Transient Vibration of Rotating Manipulator with Viscous Damping Layer in Scramming Process by Hilbert-Huang Transform

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Abstract: In this paper, the method of viscous damping layer on the surface of thin plate of a rotating manipulator is employed to inhibit the vibration espeically when it suffers scramming operation. Via the experimental verification, the viscous damping layer takes a certain effect on the vibration elimination. Hilbert-Huang transform (HHT) method is applied in this paper to distinguish the difference of vibration signals. Firstly, Hilbert-Huang transform is briefly introduced. Secondly, two different vibration signals of rotating manipulator with viscous damping layer or not are described by Empirical Mode Decomposition (EMD) and Hilbert spectra. With these results, the vibration signals are distinctly different from each other. It is proved that adding a viscous damping layer can suppress the vibration of rotating manipulator through the above comparisons.

Keywords: scramming process of rotating manipulator, viscous damping layer, vibration dessipation, Empirical mode decomposition, Hilbert-Huang transform

1 Introduction

Rotating manipulator is one of the most important and commonly used facilities in a variety of rotating equipment. The United States Robonaut, Ranger space manipulators can perform complex repair and assembly work on faulty satellites [1-2]. Because of the specificity of the space environment, vibration problem of rotating manipulator causes the task not being completed and brings a great loss[3]. Therefore, the vibration behavior of rotating manipulator has a very important effect on the equipment's work. How to suppress the vibration has been one of the significant problems to be solved urgently in the engineering field.

A huge amount of research efforts have been devoted to the vibration elimination of rotating manipulator in the literature. In 1984, Dickerson[4] and Alberts[5] use the passive vibration control method of viscous elasticity damping materials to inhibit the rotating manipulator structural vibration. Sakawa[6] uses the linear quadratic optimal control theory to define the state feedback gain, and suppress elastic deformation and vibration of flexible robot. Bailey[7] completes groundbreaking experiments that

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 ISSN 2572-4975 (Print), 2572-4991 (Online)

organically combine passive vibration control and active vibration control with using piezoelectric materials. Book[8] adopts pole assignment technique to design the state feedback controller in order to reduce the vibration of the flexible robot response.

This paper presents an experimental study on the vibration behavior of thin plate of the rotating manipulator, and the vibration of thin plate is restrained by a viscous damping layer. Through the experimental test, repeated impact phenomenon is found.

Method based on Hilbert-Huang transform (HHT) for analyzing non-stationary signals has been proposed[9], in which the expansion bases on adaptive for signals and from nonlinear and non-stationary processes. Based on this method, any complicated signals can be decomposed into a finite and often small number of 'Intrinsic Mode Functions' (IMFs) that admit well-behaved Hilbert transforms. And with the Hilbert transform, the IMFs yield instantaneous frequencies as functions of time that give sharp identifications of embedded structures. The final presentation of the results is an energy-frequency-time distribution, designated as the Hilbert spectrum. Compared to the Fourier-based linear and stationary spectral analysis and other time-frequency analysis methods, HHT is now used greatly in non-stationary analyses and processing fields[10-12].

In this paper, vibration signals of covering a viscous damping layer or not on the surface of manipulator is studied during the rotating process. By using HHT, effective distinctions between them are obtained. The results demonstrate that HHT is effective to identify the features of vibration signals. The vibration signals during the rotating process are analyzed which demonstrates very obviously that the viscous damping layer takes a certain effect on the vibration elimination.

2 Algorithm procedure of HHT

HHT involves two aspects including empirical mode decomposition (EMD) and Hilbert spectral analysis (HAS)[13]. Firstly, a time-adaptive decomposing operation named EMD is applied to a signal, in which the signal are decomposed into a set of complete and almost orthogonal components named Intrinsic Mode Functions (IMFs). Secondly, with Hilbert transforming of those IMFs, a full energy-frequency-time distribution of the signal is obtained and designated as HAS[12-14].

The IMFs, which are regarded as both the amplitude modulation and the frequency modulation, satisfy the following requirements: 1) the number of extremes and the number of zero crossings in the IMF must either be equal or different at most by one; and 2) at any point the mean value of the envelopes defined by the local maxima and local minima must be zero. The process to find the IMFs of a signal *x(t)* comprises the following steps:

1) Find the positions and amplitudes of all local maxima and minima in the input signal x(t). Then create an upper envelope by cubic spline interpolation of the local maxima, and a lower envelope by cubic spline interpolation of the local minima.

