XXI IMEKO World Congress “Measurement in Research and Industry”
August 30 − September 4, 2015, Prague, Czech Republic

# PERFOMANCE EVALUATION OF TWO LOW FREQUENCY AIR BEARING VIBRATION EXCITERS

*C.S. Veldman*[1], *T.M. Lefenya* [2]
[1] NMISA, Pretoria, South Africa, CSVeldman@NMISA.org
[2] NMISA, Pretoria, South Africa, LefenyaT@yahoo.com

***Abstract*** – The National Metrology Institute of South Africa designed an air bearing linear translation stage (LTS) used for primary low frequency accelerometer calibration. The LTS serves as a replacement of a commercial LTS. The motivation for the new design consideration is touched on. The performances of both LTSs were evaluated in terms of their flatness, straightness, roll, pitch and dynamic transverse motion; the results and findings of which are reported in some detail. The influence of the mechanical connection between the LTS and the electrodynamics exciter was also investigated.

***Keywords***: low frequency accelerometer calibration, air bearing linear translation stage, transverse motion, electrodynamic exciter

## 1. INTRODUCTION

The provision of traceability in the seismic frequency range is of importance, especially for earthquake monitoring. To facilitate the establishment of National Measurement Standards (NMS) at such low frequencies (< 1 Hz), National Metrology Institutes (NMIs) worldwide employ commercial vibration exciters with significant displacement amplitudes, typically 150 mm and 450 mm [1-3]. Systems with a displacement of some meters have been developed as part of their primary accelerometer calibration systems. Large displacements are required in order to generate measurable accelerations in terms of the accelerometer’s output.

The most commonly used commercial vibration exciter units employ an air bearing table (LTS) which is connected to an electrodynamic exciter (Exciter). The exciter essentially pushes and pulls the LTS, creating a sinusoidal motion, or vibration. Such extended recti-linear displacements place extreme requirements on the linearity of the motion of the LTS over its full travel.

NMISA has one such commercial Exciter-LTS combination system. It serves as the vibration generator for low frequency accelerometer calibration using primary methods [4]. The LTS had been modified to accept a rotary table to facilitate accelerometer transverse sensitivity calibration [5]. As a mechanical system, imperfections are inevitable with respect to the linearity of the motion of the LTS in all six degrees of freedom. Fig. 1 shows the commercial LTS. It requires that the accelerometer be mounted on top of the mounting table, using a 90° angle

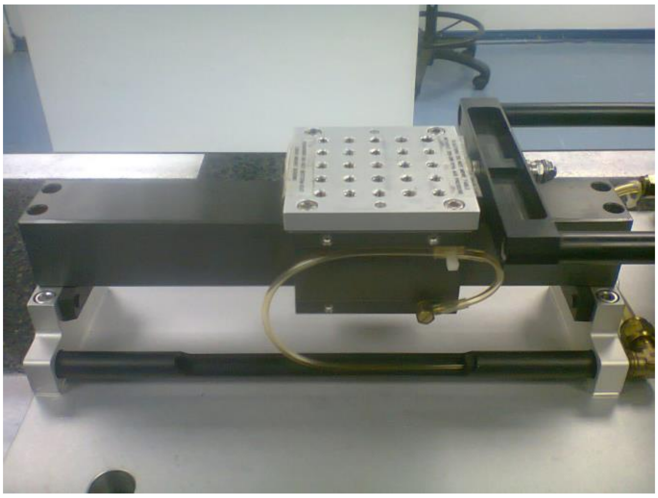

Figure 1: Commercial Air-bearing Linear Translation Stage

plate. This has the effect that any tilt motion (non-linearity) of the table is “amplified” as a function of the height from the centre of motion of the LTS.

NMISA designed a LTS, modifying the design principle so as to place the accelerometer sensitivity axis in line with the centre of the air bearing supports. This effectively brought the centre of the accelerometer sensitive axis [6] in line with the centre of motion of the LTS, as shown in Fig. 2.

Consideration was also given to the physical connection between the LTS and the Exciter. The commercial unit uses a solid M3 bolt with nuts to affix the two systems. This requires careful alignment to ensure that any relative motion between the contact points is minimised.

