Subsea Free Span Pipeline Damage Detection Based on Wavelet Transform under Environmental Load

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Abstract
During their service life, marine pipelines continually accumulate damage as a result of the action of various environmental forces. Clearly, the development of robust techniques for early damage detection is very important to avoid the possible occurrence of a disastrous structural failure. Most of vibration-based damage detection methods require the modal properties that are obtained from measured signals through the system identification techniques. However, the modal properties, such as natural frequencies and mode shapes are not adequate sensitive indicators of structural damage. In this paper, structural damage was identified based on a new method called Detail Signal Energy Rate Index (DSERI). Damage localization of offshore pipeline was then based on Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). For modeling the damage, the stiffness of 1 and 2 elements were reduced in three models and the dynamic signals were measured by finite element analysis. The dynamic signals were analyzed by applying discrete and continuous wavelet transforms. Then, by using Daubechies wavelet, a peak was clearly evident and the exact damage location was identified by the peak with the maximum absolute value in the plots of the detail signal calculated with the DWT and CWT. To eliminate the effects of the boundary conditions on the wavelet-based damage, the authors proposed a new method: DSERI. Component energies were then calculated and used for damage assessment. The results showed that the DSERI were good candidate indices sensitive to structural damage. These component energies could be used for damage assessment including identifying damage occurrence and location of damage. Wavelet coefficient was a good candidate for structural damage identification when damage occurred at the middle of pipeline but not sensitive for damaged elements near to supports.

Keywords: free span pipeline, damage detection, wavelet transform

1. Introduction
Onshore and offshore pipes are of great importance for the transportation of natural gas and oil. In these structures, regular checks are necessary because damage is accumulated during the life time of offshore-pipeline as a result of the effect of various environmental forces. For example; fatigue, buckling, bending, corrosion, collision, overloading during heavy storms and falling objects from ships. Numerous methods for damage inspection and system monitoring have been developed, (magnetic leakage detection, ultrasonic inspection, eddy current
testing, acoustic emission testing, electronic video testing, video detection, X-ray, MRI, dye penetration and visual inspection). These methods are generally slow and costly, often requiring the exposure of pipeline for detecting local damage.

Poor visibility results in the concealment of damage caused by marine growth. It is clear that the development of robust methods for detecting early damage is very important and inspection of subsea pipelines is strongly necessary to prevent leakage of the pipeline which can cause direct economic losses and pollution. Damage identification methods are generally classified into four levels: Level 1: detection of the existing damage in the structure, Level 2: determination of the geometry of the damage, Level 3: quantification of the severity of the damage and Level 4: prediction the remaining service life of the structure (Asgarian, Amiri, and Ghafoori-pour, 2009).

Damage detection techniques can be local or global. Most currently used techniques such as visual, acoustic, magnetic field, eddy current, and etc. are effective yet local in nature. They require the vicinity of the damage to be known a priori and the portion of the controlled structure to be easily assessable (Sun and Chang, 2007). In the global methods, the quantity of the safety of a structure is measured by changes in its vibration characteristics. (Han, Ren, and Sun, 2005). Most of vibration-based methods of assessment of damage require modal properties from the measured signals by system identification techniques such as Fourier Transform (FT). There are some characteristics of the FT that could affect the accuracy of the damage detection. Firstly; the FT is a process of data reduction; hence some information about structural health may be lost during the process. Secondly, the FT is not able to present the time dependency of the signals and it cannot capture the changing properties that are usually observed in the measured signals from naturally excited structures. The structural damage is typically a local phenomenon that can be captured by higher frequency signals. These higher frequencies are usually closely spaced, but poorly excited. The Fourier analysis transforms the signal from a time-based or space-based domain to a frequency-based domain (Fig. 1).

Fig. 1: Fourier analysis (Gao and Yan 2010).

