DEFINITION AND MEASUREMENT OF TRANSVERSE MOTION RATIO OF SHAKERS

Chenguang Cai [1], *Yuntai Jiang* [2], *Biao Tang*[3]

[1] National Institute of Metrology, Beijing, China, caichenguang@nim.ac.cn
[2] Dongling Technologies, Suzhou, China, yuntai_jiang@163.com
[3] Yunnan Electric Power Research Institute, Kunming, China, 416889015@qq.com

Abstract − Four different measurement methods of transverse motion ratio of shakers are used in ISO standards and practice. The theoretical analysis and experiment results reveal that the four different measurement methods lead to different results, and the maximum measurement error of the transverse motion ratio between the different measurement methods should be up to 41.4%. Based on the theoretical analysis and experiments, a unified transverse motion ratio measurement method is proposed.

Keywords: shaker, vibration, calibration, transverse motion ratio

1. INTRODUCTION

In ISO 15261: 2004 Vibration and shock generating system-Vocabulary, transverse motion ratio is defined as: "maximum ratio of the acceleration/ velocity/ displacement along a direction perpendicular to the operating axis of the vibration generator to the value of the acceleration/ velocity/ displacement along the direction of the operating axis" [1]. This is the only definition of transverse motion ratio in the standards of ISO/TC 108.

The motion along the operating axis and the motions of two orthogonal directions perpendicular to the operating axis are respectively:

$$a_z(t) \qquad (1)$$

$$a_x(t) \qquad (2)$$

$$a_y(t) \qquad (3)$$

The magnitudes of the three motions are respectively: a_z, a_x, a_y.

The transverse motion within the plane perpendicular to the operating axis of the vibration generator can be described by the vector sum of ax(t) and ay(t), and be shown as X-Y graph.

$$\overline{a_{xy}(t)} = \overline{a_x(t)} + \overline{a_y(t)} \qquad (4)$$

The magnitude of the transverse motion is:

$$A_{xy}(t) = \sqrt{a_x^2(t) + a_y^2(t)} \qquad (5)$$

So the calculation formula of transverse motion ratio, which accords with the definition in ISO 15261:2004, is:

$$T = \max\left\{ \frac{\sqrt{a_x^2(t) + a_y^2(t)}}{a_z} \right\} \times 100\% \qquad (6)$$

In ISO 5344:2004 Electrodynamic vibration generating systems — Performance characteristics, the measurement method of transverse motion is described as: This is measured at the load fixing locations on an unloaded table as a function of frequency [2]. According to the measurement method in ISO 5344:2004, if the measure direction is x axis, the transverse motion ratio can be described as:

$$T = \frac{a_x}{a_z} \times 100\% \qquad (7)$$

In ISO 8626:1989 Servo-hydraulic test equipment for generating vibration — Method of describing characteristics, the measurement method of transverse motion is described as: The manufacturer shall specify the transverse motion of the test table or the power take-off as a function of the frequency by means of two curves representing the ratio between the transverse motions and the linear motion at the central fixing point. Each of the curves shall correspond to one of the two orthogonal directions perpendicular to the axis of the moving element [3]. According to the measurement method in ISO 5344:1980 and ISO 8626:1989, the transverse motion ratio can be described as:

$$T = \frac{\max\{a_x \quad a_y\}}{a_z} \times 100\% \qquad (8)$$

In practice and some Chinese verification regulations for the testing of vibration generators [4-6], the transverse motion ratio can be described as:

$$T = \frac{\sqrt{a_x^2 + a_y^2}}{a_z} \times 100\% \qquad (9)$$

In conclusion, there are four measurement formulas of transverse motion ratio:

$$T_1 = \frac{a_x}{a_z} \times 100\% \qquad (10)$$

$$T_2 = \frac{\max\{a_x \quad a_y\}}{a_z} \times 100\% \qquad (11)$$

$$T_3 = \max\left\{\frac{\sqrt{a_x^2(t)+a_y^2(t)}}{a_z}\right\} \times 100\% \qquad (12)$$

$$T_4 = \frac{\sqrt{a_x^2+a_y^2}}{a_z} \times 100\% \qquad (13)$$

In the four measurement formulas of transverse motion ratio, only T_3 accords with the definition of transverse motion ratio (T) in ISO 15261:2004, T_1 is less than T_2, T_2, is less than T_3, T_4 is more than T_3.

