Journal of
Synchrotron
Radiation

ISSN 0909-0495

Received 30 April 2008
Accepted 9 September 2008

Dynamic performance of the beam position monitor support at the SSRF

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Electron beam stability is very important for third-generation light sources, especially for the Shanghai Synchrotron Radiation Facility whose ground vibrations are much larger than those for other light sources. Beam position monitors (BPMs), used to monitor the position of the electron beam, require a greater stability than other mechanical structures. This paper concentrates on an investigation of the dynamic performance of the BPM support prototype. Modal and response analyses have been carried out by finite-element (FE) calculations and vibration measurements. Inconsistent results between calculation and measurement have motivated a change in the soft connections between the support and the ground from a ground bolt in the initial design to full grout. As a result the mechanical stability of the BPM support is greatly improved, showing an increase in the first eigenfrequency from 20.2 Hz to 50.2 Hz and a decrease in the ratio of the root-mean-square displacement (4–50 Hz) between the ground and the top of the support from 4.36 to 1.23 in the lateral direction. An example is given to show how FE analysis can guide the mechanical design and dynamic measurements (*i.e.* it is not just used as a verification method). Similar ideas can be applied to improve the stability of other mechanical structures.

Keywords: beam stability; dynamic performance; finite element; vibration measurement; eigenfrequency.

1. Introduction

The Shanghai Synchrotron Radiation Facility (SSRF) is a future 3.5 GeV third-generation light source, which requires very high electron beam stability (Zhao, 2002; Sharma, 2005). Two well known mechanical systems have already been developed to attenuate ground vibrations: the damping pad used at the Advanced Photon Source (APS), USA (Mangra & Sharma, 1996) and the Australian Synchrotron (McKinlay & Barg, 2006) *etc.*, and the damping link used at the European Synchrotron Radiation Facility, France (Zhang, 2000).

A beam position monitor (BPM) is used to monitor the position of the electron beam, and requires a higher stability than other mechanical structures. Unfortunately the two damping systems mentioned above are not suitable for use with a BPM because the structure of its sustentation system, the BPM support, is too slim and too high to use the damping link, and the support is so light that the lateral stiffness will be greatly softened if using the damping pad (Zhang, 2000). This paper describes an attempt to increase the first eigenfrequency of the BPM support to improve its stability, which is based on the fact that the displacement power spectral densities (PSDs) of many sites of third-generation light sources generally follow $1/f^4$ and the fact that ground vibrations at the SSRF site are much larger than at other light sources (Bialowons *et al.*, 2006). To achieve this, both finite-element (FE) analysis using *ANSYS* 10.0 software and dynamic measurements have been performed on a BPM support prototype in order to investigate the dynamic performance and improve the initial mechanical design. Data analysis techniques are based on Paez (2006). The displacement given in the measurement results is the root-mean-square displacement in the 4–50 Hz band as suggested by Mangra & Sharma (1996). All measurements were carried out in the SSRF main building from 27 September to 26 October 2006.

2. Structure of the BPM support

Fig. 1 shows the mechanical structure of the BPM support, which is 1318 mm long and includes an adjustment system of length 254 mm, a support body of length 1052 mm and a bottom plate of length 12 mm. The adjustment system is used to hold the BPM and can be adjusted in different directions with wedge and screw thread mechanisms. The bottom plate is used for connection to the ground. The support body is the main component and consists of two plates, one connected to the adjustment system and one to the bottom plate, a hollow cylinder of outer diameter 100 mm and inner diameter 20 mm,

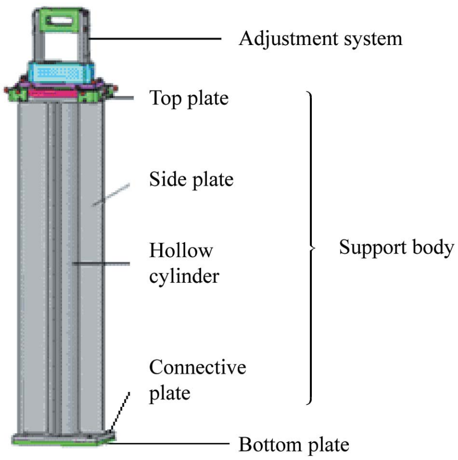


Figure 1
Structure of the BPM support.

