A Precise 6-axies Girder System with Cam Mover Mechanism

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Abstract

A precise girder system based on the cam mover mechanism was design and fabricated at NSRRC as a prototype for the future 3 GeV Taiwan Photon Source (TPS). The girder was supported with 6 cam movers on 3 pedestals to realize 6-axis adjustments and more stability. By adapting positioning sensors between consecutive girders, there would be 72 auto-tuning girders installed in TPS. The design consideration, simulation and test results of the prototype system would be described in this paper.

1. Introduction

A new 3 GeV ring called Taiwan Photon Source (TPS) could be constructed at NSRRC in the near future[1]. The New Ring will be a high brilliant one and the emittance is quite low. To meet these stringent beam dynamic specs, it demands that all the magnets should be located at precise positions and also firmly supported. There are many types of support adopted on the existed synchrotron facilities around the world. Recently, girder type support seems a good candidate for some new rings [2,3,4] cause it possesses some important advantages [5] and also had been demonstrated as the perfect operation of SLS [6].

A girder prototype system was thus constructed at NSRRC as a preliminary study in order to provide fine alignment and good support of the magnets. This prototype system consists of 3 girders to form one twenty-fourth of the whole ring. Each girder was supported with 6 cam movers on 3 pedestals to realize 6-axis adjustments. To align the girders precisely, we would installed touch sensors between consecutive girders and laser PSD system between straight section girders in addition with Nivel 20 and HLS devices on each girder.

Now the prototype system was installed at NSRRC for testing, at the first stage only one girder was tested to examine the design spec and dynamic situations. The detailed design consideration, simulation and preliminary test results of one prototype girder system would be described in this paper.

2. Girder System Design and Analysis

The design goal of the girders system for TPS is:

- Firm support and precise positioning of magnets
- Whole ring automatic alignment
- Beam based girder alignment
- precise resolution (μm)

In order to fulfill these challeging ambitions, a 6-axis motorized adjusting mechanism thus demanded.

2.1 Girder system design

The facilities such as ALS and Diamond which adopted girder type design with motorized adjusting mechanism had demonstrated that the eccentric circle cam mover is a superior candidate for adjusting mechanism because it is of good resolution and between the cam and Vee block the contact is rolling not sliding. But since we demand a 6-axis adjusting system, instead of using the Vee block type as used in the SLS and Diamond girder system, the new adjusting system that the cam mover contacts with ball transfer unit in SLS for beamline experiment station was adopted.

Considering the length of the girder, we extend the 3 grooves type kinematic mounting from 3 balls to 6 balls as in the figure 1. Each 2 balls contact with one groove can be imaged as a part of a big ball that encloses and is tangent to the 2 balls. Replacing the balls with ball transfer units, expanding them further and equally spacing along the girder, replacing the contacting groove's surfaces with cam movers, putting each 2 cam movers on opposite side of the girder on a pedestal, then a girder system with 6 cam movers on 3 pedestals was established as in the figure2.

