MULTI-EXCITER VIBRATION CONTROL FOR SPATIAL ORBIT MOTION

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Abstract: Multi-exciter vibration systems provides access to simultaneous multicomponent calibration of motion transducers. Vibration control is an essential prerequisite to generate accurate spatial orbit motion for transducer calibration. Relationship of shapes and orientations of spatial orbits and amplitudes and phases of acceleration components is discussed. Multi-exciter vibration control for both cross-coupling compensation and amplitudes and phases control of acceleration components is investigated. The experimental results show that the proposed control method can efficiently reduce cross-coupling of the tri-axial vibration exciter and a variety of spatial orbits can be generated.

Keywords: Spatial orbit; Vibration control; Multi-exciter; Cross Coupling; Tri-axial vibration exciter

1. INTRODUCTION

Multi-exciter vibration systems has ability to simulate more closely approximating to actual measurement environment, which provides access to simultaneous multicomponent calibration of motion transducers[1][2].

The tri-axial vibration exciter has the ability of generating arbitrary motion which is the linear combination of unit motion along its each of three axes. ISO 16063-31 presents approach to testing of transverse vibration sensitivity using a tri-axial vibration exciter[3]. The vibration direction in X-Y plane is changed every 30° to evaluate the transverse sensitivity[4]. The sensitivity matrix that is proposed to describe relation between input accelerations and output signals. The tri-axial vibration exciter is employed to generate three independent motion vectors to solve the sensitivity matrix[5][6]. In addition, circular orbits generated by two degree freedom mechanisms such as the resonant beam and the flat plate system are also applied for transverse sensitivity testing. Thus, qualified spatial orbits such as linear orbits and circular orbits play a quite important role in transducer calibration.

However, vibration control on a multi-exciter testing system is an essential prerequisite to generate accurate spatial orbit motion. Multi-exciter vibration control deals with not only amplitude control as in single-exciter vibration control but also cross-coupling compensation and phases control[9][10]. The linear iterative algorithm is first introduced involving correcting the command driving spectrum with the error spectrum and the system impedance[11][12].

Subsequently the adaptive iterative algorithm is present in which the system impedance keeps updated for system nonlinearity and a varied adjustment gain is used for driving spectrum correction[13][14]. While the current vibration control approach concerns more amplitudes and phases of each individual exciter instead of the spatial orbit for calibration purpose. Issues involving what is the relationship between spatial orbits and acceleration components and how to achieve a certain spatial orbit still remain to further study.

The paper is organized as follows: In Section 2, spatial orbit generation is discussed. In Section 3, multi-exciter vibration control is investigated. In Section 4, experimental investigation on the spatial orbit vibration control is carried out. In the last section, conclusions of this paper are given.

2. SPATIAL ORBITS

As illustrated in Figure 1, a tri-axial vibration exciter contains three independent vibration exciters for the X-, Y- and Z-directions, with a cross-coupling unit, appropriate to generate any vibration amplitude and phase on three axes independently.
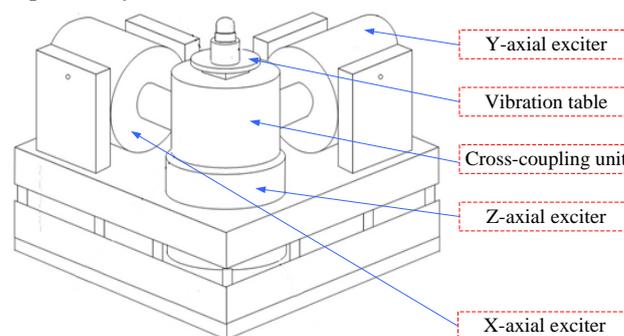