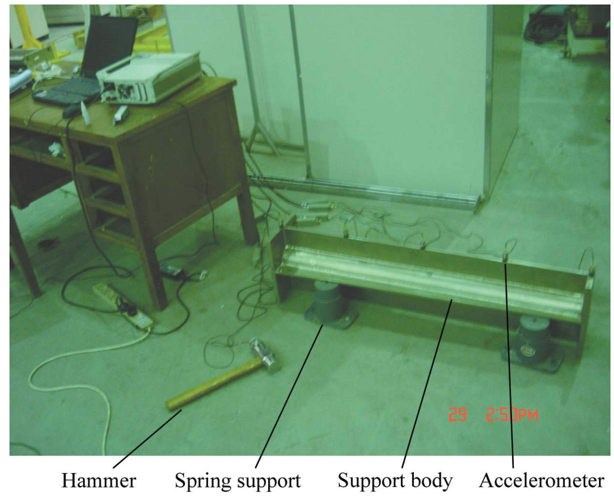


Figure 2
Modal measurement on the BPM support body.

and four side plates welded onto the hollow cylinder, of which two, of width 82 mm, lie with the lateral direction perpendicular to the beam movement and the other two, of width 50 mm, lie with the longitudinal direction parallel to the beam movement. The lateral side plates are wider because the lateral beam vibration is more of a concern than the longitudinal beam vibration from the physical demand point of view (Dai & Liu, 2001). Here, a circular cross section is used for the hollow cylinder because it is simpler in terms of machine processing than an elliptical one; a rectangular cross section is also favourable. Residual stresses caused by welding are eliminated by heat treatments such as annealing.

As a measurement reference to the position of the electron beam, heat deformation of the BPM support should be as small as possible. Therefore, Invar steel with a low thermal expansion coefficient is used in the support body and the adjustment system. Its basic properties are an elastic modulus of 135000 MPa, a Poisson ratio of 0.3 and thermal expansion coefficient of 1.2×10^{-6} K^{-1} (much lower than that for common steel, 10.6–12.2 $\times 10^{-6}$ K^{-1}; Chen, 2005). It should be noted that an Invar support will introduce a different thermal expansion with respect to other support systems made of common steel, and the influence on the beam stability will require further study.

3. Analysis of the BPM support body

The support body is the main component of the BPM support, and contributes greatly to the dynamic performance of the support. In this section, FE calculations and measurements are carried out in order to clarify the following points: (i) whether or not the FE model is credible (this is important for later design modifications); (ii) whether the support body has sufficient stiffness (*i.e.* if the body itself is weak it will become weaker in its connection to the ground); (iii) whether the welding process can soften the body.

Fig. 2 shows a photograph of the modal measurements. The support body is placed on four soft springs, which is consistent with conditions of the FE model where all boundary restrictions are ignored. Five accelerometers are adhered evenly to the side plate. Force and acceleration signals are simultaneously collected and input into the data acquisition system when the body is excited using a hammer. During the signal processing the maximum analysis frequency is 500 Hz (above which we are not concerned in this paper).

Fig. 3 shows the typical modal shapes of the support body in FE calculations and measurements, and Table 1 gives the detailed results. The three points noted above can be answered as follows: (i) the FE model is precise enough with only 0.73% maximum error in the measurements; (ii) the support body has first and second eigenfrequencies much higher than 100 Hz, which means the support body is very stiff; (iii) weld connections in the mechanical structure are substituted for stiffness connections in the FE model; however, we still obtain consistent results between the measurements and FE calculations, which implies that the welding process does not soften the body.