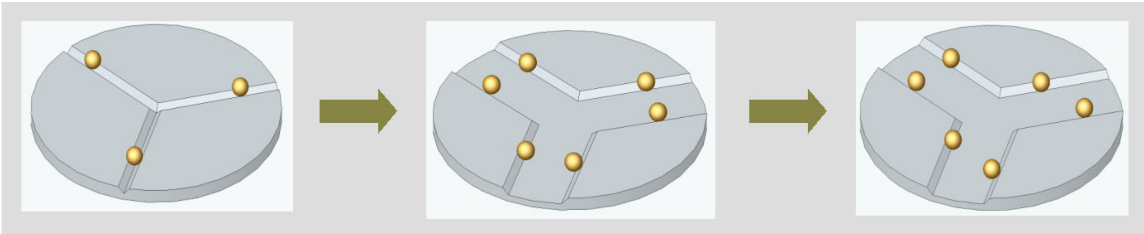

Figure 1: Expand 3-Groove Type kinematic Mounting from 3 balls to 6 balls

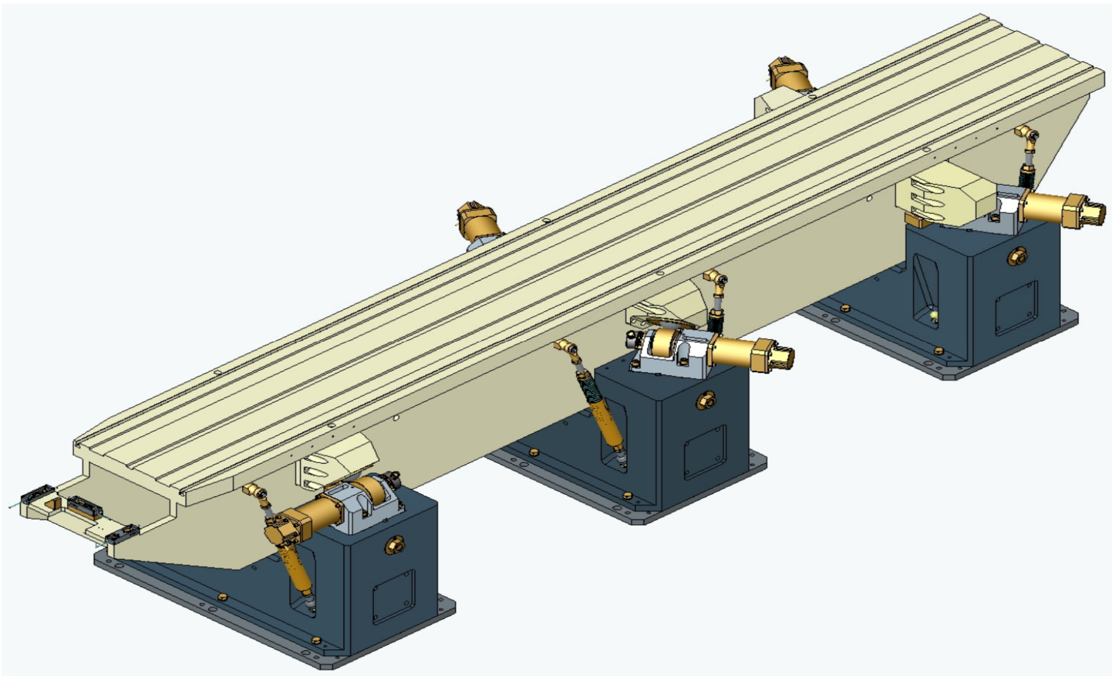

Figure 2: Girder System Concept Design

Since the ball (in the ball transfer unit) is nearly point contact with the cam, the stress would be quite high according to the Herz contact theory. In order to reduce the stress and avoid damaging the ball and cam, a few assistant springs are added between pedestals and girder. Meanwhile, using the spring, the flatness of the girder surface can also be adjusting to compensate the machining error and deflection due to gravity and when magnets are installed. In addition, further damping system can be added to reduce the vibration.

As in the preliminary TPS ring design, we use 3 consecutive girders to form one twenty-fourth of the whole ring as in the figure 3. Basically, there will be two girder types, girder1 and girder 3 are the same only will be installed in opposite direction. Girder 2 is different. The lengths of the 2 girders are 4.7m and 48m respectively. Width of the girder top plate is 600mm and the distance between pedestals is 1.5m from the center. The main ball of the ball transfer unit is 90mm in diameter and the diameter of the cam is 130mm with 5mm eccentricity. To align the girders precisely, touch sensors would be installed between consecutive girders.