2. THEORETICAL ANALYSIS

If all of the three motions are sinusoidal, the transverse motion can be described using lissajous figures.

$$a_z(t) = a_z\sin(\omega t) \qquad (14)$$

$$a_x(t) = a_x\sin(\omega t + \theta_x) \qquad (15)$$

$$a_y(t) = a_y\sin(\omega t + \theta_y) \qquad (16)$$

When $a_x=a_y$, if the phase shift between θ_x and θ_y is 0° or 180°, the transverse motion will be rectilinear, illustrated in figure 1. According to formula (10) or (11), the transverse motion ratio should be

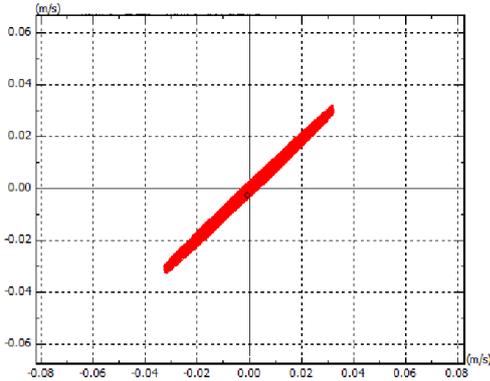$$T_1 = T_2 = \frac{a_x}{a_z} \times 100\% \qquad (17)$$

Fig. 1. Rectilinear transverse motion.

Actually according to formula (12) or (13), the transverse motion ratio is:

$$T_3 = T_4 = T = \frac{\sqrt{2}a_x}{a_z} \times 100\% \qquad (18)$$

The measurement result of T_1 and T_2 is less than T.

When $a_x=a_y$, if the phase shift between θ_x and θ_y is 90°, the transverse motion will be circular, illustrated in figure 2. According to formula (10) or (11) or (12), the transverse motion ratio is

$$T_1 = T_2 = T_3 = T = \frac{a_x}{a_z} \times 100\% \qquad (19)$$

But according to formula (13), the transverse motion ratio should be

$$T_4 = \frac{\sqrt{2}a_x}{a_z} \times 100\% = \sqrt{2}T \qquad (20)$$

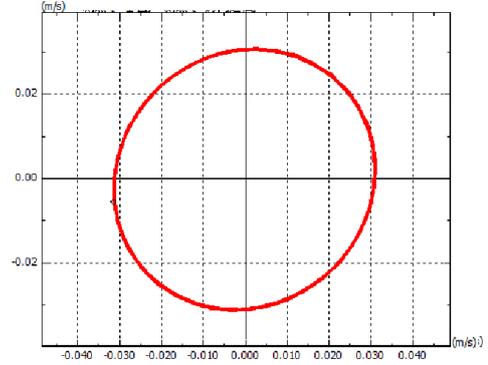The measurement error of the transverse motion ratio based on formula (13) is 41.4%.

Fig. 2. Circular transverse motion.

When $a_x=a_y$, if the phase shift between θ_x and θ_y isn't 0°, 90° or 180°, the transverse motion will be elliptic, illustrated in figure 3. According to formula (10) to (13), the different transverse motion ratio measurement results are:

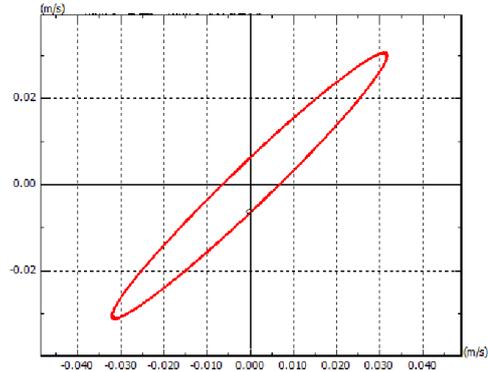$$T_1 \leq T_2 < T_3 < T_4 \qquad (21)$$

Fig. 3. Elliptic transverse motion.

When $a_x \neq a_y$, if the phase shift between θ_x and θ_y is 0° or 180°, the transverse motion will be rectilinear. According to formula (10) to (13), the different transverse motion ratio measurement results are:

$$T_1 \leq T_2 < T_3 = T_4 \qquad (22)$$

If the phase shift between θ_x and θ_y isn't 0° or 180°, the transverse motion will be elliptic. According to formula (10) to (13), the different transverse motion ratio measurement results are:

$$T_1 \leq T_2 < T_3 < T_4 \qquad (23)$$

In conclusion, when all of the three motions are sinusoidal,

$$T_1 \in [0, T] \qquad (24)$$

$$T_2 \in [0, T] \qquad (25)$$

$$T_3 = T \qquad (26)$$

$$T_4 \in [T, \sqrt{2}T] \qquad (27)$$

According to formula (10) to (13), theoretically the four measurement results of the same transverse motion ratio based on the four different measurement methods should satisfy:

$$T_1 \le T_2 \le T_3 = T \le T_4 \qquad (28)$$

3. EXPERIMENTS

3.1. Mounting of the transducers

A decahedron was designed and manufactured to mount the transducers, as shown in figure 4. The decahedron is installed on the table of the vibration generator under testing, as shown in figure 5. A transducer is mounted on the top of the decahedron to measure the magnitude of motion along the operating axis (a_z). Four transducers are mounted on the sides of the decahedron to measure the transverse motion, as shown in figure 6.
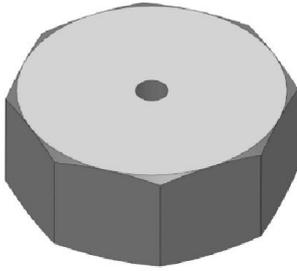
Fig. 4. Decahedron for mounting of transducers.
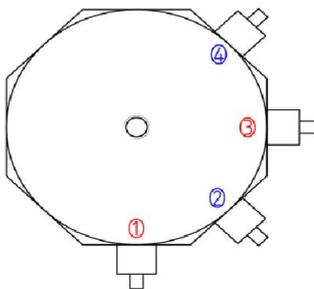

Fig. 5. Vibration generator under testing.

Fig. 6. Mounting of the transducers.

The angle between two neighbouring sides is 45°. If the direction of transducer ① is 0°, the transducers ① and ③ form an orthogonal measurement unit of transverse motion (0° - 90°), and the transducers ② and ④ form the other orthogonal measurement unit of transverse motion (45° - 135°).

3.2. Experimental results

According to the four measurement formulas shown in formula (10) to (13), the different transverse motion ratios are measured. The measurement results are shown in figure 7-13 and table 1.
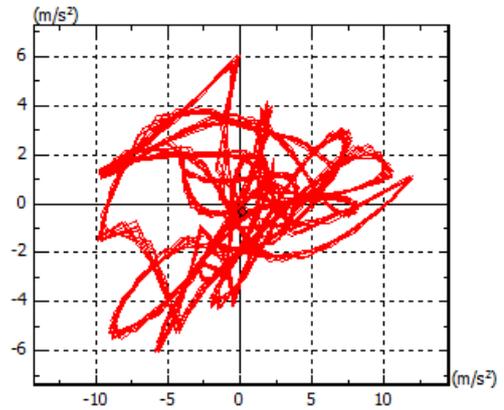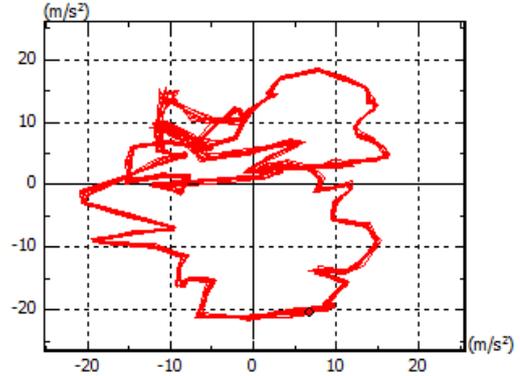

