Experimental study of self-adaptive remnant vibration suppression for flexible structure with interior inlay viscous fluid unit

Jing Dong, Xu Hui and Wang Xuwei

Journal of Vibration and Control published online 24 February 2011
DOI: 10.1177/1077546310395960

Article

Journal of Vibration and Control
0(0) 1–7

DOI: 10.1177/1077546310395960
jvc.sagepub.com

Experimental study of self-adaptive remnant vibration suppression for flexible structure with interior inlay viscous fluid unit

Jing Dong[1], Xu Hui[1] and Wang Xuwei[2]

Abstract

This paper investigates a novel self-adaptive remnant vibration suppression technology for a flexible structure using an interior inlay viscous fluid unit method (IVFUM) via experiment. The IVFU is embedded in the flexible structure that can efficiently and self-adaptively suppress the remnant vibration of the engineeering flexible structure. To envaluate the effect of the IVFUM, the self-adaptive remnant vibration suppression experiments for the IVFU Euler beam were carried out in the fixed frequency excitation and the rotation excitation. The experimental results demonstrated that the IVFUM has the validity and self-adaptability for the engineeering flexible structure remnant vibration suppression under certain conditions.

Keywords

Flexible structure remnant vibration, interior inlay viscous fluid unit method, vibration suppression effect evaluation

Received: 10 July 2009; accepted: 17 September 2010

1. Introduction

The remnant vibration of engineeering flexible structures needs to be controlled precisely, quickly and reposefully. In order to suppress the remnant vibration, various suppression techniques have been proposed, for example, increasing the structure damping (Balas and Doyle, 1994), improving the structure rigidity (Wang et al., 2003), or developing a complex control system (Ryu and Kim, 1994). Cheng et al. analyzed the structure vibration suppression using the inner mass impact damper (Cheng et al., 2005, Cheng and Xu, 2006). As a novel remnant vibration passive-control based technology, the interior inlay viscous fluid unit (IVFU) is used to suppress the remnant vibration of the engineeering flexible structure and different from the others in mechanical principle. The IVFU is embedded in flexible structure, and a compound configuration is constituted with both solid structure and viscous fluid unit. The instability of solid structures induces the fluid vibration and produces the Coriolis force and the centrifugal force in the fluid and the fluid mass distribution in the solid cavity is not uniform, that absorbs the energy from the flexible structure and suppresses its vibration.

Researchers have studied the self-adaptive remnant vibration suppression of the IVFU flexible structure in the fixed frequency excitation via the numerical simulation, discussed the remnant vibration suppression mechanism, proved the fluid units self-adaptively converge to the larger vibration locations in the fixed frequency excitation with the first and second natural frequency of the IVFU Euler beam, revealed that the

[1]School of Aerospace/Ministry of Education Key Laboratory for Strength and Vibration, Xi'an Jiaotong University, Xi'an, People's Republic of China
[2]The State Key Laboratory of Nonlinear Mechanics, Institute of Mechanics, Chinese Academy of Sciences, Beijing, People's Republic of China

Corresponding author:
Jing Dong, School of Aerospace/Ministry of Education Key Laboratory for Strength and Vibration, Xi'an Jiaotong University, Xi'an 710049, People's Republic of China
Email: jingrenzhi@163.com

fluid force plays a suppressive role on the Euler beam remnant vibration during most of time, and the larger the vibration amplitude, the stronger the suppressive effect (Zhang et al., 2006). However, the quantificational evaluation of the suppression effect on the interior inlay viscous fluid unit method (IVFUM) for the remnant vibration of the flexible structure is not investigated.

This paper, in order to evaluate the remnant vibration suppression effect on the IVFUM for the flexible structure, the self-adaptive remnant vibration suppression experiments for the IVFU Euler beam in the fixed frequency excitation and the rotation excitation were carried out. The remnant vibration attenuation signals of the rotation IVFU Euler beam were processed. The experimental results revealed that the diversity of the remnant vibration suppression effect under different conditions, proved that the IVFUM has validity for the flexible structure remnant vibration suppression. Most importantly, the remnant vibration suppression mechanism has been analyzed.