2) Calculate the mean of the upper and lower envelopes; this is defined as $m_1(t)$.

3) Subtract the envelope mean from the original input signal,

$$h_1(t) = x(t) - m_1(t) \tag{1}$$

4) Check whether $h_1(t)$ meets the requirements to be an IMF. If the sifting result $h_1(t)$ is an IMF, stop the process. Otherwise, treat $h_1(t)$ as the new signal data and iterate on $h_1(t)$ through the previous step 1) ~ 4). That is, to set

$$h_{11}(t) = h_1(t) - m_{11}(t) \tag{2}$$

Repeat this sifting procedure *k* times until $h_{1k}(t)$ is an IMF. This is designated as the first IMF, shown below

$$c_1(t) = h_{1k}(t) \tag{3}$$

5) Subtract $c_1(t)$ from the input signal and define the remainder, $r_1(t)$, which is the first residue as following,

$$r_1(t) = x(t) - c_1(t) \tag{4}$$

6) Since the residue $r_1(t)$ still contains information related to longer period components, it is treated as a new data stream and the above-described sifting process is repeated until the last IMF.

This procedure can be repeated times to generate residues, $r_n(t)$, and result in

$$r_2(t) = r_1(t) - c_2(t), ..., r_n(t) = r_{n-1}(t) - c_n(t) \tag{5}$$

The sifting process stops when either of two criteria are met: 1) the component $c_n(t)$, or the residue $r_n(t)$, becomes so small as to be considered inconsequential; or 2) the residue, $r_n(t)$, becomes a monotonic function from which an IMF can not be extracted. For example, the stopping condition for an IMF is

$$\sum_t \frac{[h_{k-1}(t) - h_k(t)]^2}{h_{k-1}^2(t)} < S \tag{6}$$

where $h_k(t)$ is the sifting result in the *k* the iteration, and *S* is typically set between 0.2 and 0.3. Besides, in order to achieve the last IMF, a simple way can be used. The last IMF could be obtained when the cubic spline fitting stops due to the number of local maxima or minima of the residue is less than 2.

Finally, we obtain

$$x(t) = \sum_{j=1}^{n} c_j(t) + r_n(t) \tag{7}$$

In other words, the original signal can now be represented as the sum of a set of IMFs plus a residue.

Now apply Hilbert transform to all IMFs,

$$H\left[c_j(t)\right] = \frac{1}{\pi}\int_{-\infty}^{\infty} \frac{c_j(\tau)}{t-\tau} \mathrm{d}\tau \tag{8}$$

After the Hilbert transform, $H\left[c_j(t)\right]$ and $c_j(t)$ form a complex signal. So, the envelope of every IMF, $c_j(t)$, is given by

$$a_j(t) = \sqrt{c_j^2(t) + (H[c_j(t)])^2} \tag{9}$$

The phase functions are

 ISSN 2572-4975 (Print), 2572-4991 (Online)

$$\Phi_j(t) = \arctan\frac{H[c_j(t)]}{c_j(t)} \tag{10}$$

And the instantaneous frequencies are obtained as

$$\omega_j(t) = \frac{\mathrm{d}\Phi_j(t)}{\mathrm{d}t} \tag{11}$$

Having obtained the components of IMFs, we will have no difficulty to apply Hilbert transform to each component of them. With the Hilbert transform of each IMF component, we can express the signal in the following form,

$$X(t) = \sum_{j=1}^{n} a_j(t)\exp(i\int \omega_j(t)dt) \tag{12}$$

Equation (12) also enables us to represent the amplitude and the instantaneous frequency as functions of time in a three-dimensional space, in which the amplitude can be contoured on the frequency-time plane. This frequency-time distribution of the amplitude is designated as the Hilbert amplitude spectrum, i.e. $H(\omega,t)$. With the Hilbert spectrum defined, we can also define the marginal spectrum, i.e. $h(\omega)$, as following

$$h(\omega) = \int_0^T H(\omega,t)dt \tag{13}$$

The marginal spectrum offers a measurement of the total amplitude (or energy) contribution.