Fig. 7. Transverse motion at 20 Hz
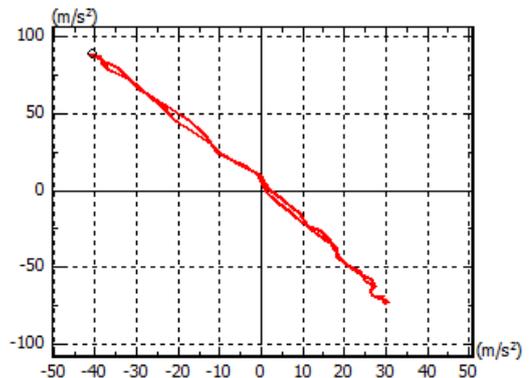

Fig. 8. Transverse motion at 80 Hz

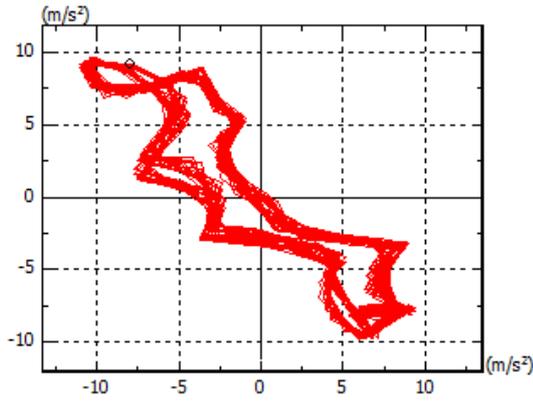Fig. 9. Transverse motion at 160 Hz

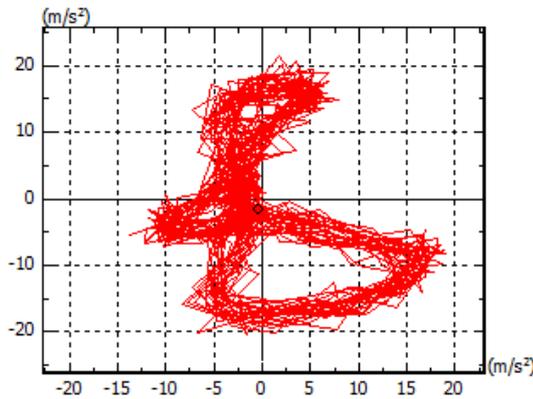Fig. 10. Transverse motion at 315 Hz

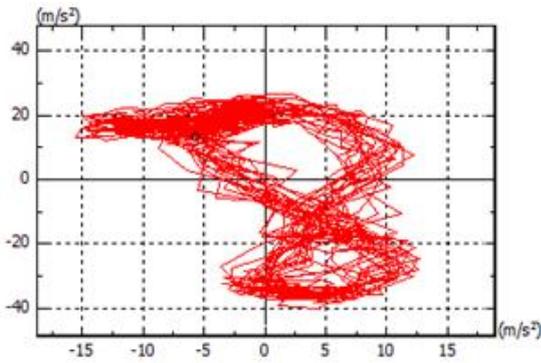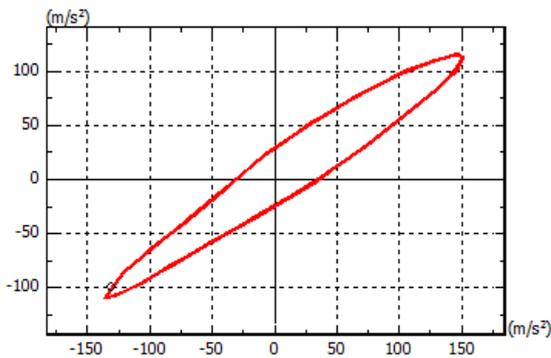Fig. 11. Transverse motion at 630 kHz

Fig. 12. Transverse motion at 1 kHz

Fig. 13. Transverse motion at 2 kHz

Table 1. Transverse motion measurement results.

Frequency (Hz)	Transverse motion (%)			
	T_1	T_2	$T_3 = T$	T_4
20	11.38	11.38	11.59	12.77
80	4.16	4.32	4.45	6.00
160	8.26	17.53	19.32	19.38
315	2.21	2.21	2.86	2.92
630	3.85	4.36	4.41	5.82
1000	2.39	7.51	7.56	7.89
2000	29.95	29.95	37.54	37.90

The measurement results shown in table 1 prove the formula (28), $T_1 \leqslant T_2 \leqslant T_3 \leqslant T_4$.

4. CONCLUSIONS

The measurement method of transverse motion ratio based on formula (6) accords with the definition in ISO 15261:2004, and the other three measurement methods based on formula (10) to (13) would bring errors. The measurement results based on the four measurement methods satisfy formula (28), $T_1 \leq T_2 \leq T_3 = T \leq T_4$.

When all of the three motions of the shaker under testing are sinusoidal, the transverse motion would be rectilinear, circular or elliptic, and the maximum measurement error of the transverse motion ratio based on the three different measurement methods could be up to 41.4%.

When the transverse motion is distorted, the harmonic components would cause complex motion path, and the transverse motion can be described using X-Y graphs and calculated using formula (6).

So it is necessary to make a unified measurement method based formula (6) which accords with the definition in ISO 15261:2004.

ACKNOWLEDGMENTS

REFERENCES

[1] ISO 15261 2004 Vibration and shock generating systems -- Vocabulary.
[2] ISO 5344 2004 Electrodynamic vibration generating systems -- Performance characteristics.
[3] ISO 8626 1989 Servo-hydraulic test equipment for generating vibration -- Method of describing characteristics.
[4] JJG 189-1997 Chinese verification regulation of mechanical vibration generator for testing.
[5] JJG 638-1990 Chinese verification regulation of hydraulic vibration generator.
[6] JJG 190-1997 Chinese verification regulation of electrodynamic vibration generator for testing.