2. The Remnant Vibration Suppression Experiment for the Ivfu Euler Beam

2.1. The Experimental Structure Model

The cantilever flexible aluminum Euler beam structure was taken as the experimental object, as shown in Figures 1 and 2. According to the IVFU remnant vibration suppression mechanism, the Euler beam cavity should have space with the interior inlay fluid unit. The dimension of the Euler beam is: $L * W * H = 600\ \text{mm} * 12\ \text{mm} * 30\ \text{mmv}$. The dimension of the cavity is: $l * w * h = 550\ \text{mm} * 8\ \text{mm} * 8\ \text{mm}$. The beam worked conditions are with air or the interior inlay fluid unit (water or silicon oil). The operating pressure and temperature are 1.0135×10^5 Pa and 25° respectively.

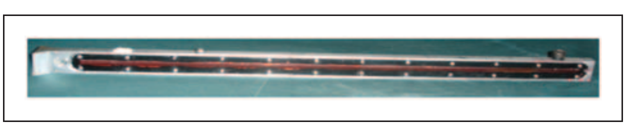

Figure 1. The view of IVFU Euler beam.

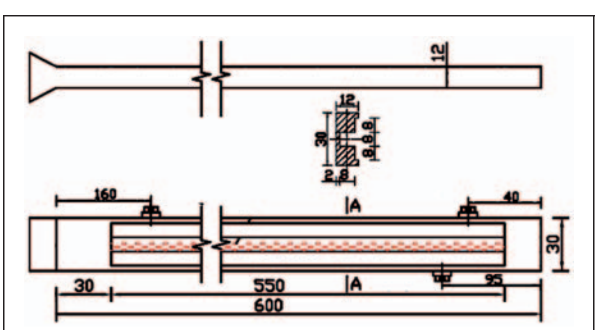

Figure 2. The Euler beam structure dimension.

2.2. The Experiment in the Fixed Frequency Excitation and Results Analysis

This section, the self-adaptive remnant vibration suppression experiment for the IVFU Euler beam in the fixed frequency excitation is presented. First, the frequency scanning technique is used to obtain the first and the second natural frequency of the IVFU Euler beam with a different interior inlay fluid unit. Second, the concentrated block with the same mass is used to substitute the IVFU, and adjust the concentrated block location to obtain the same natural frequency of the compound configuration used in the frequency scanning technique.

At the root of the Euler beam, the actuator bestir the IVFU Euler beam or the concentrated mass Euler beam with the first and the second natural frequency of the compound configuration, as is shown in Figure 3(a). The beam first and second main vibrations are arose nearly. The Euler beam vibration responses were obtained by using the accelerometer, as is shown in Figure 3(b). After obtained the vibration response, its amplitude value can be used to evaluate the remnant vibration suppression effect and discrepancy relative to the Euler beam with the concentrated block under a different fluid medium and different interior inlay fluid unit volume. Table 1 displayed the experimental results about the Euler beam in the fixed frequency excitation. From Table 1, it is certain that the IVFUM can suppress the remnant vibration under certain conditions. Different volumes or different fluid media have different suppression effects.

2.3. The Experiment of the Rotation IVFU Euler Beam

2.3.1. The experimental engineering background and principle. The experiment simulates the engineering mechanical arm under moving conditions by using the Euler beam. When the moving mechanical arm reaches the destination, the remnant vibration is caused by the sudden "moving-stopping" impulse excitation, which is harmful. The experiment intends to imitate the working process, and then to study the corresponding mechanical action from the viewpoint of the remnant vibration control.

The servo-motor drove the IVFU Euler beam during the whole rotation course. The servo-motor velocity varying is the ladder model (Figure 4), i.e., stillness $(t_0 = 0)$ $\Rightarrow$ rotation with constant acceleration

