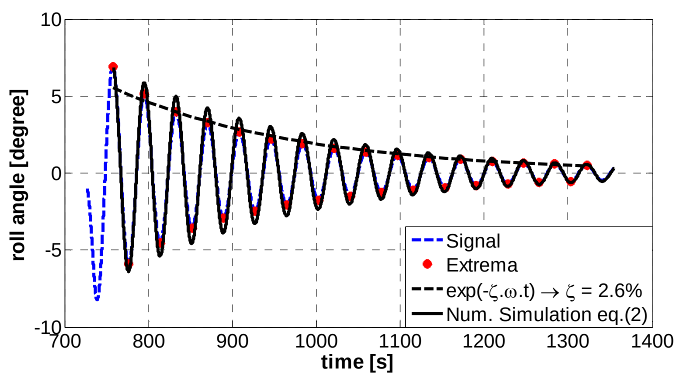

Figure 3 - ITTC Roll decay test for condition 1 using an exponential fit

Although it is not recommended to use the linear method for non-linear systems, it is possible to employ the linear equation (8), which considers logarithmic decrement for each motion amplitude using different damping levels. Figure 4 presents the results of linear damping level for different amplitude motions; the test used is the same presented in the example in Figure 3. It is possible to note that the damping level is larger for larger motion amplitude, which confirms that the damping level is dependent on the motion amplitude, i.e. $B_1(x)$.

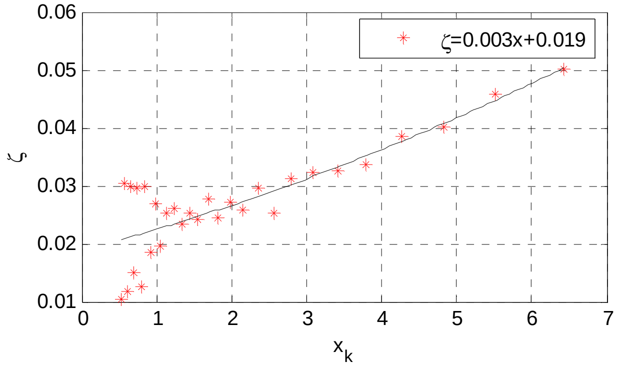

Figure 4 – Different damping levels for roll in condition 1

In general, the use of linear motion equation allows predicting the Response Amplitude Operator (RAO) once the wave exciting force is determined. The region most influenced by the damping force is the one close to the natural period. As seen previously, the damping level can be different for each motion amplitude; this fact implies a correct adjustment of RAO for a specific sea condition. Generally, the significant amplitude of motion is used to take the damping coefficient using the method presented in Figure 4.

An example of numerical RAO curve adjusted for two damping levels is presented in Figure 5; the tests were performed for heave motion. The RAO results from transient wave tests (thin line) and regular waves (points) are also presented in Figure 5. The values of linear damping used to adjust the RAO curve were $\zeta = 3\%$ and $\zeta = 5\%$ for RAO obtained from transient wave tests and regular wave tests, respectively. This difference is due to the different motion amplitudes for each test, in which the larger motions in the regular wave tests imply a larger linear damping coefficient. The use of different damping levels showed to be satisfactory in this example case to adjust the RAO curve.

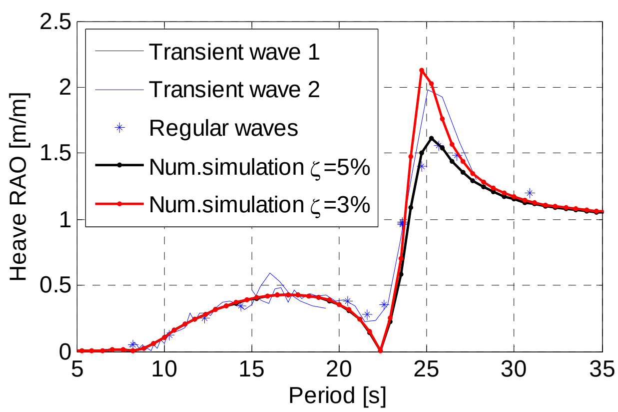

Figure 5 – Comparison of different damping levels in ITTC Heave RAO for condition 1

The example in Figure 3 did not agree very well with the linear damping simulation; therefore, the quadratic damping can be used. Non-linear systems can be more adequately represented by quadratic damping behavior, in which the damping effect should be separated in two parts (B_1 and B_2) and can represent different amplitude levels. The correct evaluation is to simulate equation (16) and to verify the result with the model test. The linearization proposed in equation (19) is presented in Figure 6 for the roll decay in condition 1, the same decay test presented in Figure 3. The linear fit for this extinction curve results in a $\zeta = 1.8\%$ and $B_2/(M + A) = 0.01$.