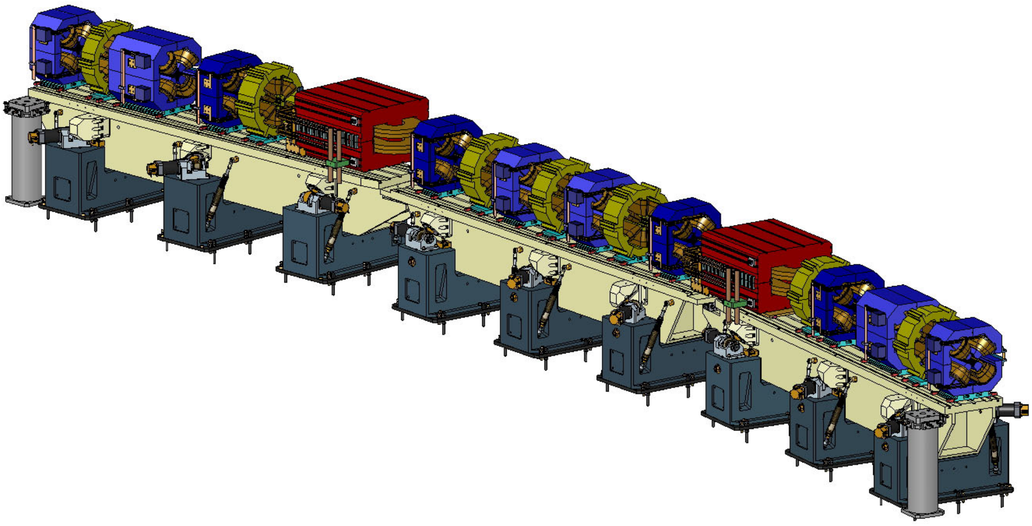

Figure 3: Scheduled consecutive 3 girders assemblage as 1/24 part of TPS ring

2.2 Adjusting Algorithm

It is not easy to determine how to adjusting the girder in each direction by movers as shown in the figure 2. An algorithm is required to transfer the directional adjusting magnitude to the motor's steps. At first the coordinate systems should be established both at girders and movers, than we can do this transformation.

As in the usual definition among synchrotron facilities, the coordinate of the girder is build at the center of girders on the beam path as shown in figure 4 [7].

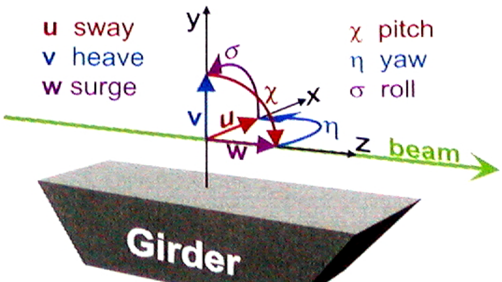

Figure 4: Definition of coordinates of the girder (This Figure borrowed From [7])

Than the rotation and translation relationship can be established as following

$$\text{Pitch (around } x\text{):} \quad R_x = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\chi & -\sin\chi \\ 0 & \sin\chi & \cos\chi \end{pmatrix} \tag{1}$$

$$\text{Yaw (around } y\text{):} \quad R_y = \begin{pmatrix} \cos\eta & 0 & \sin\eta \\ 0 & 1 & 0 \\ -\sin\eta & 0 & \cos\eta \end{pmatrix} \tag{2}$$

$$\text{Roll (around } z\text{):} \quad R_z = \begin{pmatrix} \cos\sigma & -\sin\sigma & 0 \\ \sin\sigma & \cos\sigma & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{3}$$

$$\text{Rotation} \quad : R = R_x R_y R_z \tag{4}$$

$$\text{Translation} \quad : T = \begin{pmatrix} u \\ v \\ w \end{pmatrix} \tag{5}$$

When the girder is installed, it should be in a wrong position and then the position of the balls is in *B'*.

$$B' = RB_0 + T_T \tag{6}$$

It means that the wrong position is a combination of rotation and translation. Since the rotation will affect translation and the rotation error can be measured from the sensors, so the rotation will be adjusted first. Let the new position be *B"* and the magnitudes that all balls move in each direction be T_R then

$$\begin{aligned} B'' &= B' + T_R = (RB_0 + T_T) + T_R = (RB_0 + T_R) + T_T = B_0 + T_T \\ &\Rightarrow T_R = B_0 - RB_0 = (1-R)B_0 \end{aligned} \tag{7}$$

So form the angular sensor's reading and the design positions of all balls T_R can be determined and then T_T will be the reading of the position sensors (touch sensors). B_0 can be found as $B''-T_T$.

