Analysis Methodology for Vortex-Induced Motion (VIM) of a Monocolumn Platform Applying the Hilbert–Huang Transform Method[1]

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Vortex-induced motion (VIM) is a highly nonlinear dynamic phenomenon. Usual spectral analysis methods, using the Fourier transform, rely on the hypotheses of linear and stationary dynamics. A method to treat nonstationary signals that emerge from nonlinear systems is denoted Hilbert–Huang transform (HHT) method. The development of an analysis methodology to study the VIM of a monocolumn production, storage, and offloading system using HHT is presented. The purposes of the present methodology are to improve the statistics analysis of VIM. The results showed to be comparable to results obtained from a traditional analysis (mean of the 10% highest peaks) particularly for the motions in the transverse direction, although the difference between the results from the traditional analysis for the motions in the in-line direction showed a difference of around 25%. The results from the HHT analysis are more reliable than the traditional ones, owing to the larger number of points to calculate the statistics characteristics. These results may be used to design risers and mooring lines, as well as to obtain VIM parameters to calibrate numerical predictions. [DOI: 10.1115/1.4003493]

Keywords: vortex-induced motion (VIM), Hilbert-Huang transform (HHT) method, model tests, nonstationary signals, monocolumn platform

1 Introduction

Similar to vortex-induced vibration (VIV), vortex-induced motion (VIM) is a self-excited and self-controlled phenomenon. The VIV is usually studied for rigid and flexible cylinders with large aspect ratio (L/D), for example, in a riser dynamics scenario. Distinct from VIV, VIM is investigated for rigid cylinders with low aspect ratio, e.g., spar and monocolumn production, storage, and offloading system (MPSO) platforms. The different behaviors between the phenomena arise from the 3D effects, which are attributed to the low aspect ratio in the case of VIM.

The presence of 2DOF in VIV is responsible for a distinct dynamic behavior as pointed out by Jauvits and Williamson [1] and confirmed by Gonçalves et al. [2]. This latter work discusses VIM on MPSO. The existence of motions in both directions, in-line and transverse, see Fig. 1, gives rise to larger amplitude motions, which can be the cause of decrease in the mooring and risers fatigue life, as noted by Sagrilo et al. [3].

Just as VIV, VIM appears as a highly nonlinear dynamic phenomenon. Experimental or numerical time-histories that emerge from VIV or VIM investigations are nonstationary and result from nonlinear systems, see, for example, Refs. [4,5]. Nonetheless, usual spectral analysis methods, based on Fourier transform, rely on the hypotheses of linear and stationary dynamics. A method developed to treat nonstationary signals that originate from nonlinear systems was presented by Huang et al. [6]. It is referred to as the Hilbert–Huang transform (HHT) method.

The reduced scale model, previously used at tests performed in MPSO, was around 1:200. This reduced scale model brought about tests with approximately 10 min duration in a towing tank, for instance, Refs. [7,2]; the same occurs in spar tests, in which the typical scale model varies from 1:20 to 1:150, see, for example, Ref. [8]. The VIM signal obtained from these tests yielded few completed oscillations, which is a disadvantage to calculate the signal statistics characteristics.

The present work proposes to create an analysis methodology to improve the experimental determination of statistics characteristics of VIM signal using the HHT.

Section 2 shows a brief review of the HHT and its applications, Sec. 3 develops the methodology analysis, and Sec. 4 presents the main remarks and conclusions about the use of the HHT to analyze the VIM phenomenon on MPSO.

2 The Hilbert–Huang Transform Method

A usual method to interpret nonstationary data is the wavelet analysis. In comparison with the HHT, it is possible to point some disadvantages for the wavelet, as the problem with leakage generated by the limited length of the basic wavelet function makes the quantitative definition of the energy-frequency-time distribution difficult. Another difficulty of the wavelet analysis is its nonadaptive nature; the opposite holds for the HHT. It is possible to argue that the most common wavelet is Fourier based, and then it can only provide physically meaningful interpretation to linear phenomena.

The Hilbert–Huang spectrum analysis was developed [6] as an alternative and powerful technique to deal with nonstationary signals, which arise from nonlinear systems. This method applies the

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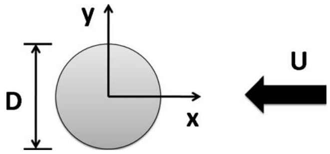

Fig. 1 Motions in the in-line direction (*x*) and transverse direction (*y*)

usual Hilbert transform to a finite set of "intrinsic mode functions" (IMFs), obtained from the original signal through an "empirical mode decomposition" (EMD). According to those authors, the name intrinsic mode function is adopted because it represents the oscillation mode imbedded in the data.