4. Analysis of the BPM support

4.1. Modal analysis

Based on the analysis of the support body above, this section aims to investigate the influences on the eigenfrequency of the whole support and how to improve it from a mechanical point of view. In the model analysis, three kinds of connections between the support and the ground are considered (Fig. 4 shows their cross sections):

(i) Ground bolt connection. This is very common and is adopted in the initial mechanical design. In this case the BPM support is tightened to the ground by using ground bolts through four holes in the bottom plate and connective plate.

(ii) Part grout connection. This was proposed during the process of mechanical optimization. In this case ground bolts are replaced by ground screws. The BMP support is lifted up by ~20 mm by four M6 bolts (not shown in the figure).

Table 1
Modal analysis results on the BPM support body.

		Eigenfrequency (Hz)		
No.	Modal shape	FE	Measurement	Relative error
1	Longitudinal bend	308.2	307.8	0.13%
2	Lateral bend	446.1	449.4	0.73%
3	Lateral torsion	516.3	>500	

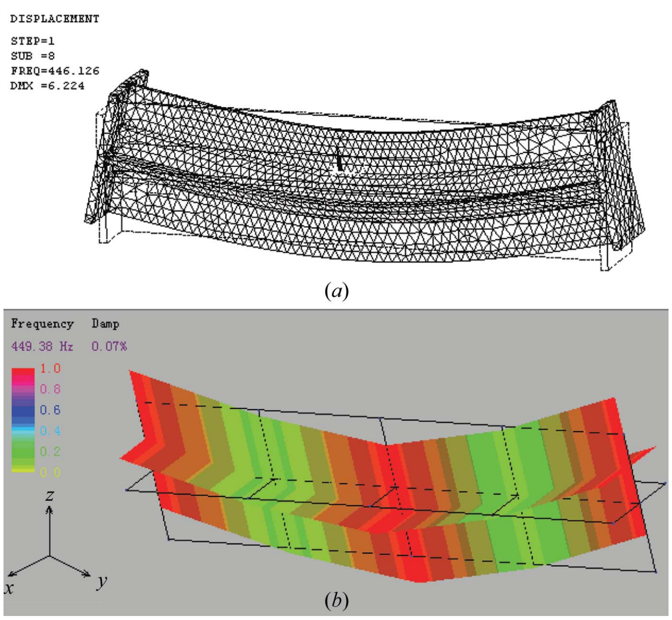


Figure 3
Modal analysis of the BPM support body in lateral bend: (*a*) FE analysis and (*b*) measurement.

Grouting material is injected into the space between the bottom plate and the ground using grouting technology.

(iii) Full grout connection. In this case grouting material is injected to a height of up to 100 mm from the ground. It should be worth mentioning that the full grout configuration actually only requires one plate at the interface of the support and the ground and the final design did indeed use only one. However, this paper still discusses the case of two plates so that the three different connections are compared under the same conditions.

In order to understand the characteristics of the grouting material and to provide precise parameters to the FE model, we firstly performed FE analysis and measurements on a block of grouting material. The block was 800 mm long, 150 mm wide and 900 mm high, with an elastic modulus close to the value of common concrete. In addition, a study on the performance of the adjustment system was also included in the modal analysis.

FE calculations and modal measurements were conducted during the analysis. In the FE model (see Fig. 5) there are a total of 21412 elements and 33245 nodes including SOLID92, SOLID95, TARGE170 and CONTA174. The wedge mechanism in the adjustment system is simulated for flexible-to-flexible and surface-to-surface contact elements, and the connection between the bottom plate and the ground is simulated for a fixed restriction. In the modal measurement (see Fig. 6) six accelerometers are adhered evenly to the side plate of the support. Force and acceleration signals are simultaneously collected and input into the data acquisition system when the body is excited using a hammer.