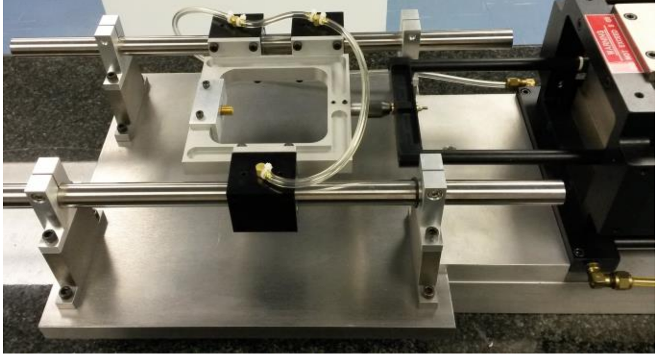

Figure 2: NMISA Air-bearing Linear Translation Stage

Ideally there should be no relative motion. A new connection mechanism was introduced that allows for some relative motion to be absorbed.

## 2. COMPARISON PARAMATERS

### *2.1. Parameters Considered*

The linearity of the movement of the two LTSs were characterised over the 150 mm travel in terms of:

- Straightness: The amount of travel in the x-axis direction over the full travel in the z-axis direction. (See Fig. 3.);
- Flatness: The amount of travel in the y-axis direction over the full travel in the z-axis direction. (See Fig. 3.);
- Roll: The amount of rotational movement in the x-y plane over the full travel in the z-axis direction. (See Fig. 4.);
- Pitch: The amount of rotational movement in the y-z plane over the full travel in the z-axis direction. (See Fig. 4.);
- Dynamically (transverse acceleration): The acceleration in the x- and y axis, relative to the acceleration in the z-axis.

It is noted that these definitions might not be in line with scientific definition, but serves as descriptions of what is defined in this work.

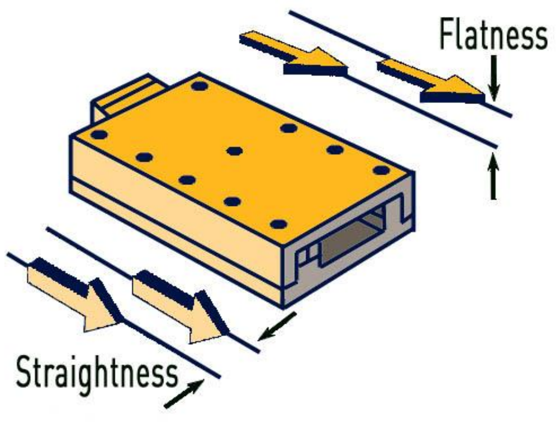


Figure 3: Straightness and Flatness as defined in this paper

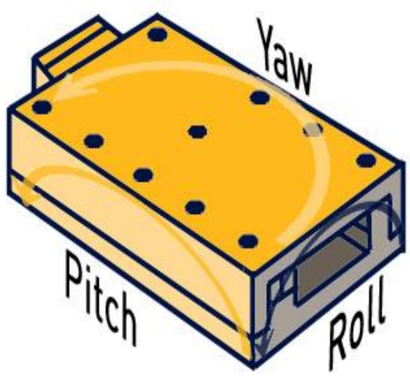


Figure 4: Roll and pitch as defined in this paper

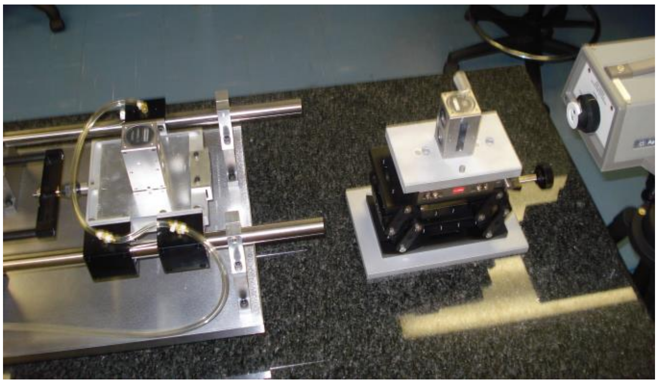

Figure 5: Straightness and flatness measurement setup

The straightness and flatness (as defined above) of the travel for both of the LTSs were measured using a dimensional laser interferometer system. The travels were characterised over the 150 mm travel, performed in 15 mm increments. The measurement setup is shown in Fig. 5.

The roll and pitch measurements (as defined above) of the travel of both the LTSs were measured using a clinometer. The roll and pitch of the travels were characterised over the 150 mm travel in 15 mm increments. The pitch measurement setup is shown in Fig. 6.

The transverse motion measurements were performed using a tri-axial accelerometer over the frequency range 1 Hz to 100 Hz in octave frequency steps.


Figure 6: Pitch and roll measurement setup

The linearity of the motion of the two LTSs were characterised with the units "loose standing" (no physical connection between the Exciter and LTS) and with the units connected to the Exciter, allowing for the effect of the connector to be evaluated. From this, three connection types could be evaluated:

- Fixed connector;
- Ball joint connector;
- Free standing.