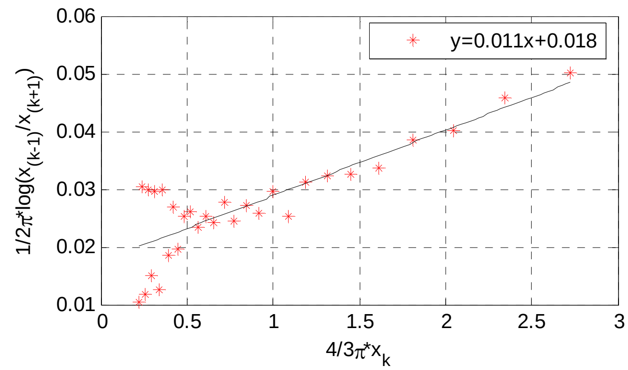

Figure 6 - Quadratic Fit for roll decay for condition 1

In Figure 7, the quadratic damping simulation and the roll decay test are compared for condition 1. The comparison shows a good agreement between them. It should be noted in the difference between the ζ that value decreases from 2.6% to 1.8%, in which this term represents the linear component of damping forces.

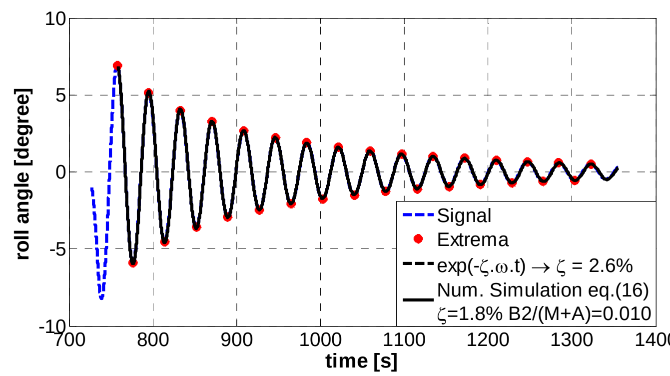

Figure 7 – ITTC Roll decay test for condition 1 using a quadratic fit

An interesting result obtained from the use of quadratic damping simulation is the comparison of the influence of the risers on the damping forces. As seen in Figure 8, the presence of the risers increases the term $B_2/(M + A)$ from 1% to almost 10%, for roll tests performed in condition 2; this increases occurred in the quadratic component of damping, i.e. the component that depends on $\dot{x}|\dot{x}|$. It is important to highlight that the quadratic fit, in this case, still yields a coherent numerical simulation.

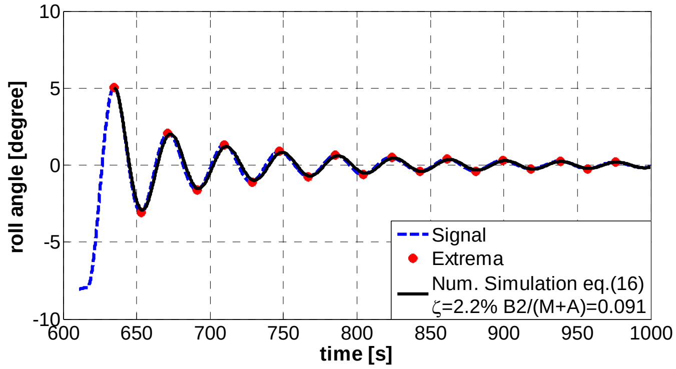

Figure 8 – ITTC Roll decay test for condition 2 using a quadratic fit

Spectral Analysis

The spectral analyses are complimentary techniques used in the damping coefficients evaluation. Two methods, the FT and HHT are compared here. The FT is easy implemented and there are many codes ready to use. However, there is a problem with broadband signal; for example, in signals in which two frequencies are close, it is hard to define the main frequency. The HHT is hard to implement and the definition of the IMF is affected by the signal length. There is the advantage of obtaining the instantaneous amplitude to create an extinction curve not only with the signal peaks using HHT. Thus, all other methods can be applied to evaluate the damping coefficient. Also, it is able to separate time scales and to verify if the system has some coupling.

The comparison was made for a roll decay signal carried out for a condition with current and risers and it is presented in Figure 9. Note that for this particular example, the implementations of an exponential fit or even a quadratic fit are not straightforward. The extreme values are not defined with the maximum values above zero and the minimum below zero. For that reason, the numerical simulation does not agree with the model test signal.