Unfortunately, the information about time or space during the execution of such a transformation is lost and it is sometimes impossible to determine where and when a particular event has occurred (Han et al. 2005; Sun and Chang, 2002). To remedy this deficiency, the Short-Time Fourier Transform (STFT) was proposed by Gabor (1946) (Gabor, 1946). However, only a small part of the signal at a time can be analyzed by this windowing technique. The STFT maps a signal into a 2-D function of time or space and frequency (Fig. 2). The drawback of the transformation is that the information about time or space and frequency can be obtained with reduced accuracy. Higher resolution in time or space and frequency range cannot be achieved simultaneously, because if the window size is chosen, it is the same for all frequencies.

Fig. 2: The Short-Time Fourier Transform (STFT) (Gao and Yan 2010)
The Wavelet Transform (WT) is a new way to precisely analyze the signals. WT overcomes the problems that other signal processing techniques display. Wavelet functions are compounded of a family of basic functions, which are able to describe a signal in time (or space) and frequency (or scale) domain, as shown in Figure 3. The main advantage which is gained by using wavelets is conducting local analysis of a signal, i.e., zooming on any interval of time or space. The use of local functions allows varying time-frequency resolution simultaneously which leads to a multi-resolution representation for non-stationary data (Fig. 3). Wavelet analysis is able to reveal hidden characteristics of data that other signal analysis techniques fail to detect. This property is particularly important for damage detection applications. Due to the time-frequency multi-resolution property, the WT has recently exhibited as a desirable tool for damage detection of machinery and structures.

![Wavelet Transform](image)

Fig. 3: The wavelet transform (WT) (Gao and Yan 2010).

![Illustration of wavelet transforms](image)

Fig. 4: Illustration of wavelet transforms (Gao and Yan 2010).

Wang and Deng developed a WT-based technique (spatial wavelet) for analyzing spatially distributed structural response signals (Wang and Deng, 1999). Gurley and Kareem emphasized the usefulness and the potential of the wavelet transform in earthquake, wind, and ocean engineering (Gurley and Kareem, 1999). Lotfollahi-Yaghin and Vakili studied nondestructive identification of internal crack based on wavelet analysis. (Lotfollahi-Yaghin and Vakili, 2008). A possible drawback of the WT is that the frequency resolution is rather poor in the higher frequency region. Therefore, it is still difficult when the discrimination involves high-frequency components of adjacent signals. The Wavelet Packet Transform (WPT) is an extension of the WT, a full breakdown provides signal level by level. The wavelet packet bases are formed by alternating linear combinations of the usual wavelet functions (Coifman and Wickerhauser, 2002; Daubechies, 1992).

Therefore, the WPT enables the extraction of features from the signals that combine the stationary and non-stationary characteristics with an arbitrary time-frequency resolution. Lotfollahi-Yaghin et al. and Shahverdi et al. proposed Wavelet Packet Energy Ratio Index (WPERI) for damage detection in jacket type offshore platforms and free span pipelines (Lotfollahi-Yaghin, Shahverdi, and Tarinejad, 2010; Lotfollahi-Yaghin et al., 2011; Shahverdi et al., 2011). They showed that WPERI was a good index for damage detection in complex structures same as jacket type platform and free span pipeline.

In those studies, they obtained that db4, db2 (Daubechies wavelet) were good wavelets for damage detection. Also, Lotfollahi-Yaghin and Koohdaragh examined the function of wavelet packet transform and Continuous Wavelet Transform (CWT) in recognizing the crack specification (Lotfollahi-Yaghin and Koohdaragh, 2011). As a result, the WPT enables the extraction of features from signals that combine stationary and non-stationary characteristics with arbitrary time-frequency resolution. All the aforementioned publications have worked with frequency or time domain. Few studies have been done for damage detection in free pipeline structures and nobody has used the wavelet packet transform in
frequency-time domain for damage detection of these structures under environmental load (sinusoidal wave load). In this study, for modeling the damage, the stiffness of 1 and 2 elements were reduced in three models and the dynamic signals were measured by finite element analysis. Then, by using Daubechies wavelet, a peak was clearly evident and the exact damage location was identified by the peak with the maximum absolute value in the plots of the detail signal calculated with the DWT and CWT. In order to eliminate the effects of the boundary conditions on the wavelet-based damage the authors proposed a new method DSERI. Component energies were then calculated and used for damage assessment.