Let $X_j(t)$ be a specific IMF and $Z_j(t)$ an analytic function defined as

$$Z_j(t) = X_j(t) + iY_j(t) = a_j(t)\exp[i\theta_j(t)] \tag{1}$$

where

$$Y_j(t) = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{X_j(\tau)}{t-\tau} d\tau \tag{2}$$

is the Hilbert transform of $X_j(t)$; P stands for principal value. The original signal is then decomposed into the IMF set, as in a "generalized Fourier series,"

$$X(t) = \mathrm{Re} \sum_{j=1}^{n} a_j(t)\exp\left[i \int \omega_j(t) dt \right] \tag{3}$$

$$\omega_j(t) = \frac{d}{dt}[\theta_j(t)] \tag{4}$$

in the sense that not only the amplitude $a_j(t)$ but also the local phase $\theta_j(t)$, and thus the local (or instantaneous) frequency of each IMF is time dependent. The concept of local frequency can be formalized through the stationary phase method, as pointed out in Ref. [6].

Equation (3) represents the amplitude and the instantaneous frequency as functions of time in a three-dimensional plot, in which the amplitude can be countered on the frequency-time plane. This frequency-time distribution of the amplitude is designated as the Hilbert spectrum, $H(\omega,t)$.

As pointed out in Ref. [4], "the EMD method, conceived to obtain the set of IMFs, is based on a recursive subtraction of successively calculated mean between the two time-envelope of extrema (maxima and minima) that are contained in the signal. The envelopes are spline fitting of the maxima (and minima). Details can be found in Refs. [6,9], where this method is referred to as a "sifting" process. Such a recursive procedure is carried out for each IMF limited by a standard deviation stopping criterion that is applied at each step. Each calculated IMF has, itself, symmetrical (maxima and minima) envelopes. The IMF set is complete by construction. The residual function coming out of this procedure is not an IMF; it is the (long-term) trend of the signal. The method precludes zero or mean references and is applicable to general transient signals.

The marginal spectrum $h(\omega)$ is obtained from $H(\omega,t)$ as

$$h(\omega) = \int_0^T H(\omega,t) dt \tag{5}$$

where T represents the duration of the signal. The marginal spectrum offers a measure of total amplitude (or energy) contribution from each frequency value. In the Fourier representation, the existence of energy at a frequency ω means a component of a sine or a cosine wave persisted through the time span of the data. In the HHT, the existence of energy at the frequency ω only means that there is a higher probability for such a wave to appear locally.

Table 1 Main characteristics of the MPSO model

Model characteristics	Real scale (1:1)	Model scale (1:200)
Diameter at the bottom	136.60 m	683 mm
Characteristic diameter	108.00 m	540 mm
Depth	55.00 m	275 mm
Full draft test	42.00 m	210 mm
Displacement in full draft	372,000 tons	46.5 kg
Natural period in the transverse direction	391.03 s	27.65 s
Natural period in the in-line direction	314.95 s	22.27 s

In addition to the marginal spectrum, the instantaneous energy (IE) level can be defined as

$$\mathrm{IE}(t) = \int_\omega H^2(\omega,t) d\omega \tag{6}$$

The IE can be used to check the energy fluctuation over time, i.e., the amplitude modulation. The parameters described before were the basis to the analysis methodology developed further.

3 Analysis Methodology

The VIM time history used to illustrate the methodology was obtained from previous tests presented in Refs. [2,10]. The small-scale model of a MPSO, the MonoBR in 1:200, was moored by means of a set of equivalent horizontal springs and towed in different velocities U ($0.05\text{m/s} < U < 0.30\text{m/s}$). The velocity reduced range tested was $3.0 < Vr_0 < 15.0$. The MPSO model had a characteristic diameter $D=540$ mm and the test was carried out in a draft condition that provided an aspect ratio $L/D=0.39$. More details about the model can be seen in Table 1.

As mentioned previously, the VIM signals for usually reduced scale model 1:200 had few oscillations, thus few peaks. A time history of a typically VIM signal in the transverse direction is shown in Fig. 2. Few peaks in the signal can be clearly seen (22 peaks including maxima and minima), which may cause a poor statistics characteristics in evaluating the characteristic amplitude in the transverse direction, i.e., mean of only 2 points in the case of 10% highest peaks.