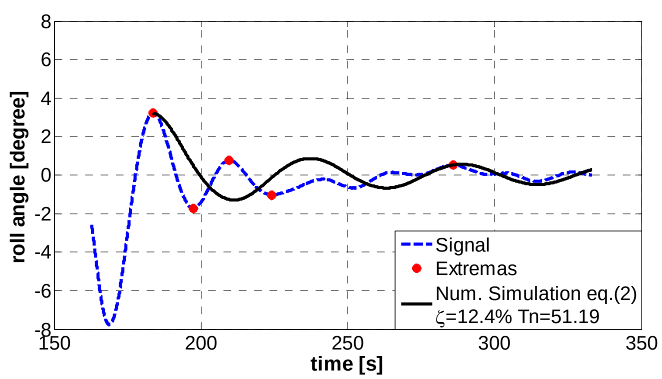

Figure 9 – ITTC Roll decay for condition 3

The spectral methods where applied to the roll decay tests in condition 3, as can be seen in Figure 10 and Figure 11. The linear damping simulation was compared to show that this kind of simulation does not agree with the model test signal. The difficulty in this type of signal is to determine the natural frequency, because it has a modulation in time. Figure 10 shows the comparison of power spectrum obtained from FT and HHT. The power spectrum obtained from HHT showed that the energy is well defined while the FT one showed a broadband spectrum that markedly complicated the natural frequency determination.

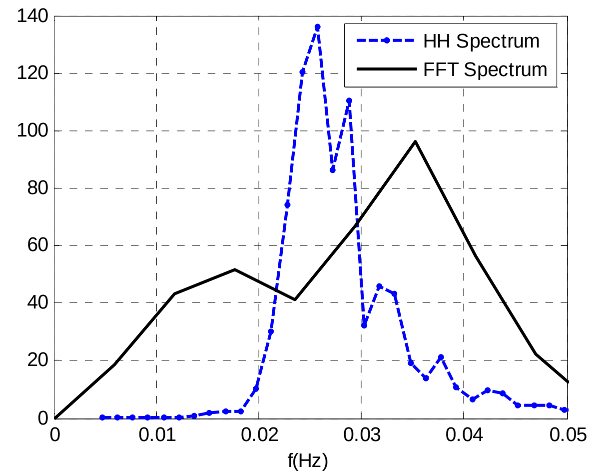

Figure 10 – Comparison of Hilbert-Huang and FFT spectrum for the signal in Figure 9

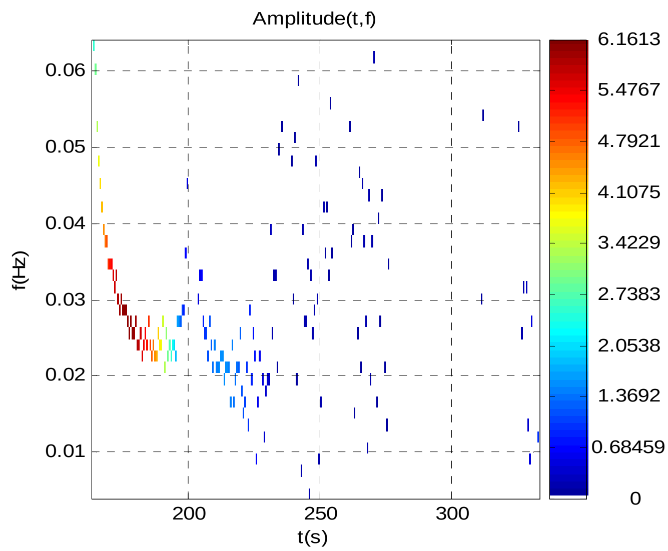

Figure 11 - Hilbert-Huang Spectrum for the signal in Figure 9

The HHT spectrum presents a frequency-amplitude-time plot. Figure 11 shows the HHT spectrum from the example signal in Figure 9. It is possible to observe that the instantaneous frequency is not constant. From this result, it can be concluded why the linear or even quadratic simulations would not agree with the model test. The reason is that both methods are based on a single natural frequency, and for the same reason, the FT spectrum presented a broadband energy.

The HHT spectrum is a good way to determine the time range at which the decay test is possible to represent the phenomena from linear or quadratic simulations.

Random Decrement Technique

Finally, the damping levels can also be evaluated from irregular signals. An example of the RDT is shown in Figure 12; and in Figure 13, the result of the damping evaluation after the use of RDT is presented. It should be noted that the ζ value of 2.2% was close to the roll decay test for condition 1 of 2.6% from the exponential fit in Figure 3 and 1.8% from the quadratic fit in Figure 7. The value obtained from RDT is most realistic because the floating unit, in an irregular wave, has motion behavior similar to that in sea conditions, thus the damping level considers the different motion amplitudes in this case.