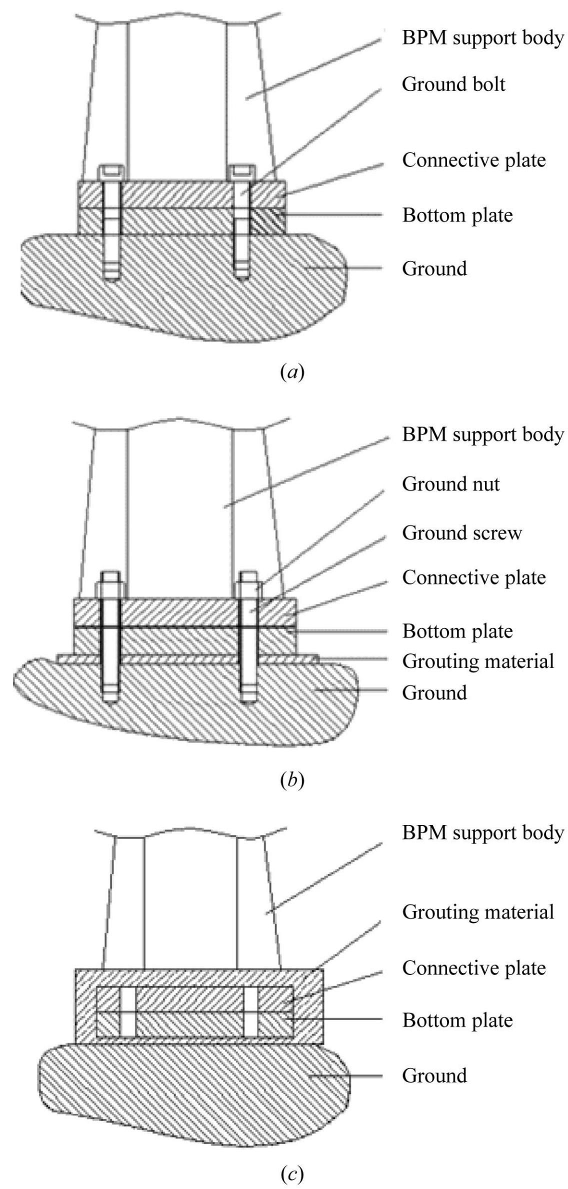


Figure 4
Cross sections of the three connections between the BPM support and the ground: (*a*) ground bolt, (*b*) part grout, (*c*) full grout.

Table 2 summarizes the results. We can see that in the ground bolt configuration the measured values are much lower than the FE calculations with the maximum relative error being 181%. Because the FE model of the support body has been validated in §3, such a huge error can only be explained by the different boundary conditions, where the FE model of the support uses a fixed restriction and the actual mechanical connection uses a ground bolt. This suggests that the ground bolt connection is much weaker than the simulated fixed restriction. This leads to the question of what kind of mechanical connection can compare with the simulated one? Grouting technology can help a lot here, which is the reason we began to study grout connections. From the measurement results shown in Table 2 we can see that grout connections greatly improve the first eigenfrequencies of the support with a minimum relative error of only 11%.

Fig. 7 shows modal analysis of the support with full grout connection. Figs. 7(*a*) and 7(*b*) show modal shapes at the first eigenfrequency rocked in the lateral direction. Figs. 7(*c*) and 7(*d*) show frequency analysis in the longitudinal and lateral directions. We can see that the frequency response curves have obvious peaks and the coherence functions are above 0.99 at their respective resonant frequencies, which indicates that the modal measurements are credible.

Table 2
Modal analysis results on the BPM support.

		Eigenfrequency (Hz)			
		With adjustment system		Without adjustment system	
		Lateral	Longitudinal	Lateral	Longitudinal
FE		56.7	42.4	71.1	54.2
Measurement	Ground bolt	20.2	24.4	24.2	32.1
	Part grout	39.4	36.9	48.1	48.4
	Full grout	50.2	36.3	64.7	47.1

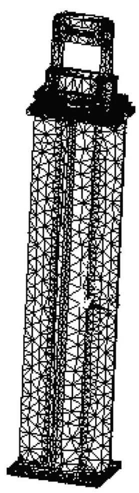


Figure 5
FE model of the BPM support.