The flawed statistics characteristics can be evidenced in a typically VIM signal in the in-line direction, due to its stronger non-

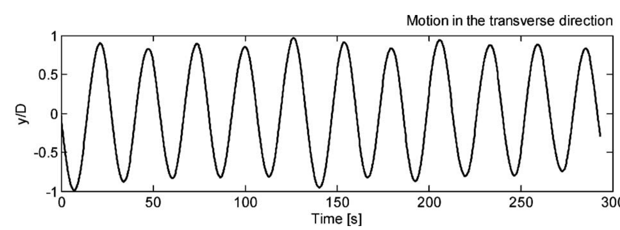

Fig. 2 Example of a time history of a typical VIM signal in the transverse direction

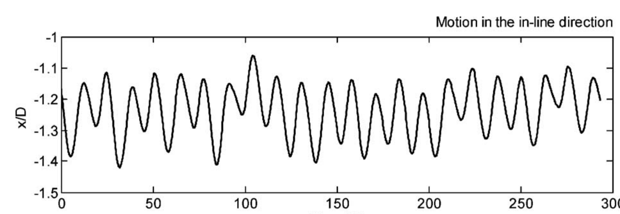

Fig. 3 Example of a time history of a typical VIM signal in the in-line direction

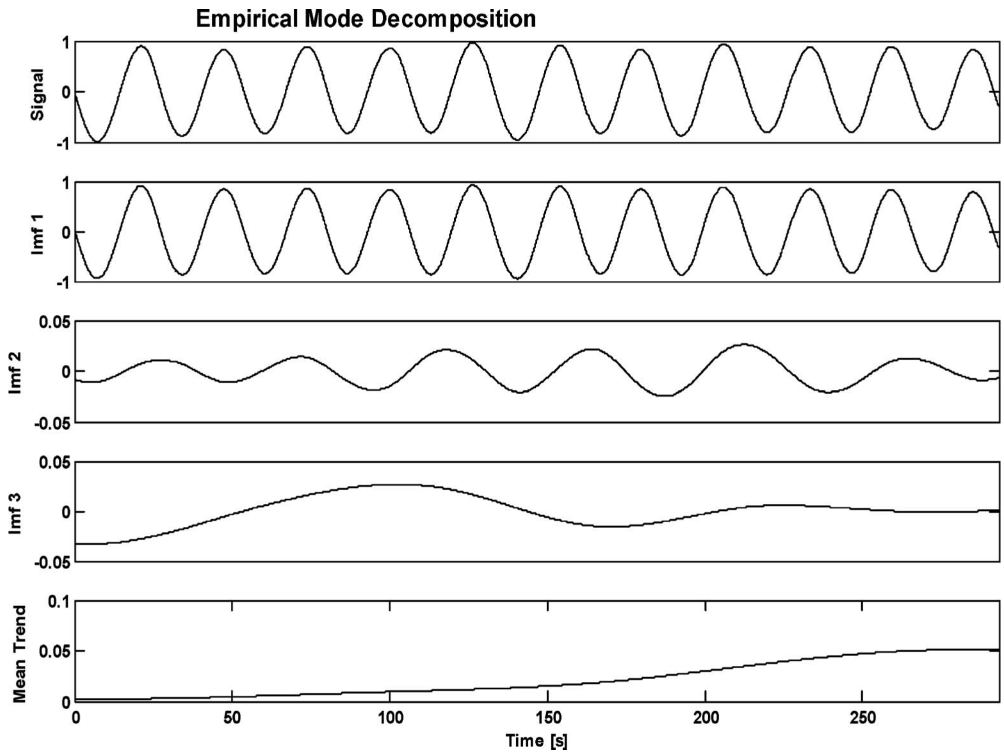

Fig. 4 IMFs generated by the signals for the motion in the transverse direction. Scales are distinct for different IMFs and trend.

stationary behavior, emerging from the variation in the mean signal, see, for example, Fig. 3. In order to improve the statistics characteristics of these signals, the HHT was applied and its results are presented as follows.