2. Wavelet Analysis

Inaccurate results may be presented by the traditional Fourier analysis of the response data of general transient nature if the occurring time of damage is unknown. This happens, due to its time integration over the whole span. In addition, progressive damage, such as stiffness degradation due to mechanical fatigue and chemical corrosion may occur, therefore, a clear change in stiffness might not be found. The wavelet analysis, as an extension of the traditional Fourier analysis, can provide a time-frequency and multi-resolution analysis for non-stationary data. This method is efficient for damage detection of structures (Shinde and Hou, 2005). In summary, a wavelet is an oscillatory, real or complex-valued function \( \Psi(x) \in L^2(\mathbb{R}) \) of zero average and finite length. Wavelets can be real or complex functions. Because real wavelets are useful to detect sharp signal transitions, this study deals exclusively with them (Lotfollahi-Yaghin and Koohdaragh, 2011). Wavelet analysis starts by selecting from the existing wavelet families a basic wavelet function that can be a function of space \( x \) or time \( t \). In this paper, we considered that the independent variable was \( x \) and \( t \) was for damage localization of elements.

This basic wavelet function, called the ‘mother wavelet’ \( \psi(x) \), was then dilated (stretched or compressed) by \( s \) and translated in space by \( \tau \) to generate a set of basic functions \( \Psi_{j,s}(x) \) as follows: (Lotfollahi-Yaghin and Koohdaragh, 2011).

\[
\Psi_{j,s}(x) = \frac{1}{\sqrt{s}} \psi\left(\frac{x - \tau}{s}\right)
\]

(1)

The function is centered at \( \tau \) with a spread proportional to \( s \). The wavelet transform (in its continuous or discrete version) correlates the function \( f(x) \), with \( \Psi_{j,s}(x) \). The continuous wavelet transform (CWT) is the sum over all time of the signal multiplied by \( s \) scaled and shifted version of a mother wavelet

\[
C(s, \tau) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(x) \Psi\left(\frac{x - \tau}{s}\right) dx = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(x) \Psi_{j,s}(x) dx
\]

(2)

where the scale \( s \) and the position \( \tau \) real numbers and \( s \neq 0 \). The results of the transform are wavelet coefficients that show how well a wavelet function correlates with the signal analyzed. Hence, sharp transitions in \( f(x) \) create wavelet coefficients with large amplitudes and this precisely is the basis of the proposed identification method. The CWT has an inverse: the inverse CWT permits to recover the signal from its coefficients \( C(s, \tau) \) and is defined as

\[
f(x) = \frac{1}{K_\psi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} C(s, \tau) \Psi_{j,s}(x) d\tau ds \frac{ds}{s^2}
\]

(3)

where the constant \( K_\psi \) depends on the wavelet type. One of the drawbacks of the CWT is that a very large number of wavelet coefficients \( C(s, \tau) \) are generated during the analysis (Ovanesova 2004). Moreover, few wavelets have an explicit expression, and most are defined with recursive equations. It can be shown (Lotfollahi-Yaghin and Koohdaragh 2011) that the CWT is highly redundant, in the sense that it is not necessary to use the full domain of \( C(s, \tau) \) to reconstruct \( f(x) \). Therefore, instead of using a continuum of dilations and translations, discrete values of the parameters are used. The dilation is defined as \( s = 2^j \) and the translation parameter takes the values \( \tau = k 2^j \), where \((j, k) \in \mathbb{Z}, \) and \( \mathbb{Z} \) is a set of integers. This sampling of the coordinates \((s, \tau)\) is referred to as dyadic sampling because consecutive
values of the discrete scales differ by a factor of 2 (Ovanesova 2004). Using the discrete scales one can define the discrete wavelet transform (DWT)
\[ C_{j,k} = \frac{1}{\sqrt{2^j}} \int f(x) \psi_{j,k}(x) \, dx \]  
(4)