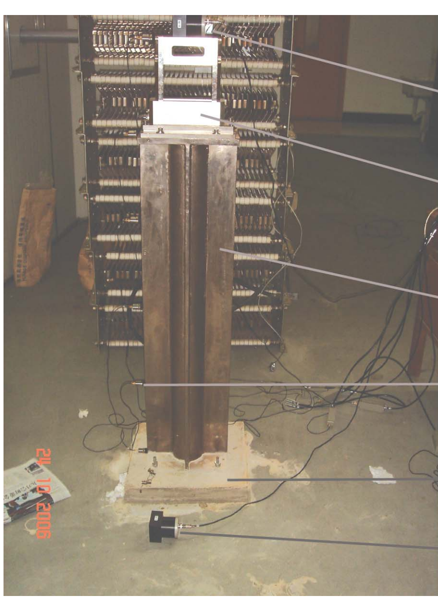


Figure 6
Measurements on the BPM support.

The still existing error between calculation and measurement in the full grout configuration may be explained by the following two reasons. First, the measurement position has a relatively softer foundation, with thin concrete slabs and no piles, than the storage-ring tunnel, which has 1450 mm-deep slabs and 48000 mm-deep piles. In our experience, a good foundation in the storage-ring tunnel can increase the first eigenfrequency of the magnet–girder assembly by about 7–8%. Second, there may exist some defects in the grouting (100% perfect grouting is impossible). These impact factors may soften the support stiffness while FE analysis cannot comprehensively take them into consideration.

In addition, we still find from Table 2 that in the full grout case the first eigenfrequency in the lateral direction is much higher than that in the longitudinal direction, which is consistent with the initial design idea that the lateral side plates of the support should be wider than the longitudinal side plates so as to attenuate the lateral beam vibration that is more of a concern. However, the same consistency is not evident in the ground bolt and part grout cases, which implies that the design idea takes effect with the full grout connection but has no effect on the other two cases.

Table 2 also shows analysis results regarding the influence of the adjustment system on the performance of the support. Both FE analysis and measurements show that all eigenfrequencies of the support without the adjustment system are larger than the corresponding values with the adjustment system, which suggests that care should be taken with the design of the adjustment system and its connection to the support body. However, unlike the support body the adjustment system is too short to have a decisive influence on the performance of the whole support system.

Finally, based on the above modal analysis, the following structure optimization methods are proposed to improve the first eigenfrequency of the BPM support. First, the ground bolt connection between the support and the ground is replaced by full grout. Second, the design of the adjustment system is optimized further, such as by shortening its height, increasing the dimensions of some relative components, enlarging the contact area between the components of the wedge system, stiffening the connection between the adjustment system and the support body *etc.* Third, similarly, other structure optimization can be taken to strengthen the support body, such as increasing the outer diameter of the hollow cylinder, thickening the side plates *etc.* However, it should be noted that all other modifications do not need to change the main mechanical structure of the support because the initial basic structure is simple to adjust and measurements on the prototype have shown that its dynamic performance has reached the SSRF design criterion, *i.e.* the first eigenfrequency is >30 Hz.

4.2. Response analysis

In order to further understand the dynamic performance, response analysis has been performed on the BPM support. During the measurements, one seismometer was placed on top of the support and another on the ground nearby, both facing in the same direction (see Fig. 6); data were derived simultaneously from the two positions.

Fig. 8 shows spectra of lateral displacement PSD and transmissibility of the support with the ground bolt, part grout and full grout connections. The Q value, defined as the peak of the transmissibility curve at the first eigenfrequency (Zhang, 2000), is 125.4, which corresponds to a low damping coefficient, 0.004. This value is credible and can be justified indirectly as follows. Bolt connections are widely used in the magnet–girder assembly of the APS storage ring, whose Q value can reach 100 when not using the damping pad (Mangra & Sharma, 1996). Thus, the SSRF BPM support should have a Q value higher than 100 because it is made of welded structure steel, which has a smaller damping effect than the bolt connections (Masuzawa *et al.*, 2004). Moreover, the relative micro-movement between the APS girder and its support on the ends can absorb the dynamic strain energy while the SSRF BPM support cannot.

