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A FAMILY OF HIGH-STABILITY GRANITE STAGES FOR SYNCHROTRON APPLICATIONS*

C.A. Preissner[†], S.J. Bean, M. Erdmann
Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60439, USA
M. Bergeret, J.R. Nasiatka
Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

Engineers at the APS have developed a granite, air-bearing stage concept that provides many millimeters of motion range and nanometer-level vibrational stability. This technique was first conceptualized and used on the Velociprobe x-ray microscope [1, 2]. The success of that design spurred adaption of the approach to over 90 devices, including many new instruments at the APS [3] and high performing instruments at other synchrotrons [4]. This paper details the design concept, some performance measurements, and new developments allowing for a six-degree-of-freedom device.

BACKGROUND

The stability needs of multi-bend achromat (MBA) synchrotrons [5] mean that both the accelerator and beam line equipment require more stable platforms as compared to those of the previous generation of synchrotrons. At facilities like the APS-U, new and more precise x-ray beam position monitors are required for the front ends and numerous fine-focusing (tens of nm or better) instruments are being deployed. Each of these requires multiple axes to align the equipment to the beam.

Many of these axes are simply to position or align the instrument and are not moved during a measurement or moved only for alignment. Conventional rolling element bearings are readily available in many forms and easily integrated into designs and make these motions easy to implement. However, there is a price to pay when using these rolling-element bearings: compliance.

Engineers at the APS were frustrated that the bearings necessary to allow for a practical and easy to use instrument also amplified floor vibration and reduced performance potential. Granite air bearing staging systems can offer advantages over conventional rolling-element bearing staging systems, including a) higher stiffness, b) lower thermal expansion, c) slow thermal changes/drift, and d) low angular position errors. While planar air bearings were in common usage, air bearing vertical stages required a novel wedge design [2] to realize a design in which there is no cantilevered load. This paper provides insight into basic aspects of the granite stage design, some measured performance, illustration of some examples, and new developments.

DESIGN CONSIDERATIONS

The basic principles of the Velociprobe-style air bearing stages are to integrate orifice-balanced air bearings [6] into granite blocks (Fig. 1), flow air to create a stiff film for movement, and vent the bearings when not moving to provide a stiff structure. All current systems are designed as positioning systems, meaning they are moved into position and then the air bearings are vented. Figure 1 shows the geometry of a typical granite block with integrated air bearings.

The integration of the bearing into the granite takes advantage of both the favorable granite thermal properties (~4E-6 m/m/°C thermal expansion coefficient) and the high level of flatness that can be achieved [7]. Normally "flat-on-flat" contacts should be avoided, as surfaces are not exactly flat. However, the high level of flatness achievable with granite enables a stiff "flat-on-flat" type of contact when the bearings are vented. The "fly height" (air film thickness) is controlled by the size of the orifice located upstream of the bearing surface. The target film thickness is between seven and ten microns, and the APS has developed a spreadsheet to estimate the orifice size necessary to achieve this fly height. Alternatively, fly height can be determined during assembly by measuring the fly height and changing orifice size to achieve the desired fly height.

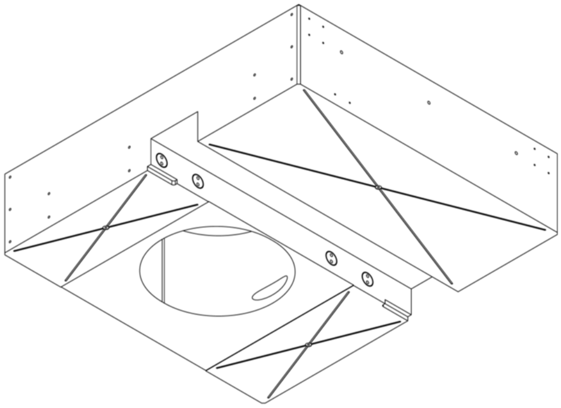

Figure 1: Picture of a typical granite block with three integrated, orifice balanced, air bearings. The orifices are located at the center of the "Xs".

Stiffness of a vented granite air bearing is over 20 times that of the stiffest configuration of rolling-element bearings. Figure 2 shows a comparison of various rolling element bearings to a flat-on-flat contact typical of granite. Hertzian contact stiffness as described in Puttock [8] is compared to the AE/L stiffness of granite, with reference

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† preissner@anl.gov

dimensions (length, width, and area) of about 6.4 mm. In practical air bearing designs the stiffness difference is likely much greater due to the large area. APS experience shows that the vented blocks behave as a monolith from the vibration standpoint.