Figure 1 Tri-axial vibration exciter

Sinusoidal vibrations of the three axes with the same frequency regardless of amplitudes and phases are bound to result in a spatial elliptical orbit as depicted in Figure 2. The shape and orientation of the spatial ellipse orbit depend on the vibration amplitudes and phases of the three axes. From the theory of coordinate transformation, any spatial ellipse can be obtained from a standard ellipse in X-Y plane by rotations of certain angles. The coordinate transformation of the two ellipses can be achieved by the rotation matrix **R** consisting of the three unit vectors.

$$\mathbf{R} = \begin{bmatrix} \mathbf{u} & \mathbf{v} & \mathbf{w} \end{bmatrix} \tag{1}$$

where $\mathbf{u}$ and $\mathbf{v}$ are parallel with the major and minor axes of the spatial ellipse respectively, and $\mathbf{w}$ is perpendicular to the spatial ellipse plane
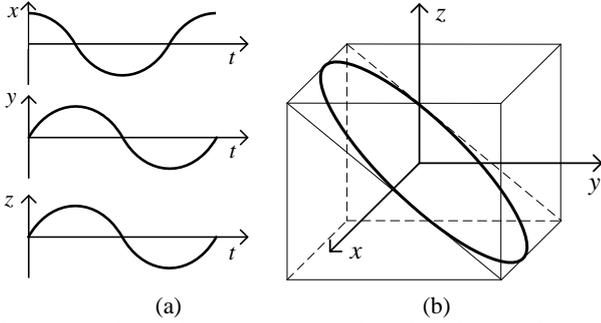

(a)   (b)

Figure 2 Spatial orbit generation. (a) Time-domain waveform; (b) Motion orbit

3. MULTI-EXCITER VIBRATION CONTROL

The vibration control flow is illustrated by means of a block diagram in Figure 3. Experimentally identify the frequency response function matrix of the multi-exciter vibration system. Then, the initial system impedance $\mathbf{Z}_0(f)$ is calculated by inverting the result. Determining the reference spectrum $\mathbf{R}(f)$ and response spectrum $\mathbf{C}_n(f)$ according to the desire waveforms and the measured response respectively. The error spectrum $\mathbf{E}(f)$ is obtained by subtracting the response spectrum $\mathbf{C}_n(f)$ from the desired spectrum $\mathbf{R}(f)$. The driving spectrum is corrected through the following iterative process:

$$\mathbf{D}_{n+1}(f) = \mathbf{D}_n(f) - \lambda \mathbf{Z}_n(f)\mathbf{E}(f) \qquad (2)$$

where $\mathbf{D}_{n+1}(f)$ is the command driving spectrum, $\mathbf{D}_n(f)$ is the current driving spectrum, λ is the adjustment gain. And the system impedance $\mathbf{Z}_n(f)$ is updated according to the formula:

$$\mathbf{Z}_{n+1}(f) = \mathbf{Z}_n(f) + \frac{(\mathbf{s}_{n+1}(f) - \mathbf{Z}_n(f)\mathbf{y}_{n+1}(f))\mathbf{s}_{n+1}^{\mathrm{T}}(f)\mathbf{Z}_n(f)}{\mathbf{s}_{n+1}^{\mathrm{T}}(f)\mathbf{Z}_n(f)\mathbf{y}_{n+1}(f)} \qquad (3)$$