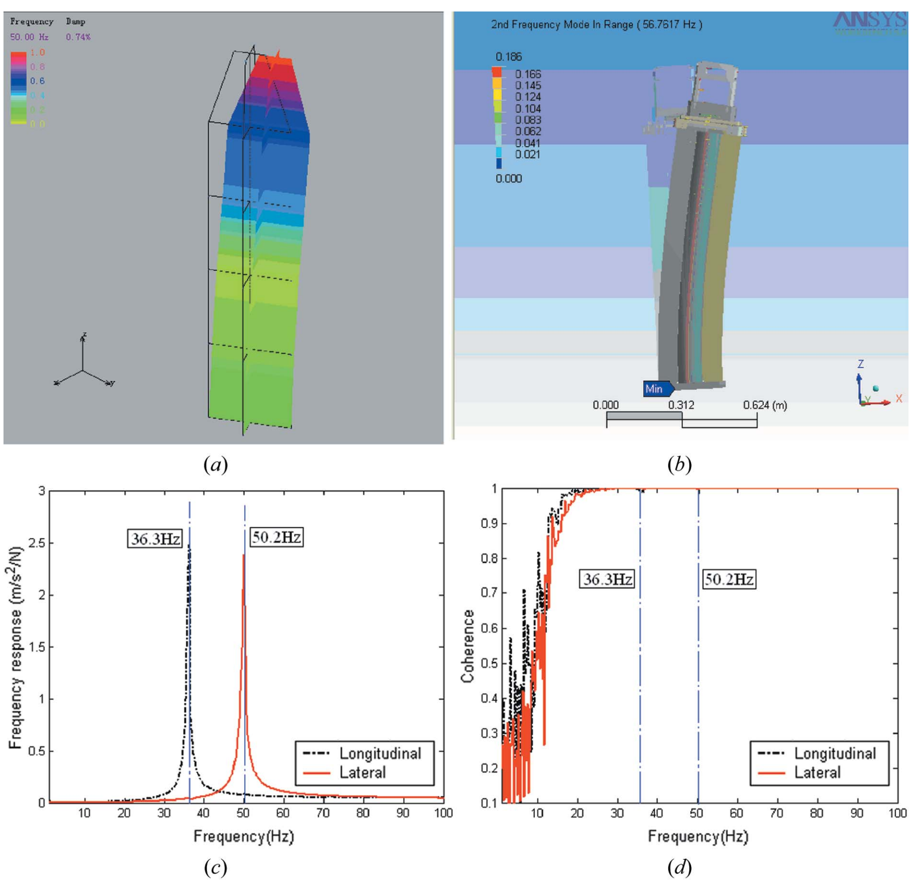
Table 3
RMS lateral displacement of the BPM support at 4–50 Hz (nm).

	Connection	Ground	Top of BPM support	Ratio
Measurement	Ground bolt	22.3	97.2	4.36
	Part grout	20.8	27.5	1.32
	Full grout		27.2	1.23
FE	Full grout	22.1	26.4	1.19
	Full grout (improved)		25.4	1.15

Table 3 shows measurement results of the integrated root mean square (RMS) lateral displacement (4–50 Hz), from which we can see that the ratio between the ground and the top of the BPM support decreases from 4.36 to 1.32 and 1.23 with the different connections, and the full grout configuration achieves the best damping effect on ground vibrations.

Next we consider the support with the full grout connection. Response analysis results in the lateral direction are shown in Table 3 and Fig. 9, where measured curves for ground vibrations and the full grout case are the same as in Fig. 8(*a*). In the FE model, points are sampled at every 0.5 Hz intervals when the frequency is below 20 Hz, and at 10 Hz intervals when it is above 20 Hz (see circles in Fig. 9). Such an uneven sampling period results from the fact that *ANSYS* software only admits a maximum of 50 points in the PSD calculation (ANSYS Inc., 2005) and the fact that the PSD spectrum of the ground motion drops sharply before 20 Hz and becomes more even after that (see blue line in Fig. 9). After analysis we can see that the FE result (red line in Fig. 9) is generally similar to the measurement result (black line in Fig. 9) with the relative error of the RMS displacement ratio only 3% (see Table 3), which suggests that the FE analysis is credible. In addition, further FE analysis is made on an improved support structure where the outer diameter of the hollow cylinder is increased from 100 mm to 125 mm. Results show that this improvement increases the first eigenfrequency from the original 50.2 Hz to 66.7 Hz (see the blue line in Fig. 9) and decreases the RMS displacement ratio from 1.19 to 1.15 (see Table 3).