Geometry and friction play key roles in both the kinematics of the stage and the static stability. Figure 3 shows the basic layout for an independent, three-axis system. Constraints are provided to the horizontal block by mechanical or air bearings resulting in two in-plane degrees of freedom. The granite-to-granite contact provides constraints for rotations about the X and Z axes and it is important that some compliance or a flexure is provided between the block and the horizontal constraints such that the block is not overconstrained. In addition, the horizontal block can be used to provide small rotations (a few degrees) about the Y axis if the proper actuation and constraints are incorporated.

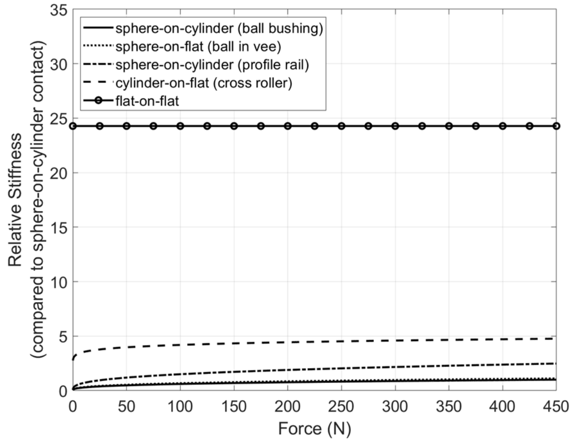


Figure 2: Plot showing the relative stiffness of various rolling element bearing types compared to a flat-on-flat type of contact. For similar reference dimension (6.4 mm), the flat-on-flat contact is approximately 25 times stiffer. In a practical application this difference can be even larger due to the large extent of the area contact.

The Y axis motion is provided by driving the bottom wedge (driving wedge) under a properly constrained top wedge (follower wedge). The kinematics and resulting forces are determined by the wedge angle, α.

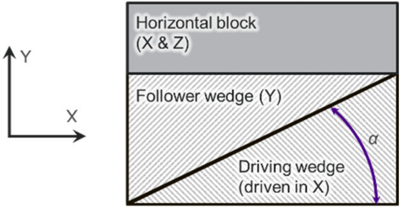
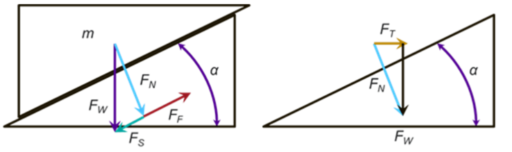


Figure 3: Diagram showing the basic structure of a three-axis system. The driving wedge (bottom) is moved in the X direction to cause a Y motion from the follower wedge (top). The wedge angle is denoted by α.

The expression $Y = X * \tan \alpha$ relates the vertical motion to the wedge angle and driving motion, including the friction and thrust forces. The friction force is what ensures the system is statically stable when the air bearings are vented, while the thrust force is relevant for sizing the driving mechanism and needs to be known to prevent back driving.

A smaller wedge angle reduces the thrust force, increases the friction force, and increases the amount of X travel required for a given amount of Y travel. Figure 4 shows the resultant forces for a pair of wedges.



$F_W = mg$

$F_S = F_W{*}\sin\alpha = mg{*}\sin\alpha$

$F_N = F_W{*}\cos\alpha = mg{*}\cos\alpha$

$F_F = F_N{*}\mu$

$F_T = F_N{*}\cos\alpha = mg{*}\sin\alpha{*}\cos\alpha$

Figure 4: Wedge force diagram.

Figure 5 shows the relation of these forces and wedge angle. About 20 mm of Y travel is possible with a 7.5-degree wedge angle and 151 mm of driving wedge travel. The support for the driving wedge needs to be long enough to support the air bearings of the driving wedge, plus the motion range. This requirement places a practical limit on the Y (vertical) travel range of the air-bearing wedge stage Though the APS has found 20-25 mm of travel to meet most needs.