3 Experimental

An aluminum tube with the length of 73mm, the width of 25mm, the height of 500mm and the wall thickness of 1mm fixed on a rotating plate acts as a rotating manipulator (Fig.1.). Measuring points and the direction of the rotating manipulator rotation are shown in Fig.1..

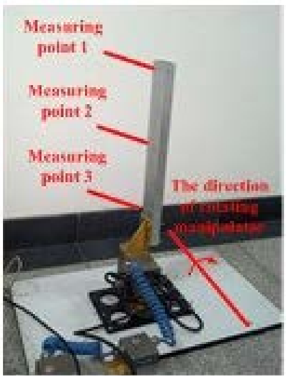


Fig. 1. The rotating manipulator

Fig. 2. The rotating manipulator with a viscous damping layer

Three acceleration sensors are respectively attached to the three points of the rotating manipulator. The rotating plate is controlled under the rotational speed of five working conditions as shown in table 1. In the five working conditions, the vibration behaviors of the three measuring points are tested.

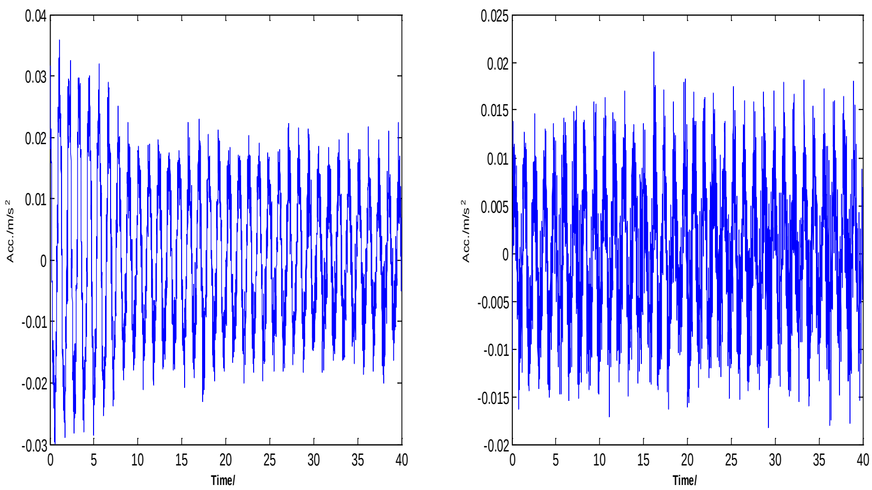
Table 1. The rotational speed of five working conditions

Conditions	1	2	3	4	5
Rotational speed(rad/s)	1.57	0.785	0.523	0.392	0.314

In order to restrain the vibration, a damping layer is added to the surface of the rotating manipulator (Fig.2.). The rotating plate is controlled at the rotational speed on five working conditions as shown in table 1 to do the experimental test.

4 Results and analysis

The rotating manipulator with a viscous damping layer and without a viscous damping layer are compared shown in figure 3 of time domain and frequency spectrum of Fi.4.. From Fig.3. and Fig. 4, one cannot identify one from each other easily.

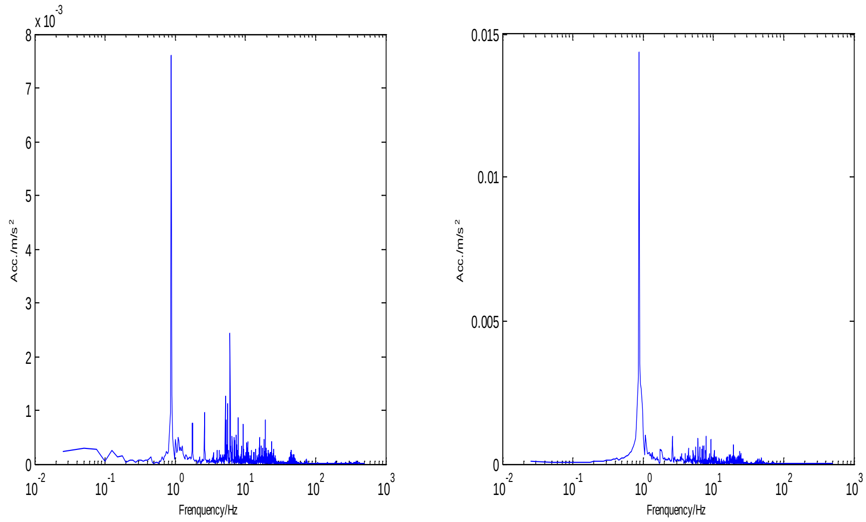


(a)Vibration signals of rotating manipulator without a viscous damping layer

(b)Vibration signals of rotating plate with a viscous damping layer

Fig.3. Original vibration signals of rotating manipulator

ISSN 2572-4975 (Print), 2572-4991 (Online)