Figures 4 and 5 present the IMFs generated from the EMD process by the signals for the motion in the transverse and in-line directions, respectively. Observing the motions in the transverse direction, it is clear that the energy is more equally distributed among the IMFs. Particularly, one IMF concentrates the relevant information, recovering the original signal. On the other hand, observing the motions in the in-line direction, it is possible to observe at least two IMFs with representative energy level, which

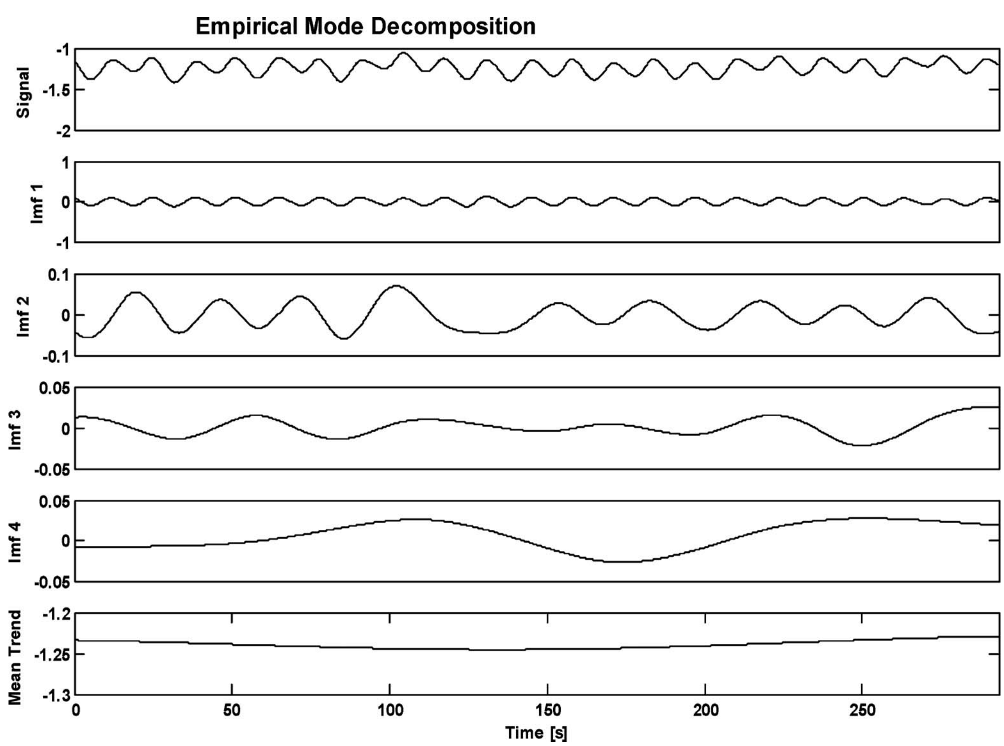

Fig. 5 IMFs generated by the signal of the motion in the in-line direction

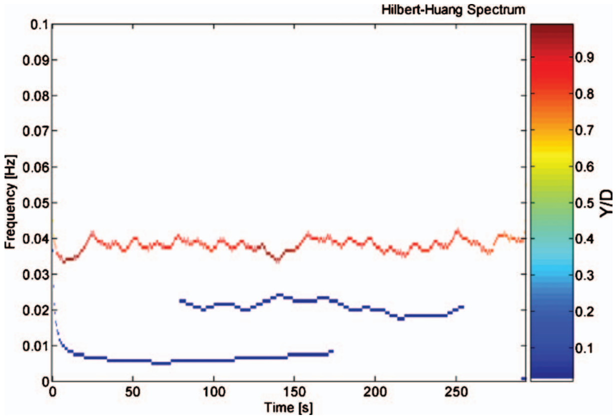

Fig. 6 Hilbert spectrum for the motions in the transverse direction

can be attributed to the stronger nonstationary behavior observed in the signal. The low frequency motion indebted in the signal in the high IMFs, as well as the nonzero mean trend, derived from the nonstationary signal behavior.

From the IMFs, it is possible to create a Hilbert spectrum illustrated in Figs. 6 and 7. The Hilbert spectrum is presented for motions in the transverse and in-line directions, respectively.

The frequency-time-trace for the motions in the transverse direction, see Fig. 6, is very energetic ($Y/D \cong 0.95$) but presents small fluctuations around 0.35 Hz. Energy for all other frequencies can be neglected. Different from the motions in the transverse direction, the frequency-time-trace for the motions in the in-line direction presents large fluctuations, see Fig. 7. This fact, in addition to the modulation amplitude, shows the highly nonstationary nature of the VIM.

The marginal spectra for the motion in the transverse and in-line directions are presented in Figs. 8 and 9, respectively. The comparison between them shows that the high energy level is comprised of a low width range of frequencies for the motions in the transverse direction, whereas the energy level is significant in a larger width range for the motions in the in-line direction.

Evidence that corroborates the higher nonstationary nature of motions in the in-line direction is the IE. Results can be seen in Figs. 10 and 11 for the motions in the transverse and in-line directions, respectively. The in-line motion IEs are more irregular than the transverse direction ones. This fact confirms the high modulation amplitude present in the signal.