The measured results are presented in tabular as well as and graphical format, with the author's interpretation of the graphical result in the sections to follow.

## 3. MEASUREMENT DATA

### *3.1. Commercial LTS*

The measurement results for the commercial LTS are reported in Tables 1 to 6. Each table reflects three sets of measurements; Fixed Connector – where the LTS was connected to the exciter using a 4 mm bolt, Ball Joint Connector – where the LTS was connected to the Exciter using a ball joint connecting mechanism, and Free Standing – where the LTS was not connected to the Exciter. The measurement results obtained for linear translational movement (flatness and straightness) are reported in Tables 1 and 2 respectively, while the measurement results obtained for rotational movement (roll and pitch) are reported in Tables 4 and 5 respectively. The calculated transverse motion as a result of the flatness and straightness is reported in Table 3 and depicted in Fig. 7. The calculated rotational motion as a result of roll and pitch is reported in Table 6 and depicted in Fig. 8.

Table 1: Commercial LTS flatness measurements

| **Position** | **Fixed Connector** | **Ball Joint Connector** | **Free Standing** |
|---|---|---|---|
| **(mm)** | **(µm)** | **(µm)** | **(µm)** |
| 0 | 0,00 | 0,00 | 0,00 |
| 15 | -1,62 | -1,09 | -1,09 |
| 30 | -2,86 | -1,94 | -1,93 |
| 45 | -3,73 | -2,55 | -2,53 |
| 60 | -4,31 | -2,91 | -2,90 |
| 75 | -4,48 | -3,03 | -3,02 |
| 90 | -4,30 | -2,91 | -2,90 |
| 105 | -3,79 | -2,55 | -2,53 |
| 120 | -2,90 | -1,94 | -1,93 |
| 135 | -1,63 | -1,09 | -1,09 |
| 150 | 0,00 | 0,00 | 0,00 |

Table 2: Commercial LTS straightness measurements

| **Position** | **Fixed Connector** | **Ball Joint Connector** | **Free Standing** |
|---|---|---|---|
| **(mm)** | **(µm)** | **(µm)** | **(µm)** |
| 0 | 0,00 | 0,00 | 0,00 |
| 15 | 0,19 | 0,13 | 0,06 |
| 30 | 0,30 | 0,23 | 0,10 |
| 45 | 0,36 | 0,30 | 0,13 |
| 60 | 0,36 | 0,35 | 0,15 |
| 75 | 0,34 | 0,36 | 0,15 |
| 90 | 0,32 | 0,35 | 0,15 |
| 105 | 0,25 | 0,30 | 0,13 |
| 120 | 0,16 | 0,23 | 0,10 |
| 135 | 0,08 | 0,13 | 0,06 |
| 150 | 0,00 | 0,00 | 0,00 |

Table 3: Commercial LTS calculated transverse motion results

| **Position** | **Fixed Connector** | **Ball Joint Connector** | **Free Standing** |
|---|---|---|---|
| **(mm)** | **(µm)** | **(µm)** | **(µm)** |
| 0 | 0,0 | 0,0 | 0,0 |
| 15 | -1,6 | -1,1 | -1,1 |
| 30 | -2,9 | -2,0 | -1,9 |
| 45 | -3,7 | -2,6 | -2,5 |
| 60 | -4,3 | -2,9 | -2,9 |
| 75 | -4,5 | -3,1 | -3,0 |
| 90 | -4,3 | -2,9 | -2,9 |
| 105 | -3,8 | -2,6 | -2,5 |
| 120 | -2,9 | -2,0 | -1,9 |
| 135 | -1,6 | -1,1 | -1,1 |
| 150 | 0,0 | 0,0 | 0,0 |

