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Measured Data Processing Method for Relative Motions Between Two Side-by-side Ships

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Abstract

In order to design and implement a wave compensation system to reduce the relative motion between two side-by-side ships in waves, a new method to process measured data of ship model test with contact measurement to study the characteristics of relative motion was presented. The reference co-ordinate systems and relative motions were defined, and the scheme of the model test was described. Then the Empirical Mode Decomposition (EMD) adaptive filter were designed, the frequency domain integration transform method based upon Fast Fourier Transform (FFT) were established. The procedure to transform acceleration signal into displacement was proposed and verified, and the processing results with and without EMD adaptive filter were compared. Finally, the relative motions consistent with reality were acquired, which indicates this method is effective for measured data processing.

Keywords*: relative motion, ship model test, acceleration, frequency domain integration, empirical mode decomposition (EMD)*

1. Introduction

When two vessels are positioned side-by-side at sea to do replenishment, the relative motions between them are of considerable importance. Due to the close proximity of the two vessels, hydrodynamic interaction between them is highly increased and it has great effect on relative motion. The large relative motion may cause replenishment work difficulties, the cargo which is descending will be colliding with the ship board which is ascending and the cargo which has loaded on ship board will be suspended in the air again, sometimes even leading to the collision between the superstructures of two vessels. Because of these serious problems caused by the hydrodynamic interaction effect, it is very important to study the relative motion behaviors between two side-by-side moored vessels[1,2]. The hydrodynamic interactions between multiple bodies have been reported by many reporters[3,4], but only several authors dealt with the corresponding problems for the ship-like bodies and few authors discussed the relative motions for various loading position.

In order to understand the relative motion characteristics of two side-by-side positioned ships in waves, the contact measurement method is used in ship model experiment under different wave conditions. In the experiment, the accelerometers were used to measure the accelerations of surge, sway and heave of each ship model, so it is necessary to convert the acceleration signal into displacement. It needs double integration to transform acceleration into displacement. But because of the noises embedded in the measured data, the resulting displacement by direct double integration is hardly useful. The method to filter the noises and improve the accuracy of resulting displacement is needed. To obtain the relative motion between two side-by-side ships, the reference coordinate systems and relative motions should be defined. The paper is dedicated to resolve these problems, and to present an effective method to process measured data of model test to acquire the characteristics of relative motions between two side-by-side ships in waves.

This paper is organized as follows. The next section describes the definition of reference co-ordinate system and relative motion and the scheme of model test. The section that follows describes EMD Adaptive Filter and Frequency Domain Integration. Then the method

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to process meassured data to calculate the relative motion between two side-by-side ships is described and the relative motion is acquired. In the last section, conclusions are made.

2. Definition of Relative Motion and Model Test Scheme

Two side-by-side positioned vessels show different characteristics from one single vessel in waves. In order to study the characteristics of relative motion between two side-by-side positioned ships in waves, it is essential to define the reference coordinate system and the relative motion. The relative motion characteristics were studied by model test, so the scheme of ship model test is also briefly described here.

2.1. Reference Co-ordinate System

In order to describe the relative motion between two side-be-side ships in waves, three sets of right-handed orthogonal coordinate systems are adopted, which are shown as Fig.1. The O-XYZ system is the inertial coordinate system. The O_A-X_A-Y_A-Z_A and O_B-X_B-Y_B-Z_B are the oscillatory coordinate systems fixed with respect to ship A and ship B, respectively. The O-XY plane rests on the calm water surface, the X-axis points forward and the Z-axis vertically upward. The oscillatory coordinate systems O_A-$X_AY_AZ_A$ and O_B-$X_BY_BZ_B$ are used to describe the ship's motion in six degrees of freedom.

2.2. Relative Motion Between Two Side-By-Side Ships

Each vessel takes 6-DOF(degree of freedom) motions. Assuming that the loading point is on Ship-B. The position of the loading point is shown as Figure 1. The coordinates of the position with respect to each ship's reference coordinates system are (x_a, y_a, z_a) and (x_b, y_b, z_b), respectively.