As a consequence of the nonstationary nature of the VIM, discussed thoroughly in the examples before, and the poor statistics characteristics mentioned earlier, the HHT seems to be more adequate to improve the statistics characteristics of the VIM. Thus, the characteristic motion amplitude is evaluated applying the mean of the 10% largest amplitudes from $H(\omega,t)$. The characteristic motion frequency is the mean of the frequency related to the 10% largest amplitudes from $H(\omega,t)$. Now, the numbers of points to calculate the mean is proportional to the number of points in the signal time history, which provides a better statistics.

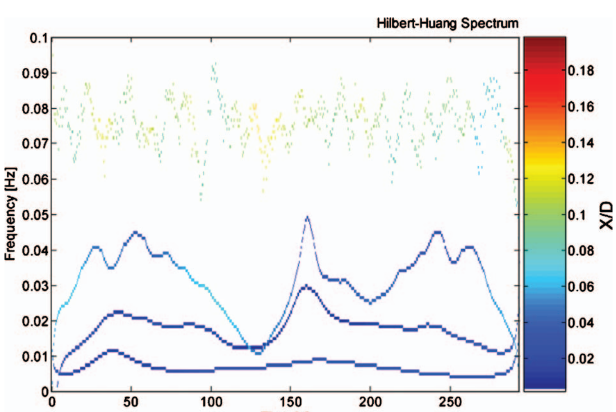

Fig. 7 Hilbert spectrum for the motions in the in-line direction

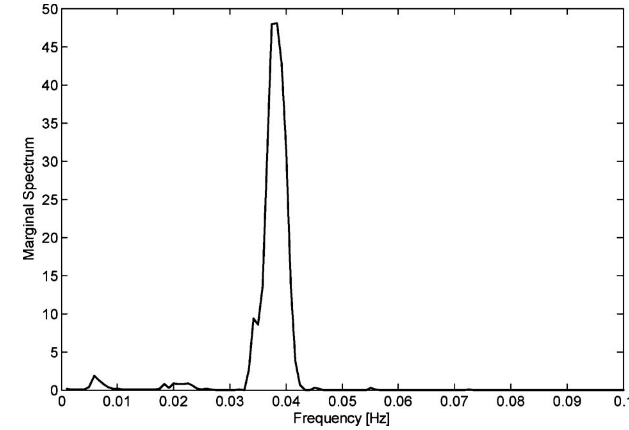

Fig. 8 Marginal spectrum for the motion in the transverse direction

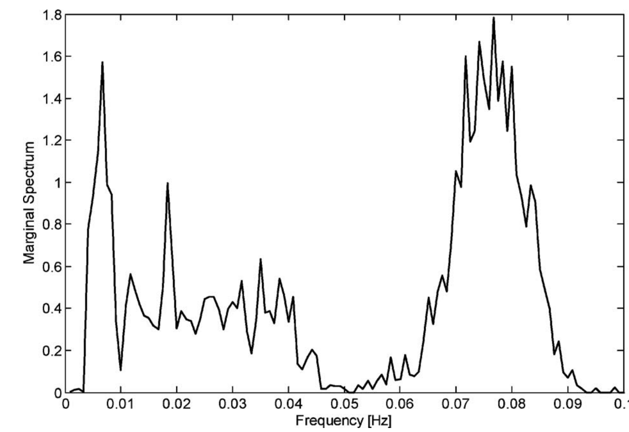

Fig. 9 Marginal spectrum for the motion in the in-line direction

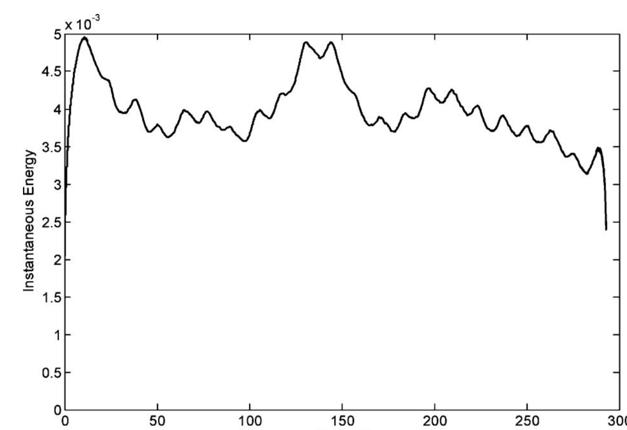

Fig. 10 Instantaneous energy level for the motion in the transverse direction

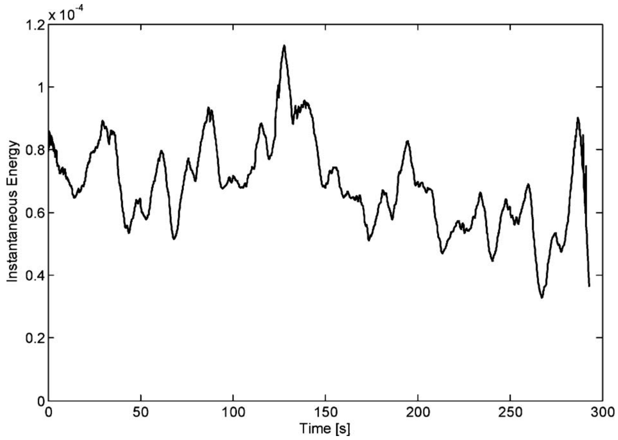

Fig. 11 Instantaneous energy level for the motion in the in-line direction

4 Results