Now, from the sensors, the adjusting magnitudes of all balls in each direction can be determined. We still need to transfer the magnitudes to the adjusting angle or steps of each motor .As shown in the figure 5, the relation between ball the mover can be found. A coordinate system is to establish at the center of the ball when it is not adjusted. Since the ball is free in the Z direction, only the magnitudes of u and v are required to determine the rotating angle of the cam. Form figure 6, we see that Y direction in the two coordinate are identical. The transformation between these two coordinates is merely a yaw rotation of the girder and the angles of all balls are 180°, 0°, 120°, 60°, 300°, and 240° respectively.

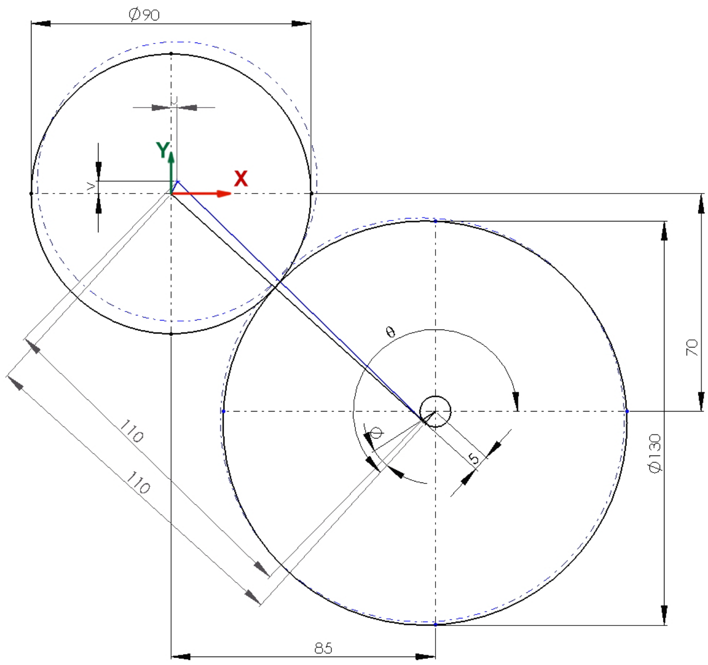

Figure 5: The relations between ball and mover and the coordinate at this system

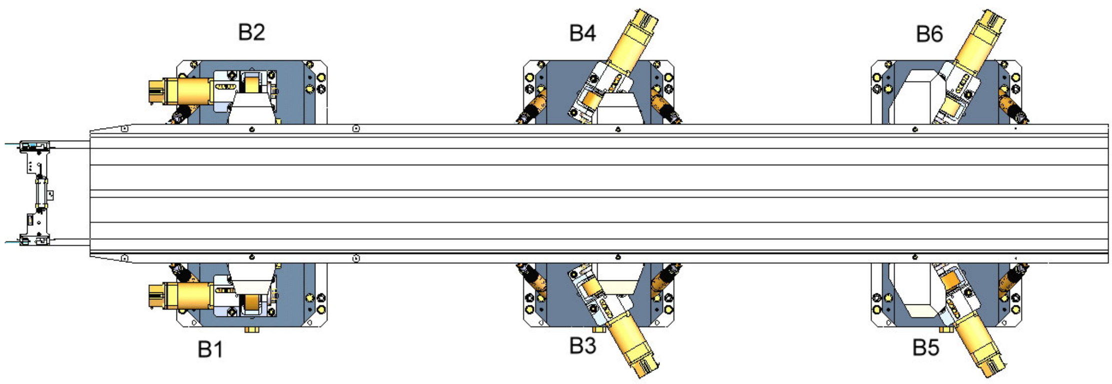

Figure 6: Definition and orientation of the movers

2.3 FEM simulation

A few preliminary FEM analyses were carried out to examine the girder system design at first. As in the figure 7, with the assistant springs, it is possible to adjust the flatness of the girder surface within 5μm. Also, the natural frequencies of modal type were also simulated to examine the mechanism arrangement. In the figure 8, we see the first modal is in the roll direction. It must be dominate by the span of the balls in the X direction and difficult to be extended cause the width of the tunnel is limited. Since the modal analysis is merely a simple analysis by setting the girder and the ball down 10 μm and simulating the whole system as one body. The results are quite different from measurement but the phenomena are similar. A detailed contact elements simulation should be carried out soon. Nevertheless, the comparison is listed in the table 2 in the nest section as a reference.