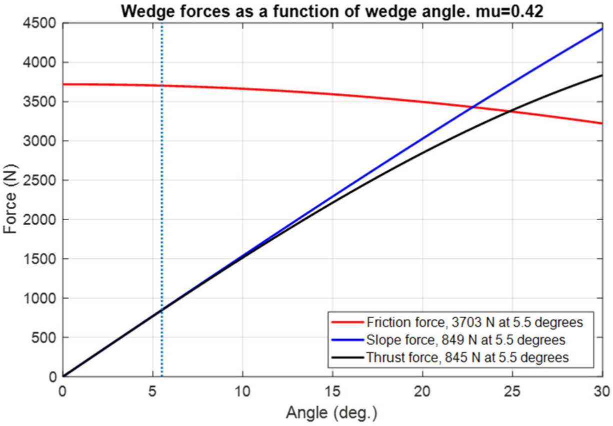


Figure 5: Chart showing how the vertical axis friction, slope (force parallel to wedge surface), and thrust forces change as a function of wedge angle. The vertical line is at the design point of 5.5 degrees for the APS-U PtychoProbe stage. The coefficient of friction (mu) has been measured.

Key to both the good static performance and achieving low fly height is the granite flatness. Fortunately, granite finishing is a well-known and common practice. Granite pieces of approximately 700 mm by 800 mm have been shown with autocollimator measurements to have flatness of around 2 microns, exceeding the tolerance of an “AA” grade surface plate [7].

PERFORMANCE

The vibrational performance is likely the main reason for selecting a granite air bearing stage for a particular application. Air bearing granite stages have demonstrated over a 100 times reduction in relative vibration level as compared to a similar instrument using stages with all rolling element bearings. Figure 6 shows the measured relative vibration on the APS Velociprobe granite stage system.

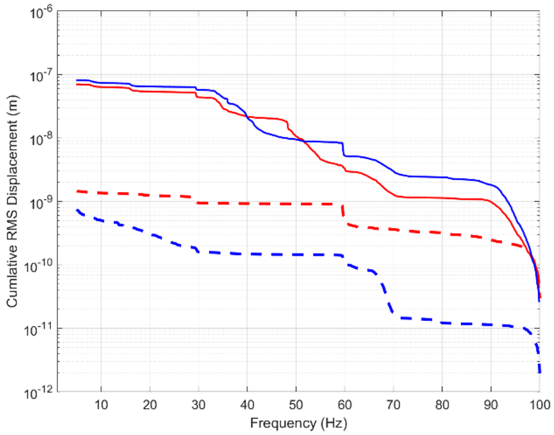


Figure 6: Chart showing comparing the relative vibration between the optic and sample mounting points for a granite stage system (dashed) and a conventional stage system (solid). Blue curves are for vertical vibration and red for the horizontal directions. The measurements show the granite stage system has nanometer level relative vibration whereas the conventional system is in the 70 to 80 nm range.

The angular errors that are present when the stage system is move are another important aspect of performance. For the example system shown in Fig. 3, the angular errors about the X and Z axes have the main contribution from the flatness of the granite (when the components are properly constrained). The angular errors about the Y axes have the main contribution from the bearings that guide blocks on their trajectories. These bearings can be either rolling element or air bearings. Air bearing guides will provide the lowest errors about the Y axis.

The angular errors are better than typical rolling element stage system and Fig. 7 shows angular errors as measured on the Velociprobe. Note: this system was not designed with particular consideration to minimize such errors.

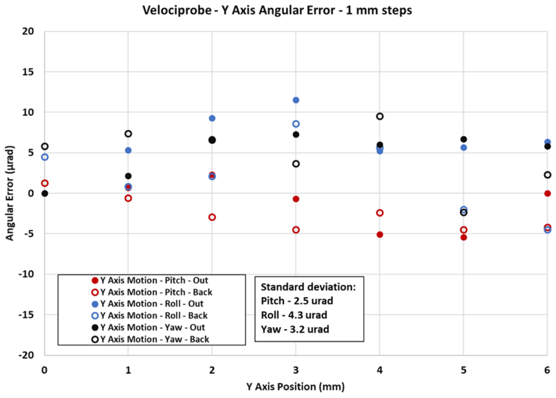


Figure 7: Chart showing angular errors in the pitch (rotZ), roll (rotX), and yaw (rotY) directions, as measured on the Velociprobe.

RECENT EXAMPLES AND NEW DEVELOPMENTS

Recent developments have reduced the volume for a given number of axes by combining multiple degrees of freedom into one block (horizontal motion of top wedge and in-plane rotations, used in many APS-U designs). Engineers at the ALS have improved the angular error performance (Fig. 8). APS engineers recently applied for a patent to realize six degrees of freedom by adding pitch and roll (Fig. 9) [9].