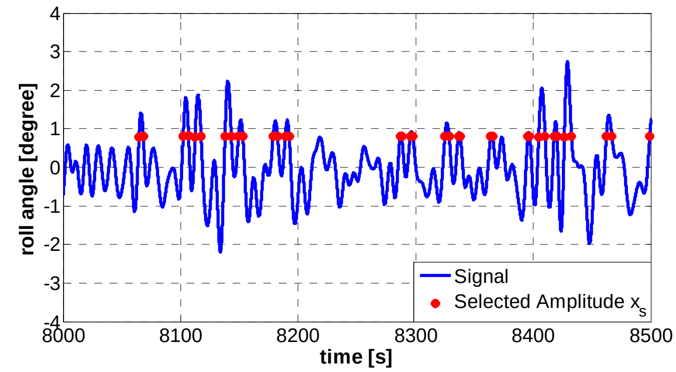

Figure 12 – Roll motion at irregular waves for condition 1 with RDT amplitudes

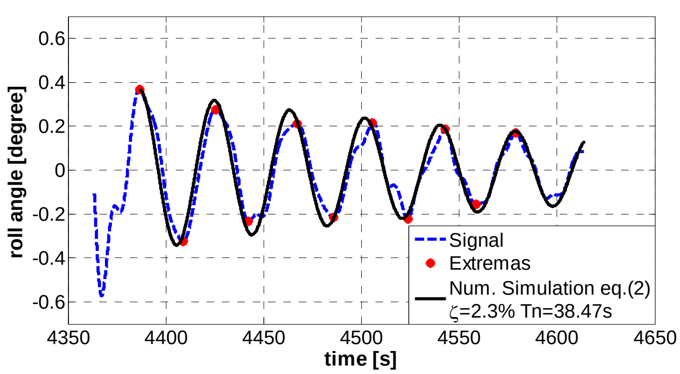

Figure 13 – Random Decrement Technique for signal in Figure 12

4. CONCLUSION

The method to obtain external damping for numerical models should be applied to adjust damping coefficients for each degree of freedom. The paper presented some methods using as an example mainly the roll motion for the ITTC-RS192 model test from (Rateiro *et al.*, 2010).

The exponential fit is a coherent choice when the system damping is purely linear. For quadratic damping, the option is the linearization for each amplitude level or a quadratic fit for the extinction curve.

Also presented is how to evaluate the signal characteristics through spectral analysis in cases where the motion analysis is coupled with other effects, such as the presence of current and risers, in which the HHT spectrum using EMD is a better alternative for identifying the phenomenon.

In summary, the paper presented different methods to evaluate the damping coefficients for different motion behaviors. It is important to help designers to choose the best alternative in motion simulation in preliminary phases in a project.

REFERENCES

[1] Chakrabarti, S.K., 1994, Offshore Structure Modeling, Advanced Series on Ocean Engineering, Volume 9, pp.445-451

[2] Gaspar, H.M., Fucatu, C., Nishimoto, K., 2009, Design of Conceptual Offshore Systems based on Numerical Model-Basin Simulations, IMDC2009

[3] Huang, N. E., Shen, Z., Long, S. R., Wu, M. C., Shih, H. H., Zheng, Q., Yen, N-C., Tung, C. C., & Liu, H. H., 1998, The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Non-stationary Time Series Analysis, Proceedings of the Royal Society London A, pp. 903-995.

[4] Lewis, E.V., Principle of Naval Architecture, 1989, Motion in Waves and Controllability, SNAME, Volume 3, pp. 73-83

[5] Malta, E.B., Cueva, M., Nishimoto, K., Gonçalves, R.., Masetti, I.Q., 2006, Numerical Moonpool Modeling, OMAE2006-92456

[6] Malta, E.B., Rampazzo, F.P., Cruz, R.E., Oliveira, A.C., Nishimoto, K., 2009, FPSO and TLWP interacting at a reduced distance for dry tree completion system, OMAE2009-79098

[7] Rateiro, F., Malta, E.B, Fujarra, A.L.C., Vieira, D.P., Nishimoto, K., 2010, Investigation on the effects of risers in the dynamics of floating systems OMAE2010-20408

[8] Yang, J.C.S., Marks, C.H., Jiang, J., Chen, D., Elahi, A., Tsai, W., Determination of fluid damping using random excitation, Journal of Energy Resources Technology, ASME, Vol. 107, June 1985, pp. 220-225