The signal resolution is defined as the inverse of the scale \( \frac{1}{\sqrt{2^j}} \), and the integer \( j \) is referred to as the level. As the level and the scale decrease, the resolution increases and the smaller and finer components of the signal can be accessed. The signal can be reconstructed from the wavelet coefficients \( C_{j,k} \) and the reconstruction algorithm is called the inverse discrete wavelet transform (IDWT)
\[ f(x) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} c_{j,k} \psi(2^{-j} x - k). \]  
(5)

Substituting \( \psi(x) \) by \( \phi(x) \) in eq. (2) one obtains a function D (s, \( \tau \)):
\[ D(s, \tau) = \int f(x) \frac{1}{\sqrt{s}} \phi\left( \frac{x - \tau}{s} \right) \, dx = \int f(x) \phi_{s, \tau}(x) \, dx \]  
(6)

The scaling function does not exist for every wavelet. The existence of the function \( f(x) \) is important for the numerical implementation of the fast wavelet transform discussed later. Suppose now that the dyadic scale is used for \( s \) and \( \tau \), and consider a reference level \( J \). Applying eq. (4) for this case one obtains a set of coefficients
\[ cD_j(k) = \int f(x) \psi_{j,k}(x) \, dx \]  
(7)

The coefficients \( cD_j(k) \) are known as the level-J detail coefficients. Using the dyadic scale and level \( J \), eq. (6) yields another set of coefficients
\[ cA_j(k) = \int f(x) \phi_{j,k}(x) \, dx \]  
(8)

The new coefficients \( cA_j(k) \) are known as the level-J approximation coefficients. Then \( f(x) \) reconstructed as:
\[ f(x) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} cD_j(k) \psi_{j,k}(x) \]  
\[ \quad + \sum_{j=-\infty}^{\infty} cA_j(k) \phi_{j,k}(x). \]  
(9)

The function in the parentheses is known as the detail function at level \( J \):
\[ f(x) = \sum_{k=-\infty}^{\infty} cD_j(k) \psi_{j,k}(x) \]  
(10)

The function defined by the second summation in eq. (9) is called the approximation function at level \( J \)
\[ A_J(x) = \sum_{j=-\infty}^{\infty} cA_j(k) \phi_{j,k}(x). \]  
(11)

Eq. (9) thus tells that the original function can be expressed as the sum of its approximation at level \( J \) plus all its details up to the same level. i.e.
\[ f(x) = A_J(x) + \sum_{j<J} D_j(x). \]  
(12)

For this study, we were interested in the detail signals. As shown with the numerical examples, if \( f(x) \) were a response signal, typically the acceleration curve, the signals \( D_j(x) \) could contain the information necessary to detect the damage in the structure. Eqs. (7) and (8) describe the DWT whereas eqs. (10), (11) and (12) constitute the IDWT Fig. 5.

![Fig. 5: Discrete Wavelet Transform Decomposition Tree](image)

Many types of wavelets were developed whose features and performance vary based on their associated properties and some of the most pertinent properties are: (1) regularity; (2) support; (3) number of vanishing moments; and (4) symmetry. A summary definition of these properties were described as follows: (1) Regularity, a property useful for getting nice features, such as smoothness, of the reconstructed signals; (2) Support of a function, the smallest space-set (or time-set) outside of which function is dientically zero; (3) Number of vanishing moments of wavelets determining the order of the polynomial that can be approximated and useful for compression purposes 4: The wavelet symmetry relates to the symmetry of the filters and helps to avoid dephasing in image...
processing. Among the orthogonal families, the Haar wavelet is the only symmetric wavelet. For biorthogonal wavelets, it is possible to synthesize wavelet functions and scaling functions that are symmetric or antisymmetric.