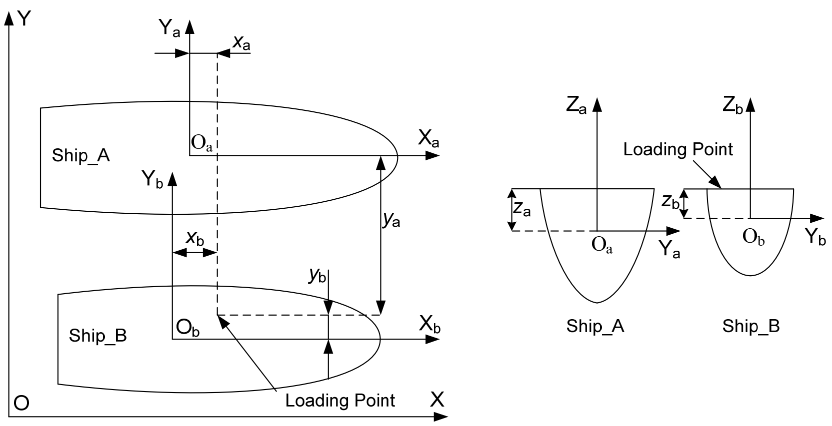

Figure 1. The general coordinates of the loading point

When Ship-B takes 6-DOF motions, the position vector of the loading point in O_B-X_B-Y_B-Z_B coordinate system is as follows:

$$(\zeta_{1b}+\zeta_{5b}z_b+\zeta_{6b}y_b,\ \zeta_{2b}+\zeta_{6b}x_b-\zeta_{4b}z_b,\ \zeta_{3b}+\zeta_{4b}y_b-\zeta_{5b}x_b)$$

When Ship-A takes 6-DOF motions, the position vector of the loading point in O_A-X_A-Y_A-Z_A coordinate system is as follows:

$$(\zeta_{1a}+\zeta_{5a}z_a+\zeta_{6a}y_a,\ \zeta_{2a}+\zeta_{6a}x_a-\zeta_{4a}z_a,\ \zeta_{3a}+\zeta_{4a}y_a-\zeta_{5a}x_a)$$

Thus, the longitudinal, lateral and vertical relative motion (represented by X, Y and Z) between ship A and ship B at any position can be calculated by the following three equations:

$$X=(\zeta_{1b}+\zeta_{5b}z_b-\zeta_{6b}y_b)-(\zeta_{1a}+\zeta_{5a}z_a-\zeta_{6a}y_a) \quad (1)$$

$$Y = (\zeta_{2b} - \zeta_{4b}z_b + \zeta_{6b}x_b) - (\zeta_{2a} - \zeta_{4a}z_a + \zeta_{6a}x_a) \quad (2)$$

$$Z = (\zeta_{3b} + \zeta_{4b}y_b - \zeta_{5b}x_b) - (\zeta_{3a} + \zeta_{4a}y_a - \zeta_{5a}x_a) \quad (3)$$

Where, the subscript of a and b denote ship A and ship B, and the subscript of 1~6 denote surge, sway, heave, roll, pitch and yaw, respectively.

2.3. Model Test Scheme

The objective of the model test is to study the relative motion characteristics of two side-by-side moored ships in different wave conditions. The model test was carried out in the tank of the Coastal and Offshore Engineering Laboratory in South China University of Technology. The dimension of the tank is 32m×18m×1m and the depth of the water is 0.8m. The tank is equipped with a wave generator at one end, which can produce two-dimensional regular and irregular waves; the other end is paved with the 1:7 wave dissipation ramp, which can eliminate 90% of the reflected wave. The two ship models used in the experiment were made according to the similarity criteria, the similarity scale is 25. Figure 2 shows the photo of the two side-by-side positioned ship models in experiment. The main parameters for the two ships and models are given in Table 1.

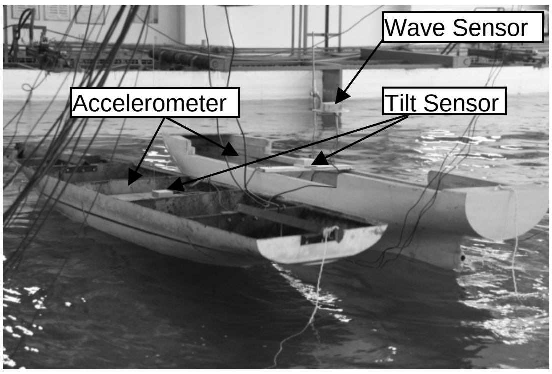

Figure 2. Two ship models positioned side-by-side in wave

Table 1. Main Parameters of Ship Models

Item	unit	Supplying		Receiving	
		ship	model	ship	model
L_{pp}	m	72	2.88	77	3.08
B	m	13.9	0.56	15.7	0.63
LCG	m	-1.25	-0.05	-1.64	-0.07
GM	m	3.1	0.16	4.46	0.18
Z_g	m	4.5	0.19	4.37	0.18
Displacement	m^3	3900	0.249	2673	0.17