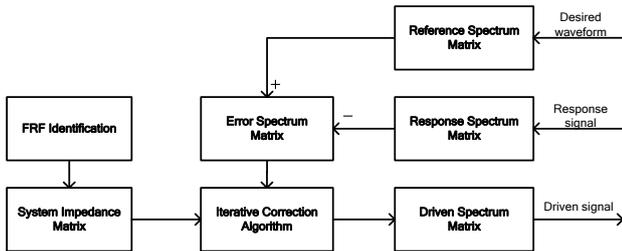Figure 3 Spatial orbit generation

4. EXPERIMENTAL INVESTIGATION

We will apply a tri-axial vibration exciter to generate spatial orbits, as shown in Figure 4. Three accelerometers are fixed on the vibration table to observe the motion orbit. The sensing axes of the monitor accelerometers are aligned with the three vibration exciters. The proposed control method is imposed on the tri-axial vibration exciter.
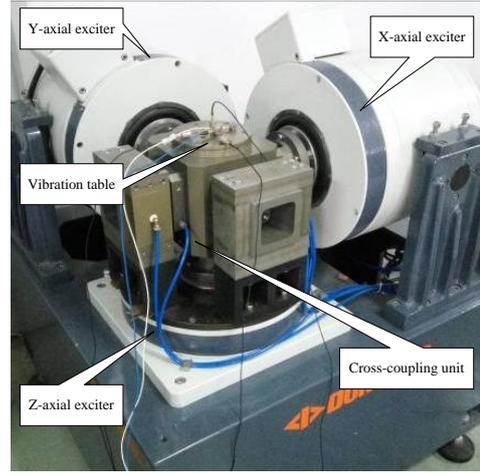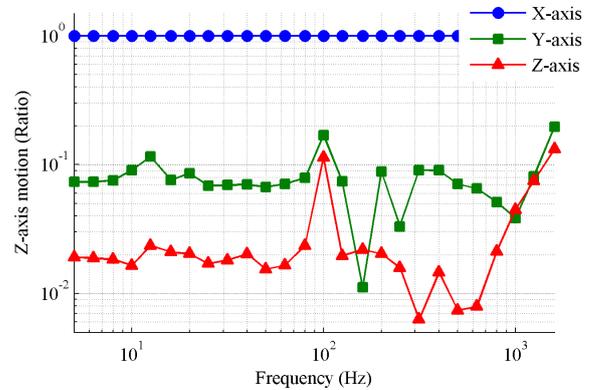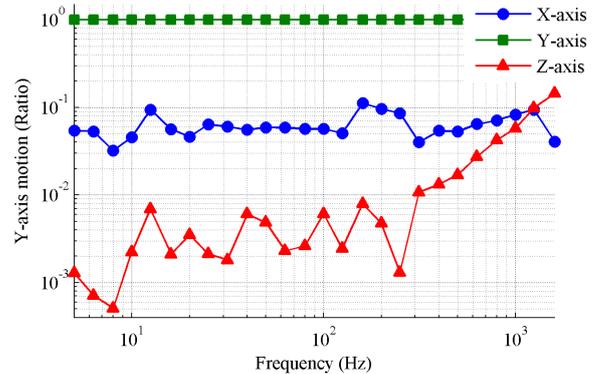