To apply the wavelet transform in any application it is important to select the most appropriate wavelet for the analysis. The selection is usually done by trial and error but in (Ovanesova, 2004) some criteria to choose the optimal wavelet are presented and they selected (db2 and db4) for damage detection in free span offshore pipeline structure. To analyze the response signals in this study, the optimal wavelet was chosen by trial and error.

3. Wavelet Packet Transform

As a result of decomposition of only the approximation component at each level using the dyadic filter bank, the frequency resolution is low in lower-level e.g. A1 and D1. DWT decompositions in a regular wavelet analysis may be lower. It may cause problems while applying DWT in certain applications, where the important information is located in higher frequency components. The frequency resolution of the decomposition filter may not be fine enough to extract necessary information from the decomposed component of the signal. The necessary frequency resolution can be achieved by implementing a wavelet packet transform to decompose a signal further. The wavelet packet analysis is similar to the DWT with the only difference that in addition to the decomposition of only the wavelet approximation component at each level, a wavelet detail component is also further decomposed to obtain its own approximation and detail components as shown in Figure 6.

At the top of the tree, the time resolution of the WP components is good but at an expense of poor frequency resolution whereas at the bottom of the tree, the frequency resolution is good but at an expense of poor time resolution. Thus, with the use of wavelet packet analysis, the frequency resolution of the decomposed component with high frequency content can be increased. As a result, the wavelet packet analysis provided better control of frequency resolution for the decomposition of the signal. Wavelet packets consist of a set of linearly combined usual wavelet functions. The wavelet packets have the properties such as orthonormality and time-frequency localization from their corresponding wavelet functions. A wavelet packet $\psi_{j,k}^i$ is a function with three indices where integers $i$, $j$ and $k$ are the modulation, scale and translation parameters, respectively, $\psi_{j,k}^i = 2^{i/2} \psi^i(2^{j/2}(t-k))$, $i=1,2,3,...$ (13)

Fig. 6: Wavelet Packet Decomposition Tree

After $j$ level of decomposition, the original signal $f(t)$ can be expressed as

$$f(t) = \sum_{i=1}^{2^j} f_j^i(t),$$ (14)

The wavelet packet component signal $f_j^i(t)$ can be represented by a linear combination of wavelet packet functions $\psi_{j,k}^i(t)$ as follows:

$$f_j^i(t) = \sum_{k=1}^{2^j} c_{j,k}^i(t) \psi_{j,k}^i(t),$$ (15)

Where the wavelet packet coefficients $c_{j,k}^i(t)$ can be obtained from:

$$c_{j,k}^i(t) = \int_{-\infty}^{\infty} f(t) \psi_{j,k}^i(t)dt,$$ (16)

Providing that the wavelet packet functions are orthogonal

$$\psi_{j,k}^m(t) \psi_{j,k}^n(t) = 0 \quad \text{if} \ m \neq n$$ (17)

Each component in the WPT tree can be viewed as the output of a filter tuned to a particular basis function, thus the whole tree can be regarded as a filter bank. At the top of WPT tree (lower level), the
WPT yields a good resolution in the time domain but a poor resolution in the frequency domain. At the bottom of WPT tree (higher level), the WPT results in a good resolution in the frequency domain yet a poor resolution in the time domain. The wavelet transform tree is shown in Figure 6, and the decomposition formulation of signal $f(t)$ is:

$$(t)=AAA3+DAA3+ADA3+DDA3+ADD3+DDD3 \quad (18)$$

### 4. Detail Signal Energy Rate Index of Wavelet Packet (DSERI)

The feasibility of applying the WPT to the vibration signals was investigated by Yen and Lin (Yen and Lin 2000). They defined a wavelet packet node energy index and concluded that the node energy representation could provide a more robust signal feature for classification than using the wavelet packet coefficients directly. In this study, the wavelet packet energy index is proposed to identify the locations of damage. To do that, the signal energy $E_i$ at j level is first defined as:

$$E_i^j = \int_{-\infty}^{\infty} |f_i^j(t)|^2 dt = \sum_{m=1}^{m} \sum_{n=1}^{n} |f_i^{j,m}(t)|^2 dt. \quad (19)$$