The dynamics of the support in the vertical direction are also a concern from the physical demand point of view, and relevant response measurements



(*a*) (*b*) (*c*) (*d*)

Figure 7
Modal analysis of the BPM support with full grout connection. Modal shapes rocked in the lateral direction by (*a*) measurement and (*b*) FE analysis, and spectra of frequency response functions (*c*) and coherence functions (*d*) in the longitudinal and lateral directions.

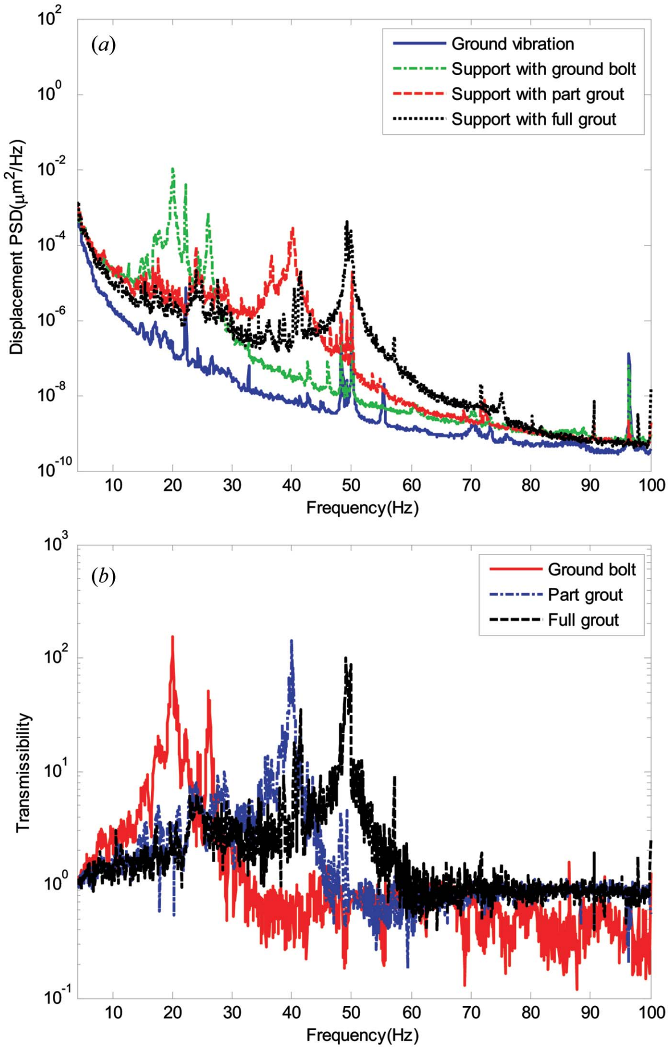


Figure 8
Lateral response measurements on the BPM support with ground bolt, part grout and full grout connections: (*a*) displacement PSD, (*b*) transmissibility.

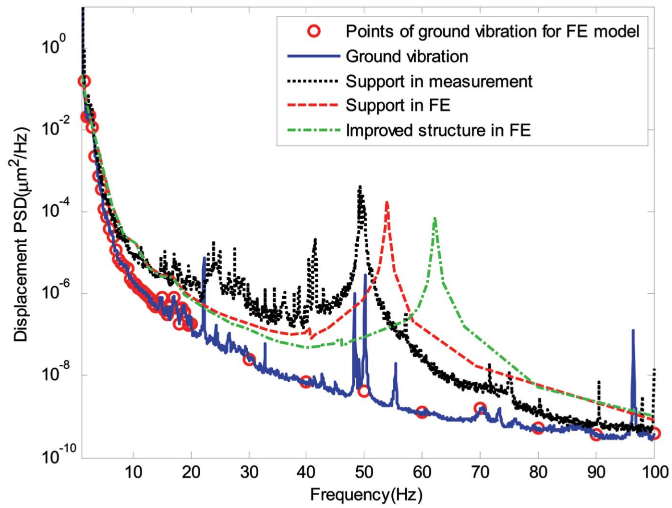


Figure 9
Lateral response measurement and FE analysis of the BPM support with full grout connection.