Results of the comparison between traditional analysis (mean of the 10% highest peaks and Fourier transform) and HHT analysis for VIM on a MPSO were reported in Ref. [10]. Figures 12 and 13 and illustrate one of the results presented in the referred work in terms of the characteristic amplitudes. The results concern the motions in the transverse and in-line directions.

The comparison between characteristic amplitude results from traditional analysis and HHT analysis for the motions in the transverse direction, Fig. 12, showed that the difference is nonsignificant. The reason for this is the fact that the signals had no significant amplitude modulation, as can be similarly seen in Fig. 2,

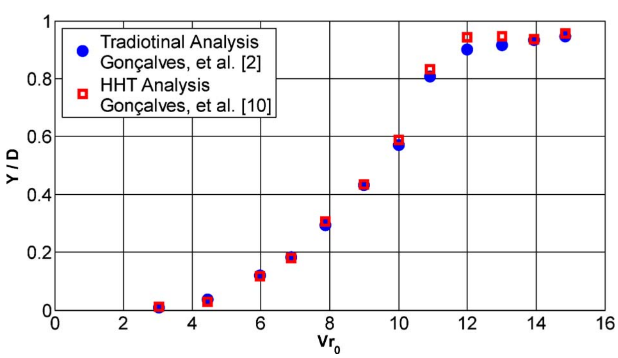

Fig. 12 Comparison between characteristic amplitude results from traditional analysis and HHT analysis for the motions in the transverse direction

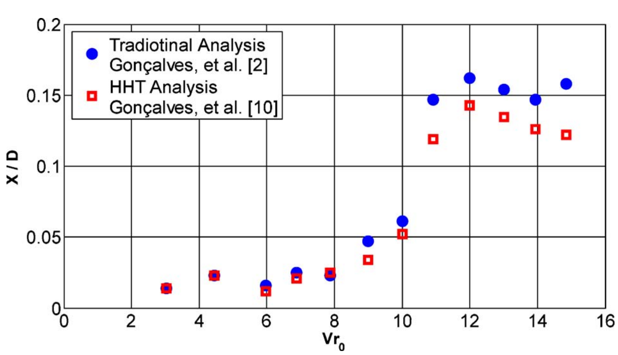

Fig. 13 Comparison between results from traditional analysis and HHT analysis for the motions in the in-line direction

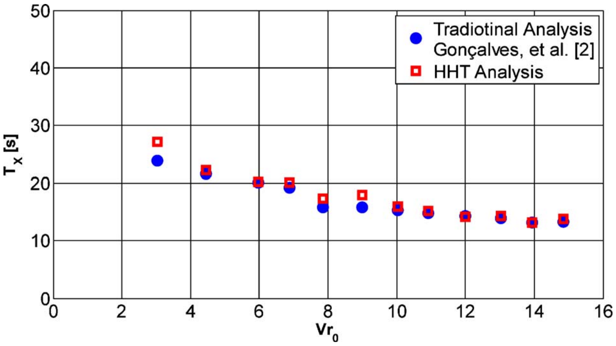

Fig. 14 Comparison between oscillation period results from traditional and HHT analysis for the motions in the in-line direction, 0 deg incidence

where the signal corresponds to a motion at $Vr_0 \cong 9.0$. The difference between characteristic amplitude results obtained for this example signal was less than 2%.