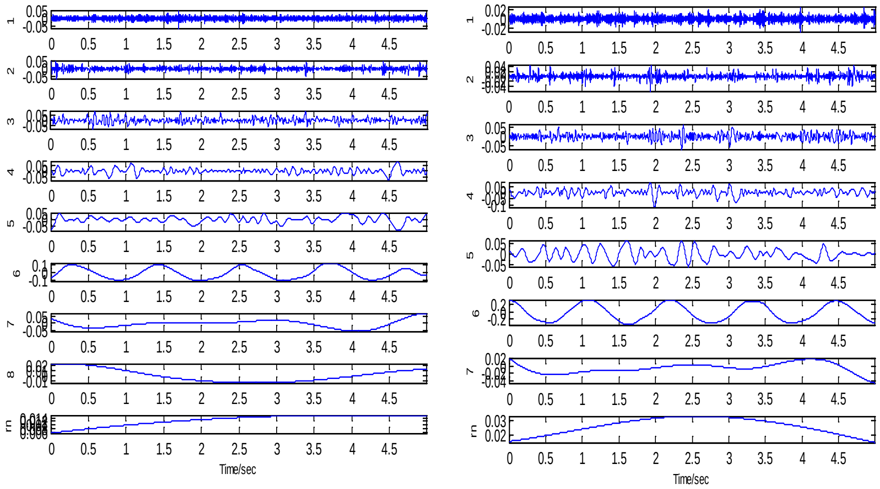
(a) Rotating manipulator without viscous damping layer (b) Rotating manipulator with viscous damping layer

Fig.4. Frequency spectrum of vibration signals of rotating manipulator

4.1 EMD analysis of vibration signals of rotating plate with viscous damping layer

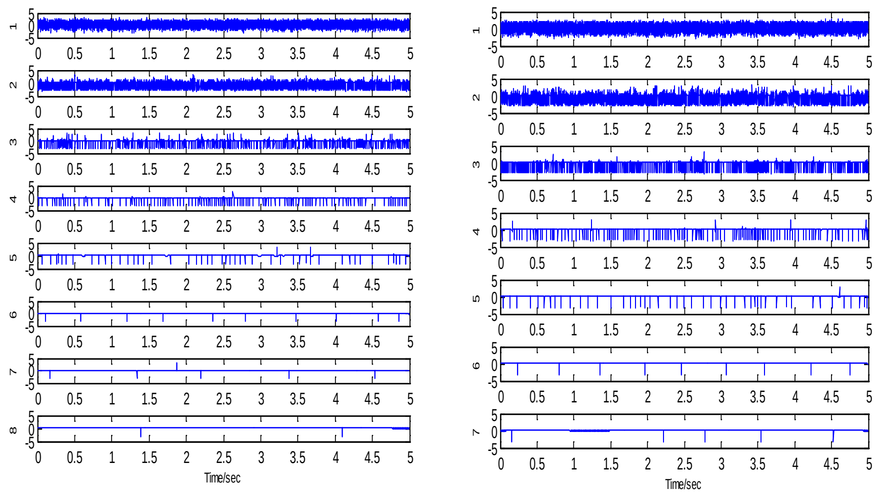
Now apply HHT for the two signals. The calculated IMFs and instantaneous frequencies (IFs) of vibration signals of rotating manipulator with a viscous damping layer and vibration signals of rotating manipulator without viscous damping layer are shown in Fig.5. and Fig.6.