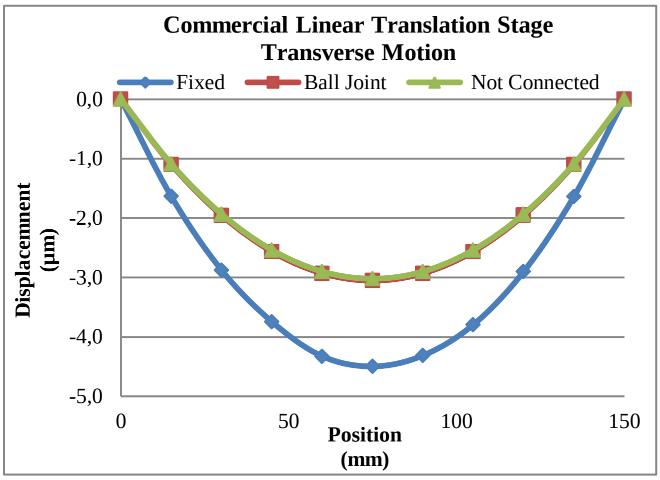


Figure 7: Commercial LTS transverse motion

Table 4: Commercial LTS pitch measurements

| **Position** | **Fixed Connector** | **Ball Joint Connector** | **Free Standing** |
|---|---|---|---|
| **(mm)** | **(µm)** | **(µm)** | **(µm)** |
| 0 | 0,21 | 0,02 | -0,07 |
| 15 | 0,16 | 0,02 | -0,06 |
| 30 | 0,11 | -0,01 | -0,03 |
| 45 | 0,06 | -0,02 | -0,01 |
| 60 | 0,00 | 0,00 | 0,00 |
| 75 | -0,13 | 0,00 | 0,00 |
| 90 | -0,11 | 0,00 | 0,00 |
| 105 | -0,14 | -0,01 | 0,01 |
| 120 | -0,25 | 0,01 | 0,03 |

Table 5: Commercial LTS roll measurements

| Position | Fixed Connector | Ball Joint Connector | Free Standing |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | -0,01 | 0,21 | 0,20 |
| 15 | -0,02 | 0,13 | 0,17 |
| 30 | -0,01 | 0,10 | 0,12 |
| 45 | 0,00 | 0,08 | 0,04 |
| 60 | 0,00 | 0,00 | 0,00 |
| 75 | -0,01 | -0,47 | -0,46 |
| 90 | -0,02 | -0,49 | -0,52 |
| 105 | -0,04 | -0,53 | -0,53 |
| 120 | -0,06 | -0,54 | -0,56 |

Table 6: Commercial LTS calculated rotational motion results

| Position | Fixed Connector | Ball Joint Connector | Free Standing |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,20 | 0,16 | 0,08 |
| 15 | 0,15 | 0,10 | 0,07 |
| 30 | 0,10 | 0,06 | 0,05 |
| 45 | 0,06 | 0,04 | 0,02 |
| 60 | 0,00 | 0,00 | 0,00 |
| 75 | -0,12 | -0,25 | -0,24 |
| 90 | -0,11 | -0,26 | -0,26 |
| 105 | -0,14 | -0,29 | -0,26 |
| 120 | -0,25 | -0,27 | -0,25 |

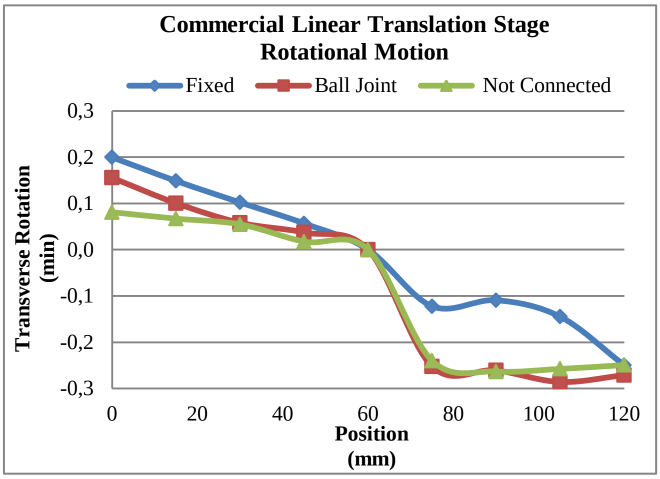


Figure 8: Commercial LTS rotational motion

### *3.2. NMISA LTS*

The measurement results for the NMISA LTS are reported in Tables 7 to 12. Each table reflects three sets of measurements; Tight Connector – where the LTS was connected to the Exciter using the ball joint connector firmly tightened - allowing minimal misalignment absorption, if any. Loose Connector – where the LTS was connected to the Exciter using the ball joint connector lightly tightened allowing misalignment absorption and Not Connected - where the LTS was not connected to the Exciter. The measurement results obtained for linear translational movement (flatness and straightness) are reported in Tables 7 and 8, while the measurement results obtained for rotational movement (roll and pitch) are reported in Tables 10 and 11. The calculated transverse motion as a result of the flatness and straightness is reported in Table 9 and depicted in Fig. 9. The calculated rotational motion as a result of roll and pitch is reported in Table 12 and depicted in Fig. 10.