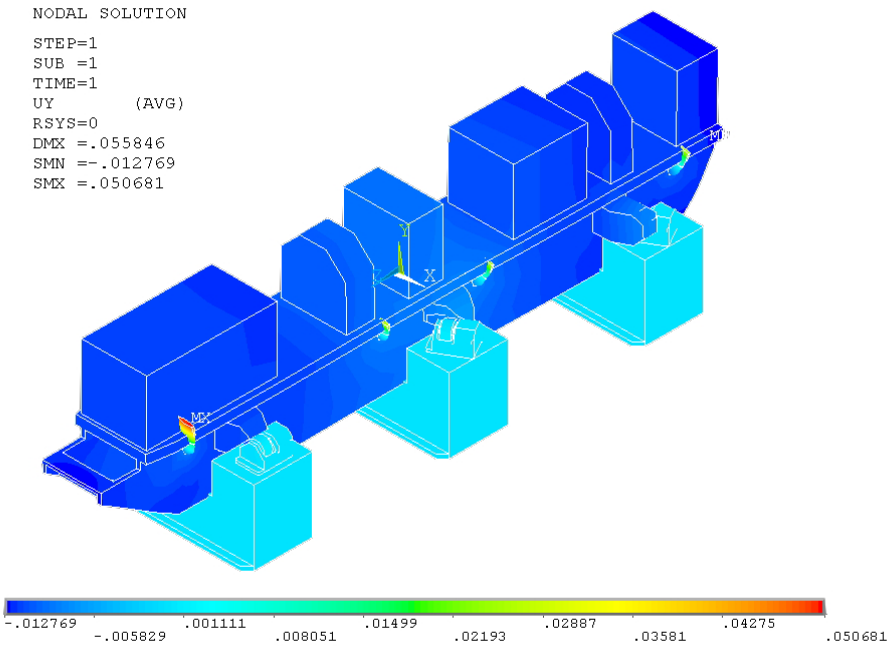

Figure7: With the compensation of assistant springs it is able to keep the girder surface flatness within 5mm from simulation

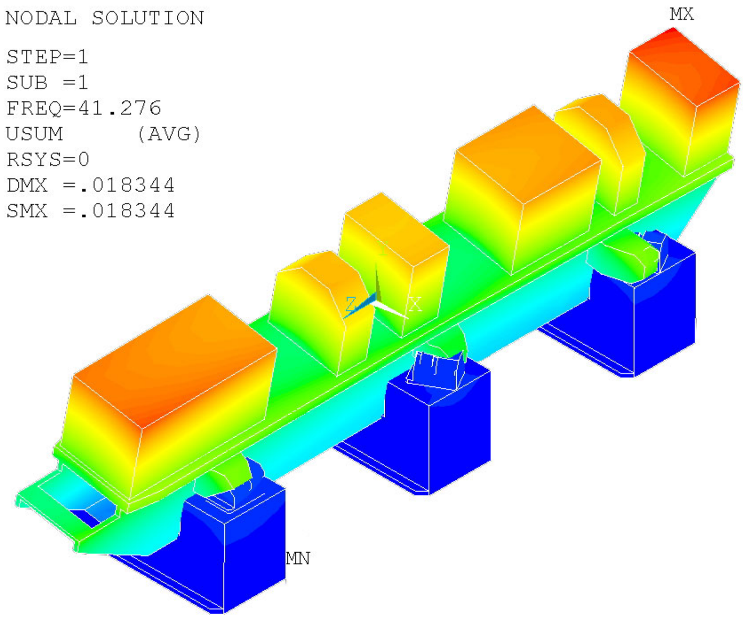

Figure 8: A simple modal analysis by setting the girder and the ball down 10 μm and simulating the whole system as one body.

3. Prototype fabrication and Test

The girder is made from mild steel (SS41) with normal welding processes. The pedestals are made of two types: steel and polymer concrete as a comparison. For the cam mover we used the 1:320 gearbox from Newgard and the motor is a 5 phase 500 steps per circle stepping motor from Oriental. The motor encoder is a 19 bits virtual absolute encoder from Gurley (model 7700) and the touch sensors were made with 0.1 μm resolution linear encoders from Renishaw. After all the parts were fabricated and received, a testing prototype system was set up as shown in the figure 9.