Substituting Eq. (14) into Eq. (19) and using the orthogonal condition Eq. (16) yields

$$E_i^j = \sum_{m=1}^{m} E_i^{j,m} \quad (20)$$

Where the wavelet packet component energy $E_i^{j,m}$ can be considered to be the energy stored in the component signal $f_i^{j,m}(t)$:

$$E_i^{j,m} = \int_{-\infty}^{\infty} |f_i^{j,m}(t)|^2 dt. \quad (21)$$

It can be seen that the component signal $f_i^{j,m}(t)$ is a superposition of wavelet functions $\psi_{ik}^{j,m}(t)$ of the same scale as j but translated into the time domain $-\infty < k < \infty$.

In physical terms, Eq. (20) illustrates that the total signal energy can be decomposed into a summation of wavelet packet component energies that correspond to different frequency bands. Corresponding to (Han et al., 2005) the WPERI is a good candidate to indicate the structural damage. But, the volume of data for transportation to calculation center was large and computation of WPERI was time consuming. So, in this paper we used DSERI, for damage detection in offshore free span pipeline structure. The rate of detail signal energy at j level of wavelet packet transform, shown in Fig. 6 in red (for example $j=3$) were defined as,

$$\Delta(E_i^j) = \sum_{m=1}^{m} \left( \frac{(E_i^{j,m})_a - (E_i^{j,m})_b}{(E_i^{j,m})_a} \right) \quad (22)$$

Where $\left( E_i^{j,m}\right)_a$ was the component energy of detail signals $E_i^{j,m}$ at j level without damage, and $\left( E_i^{j,m}\right)_b$ was the component signal energy $E_i^{j,m}$ with some damage. It was assumed that structural damage would affect the detail signal component energies and consequently alter this damage indicator. It is desirable to select the DSERI that is sensitive to the changes in the signal characteristics.

### 5. Methodology of Damage Detection

#### 5.1. Methodology of Damage Detection using DWT

The main idea behind the use of wavelets for structural identification purposes was established on the fact that the presence of damage introduced small discontinuities in the structural response at the damaged location (Ovanesova 2004). Often these discontinuities could not be observed from the examination of the structural response, but they were detectable from the distribution of the detail signals from the DWT. The following procedure was proposed to detect damage in a free span pipeline by the DWT as follows:

1. The signal associated with the dynamic structural response, usually the transverse accelerations was measured. For the numerical simulations of free span pipeline, one can use at the damage location short length elements with reduced area and moment of inertia. Alternatively, if 3D solid elements were used, it would have been possible to simulate the damage simply by removing elements or decreasing their elastic
modulus. In this paper, this method was used for modeling of damage in structure.

2. Using the measured signal, the detail signals associated with the discrete transform was computed from eqs. (8) and (11).

3. The wavelet coefficients for the detail signals were plotted and examined. Provided that a suitable wavelet was selected for the analysis by trial and error, any signal discontinuity would be detected by the distribution of coefficients on the wavelet coefficients plot. In order to observe the signal discontinuities, it was recommended to perform a low-level analysis for the DWT.

4. The level at which the wavelet analysis must have been performed could not be determined beforehand. It depends on the nature of the signal, the characteristics of the structure, the location, type and severity of the damage, etc. It is suggested to try with different levels. As it is shown, in order to identify discontinuities due to damage in simple structures, it was sufficient to perform only one level of analysis or consider only the first level detail signal.

5.2. Methodology of Damage Detection Using DSERI

Continuous monitoring assumes even greater significance in the case of offshore free span pipeline, which is highly susceptible to damage due to the corrosive environment and the continuous action of waves. Also, since a major part of the structure is under water and covered by marine growth, even a trained diver cannot easily detect damage in the structure. In this paper, vibration criterion was adopted for damage detection of free span pipeline. Damage in a system causes a change in dynamic properties of a system. The structural damage is typically a local phenomenon, which tends to be captured by higher frequency signals and in this paper, the authors suggested detail signal ratio index of wavelet packet transform for non-destructive damage identification method of offshore pipeline structures.