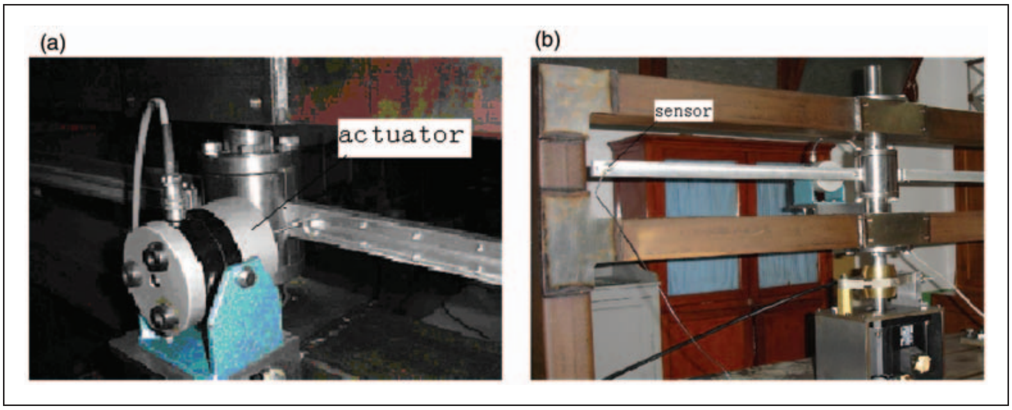

Figure 3. The IVFU Euler beam fixed frequency excitation experiment.

Table 1. The experimental results comparison of the vibration suppression effect of the IVFU Euler beam in the fixed frequency excitation with different fluid medium

		Water			Silicon oil		
	Vibration suppression effect	1/3	2/3	3/3	1/3	2/3	3/3
First mode	Gross (+/−, %)	−6.0	−40.9	−71.1	−39.6	−55.7	−71.8
	The fluid moving effect	−6.0	−8.0	0.0	−6.7	+5.4	−0.7
	The fluid mass tuned frequency effect	0.0	−32.9	−71.1	−32.9	−61.1	−71.1
Second mode	Gross (+/−, %)	−50.9	−77.3	−89.7	−80.5	−90.1	−92.2
	The fluid moving effect	+3.2	+6.7	+3.6	−6.7	−1.4	−0.2
	The fluid mass tuned frequency effect	−54.1	−84.0	−93.3	−73.8	−88.7	−92.0

Note: "−" suppression, "+"no suppression

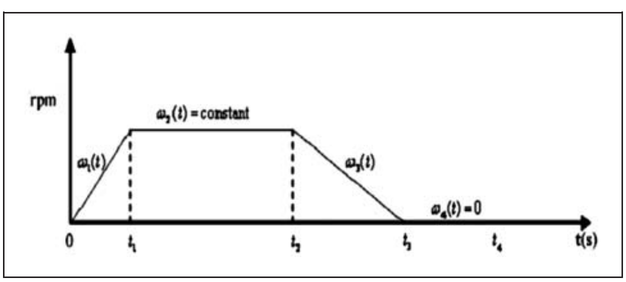

Figure 4. The servo-motor speed control diagram.

$(t_0 \le t \le t_1)$ ⇒ rotation with constant velocity $(t_1 \le t \le t_2)$ ⇒ the servo-motor interrupted (t_2) ⇒ rotation with speed-down $(t_2 \le t \le t_3)$ ⇒the servo-motor stopping (t_3) ⇒ the IVFU Euler beam vibration stopping (t_4). The IVFU Euler beam end forced vibration response signal from t_2 to t_3 and the free attenuation vibration signal from t_3 to t_4 can be obtained by the accelerometer.

2.3.2. The rotation IVFU Euler beam remnant vibration signal properties. In rotation condition, the IVFU Euler beam is driven by the Panasonic MHMA digital servo- motor. The sudden stopping of the servo-motor can offer an impulse power to the IVFU Euler beam and the remnant vibration is produced. The rotation IVFU Euler beam end response signal is gained by using the accelerometer. The signal recording equipment is the HP35670A dynamic signal analyzer. The signal waveform and its spectrum are shown in Figure 5. From Figure 5, the first main vibration of

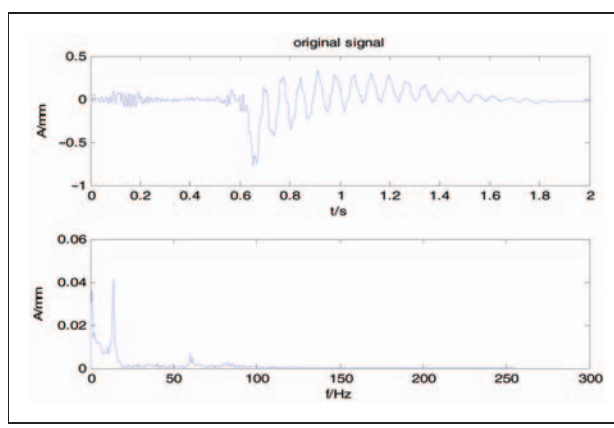

Figure 5. The remnant vibration signal in rotation excitation and its spectrum.