The model test was conducted under different wave conditions, including different incident wave angles, different wave frequencies and different wave heights. In the experiment, the history of the wave elevation was measured by a wave height recorder; the surge, sway and heave motions of the two ships were measured by accelerometers, and the roll, pitch and yaw motions were measured by tilt sensors. So, in order to get the relative motion, it is necessary to transform acceleration into displacement.

3. EMD Adaptive Filter and Frequency Domain Integration

The surge, sway and heave motions are measured by three accelerometers. To obtain the desired relative motion of the loading position, the acceleration signals have to be integrated twice to be transformed into displacement, but the resulting displacement got by direct double integration is not too good and even hardly useful. To reduce typical errors like sensor noise, bias and misalignment of the accelerometers, and ensure a stable integration, signal conditioning can be realized, as presented by Godhaven [5]. But the selection of the threshold frequency of the filter is not easy. In order to improve the accuracy, a new integral transform method based upon FFT and EMD is presented., and frequency domanin integration based upon FFT used to transform filtered acceleration into displacement.

3.1. Empirical Mode Decomposition(EMD) Adaptive Filter

EMD is used to filter the noises embedded in the acceleration signal adaptively. EMD has been widely used to analyze non-stationary and nonlinear signal by decomposing into a series of intrinsic mode functions (IMFs) and a trend function[7]. EMD is adaptive, and IMFs become the basis representing the underlying data. An IMF is a function that satisfies two conditions: (1) in the whole data set, the number of extrema and the number of zero crossings must either equal or differ at most by one; and (2) at any point, the mean value of the envelope defined by the local maxima and the envelope defined by the local minima is zero.[8,9]

For any given signal $x(t)$, EMD is implemented through a sifting process that is summarized as follows:[10]

(1) To identify all the local extrema. Seperately connect all the maxima and minima with natural cubic spline lines to form the upper and lower envelopes.

(2) Find the mean of the envelopes as $m_1(t)$, and take the difference between the data and the mean as $h_1(t)$, which is the proto-IMF:

$$h_1(t) = x(t) - m_1(t) \tag{4}$$

(3) Check the proto-IMF $h_1(t)$ against the definition of IMF and the stoppage criterion to determine if it is an IMF. If $h_1(t)$ does not satisfy the definition, repeat step 1 to 3 on $h_1(t)$:

$$h_{11}(t) = h_1(t) - m_{11}(t) \tag{5}$$

...
...

Repeat step 1 to 3 on $h_{1i}(t)$ till it satisfies the definition after k times of sifting.

$$h_{1k}(t) = h_{1(k-1)}(t) - m_{1k}(t) \tag{6}$$

If h_{1k} does satisfy the definition, assign it as an IMF component, $c_1(t)$.

$$c_1(t) = h_{1k} \tag{7}$$

The first residue can also be got as follows:

$$r_1(t) = x(t) - c_1(t) \tag{8}$$

Now, the first IMF component($c_1(t)$) has been got from the original signal, it contains the best signal scale or the shortest period component. The stoppage criterion is as follows:

$$\sum_t \frac{[h_{1(k-1)}(t) - h_{1k}(t)]^2}{h_{1(k-1)}^2} < SD \tag{9}$$

Where, $h_{1k}(t)$ is the result of x(t) after k times of sifting, SD range between 0.2 and 0.3.

(4) Repeat the operation from step 1 to 3 on the residue, r(t) = x(t) – c(t), as the original signal. The operation ends when the residue, $r_n(t)$, becomes a monotonic function or a function containing only one internal extremum from which no more IMF can be extracted.

So, any given signal x(t) can be decomposed by EMD as follows:

$$x(t) = r_n(t) + \sum_{i=1}^{n} c_i(t) \tag{10}$$

where $r_n(t)$ stands for a residual "trend" and the "modes" $\{c_i(t), i = 1,...,n\}$ are constrained to be zero-mean amplitude modulation frequency modulation waveforms.