However, the difference between the results of both analysis techniques is evidenced in the motions in the in-line direction, Fig. 13. The difference is larger owing to highly nonstationary behavior of the signal, i.e., modulation amplitude and large width frequencies range. In this case, the nondimensional amplitude calculated by using the traditional analysis is quite affected for the long-term trend and the amplitude modulation of the signals; an example of this signal can be found in Fig. 3, at $Vr_0 \cong 9.0$. The difference between characteristic amplitude results obtained for this example was approximately 25%. In general, the results of characteristic motion amplitude in the in-line direction from traditional analysis showed to be more conservative, which might affect the riser and mooring line design.

In terms of periods in the transverse and in-line directions, both procedures presented almost no difference, as can be seen, respectively, in Figs. 14 and 15.

In order to illustrate the results from traditional and HHT analyses, Fig. 16 compares the relative differences for the motions in both directions. In general, it is quite clear that the in-line result differences are larger, particularly for the reduced velocities above 6, in a direct relation to the nonstationary and modulated oscillation in this direction. It is important to explain that the differences observed for the transverse direction in reduced velocities below 6 are related to the small level of oscillations (energy), according to which it is practically impossible to perform a precise comparison between the procedures of analysis.

Additionally, a simple method to verify the significant improvements using HHT over the traditional method is to obtain the statistics for different sample lengths (or number of peaks) of the

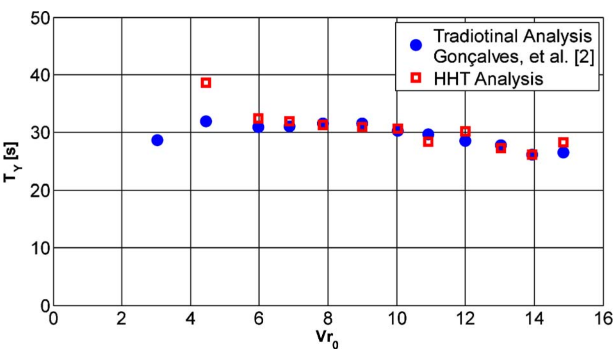

Fig. 15 Comparison between oscillation period results from traditional and HHT analysis for the motions in the transverse direction, 0 deg incidence

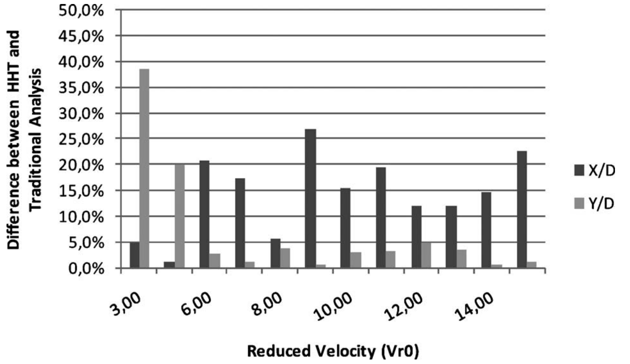

Fig. 16 Percentage difference between characteristic amplitude results from traditional and HHT analysis for the motions in both directions

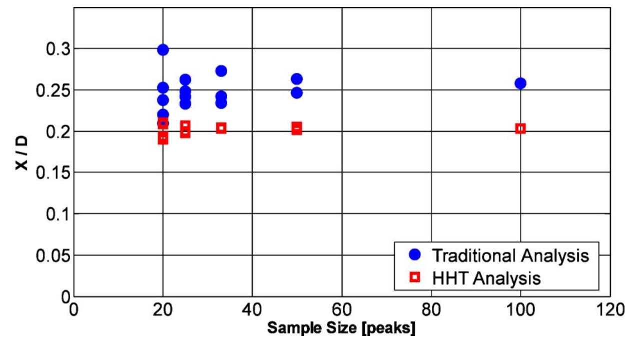

Fig. 18 Sensitivity study on the number of sample points sufficient for convergence between traditional and HHT analysis

same VIM time history. The method consists on breaking the original time history in parts and analyzing them independently by means of both approaches: HHT and traditional. Figure 17 shows a typical example of in-line VIM time history with different sample lengths: (a) the whole sample, (b) one half of the original sample, (c) a third, (d) a quarter, and (e) a fifth. All the samples are taken from the same time history obtained by Gonçalves et al. [11]. Figure 18 presents a sensitivity study, considering the number of sample points sufficient for convergence, comparing the statistics calculated from traditional and from the HHT analyses, based on the chosen sample length. It can be seen that, even taking the entire sample with 100 peaks, there is a significant difference between the statistics obtained with the alternative methods. This fact is due to the highly nonstationary behavior of the motions in the in-line direction, as previously pointed out and seen in Fig. 13. The statistic results for the broken parts of the time history obtained from traditional analysis show larger scatter than those from the HHT, Fig. 18. This simple sensitivity result shows that HHT is very well suited for analysis of nonstationary and even short test samples, in which only a few cycles of oscillations are available, where obtaining significant statistics is a challenge.