Figure 9: Prototype girder system with quadruples (TLS) for testing

3.1 Surface Machining

The flatness of the girder surface (machined) was measured at the factory as in the figure 10 and also measured after installed at NSRRC (without magnets installed) as in the figure 11. The results shows that after installation the flatness is not changed quite much and with the assistant springs the flatness become better though the spring forces are still not optimized.

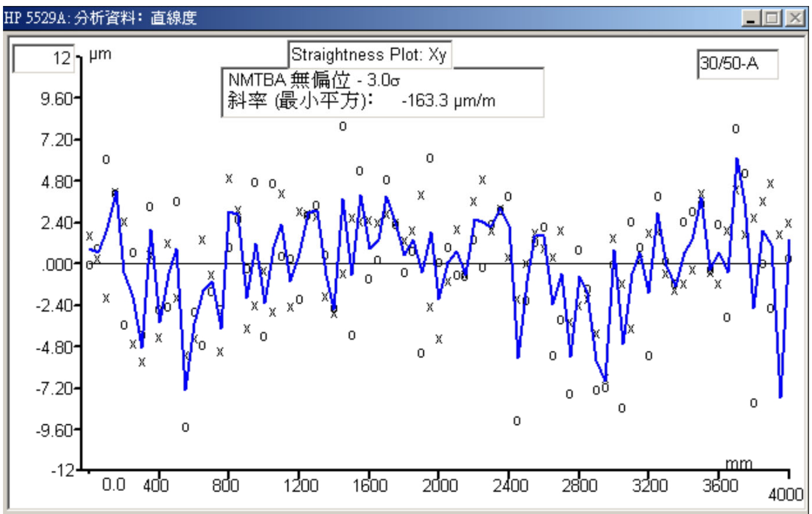

Figure 10: Girder surface flatness measurement by HP 5529A laser at factory.

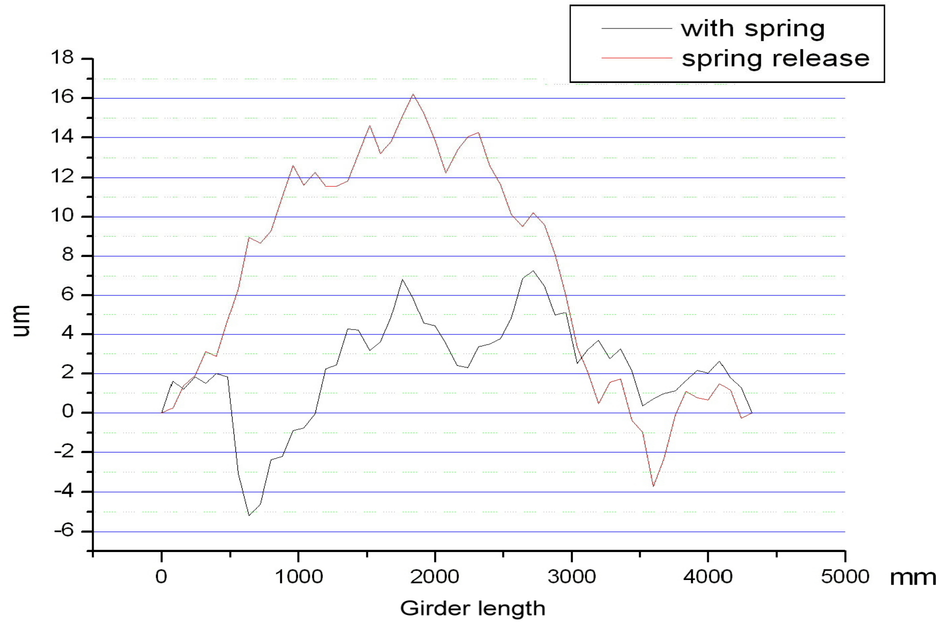

Figure 11: Girder surface flatness measurement by autocollimator after installed

3.2 *vibration and modal test*

During the prototype system installation a series of vibration tests were performed. Since there are two types of girder, we measured the natural frequency of each type singly when connected with the base plate. The first NFs are 151 and 185 respectively. With the girder installed, the NFs measured are listed as in table 1. It shows that due to the smaller stiffness the NF of the polymer concrete pedestal type is lower than the steel one. With the assistant springs carrying loads the NF will be lower, more load on the spring introduces even lower NF. But with the assistant spring the NF can be tuned. The modal measurement was also carried out and compared with the FEM simulation as shown in table 2. The magnification from base pate to the top of magnets also measured and the largest is about 1.68 in the Z direction as shown in the figure 12.