It can be seen from the EMD, each IMF has different characteristic of frequency band, and the residue is a mean "trend" or constant. Frequency band of IMF decreases from c_1 to c_n, with c_1 the highest and c_n the lowest.In the decomposition, the IMF function depend on the signal itself, different signal can generate different IMF function, so the EMD is adaptive. According to this feature, an EMD based self-adaptive filter can be implemented. The idea of the adaptive filter is to decompose the signal by EMD, and then the IMF components are filtered according to the band characteristics of the noise.[11]

High-Pass Filter. If the noise in the signal is low-frequency oscillation noise, then a high-pass filter based upon EMD decomposition can be constructed to filter the noise. The result of the filtering can be expressed as follows:

$$x_{hp}(t) = \sum_{i=1}^{\alpha} c_i(t) \tag{11}$$

Low-Pass Filter. If the noise in the signal is high-frequency oscillation noise, then a low-pass filter based upon EMD decomposition can be constructed to filter the noise. The result of the filtering can be expressed as follows:

$$x_{lp}(t) = \sum_{i=\beta}^{K} c_i(t) + r_n(t) \tag{12}$$

Band-Pass Filter. If the noise in the signal contains both high and low frequency oscillation noise, then a band-pass filter based upon EMD decomposition can be constructed to filter the noise. The result of the filtering can be expressed as follows:

$$x_{bp}(t) = \sum_{i=\alpha}^{\beta} c_i(t) \tag{13}$$

3.2. Frequency Domain Integration

The principle of frequency domain integration is as follows: The FFT is applied to the measured time domain acceleration sequence, and then the resulting frequency domain acceleration sequence is integrated twice to get displacement.

Consider a time domain signal x(t) of time windows length T, which is sampled N times to obtain the discrete time series x(n). Then the normalized DFT of x(n) is defined as:

$$X(k) = DFT[x(n)] = \sum_{n=0}^{N-1} x(n) e^{-(j\frac{2\pi}{N})nk} \tag{14}$$

Where, n and k take values of 0,1,2,……,(N-1).

DFT is implemented with Fast Fourier Transform(FFT) algorithm. X(k) is a complex valued series of length N(frequency spectrum):

$$X(k) = DFT[x(n)] = [(a_0, jb_0), (a_2, jb_2), ..., (a_{N-1}, jb_{N-1})] \tag{15}$$

The amplitude, circular frequency and initial phase angle of each harmonic component of x(n) can be calculated as follows:

$$\begin{cases} A_k = \sqrt{a_k^2 + b_k^2} \\ w_k = 2\pi k / T \\ \varphi_k = \arctan \dfrac{b_k}{a_k} \end{cases} \tag{16}$$

According to the signal superposition principle, any periodic signal can be obtained through the superposition of certain harmonic signal. If the acceleration signal is expressed as formula (17), the displacement signal can be expressed as formula (18).

$$a = A_{a_0} \cos(w_0 t + \varphi_{a_0}) + A_{a_1} \cos(w_1 t + \varphi_{a_1}) + ... + A_{a_{N-1}} \cos(w_{N-1} t + \varphi_{a_{N-1}}) \tag{17}$$

$$d = A_{d_0} \cos(w_0 t + \varphi_{d_0}) + A_{d_1} \cos(w_1 t + \varphi_{d_1}) + ... + A_{d_{N-1}} \cos(w_{N-1} t + \varphi_{d_{N-1}}) \tag{18}$$

In the frequency domain, the displacement can be obtained by scaling the acceleration by the square of the frequency. Both the amplitude and phase relationships between acceleration and displacement are shown as formula (19) and (20):

$$A_{d_i} = A_{a_i} / w_i^2 \tag{19}$$

$$\varphi_{d_i} = \varphi_{a_i} - \pi \tag{20}$$

In order to attenuate the effect of random noises embedded in acceleration signal, it is necessary to filter them. In the frequency domain, it can be done by setting the potion of frequency that need to be filtered to zero. Frequency domain filtering method can be expressed as follows:

$$y(n) = \sum_{k=0}^{N-1} -\frac{1}{(2\pi\Delta f)^2} H(k) X(k) e^{-j2\pi nk/N} \tag{21}$$

$$H(k) = \begin{cases} 1, (f_d \le k\Delta f \le f_u) \\ 0, others \end{cases} \tag{22}$$

In which, k, n and r takes values of 0, 1, 2, …, N-1; f_d and f_u are the lower cut-off frequency and upper cut-off frequency of band-pass filter; X(k) is the FFT transformation of time domain signal x(n); Δf is frequency resolution; H(k) is the bandpass filter frequency response function.