5 General Conclusions

To summarize, the observations reported in this study clearly indicate that the analysis methodology of VIM applying the Hilbert–Huang transform method improves the statistics characteristics analysis of the phenomenon. The values of characteristic motion amplitudes showed to be more reliable owing to the large number of points to calculate the statistics.

The comparison between traditional analysis (mean of the 10% highest peaks) and HHT analysis for VIM on a MPSO pointed out to larger differences observing the motion in the in-line direction.

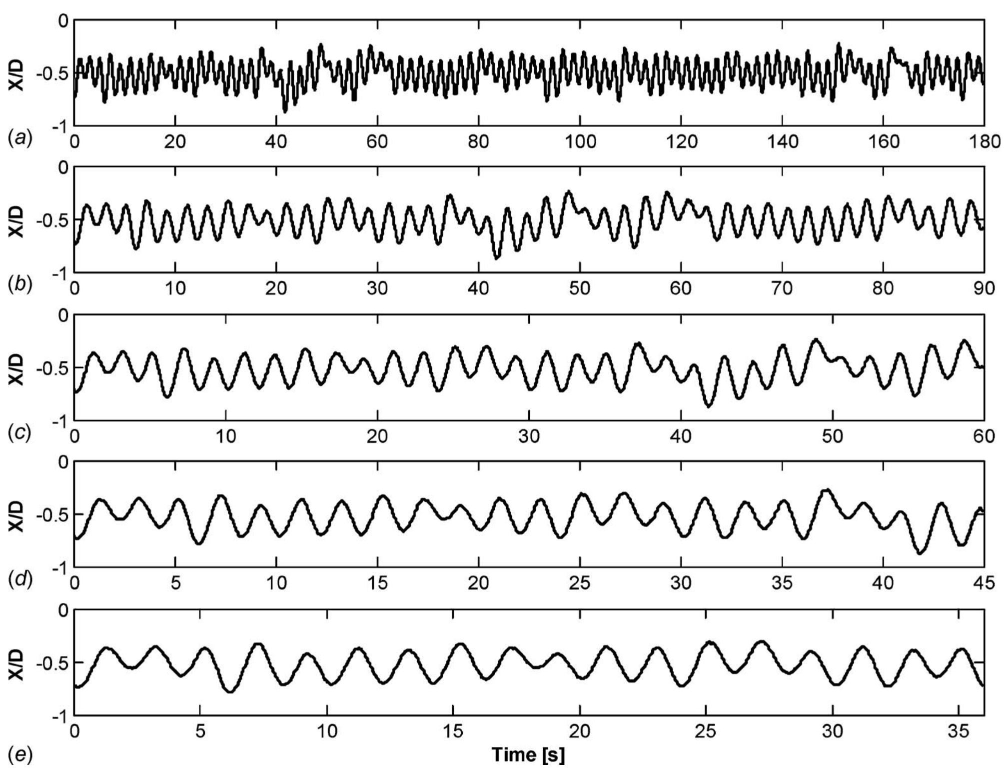

Fig. 17 Example of a typical VIM time history in the in-line direction for a cylinder with L/D =2.00 and Vr_0=9.5 with different sample sizes: (*a*) 100, (*b*) 50, (*c*) 33, (*d*) 25, and (*e*) 20 peaks

The difference is due to the nonstationary behavior of the VIM phenomenon (a nonperiodic modulation in amplitude and frequency).

The analysis methodology supported by the results is presented before demonstrated to be a robust tool to analyze VIM phenomenon on MPSO. The emerging statistics can be used in both the design of riser and mooring lines. The proposed methodology can be employed to obtain other parameters from the VIM (added mass, drag, and lift coefficients), useful to calibrate numerical predictions. Finally, it is important to emphasize that the HHT can be applied for other cases of fluid-structure interactions, such as VIM of spar platforms and VIV of flexible cylinders, turning the analysis more reliable and precise.

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Nomenclature

ω = instantaneous frequency
D = characteristic diameter of the platform
$h(\omega)$ = marginal spectrum
$H(\omega,t)$ = Hilbert spectrum
$\mathrm{IE}(t)$ = instantaneous energy level
T = length time of the signal
U = flow velocity
Vr_0 = reduced velocity in still water
x = in-line direction
X/D = characteristic motion amplitude in the in-line direction
y = transverse direction
Y/D = characteristic motion amplitude in the transverse direction

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