Table 7: NMISA LTS flatness measurements

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,00 | 0,00 | 0,00 |
| 15 | 0,35 | 0,69 | 0,14 |
| 30 | 0,76 | 1,48 | 1,59 |
| 45 | 1,25 | 2,42 | 2,52 |
| 60 | 1,77 | 3,39 | 3,46 |
| 75 | 2,28 | 4,36 | 4,34 |
| 90 | 2,71 | 5,26 | 4,96 |
| 105 | 2,90 | 4,87 | 5,14 |
| 120 | 2,69 | 4,20 | 4,49 |
| 135 | 1,77 | 2,48 | 2,93 |
| 150 | 0,00 | 0,00 | 0,00 |

Table 8: NMISA LTS straightness measurements

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,00 | 0,00 | 0,00 |
| 15 | -0,87 | -1,67 | -2,37 |
| 30 | -1,54 | -2,82 | -3,91 |
| 45 | -2,13 | -3,45 | -4,53 |
| 60 | -2,66 | -3,75 | -4,56 |
| 75 | -3,12 | -3,86 | -4,30 |
| 90 | -3,41 | -3,70 | -3,70 |
| 105 | -3,41 | -3,30 | -2,92 |
| 120 | -2,95 | -2,39 | -2,05 |
| 135 | -1,87 | -1,56 | -1,18 |
| 150 | 0,00 | 0,00 | 0,00 |

Table 9: NMISA LTS calculated transverse motion results

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,00 | 0,00 | 0,00 |
| 15 | 0,94 | 1,81 | 2,37 |
| 30 | 1,71 | 3,19 | 4,22 |
| 45 | 2,47 | 4,22 | 5,18 |
| 60 | 3,20 | 5,05 | 5,73 |
| 75 | 3,86 | 5,82 | 6,11 |
| 90 | 4,35 | 6,43 | 6,19 |
| 105 | 4,48 | 5,88 | 5,91 |
| 120 | 3,99 | 4,83 | 4,93 |
| 135 | 2,58 | 2,94 | 3,16 |
| 150 | 0,00 | 0,00 | 0,00 |

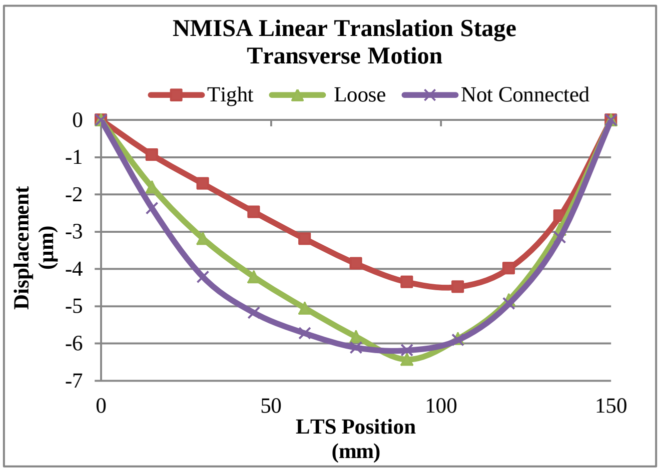


Figure 9: NMISA LTS transverse motion

Table 10: NMISA LTS pitch measurements

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,88 | 0,73 | 0,73 |
| 15 | 0,57 | 0,42 | 0,42 |
| 30 | 0,30 | 0,23 | 0,15 |
| 45 | 0,17 | 0,03 | 0,05 |
| 60 | -0,02 | 0,03 | 0,08 |
| 75 | 0,00 | 0,00 | 0,00 |
| 90 | -0,13 | 0,00 | -0,05 |
| 105 | -0,13 | -0,03 | -0,03 |
| 120 | -0,12 | 0,05 | 0,00 |
| 135 | -0,07 | 0,07 | 0,00 |
| 150 | -0,05 | 0,03 | 0,00 |

Table 11: NMISA LTS roll measurements

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,20 | 0,27 | 0,27 |
| 15 | 0,20 | 0,27 | 0,25 |
| 30 | 0,25 | 0,22 | 0,22 |
| 45 | 0,13 | 0,18 | 0,15 |
| 60 | 0,10 | 0,05 | 0,12 |
| 75 | 0,00 | 0,00 | 0,00 |
| 90 | -0,15 | -0,15 | -0,15 |
| 105 | -0,23 | -0,23 | -0,28 |
| 120 | -0,38 | -0,37 | -0,42 |
| 135 | -0,52 | -0,55 | -0,52 |
| 150 | -0,63 | -0,65 | -0,65 |

Table 12: NMISA LTS calculated rotational motion

| Position | Tight Connection | Loose Connection | Not Connected |
|---|---|---|---|
| (mm) | (µm) | (µm) | (µm) |
| 0 | 0,96 | 0,85 | 0,91 |
| 15 | 0,82 | 0,73 | 0,77 |
| 30 | 0,75 | 0,61 | 0,65 |
| 45 | 0,59 | 0,51 | 0,55 |
| 60 | 0,48 | 0,38 | 0,53 |
| 75 | 0,40 | 0,32 | 0,39 |
| 90 | 0,21 | 0,18 | 0,24 |
| 105 | 0,13 | 0,09 | 0,11 |
| 120 | 0,00 | 0,00 | 0,00 |
| 135 | -0,10 | -0,16 | -0,09 |
| 150 | -0,20 | -0,27 | -0,22 |