Finally, the resulting frequency domain integration signal is converted back to the time domain by inverse FFT transform, and thus the displacement signal y(t) of time domain is obtained.

4. Acquisition of Relative Motion between Two Side-By-Side Ships

After ship model test, measured data were processed to obtain the relative motion between two side-by-side ships in waves. This section describes the method to process the measured data of model test for relative motion between two side-by-side ships, and the key to the method is the processing of acceleration signal.

4.1. EMD adaptive filter of acceleration data

In order to get accurate displacement, accelerations signal should be adaptively filtered at first. If there are high frequency random noises or some band noises, the acceleration signal should be decomposed by EMD to filter the corresponding frequency band of noises. Otherwise, only the unavoidable low-frequency oscillation noise need to be filtered, which can be achieved by the summation of all the IMF components but residue.

Because the calculation of a relative motion need to use two ship's six kinds of motion, including each ship's surge, sway, heave,roll, pitch and yaw motions, all of which need to be EMD adaptively filtered, but only the processing of heave motion of ship A is described here, other motions can be processed similarly.

The measured heave acceleration data of ship A is shown as Fig. 3.

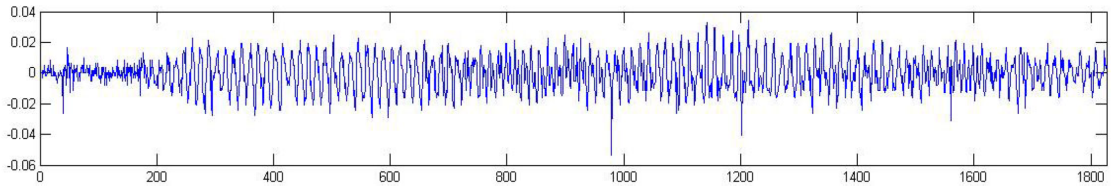

Figure 3. Original measured heave acceleration signal

In order to study the internal frequency characteristics, the heave acceleration signal is decomposed into 10 IMF(c1,c2,...,c10) by EMD, as is shown in Figure 4.