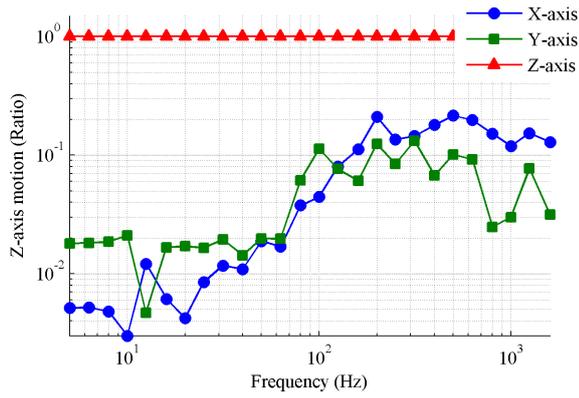Figure 4 Tri-axial vibration exciter

The cross-coupling of the tri-axial vibration exciter is evaluated by sequentially applying single axis vibration along its three axes (X, Y and Z). Firstly, no vibration control is performed on the tri-axial vibration exciter in which only the exciter along the vibrating direction is in working condition. The ratios of the cross-coupling motion to the principal axis motion are shown in Figure 5. As shown in Figure 5(a), the Y-axial cross-coupling is about 0.1 and is close to 0.2 at certain frequencies such as 100 Hz and 1600Hz. The X-axial cross-coupling is close to 0.1 in Figure 5(b). The X-axial cross-coupling in Figure 5(c) exceeds 0.1 and reaches 0.2 above the frequency of 100Hz and the Y-axial cross-coupling is close to 0.1. The cross-coupling motion of the tri-axial vibration exciter is so large that it's impossible for calibration purpose.
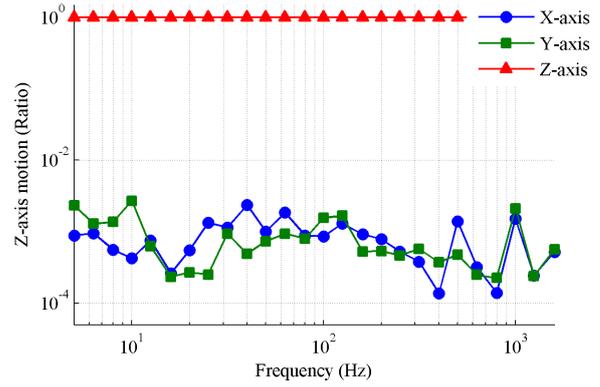

(a)

(b)

(c)

Figure 5 Cross-coupling without vibration control. (a) X-axial main motion; (b) Y-axial main motion; (c) Z-axial main motion.

Then, the proposed multi-exciter vibration control is performed on the tri-axial vibration exciter. All the three exciters are in working condition among which the principal axis exciter provides stimulus and the other two are used for cross-coupling compensation. The ratios of the cross-coupling motion to the principal axis motion are shown in Figure 6. It can be obviously seen in Figure 6 that ratios of the cross-coupling motion to the principal axis motion is less than 0.01 which is really small. Comparing Figure 6 with Figure 5, we can get that the proposed multi-exciter vibration control can efficiently reduce cross-coupling of the tri-axial vibration exciter.


(a)

(b)

(c)

Figure 6 Cross-coupling with vibration control. (a) X-axial main motion; (b) Y-axial main motion; (c) Z-axial main motion.

Three spatial linear orbits that are parallel to the coordinate axes are generated as shown in Figure 7. And four spatial circular orbits that rotates rotating every 30 degrees about the X-axis are generated as shown in Figure 8. The plots in Figure 7 and Figure 8 demonstrate that the proposed multi-exciter vibration control has the ability to generate spatial orbits for further calibration application.
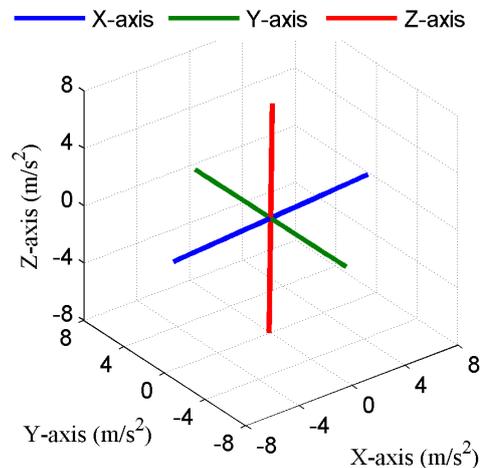

(a)