the IVFU Euler beam is evoked mainly. The remnant vibration response is a non-stationary complex attenuation signal. The signal is characterized by the coupled feature of the slowly-varying signal of the rigid body attenuation rotation and the quickly-varying signal of the flexible structure remnant vibration.

3. Theoretical Analysis for the Remnant Vibration

3.1. Choice of the Evaluation Criterion of the Remnant Vibration Suppression Effect

In order to evaluate the effect of the IVFUM on the moving flexible structure, the proper evaluation criterion should be chosen. As a basic evaluation criterion of the remnant vibration suppression effect, it should comply with the following principles. Firstly, it must have the capability to describe the attenuation characteristics of the signal; secondly, the parameters must be available and reliable. The equivalent damping ratio should be considered for system energy-consuming capacity firstly. The bigger the damping is, the better the remnant vibration suppression effect is. The damping is an important factor for the evaluation of the flexible structure remnant vibration suppression effect especially for the resounding vibration response.

Consequently, the "equivalent damping ratio (ζ)" is chosen to evaluate the moving IVFU flexible structure remnant vibration suppression effect.

3.2. Theoretical Modeling for the Remnant Vibration Signal

In rotation condition, the IVFU Euler beam remnant vibration is presented as a complex attenuation signal. It is noticed that the IVFU distribution in the cavity is difficult to control and is non-uniformly distributed, which significantly increases the natural complexity. The signal has the coupled characteristics of the slowly-varying signal of the rigid body attenuation rotation and the quickly-varying signal of the flexible structure remnant vibration. The free attenuation vibration characteristic of the single degree-of-freedom (d.f.) damping system appeared extremely on the signal tail. The choice for proper signal processing method is limited, and in our consulted references, the other similar research work has not been found. According to this property, an evaluation criterion is proposed regarding vibration suppression effect in this paper, i.e., single d.f. system equivalent damping ratio method combining with the non-linear least square fitting method are used to identify the equivalent mode damping ratio (ζ).

The following techniques are proposed:

1. Transform the theoretical expression $y(t) = Ae^{-\zeta\omega_n t}\sin(\omega_d t + \varphi)$ into the identified one $y(t) = b_1 e^{-b_2 t}\sin(b_3 t + b_4)$.
2. The signal's maximum value normalization, searched the sampling signal $\tilde{y}_i$ and its maximum value, make $\tilde{y}_{\max}$ the transformation $y_i = \tilde{y}_i/\tilde{y}_{\max}$, and then $y_{i\max} = 1$.
   Thus the parameter b_1 is eliminated.
3. Eliminate the phase angle parameter b_4, move the vertical coordinates to $y_{i\max}$.

Thus this instantaneous phase angle ($b_4 = \pi/2$) is obtained.

Using the above-mentioned techniques, the 4-parameters model is transformed into the 2-parameters model.

$$y(t) = e^{-b_2 t}\sin\left(b_3 t + \frac{\pi}{2}\right) = e^{-b_2 t}\cos(b_3 t) \quad (1)$$

Then, the identified objective parameters are obtained:

$$\left.\begin{array}{l} b_2 = n = \zeta\omega_n \\ b_3 = \omega_d = \omega_n\sqrt{1-\zeta^2} \end{array}\right\} \Rightarrow \left\{\begin{array}{l} \omega_n = \sqrt{b_2^2 + b_3^2} \\ \zeta = \dfrac{b_2}{\sqrt{b_2^2 + b_3^2}} \end{array}\right. \quad (2)$$

So the equivalent damping ratio and the damping natural frequency of the IVFU Euler beam can be obtained according to the tested data.