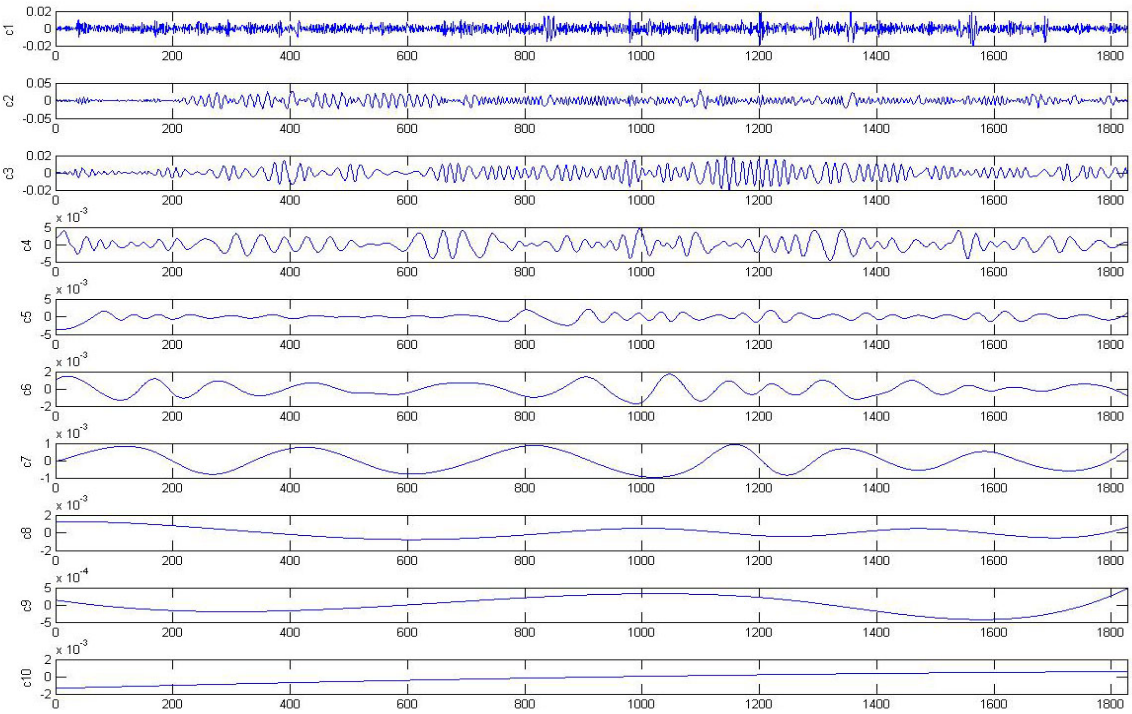

Figure 4. Decomposition of heave acceleration signal by EMD

It can be seen from Figure 4 that, c1, c2, c3, and c4 correspond to the high frequency part of the acceleration signal, c5, c6 and c7 correspond to the operating frequency of the signal, c8, c9 and c10 correspond to the low frequency of the signal, and c10 is the trend term.

Figure 5 gives the reconstructed heave acceleration signal after EMD adaptive filtering, which represents the results of low pass filtering, band pass filtering and high pass filtering from up to down respectively. Low pass filtering is the summation of c3, c4, c5, c6, c7, c8, c9 and c10, band pass filtering is the summation of c3, c4, c5, c6, c7 and c8, high pass filtering is the summation of c2, c3, c4, c5 and c6.

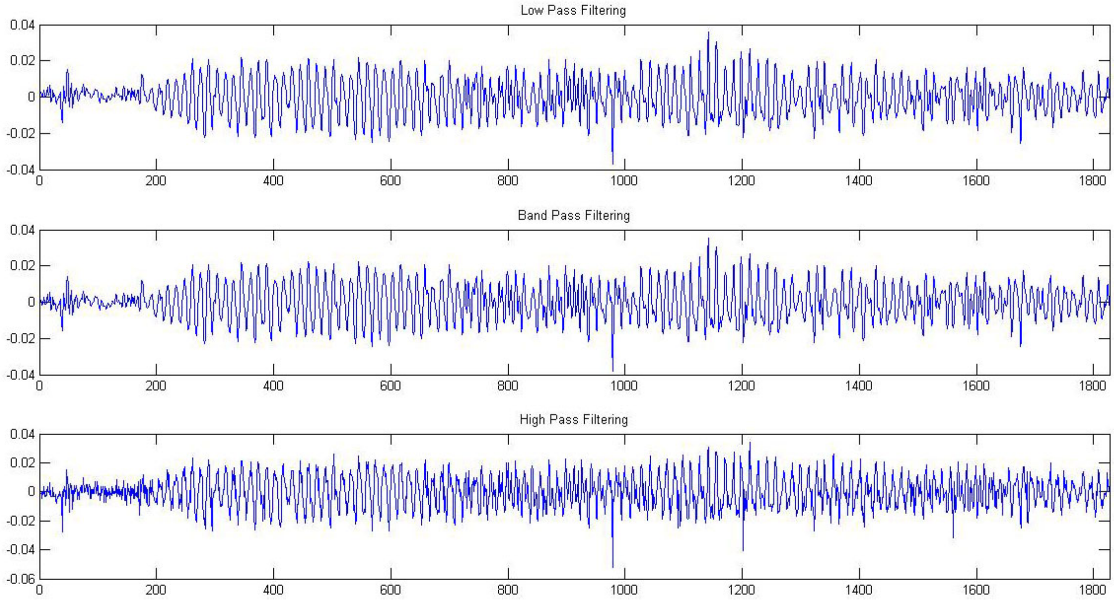

Figure 5. Reconstructed heave acceleration signal after EMD adaptive filtering

It can be seen from Figure 5 that: the reconstructed signal after low frequency filtering has removed high frequency intereferences, but the signal is not too stable; the signal after high pass filtering has high frequency interference, but it is stable; the signal after bandpass filtering not only removed high frequency interference, but also is stable. So, EMD based adaptive filtering technology has good effect on ship's motion data filtering.

4.2. Processing of Acceleration

After the measured acceleration signal has been filtered by EMD adaptive filter, it is processed to be transformed into displacement. The procedure to process acceleration signal is as follows: (1) To transform the time domain acceleration signal into frequency domain signal by Fast Fourier Transformation(FFT); (2) Integrate the frequency domain signal twice to obtain the frequency domain displacement; (3) Inverse FFT transformation of the frequency domain displacement to obtain the time domain displacement; (4) EMD adaptive filtering of the resulting displacement.