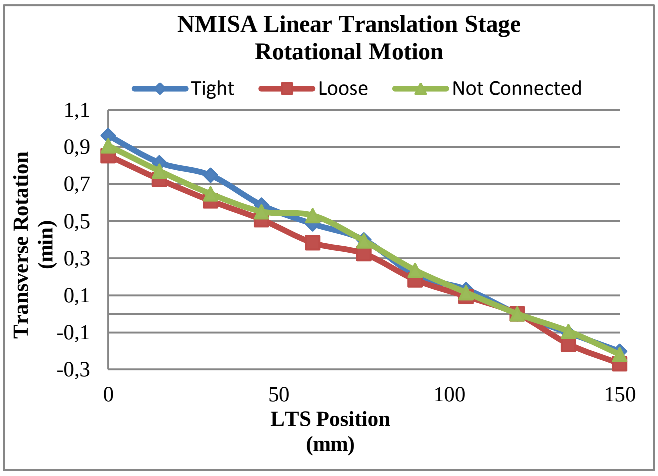


Figure 10: NMISA LTS rotational motion

The transverse effect ($E_T$), as reported in Tables 3, 6, 9 and 12, was calculated using $-E_T = \sqrt{x^2 + y^2}$ , where $x$ and $y$ was the flatness and straightness respectively for linear movement and roll and pitch respectively for rotational movement.

### *3.3. Transverse Acceleration*

The transverse acceleration for both systems was measured by measuring the acceleration in the x- and y direction using accelerometers, while the acceleration in the z direction was measured by laser interferometry. With the acceleration known in all three axis directions, the relative transverse acceleration was calculated using $\acute{a}_z = \sqrt{a_x^2 + a_y^2}/a_z$. The measurements were performed over the frequency range 1 Hz to 100 Hz in octave steps, using sinewave vibration excitation. The results obtained for the Commercial LTS and NMISA LTS systems are plotted in Fig. 11.

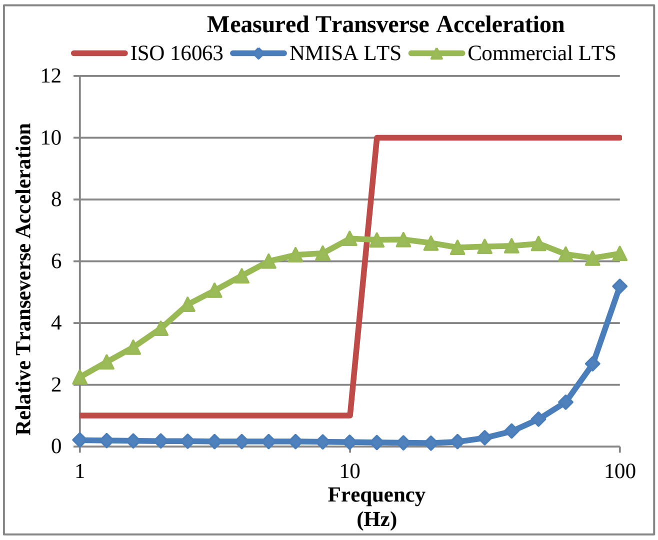


Figure 11: Transverse acceleration results

In Fig. 11, the green line depicts the Commercial LTS transverse acceleration. The blue line depicts the NMISA LTS transverse acceleration. The red line represents the requirements for the vibration exciter specified in [7] for primary accelerometer calibration.

## 4. MOTION EVALUATION

The performance of each system will be evaluated individually in terms of that system's measured data, for both the linear motion as well as the rotational motion. A performance comparison of the two systems will be done.

### *4.1. Commercial LTS Transverse Motions*

We considered the transverse motion plotted in Fig. 7, using the data presented in Table 3. The Commercial LTS exhibited a flatness of about 4,5 µm when attached to the Exciter, improving to about 3 µm when connected using the ball joint and free standing. This difference in the flatness with the LST free standing and connected to the exciter using a bolt was interpreted as an indication that some imperfections existed in the alignment between the LTS and the exciter, resulting in relative forces between the LTS and exciter.

In contrast, there was very little, if any difference in the transverse motion with the LTS free standing and the LTS connected to the exciter using the ball joint, indicating that the ball joint compensated for any miss-alignment between the LTS and the exciter. For the commercial LTS system, the ball joint resulted in a 30 % improvement of the transverse motion effect over the 150 mm travel of the LTS.