3.3. Case Analysis

Here, the remnant vibration attenuation signal of the rotation IVFU Euler beam with 1/3 water in 2 Hz rotation frequency is chosen as the example to process by using the above-proposed method. In rotation condition, the slowly-varying signal of the rigid body attenuation rotation of the IVFU Euler beam remnant vibration response is the trend, which is the non-linear low frequency curve. According to the 2-parameter model (equation (1)), the low frequency trend is eliminated with the polynomial fitting midline method firstly. The free attenuation vibration characteristic of the single d.f. damping system extremely appeared on the signal tail. Secondly, two points from the signal is chosen according to the fitting model, and intercepted the part of the signal by using the mouse. Then the intercepted part signal waveform's maximum value is moved to the vertical coordinate origin, and the signal mode cosine phase was zero. Finally, the single d.f.

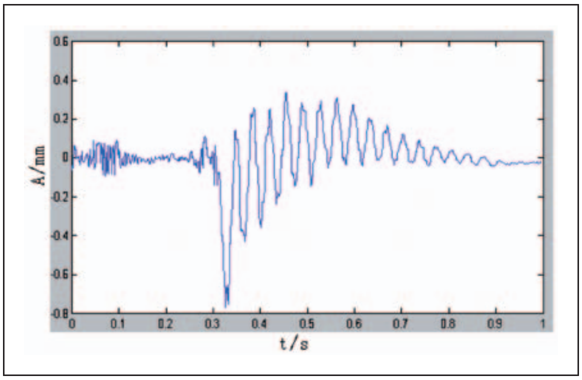

Figure 6. The remnant vibration signal of the IVFU Euler beam in 2 Hz rotation frequency.

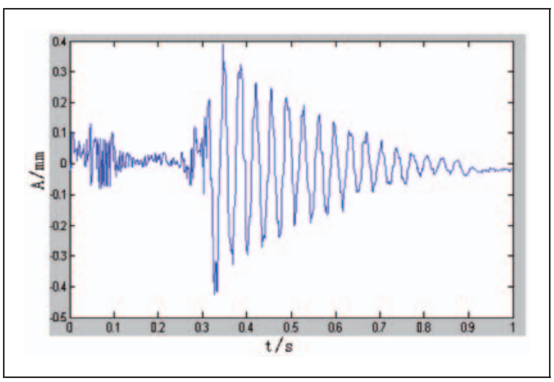

Figure 7. The signal after eliminated trend.

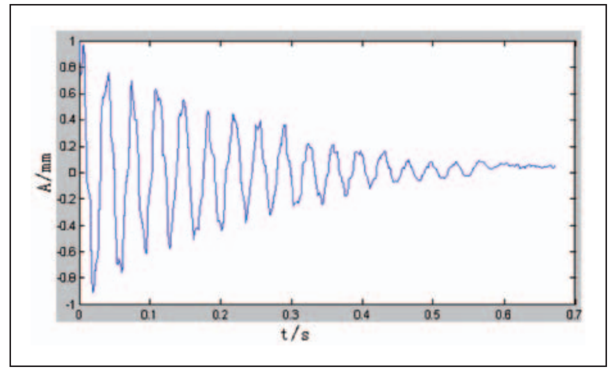

Figure 8. The intercepted part of the signal.

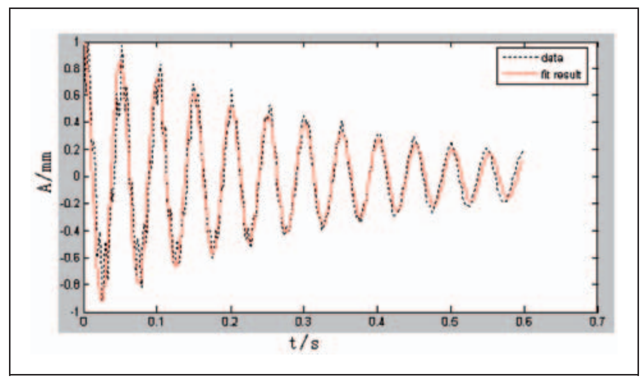

Figure 9. The non-linear least square fitting result of the signal intercepted part.

damping model combined with the non-linear least square fitting method were used to identify the mode parameters, and accomplished the corresponding program. The mode parameters were given by the program: the equivalent damping ratio ζ and the first damping natural frequency $\boldsymbol{\omega_n}$. Figures 6 to 9 presented the processing course of the case signal.