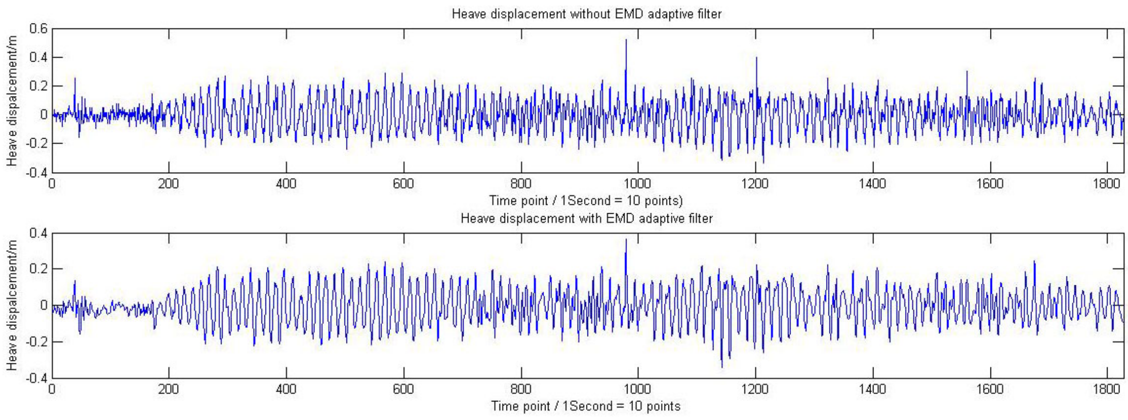

Figure 6. Integration of Heave acceleration with and without EMD adaptive filter

In order to validate the efficiency of the method, the integration results from acceleration to displacement are calculated with and without EMD adaptive filter separately. Figure 6 gives the result of integration of one ship's heave acceleration with and without EMD adaptive filter. It can be seen from the results that the EMD adaptive filter can effectively eliminate the noise embeded in the measured data.

4.3. Acquisition of Relative Motion

After the surge, sway and heave acceleration signal of two ship models have been transformed into displacement according to the above-mentioned, and the roll, pitch and yaw signal have been filtered by EMD adaptive filter, the surge, sway, heave, roll, pitch and yaw of two ship models can be substituted into (1),(2) and (3), and the longitudinal, lateral and vertical relative motion can be acquired. Figure 7 gives the longitudinal, lateral and vertical relative motion with EMD adaptive filter, which are consistent with the theoretical calculation results and practical situation.

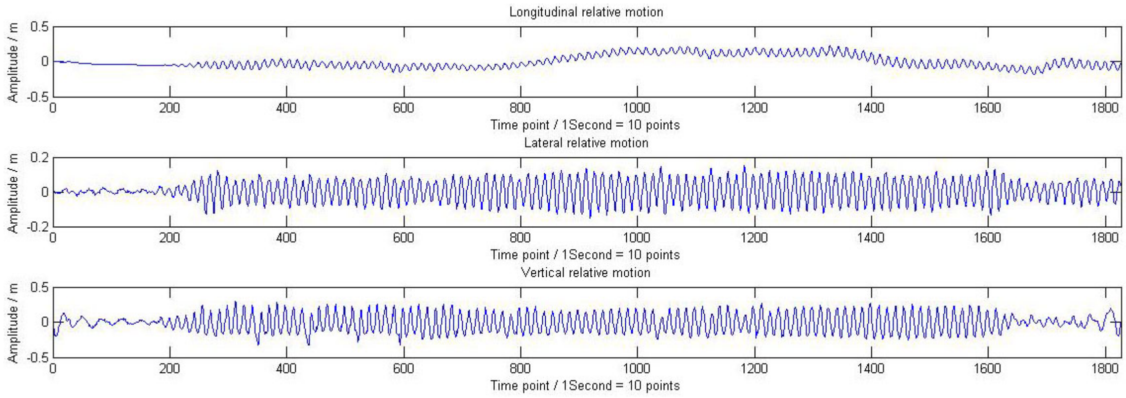

Figure 7. Vertical relative motion with EMD adaptive filter

5. Conclusions

The paper is dedicated to present an effective method to process measured data of model test with contact measurements for the relative motions between two side-by-side ships in waves. The key to the method is the transformation of accelerations to displacements, for which the EMD adaptive filter and frequency domain integraion transform based on FFT were applied. The relative motion obtained through this method agree with the practical situation, which confirmed the effectiveness of the proposed method.

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