Two assumptions are adopted in this study: (1) the reliable undamaged and damaged structural models are available; (2) the structure is excited by the same environmental wave load, and acts at the same location. Vibration signals measured from the structure, in the finite element software package, ANSYS, are first processed using the WPT. The level of wavelet packet decomposition is determined through a trial and error analysis using the undamaged and damaged structural models. Then, by eliminating some of the signals (component energy of approximation signal in this study), component energies of remained signal DSERI (the energy of detail signal that is showed by red color in Fig. 2) are calculated and used for damage assessment. The wavelet coefficient is then calculated for every suspected damaged element.

6. Numerical Studies

An existing pipeline in Persian Gulf which is located at a water depth of 70.2 m is numerically modeled in this study. PIPE59 is used for modeling in the finite element analysis package. PIPE59 is a uniaxial element with tension-compression, torsion, and bending capabilities, and with member forces simulating ocean waves and current. The element has six degrees of freedom at each node: translations in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. It is demonstrated in Figure 7. The free span pipeline shows in Figure 7 is considered. When the L/D of pipeline is less than 200, the numerical modeling can be same as simple support beam (Bai, 2001; Nielsen, Kvarme, and Søreide, 2002; Veritas, 2006). The free span pipeline is subjected to wave loads by specific wave height (Hs)=10m and period (Ts)=8 sec.
7. Identification of Damage

7.1. Identification of Damage using DWT

To simulate damage, three damage scenarios with different levels of location are conceived. The undamaged free span pipeline is denoted by P0 as a reference. The other three different damage scenarios, denoted as P1, P2 and P3, are described as follows: (1) P1: stiffness reduced 40% in the 50th element; (2) P2: stiffness reduced 40% in the 11th element; and (3) P3: stiffness reduced 40% in the 11th and 89th elements.

The free span pipeline in Figure 7, was subdivided into 100 finite elements and the damage with stiffness reduced 40% in the 11th element was introduced at distances $L_{\text{damaged element}} = L/2$ (element 50) from the left support. The dynamic response of the undamaged and damaged pipeline at time $t=5$ s after wave load was applied is given in Figure 8.

![Figure 7: FE modeling of free span pipeline, a) P0 undamaged model, b) P1 model, c) P2 model, d) P3 model.](image)

![Figure 8: acceleration at t=5sec after apply wave load](image)
likely, these perturbations would go undetected if the response was measured experimentally and a simple visual inspection was conducted. When the acceleration signals of the damaged pipeline were analyzed with the DWT, these small disturbances were detected by the db4 wavelet (Fig. 9). Note that in this and in the following cases, the exact damage location was identified by the peak with the maximum absolute value in the plots of the detail signal calculated with the DWT.

To show the effect of the type of wavelet on the detection capabilities, Figure 10 shows the results obtained applying the first wavelet discovered the well-known Haar wavelet (Ovanesova, 2004). In this case, the method was not quite reliable: but by using Daubechies wavelet, a peak is clearly evident in Figure 9. However, by using Haar wavelet, the corresponding peak could not be detected from Figure 10. The poor regularity of the Haar wavelet explained the inconsistent results during the analysis compared to the Daubechies wavelet (Ovanesova, 2004).

With the purpose of providing an alternative to the DWT as well as to show the importance of using low-scale analysis, the CWT was applied to the acceleration response signal. Although, as discussed previously, the CWT was redundant, it could help to interpret the results. Figure 11 shows plots of the wavelet coefficients for the case of the P1 model. In this figure, the color at each point is associated to the magnitude of the wavelet coefficients with the lighter color corresponding to the larger coefficients and darker color to the smaller ones. In the case of the damaged pipeline, the discontinuity due to the damage was clearly detected as shown in Figure 11. For case P2 and P3, when the acceleration signals of the damaged pipeline were analyzed with the DWT, the exact damage location was identified by the peak with the maximum absolute value in the plots of the detail signal calculated with the DWT Figure as shown in Figure 11 and Figure 11 by the db4 at level 1. Also, by applying the CWT, the discontinuity due to the damage was clearly detected as shown in Figures 14 and 15.