3.4. The Results of the Rotation Experiment Data and Analysis

In this section, the above-proposed methods are used to process the rotation IVFU Euler beam remnant vibration attenuation signal. The relation of the mode parameters with the rigid body rotation frequency can be obtained. The Euler beam working condition with air, or with interior inlay fluid (water or silicon oil), the fluid volume occupied 1/3, 1/2, 2/3, 3/3 of the Euler beam cavity.

Figures 10 and 11 show the relation of the mode parameters (equivalent mode damping ratio ζ and damping natural frequency $\boldsymbol{\omega_n}$) in different fluid media with different rotation frequencies. From the analysis results, the equivalent damping ratio and natural frequency of the rotation IVFU Euler beam with sudden stop decrease with the increase of the rotation frequency can be inferred, and the absolute values of the equivalent mode damping ratio are small (under 4.5%). The IVFU can suppress the Euler beam remnant vibration in 5 Hz of the rotation frequency, especially on the condition with 1/3 water. The IVFUM can suppress the Euler beam remnant vibration that is on the low rotation frequency. The equivalent mode damping ratio of the empty beam is bigger than that of the IVFU beam above 5 Hz. It is not shown that the IVFU has the suppression effect on the Euler beam.

4. Conclusions

The self-adaptive vibration suppression technology using the IVFUM is a novel remnant vibration control theory and approach, which is of great significance in the theoretical investigation and engineering application. In order to evaluate and quantify the effect on the IVFUM, the self-adaptive vibration suppression experiments for the IVFU Euler beam were carried out. The experimental results demonstrated that the IVFUM has the validity and self-adaptability for

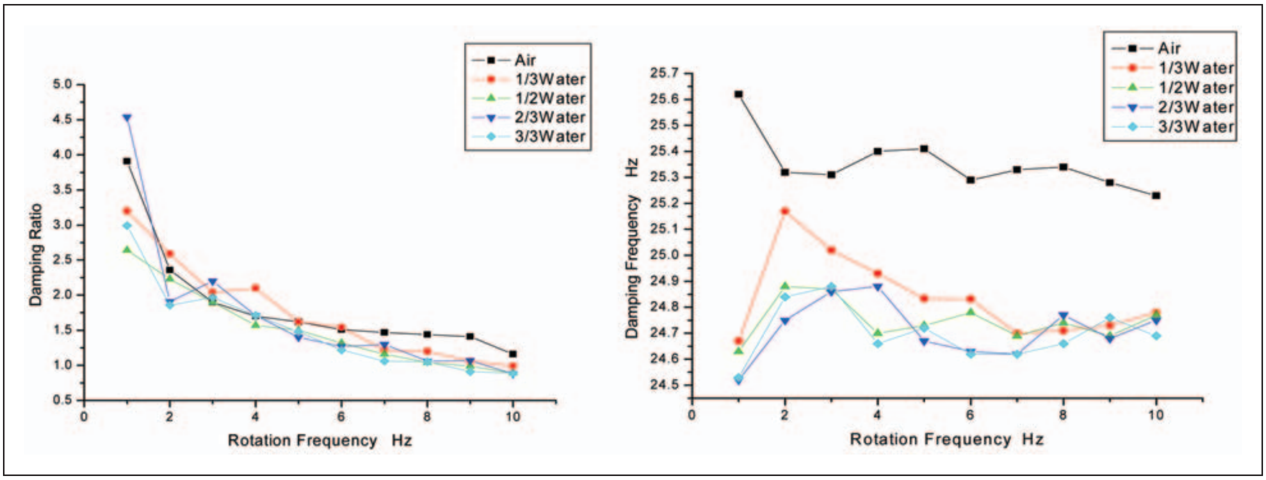

Figure 10. The relation of the mode parameters with the rotation frequency in water.