### *4.2. Commercial LTS Rotational Motions*

Figure 12 shows the pitch movement of the Commercial LTS as reported in Table 4. It reveals no discernible pitch over the 150 mm travel with the LTS free-standing or connected to the exciter using the ball-joint. However with the fixed connection, the LTS demonstrated a 0,5 minute pitching as it moves from 0 mm to 120 mm. This continuous pitching movement with the fixed connection suggests some misalignment between the exciter- and LTS horizontal planes.

Figure 13 shows the rotational movement of the Commercial LTS as reported in Table 5. It reveals no discernible roll over the 150 mm travel with the LTS connected to the exciter using the fixed connection. In contrast with the linear motion (flatness), the fixed connector prevented this rolling effect.

For rotational movement, the free-standing and the ball-joint connection produced very similar roll results. This provides more data supporting the proposal that the ball-joint connection allows for motion between the LTS and exciter as the LTS moves over its full travel.

In Fig. 8, a resulting 0,6 minute roll is observed. This was effectively caused by a roll effect observed almost halfway through the LTS's travel as shown in Fig. 13, for Ball Joint and Free Standing. These measurement results are interpreted as showing that the surface exhibits, in essence, no rotational movement as it travels from one end to the opposite end, before the 60 mm position, and after the 80 mm position. But from the 60 mm to 80 mm position, the surface rolls to one side by 0,6 minutes. That was the case for all connections that permit movement between the exciter and the LTS.

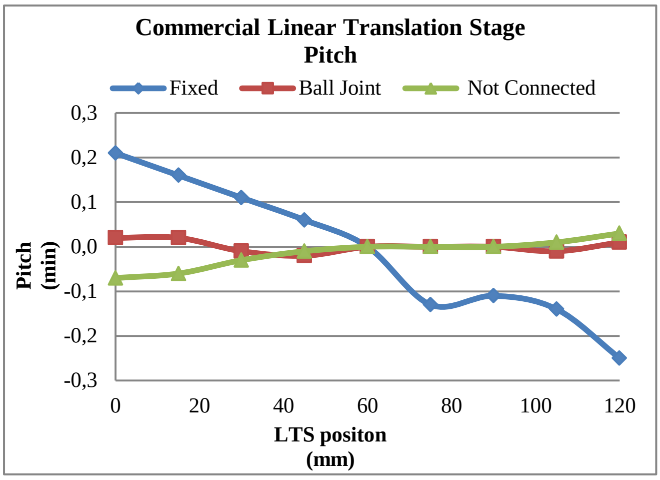


Figure 12: Commercial LTS pitch

### *4.3. NMISA LTS Transverse Motion*

Considering the transverse motion plotted in Fig. 9, representing the data presented in Table 9, the NMISA LTS exhibited a flatness of about 4,5 µm when tightly attached to the exciter using the ball join and deteriorating to about 6 µm when loosely connected using the ball joint and free standing. This difference in the linear motion with the LST free standing and tightly connected to the exciter is an indication that some imperfections exist in the alignment between the LTS and the exciter.

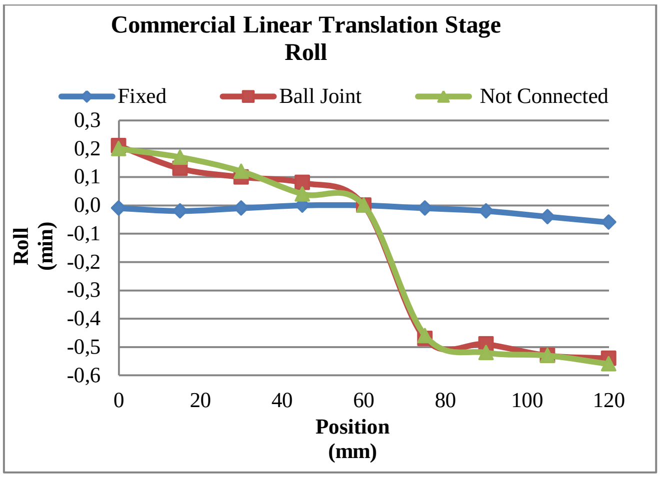


Figure 13: Commercial linear translation stage roll

As with the Commercial LTS, there was very little, if any, difference in the transverse motion with the NMISA LTS free standing and the LTS connected to the exciter using the ball joint.