![Fig. 9: Case P1, DWT by applying db4 at level, damaged at element 50th](image)

![Fig. 10: Case P1, DWT by applying Haar wavelet, damaged at element 50th](image)
Fig. 11: Case P1, CWT by applying db4 wavelet, damaged at element 50th, a) a=1 to 20, b) a=1.

Fig. 12: Case P2, DWT by applying db4 wavelet, damaged at element 11th.

Fig. 13: Case P3, DWT by applying db4 wavelet, damaged at elements 11th and 89th.

Fig. 14: Case P2, CWT by applying db4 wavelet, element 11th damaged.

Fig. 15: Case P3, CWT by applying db4 wavelet, elements 11th and 89th damaged.

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7.2. Identification of Damage using DSERI

Two damage scenarios with different levels of location to simulate damage are conceived. The damage was implemented by reducing the stiffness of specific elements. After decomposing the signals, the detail signal energy rate indices (DSERI) $\Delta(E_{rj})$ of each node are calculated using Eq. (22). The undamaged offshore free span pipeline structure is denoted by P0 (fig. 7-a). The other two different damage scenarios, denoted as P1 and P3, are described as follows: (1) P1: stiffness reduced 40% in the 50th element; and (2) P3: stiffness reduced 40% in the 11th and 89th elements. They are shown in Fig. 7. For every damaged structure, the histogram can be drawn. The damage location can be intuitively shown in histograms. Those histograms of two damaged structures; P1 and P3 are shown in, Figures 16, 17 and Figures 18, 19, respectively.

![Damage detection of P1 model applying db4.](image)

Fig. 16: Damage detection of P1 model applying db4.

![Damage detection of P1 model applying db3.](image)

Fig. 17: Damage detection of P1 model applying db3

In Fig. 16 for instance, it can be seen that DSERI in 50th element are larger than another elements, then we can suspect that this element is damaged. And in Figure 18, it can be seen that the DSERI in 11th and 89th elements are larger than another elements then we can suspect that these elements are damaged.

![Damage detection of P3 model by db2 at level=2.](image)

Fig. 18: Damage detection of P3 model by db2 at level=2

![Damage detection of P3 model by db2 at level=3.](image)

Fig. 19: Damage detection of P3 model by db2 at level=3

8. Conclusions

The structural damage is typically a local phenomenon which tends to be captured by higher frequency signals. Wavelet transformation has emerged recently as a powerful mathematical tool for capturing change of structural characteristic induced by damage. Wavelet-based methods can be applied to full structures as well as to structural members in contrast to other damage identification techniques. Another fact that makes the wavelet-based methodology easy to implement in practice, is that it can be used for structural monitoring at the expected areas of damage only. All these properties make the method a potentially reliable and cost-effective assessment technique that can be applied to the maintenance of the offshore free span pipeline and other complex
structures. However, a possible drawback of the WT is that the frequency resolution is rather poor in the higher frequency region. To solve this disadvantage, effects of the boundary conditions on the wavelet-based damage identification can be eliminated. The author’s proposed new method based on wavelet packet analysis which is called detail signal energy rate index (DSERI). We have shown that the method can be applied when the damage is near a support or middle of pipelines without any effects of the boundary conditions on results. The sensitivity of this method to the change of structural parameters is derived. Results show that the DSERI is significantly more sensitive to the stiffness change. The DSERI in the damaged elements is larger than other elements; therefore DSERI of detail signal is a good indicator for damage location detection.

Experimental studies are urgently needed to validate the results obtained from the numerical simulations.

References