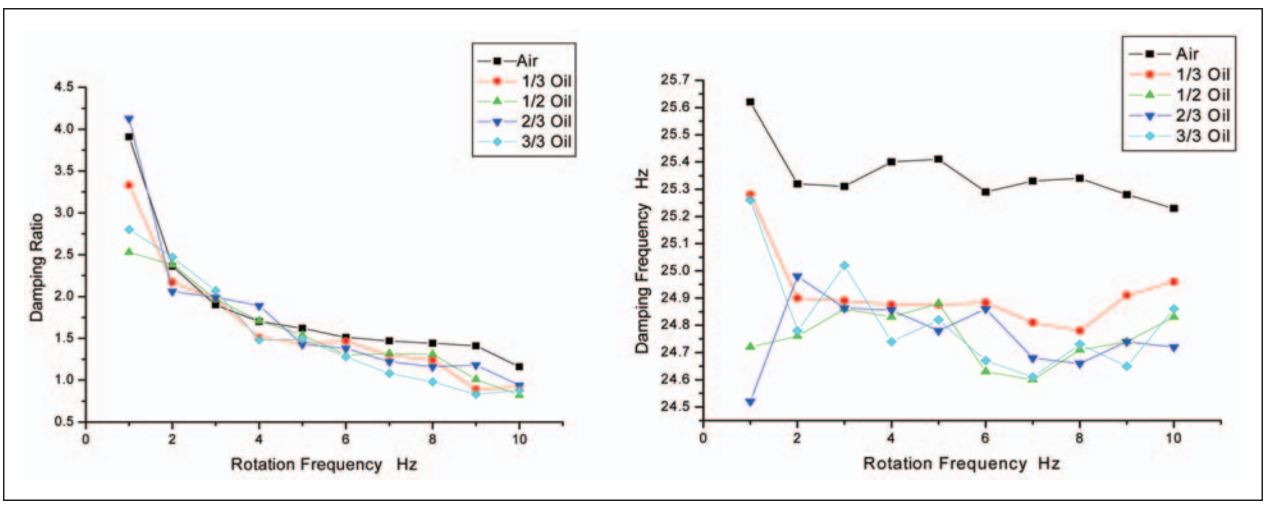

Figure 11. The relation of the mode parameters with the rotation frequency in silicon oil.

remnant vibration suppression of engineeering flexible structures under certain conditions.

Due to the signal has the coupled feature of the slowly-varying signal of the rigid body and the quickly-varying signal of the Euler beam remnant vibration, and the free attenuation vibration characteristic of the single d.f. damping system is extremely appeared on the signal tail, the method combined with the single d.f. damping system model and the non-linear least square method is proposed to identify the rotary IVFU Euler beam modal parameters. The equivalent mode damping ratio is taken as the evaluation criterion, which can evaluate qualitatively and semi- quantitatively the remnant vibration suppression effect on the moving IVFU flexible structures.

Since the IVFU is out of control and the fluid unit distribution in the cavity is not uniform, this brings about the natural complexity of the problem. Although some good results were obtained, this is a simple attempt. More and better signal processing methods need to be further explored and investigated.

Acknowledgement

This study is financially supported by National Nature Science Foundation of China (NSFC 10372076).

References

Balas GJ and Doyle JC (1994) Control of light damped flexible modes in the controller crossover region. *Journal of Guidance, Control, and Dynamics* 17(2): 370–377.

Cheng J and Xu H (2006) Inner mass impact damper for attenuating structures vibration. *International Journal of Solids and Structures* 43(17): 5355–5369.

Cheng J, Xu H, Yan A, et al. (2005) Using inner mass impact damper for attenuating structural vibration and experimental research. In: *Proceedings of the International*

Conference on Mechanical Engineering and Mechanics, 26–28 October 2005, Monmouth Junction, NJ: Science Press USA Inc., pp.1016–1022.

Ryu J and Kim SS (1994) A general approach to stress stiffening effects on flexible multi body dynamics systems. *Journal of Mechanics of Materials and Structures* 22(2): 221–227.

Wang JF, Lin CC and Chen BL (2003) Vibration suppression for high-speed railway bridges using tuned mass damper. *International Journal of Solids and Structures* 40: 255–265.

Zhang X, Li J, Xu H and Li G (2006) Numerical study of self-adaptive vibration suppression for flexible structure using interior inlay viscous fluid unit method. *Journal of Sound and Vibration* 297: 627–634.