Table 1: Natural frequencies measurement

Natural frequency			Without magnets	With magnets
Steel pedestal	With spring force	X direction	30.2	30.6
		Y direction	40.2	36.8
		Z direction	29.2	26.9
	Spring released	X direction	43.1	32.2
		Y direction	45.8	38.5
		Z direction	40.1	33.3
Polymer concrete Pedestal	With spring force	X direction	19.2	16.3
		Y direction	35.2	24.6
		Z direction	19.7	18.3
	Spring released	X direction	29.6	22.5
		Y direction	37.0	30
		Z direction	27.7	21.1

Table 2: Modal measurement and compared with simulation

Modal (natural frequency)	1	2	3	4	5	6
Measurement	27.6	41.4	55.7	68.2	83	89.9
Simulation	43.1	51.9	55.6	57.2	61.8	83

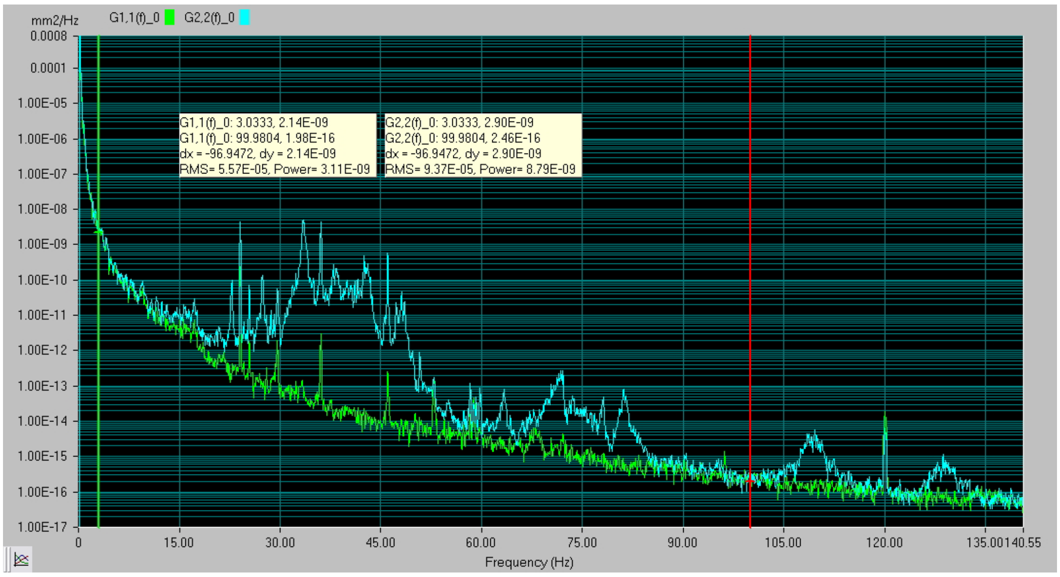

Figure 12: the largest magnification from base to the top of magnet (quadruple) measurement

3.3 Resolution and coupling

The moving system is just beginning to test the control program incorporated with algorithm and sensor's reading. Auto-tune is still not available. From the very preliminary test, the coupling is still large but we can see 1μm step and the flatness in Z direction can be adjusted to 1μrad by Nivel 20.

4. Discussion and Summary

The prototype girder system is now still under test. The preliminary test results showed that it is difficult to push the first natural frequency in this girder system type with larger magnets of TPS on the girder high than 30Hz unless we expand the transverse support span. But this is not easy for the limited tunnel width. However, we can use assistant spring to shift the natural frequency away from the vibration sources, meanwhile, with proper damper added, the vibration magnification may be reduced and this will be test soon.

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