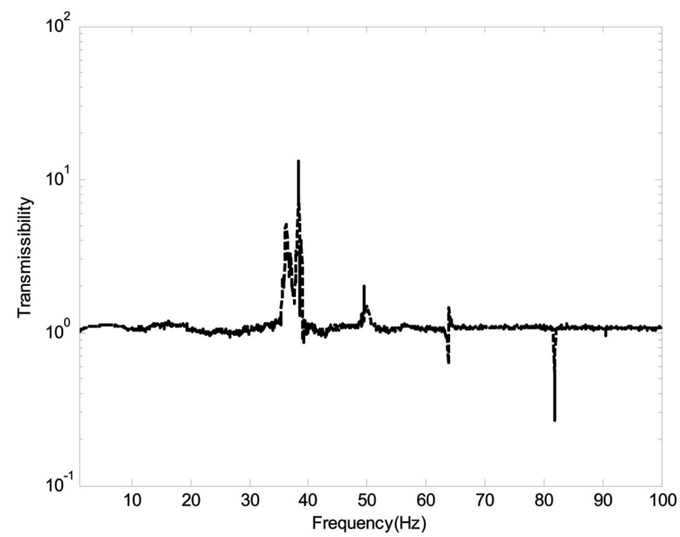


Figure 10
Vertical transmissibility of the BPM support with full grout connection.

have been carried out. Fig. 10 shows the vertical transmissibility spectrum of the support with full grout connection. Comparing this with Fig. 8, which concerns the lateral direction, we find that not only is the vertical Q value (21.2) much smaller than the lateral one (125.4), but the width of the vertical peak pulse is also narrower than the lateral one. This indicates that vibrations in the vertical direction are far weaker than those in the lateral direction. In addition, the RMS displacement ratios between the ground and the top of the support have been derived in the three different connection configurations: 1.10, 1.09 and 1.08 for the ground bolt, part grout and full grout, respectively. Vibrations of the BPM support are almost the same as for the ground, and the grouting technology appears to have no obvious effect in the vertical direction compared with in the lateral direction. This can be explained by that fact that the initial mechanical design has already guaranteed sufficient support stiffness in the vertical direction.

Also, from Fig. 10, for the vertical direction, we can see some coupling phenomena with other directions because two peaks appear at 36.3 Hz and 50.2 Hz, which are the first eigenfrequencies in the longitudinal and lateral directions, respectively (see Table 2).

5. Conclusions

In this paper the dynamic performance of the SSRF BPM support has been studied by modal and response analysis. Both FE calculations and dynamic measurements have been performed on a prototype. Conclusions to be drawn are as follows.

(i) The support body has sufficient stiffness and its FE model is credible with a maximal error of 0.73% compared with measurements.

(ii) Connections between the support and the ground should be changed from ground bolts in the initial design to full grout. With this improvement the lateral first eigen-frequency can be increased from 20.2 Hz to 50.2 Hz, and the ratio of the RMS lateral displacement (4–50 Hz) between the ground and the top of the support can be decreased from 4.36 to 1.23. The mechanical stability of the BPM support is greatly improved.

This paper shows an example of how FE analysis can instruct dynamic measurement and mechanical design by inconsistent results between calculation and measurement. Similar ideas can be applied to other mechanical structure optimization.

The authors thank the ME group of Shanghai Institute of Applied Physics, Chinese Academy of Science, for their assistance throughout the measurements, and thank the referees and the editor for their valuable comments and suggestions. This work was supported by the National Nature Science Foundation of China under Grant no. 10805072.

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