### *4.4. NMISA LTS Rotational Motions*

From the data presented in Tables 10 and 11, it is observed that the NMISA LTS presented about a one minute pitch effect (see Fig. 14), as well as a one minute roll effect (see Fig. 15), over the 150 mm travel. The two figures also indicate that the connection method had very little (if any) effect the LTS's pitch and roll.

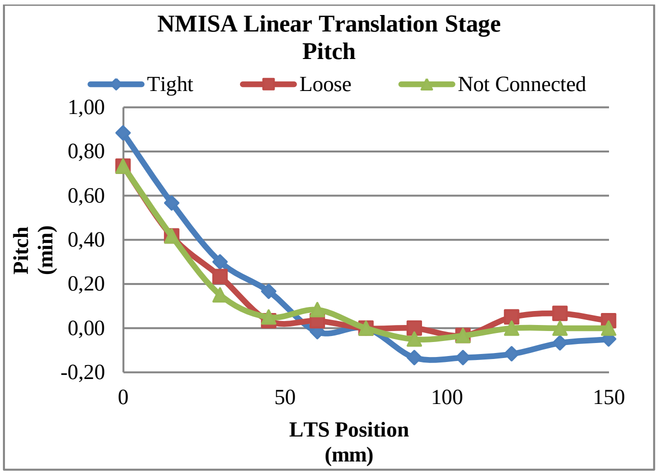


Figure 14: NMISA LTS pitch

Figure 10 shows the calculated rotational movement of the NMISA LTS as reported in Table 12. It indicates a constant rotational motion of approximately 0,45"/mm (approximately 1' over 150 mm) as the LTS traverses over the 150 mm distance.

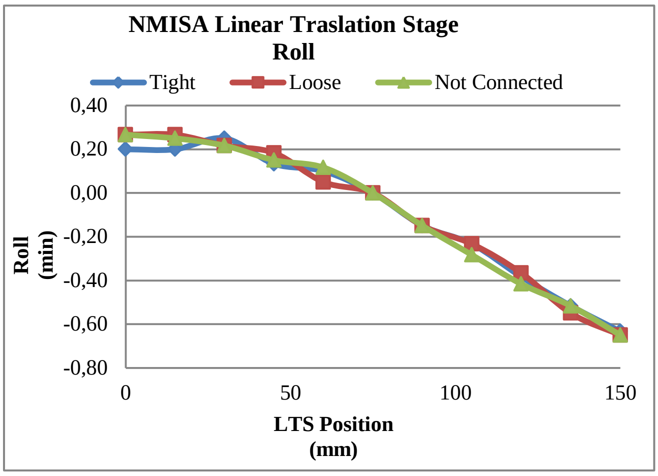


Figure 15: NMISA LTS Roll

## 5. CONCLUTIONS

We compared the linearity of two air-bearing linear translation stages. The two LTSs differ in design in terms of the number of air-bearings employed, as well as the mounting position for of the intended unit under test (UUT). The influence of the connection mechanism linking the LTS to the electrodynamic exciter was also investigated.

From the measurement data, it was evident that a ridged connection introduced non-linearities, which exist as a result of misalignment between the exciter and LTS. The ball joint "absorbed" minor alignment errors.

No discernible difference was noticed between the two LTSs w.r.t. the resulting transverse motions, when using the ball joint connection. With the ball joint connection, the NMISA LTS demonstrated a linear rotation over the travel distance, which has a lesser effect on the calibration than the sudden rotation exhibited by the Commercial LTS between 60 mm and 80 mm.

The NMISA design showed noticeable improvement in the transverse motion measurements, meeting the ISO 16063-11 requirements for vibration exciters.

## REFERENCES


[1] H.J. von Martens, *Current state and trends of ensuring traceability for vibration and shock measurements*, Metrologia, 1999, 36, 357-373.

[2] W. He, X. Zhang, C. Wang, R. Shen, M. Yu, A long-stroke horizontal electromagnetic vibrator for ultralow-frequency vibration calibration *Meas. Sci. Technol*, 2014, **25** 085901.

[3] G.P. Ripper, C.D. Ferreira, D.B. Teixeira, R.S. Dias, G.B. Micheli, A new system for primary interferometric calibration of vibration transducers at low frequencies, IMEKO November 2010.

[4] C.S.Veldman, G. Ripper, Final report on supplementary comparison CCAUV.AUV.V-S2, Metrologia, 2012, 49, 09001.

[5] C.S. Veldman, "Implementation of an Accelerometer Transverse Sensitivity Measurement System", NCSL International, June 2013.

[6] ISO 2041, Mechanical vibration, shock and condition monitoring — Vocabulary.

[7] ISO 16063-11, Methods for the calibration of vibration and shock transducers -- Part 11: Primary vibration calibration by laser interferometry.