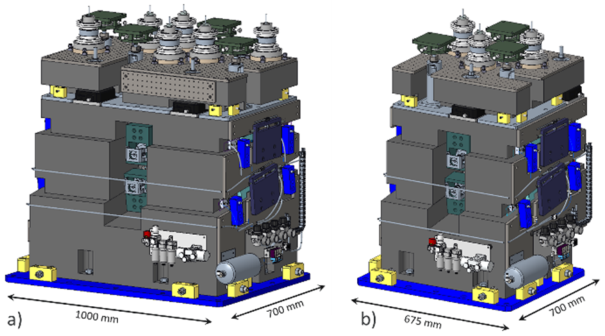


Figure 8: Image showing the a) AlS dual mirror, and b), single mirror granite positioning systems. Each uses commercial off-the-shelf, porous-media air bearings for lateral guiding.

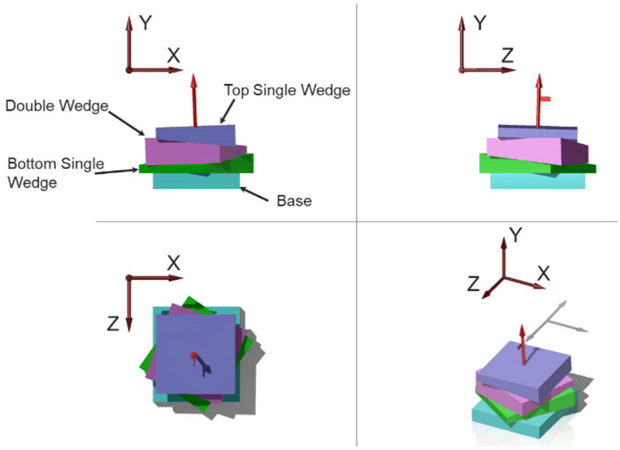


Figure 9: A new design that can provide small pitch and roll rotations through the addition of a orthogonal double width and by rotating the blocks about the Y axis. The motions are coupled, and this arrangement is best used for small rotations of a few tens of mrad.

CONCLUSION

Granite stage systems offer nanometer level vibrations and low angular errors. New developments offer small but useful rotations. They can be a good choice for sensitive instruments and vertical travel ranges of a few tens of mm.

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REFERENCES

[1] J. Deng *et al.*, “The Velociprobe: An ultrafast hard X-ray nanoprobe for high-resolution ptychographic imaging,” *Rev. Sci. Instrum.* vol. 90, p. 083701, 2019. `doi:10.1063/1.5103173`

[2] C. Preissner *et al.*, “Method and apparatus for implementing ultra-high stability long-vertical travel stage,” US Patent and Trademark Office 10,393,242, August 27, 2019.

[3] S. Bean *et al.*, “A New Ultra-Stable Variable Projection Microscope for the APS Upgrade of 32-ID”, presented at the 11th Int. Conf. on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI2020), Chicago, IL, USA, virtual conference, July 2021, paper TUPC15, this conference.

[4] R. R. Geraldes *et al.*, “Granite Benches for Sirius X-ray Optical Systems”, in *Proc. 10th Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation Int. Conf. (MEDSI'18)*, Paris, France, Jun. 2018, pp. 361-364. `doi:10.18429/JACoW-MEDSI2018-THPH12`

[5] Z. Liu *et al.*, “Validation of APS-U Magnet Support Design Analysis and Prediction”, presented at the 11th Int. Conf. on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI2020), Chicago, IL, USA, virtual conference, July 2021, paper MOPC16, this conference.

[6] Newway Technical Report 1, `https://www.newwayair-bearings.com/technical-report/technical-report-1-orifice-vs-porous-media-air-bearings/`.

[7] *GGG-P-463C, Amendment 1, Federal Specification Plate, Surface, (Granite).* National Bureau of Standards Publications, June 1977.

[8] M. J. Puttock *et al.*, “Elastic Compression of Spheres and Cylinders at Point and Line Contact,” Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia, National Standards Technical Paper No. 25, 1969.

[9] C. Preissner *et al.*, “Method and apparatus for implementing ultra-high stability stages with combined degrees of freedom for multiple axes of motion,” USPTO Application SN 17/034 September 28, 2020.