From Fig.5. (a) and (b), we can see that there are 8 IMF components for signal of rotating manipulator without viscous damping layer, and 7 IMF components for signal of rotating manipulator with viscous damping layer separately. So we can say the vibration signals of rotating manipulator with a viscous damping layer or not contain different frequency components which embody their different complexity in quantitative way. The first IMF of signal of rotating manipulator without viscous damping layer, c1, appears as amplitude modulation, is also completely different from that with viscous damping layer. The second and third orders of the IMFs of signal of rotating manipulator without viscous damping layer, i.e. c2 and c3, appear frequency modulations, while signal of rotating manipulator with viscous damping layer is not. Correspondingly, IF of every IMF of signal signal of rotating manipulator with viscous damping layer or not are shown in Fig.6. (a) and (b), which are physically meaningful, and the differences between signal of rotating manipulator with viscous damping layer ot not are clearer.



(a) Rotating manipulator without viscous damping layer
(b) Rotating manipulator with viscous damping layer

Fig. 5. IMFs and residual of vibration signals of rotating manipulator



(a) Rotating manipulator without viscous damping layer
(b) Rotating manipulator with viscous damping layer

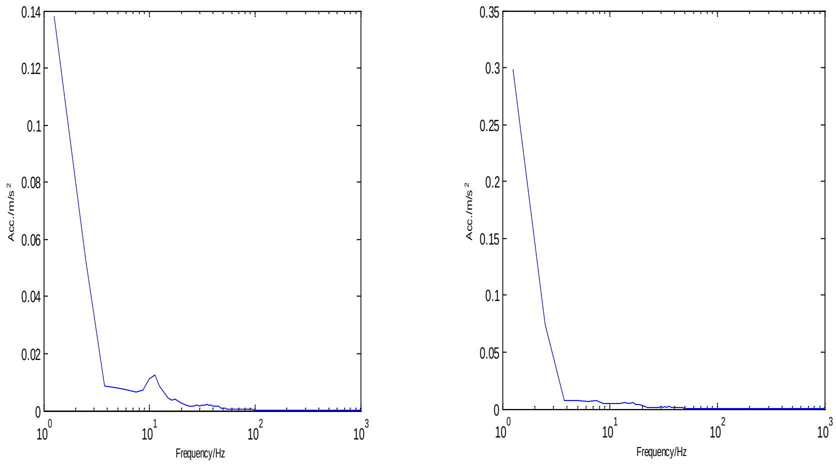
Fig. 6. Instantaneous frequencies of vibration signals of rotating manipulator

4.2 Hilbert spectra and marginal spectra analysis of vibration signals of rotating manipulator with viscous damping layer

Furthermore, their marginal spectra are also obtained according to the results of IMFs. They are shown in Fig.7.

 ISSN 2572-4975 (Print), 2572-4991 (Online)

For the marginal spectra of vibration signals of rotating manipulator with a viscous damping layer or not are shown in Fig.8., they offer the measurements of the total amplitude contributions from each frequency value. From Fig. 7, we can find the values and their tendency of the total amplitude contributions of vibration signals of rotating manipulator with viscous damping layer or not are remarkable different. Vibration signals of rotating manipulator without viscous damping layer reaches to the maximum accumulation around 4.3Hz, as the peak of frequency around 4.3 Hz of vibration signals of rotating manipulator with viscous damping layer disappeared. We can distinguish the differences between them as well.



(a) Rotating manipulator without viscous damping player

(b) Rotating manipulator with viscous damping layer

Fig.7. The marginal spectrum of vibration signals of rotating manipulator

5 Conclusions

Experimental study on the vibration behavior of rotating manipulator during rotating process has been made. Repeated impact phenomenon is found in the process of the rotating manipulator. Conclusions obtained are as follow. Dynamics parameters of the rotating manipulator are identified by the feature extraction of the first impact. A viscous damping layer added to the surface of the rotating manipulator is used to suppress the vibration.

Two different non-stationary signals are used as examples to be described and distinguished in the time-frequency analyses of HHT in the paper. The technique of HHT is proved to be effective on processing and distinguishing the differences of the vibration signals of rotating manipulator with viscous damping layer or not.

For the original signals given here, the obtained IMFs with HHT are easily distinguished from each other. The margin spectra are also different between them. These results demonstrate that the HHT can offer a more effective way for identifying the different features of vibration signals of the rotating manipulator. It also proves that adding a viscous damping layer can suppress the vibration of the rotating manipulator through the above comparisons.

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 ISSN 2572-4975 (Print), 2572-4991 (Online)