(b)
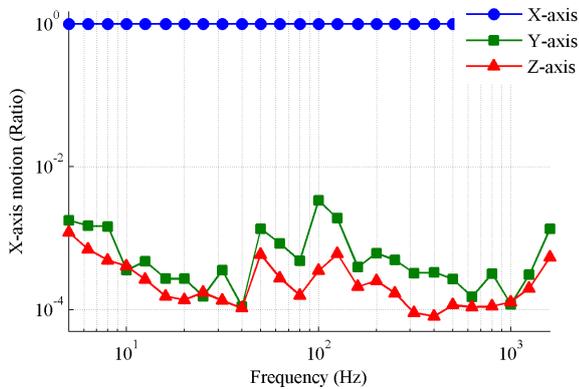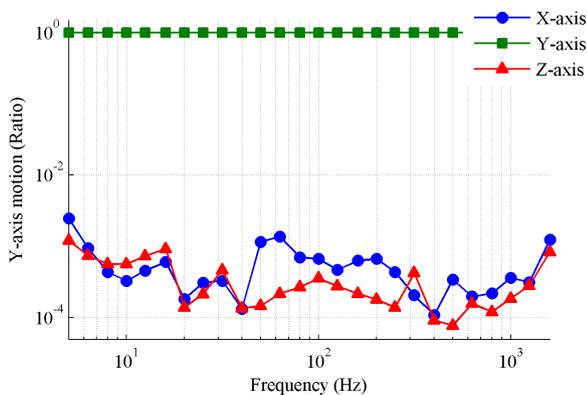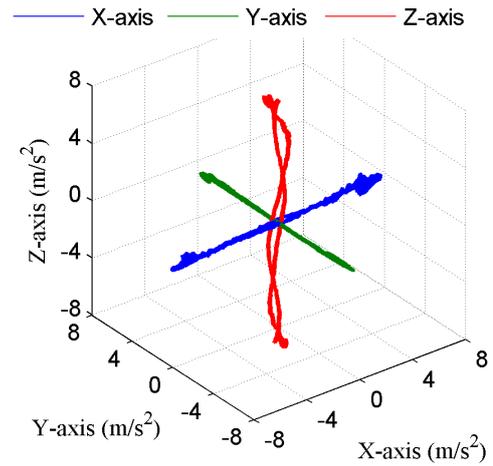
Figure 7 Spatial linear orbits. (a) Original signals; (b) Filtered signals.
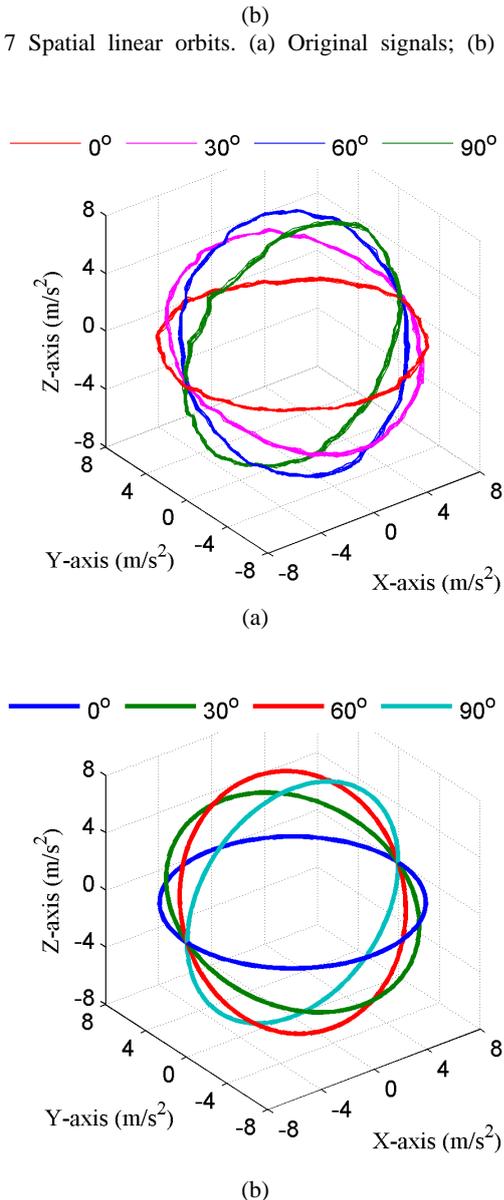

(a)

(b)

Figure 8 Spatial circular orbits. (a) Original signals; (b) Filtered signals.

5. CONCLUSIONS

Multi-exciter vibration control to compensate cross-coupling and control amplitudes and phases control of acceleration components is proposed. The experimental results show that the proposed control method can efficiently reduce cross-coupling of the tri-axial vibration exciter and has ability to generate a variety of spatial orbits.

ACKNOWLEDGMENTS

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