Precision Motion Control for Sample Manipulation in Ultra-High Resolution Tomography

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In the constantly evolving field of ultra-high resolution tomography, x-rays are used to create nondestructive, high-resolution images of a sample at the sub-100 nm level. Precision motion equipment, such as linear and rotation stages, position and manipulate the various elements in a tomography experiment, including the sample that is being imaged, the x-ray beam, and the detector or camera. As x-ray beam cross-sections shrink and detector resolutions improve to nanometer-levels, the positioning performance of the motion equipment must be better than the desired resolution and measurement accuracy. This article will review the motion elements used in a typical synchrotron end station and discuss critical items that designers and engineers must consider when attempting to achieve reliable ultra-high resolution tomography results.

In a synchrotron, the x-rays exit the synchrotron storage ring and enter a beamline. A beamline typically consists of three main areas: the beam conditioning section, sometimes referred to as the optics hutch; the experimental end station, or experimental hutch; and the controls area/cabin where the instrumentation and control systems are located. In the beam conditioning section, the x-ray beam is conditioned to the desired size, shape and wavelength. Devices in this section include shutters, filters, slits, attenuators, collimators, monochromators and focusing mirrors. While high resolution, repeatability, accuracy and stability are necessary characteristics of the motion equipment used to manipulate these devices, the design and selection of those elements are outside the scope of this paper.

Figure 1 shows a schematic illustration of a typical beamline end station setup.

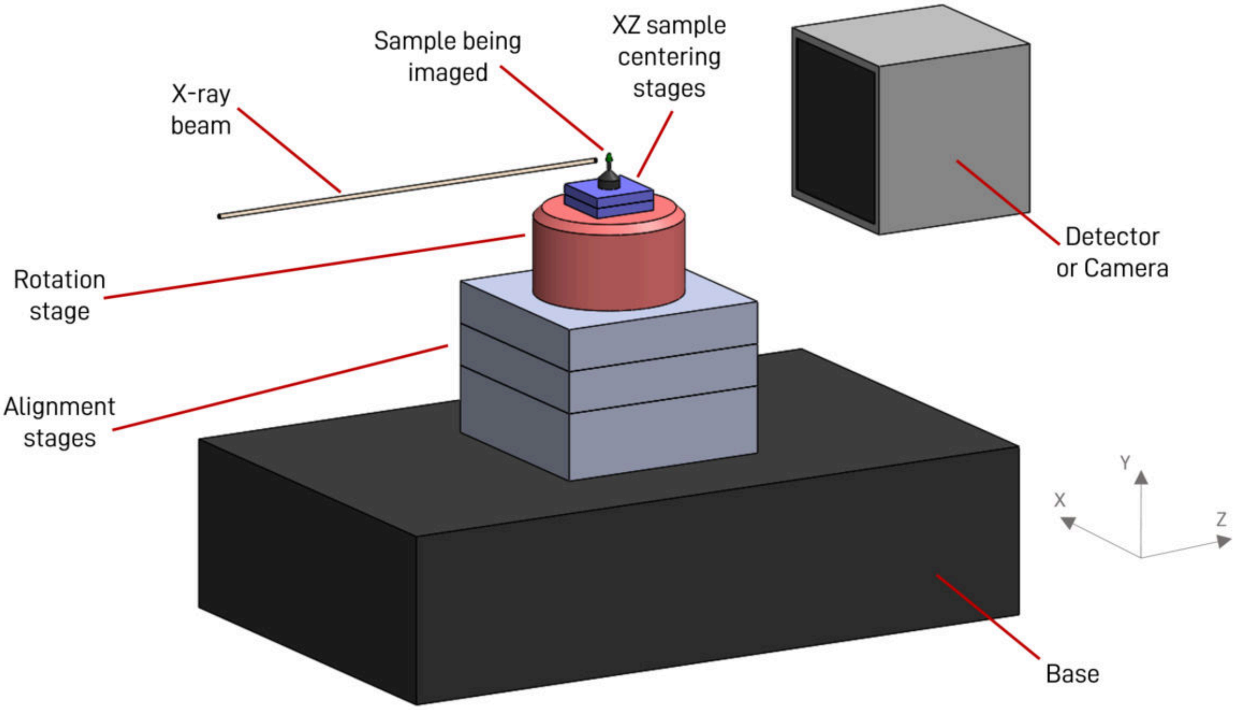

Figure 1. *Schematic illustration of a beamline end station sample positioning setup.*

In this setup, the x-rays are produced from the synchrotron and exit the storage ring into the beamline. As a result, the beam is generally fixed relative to the experiment. The detector is also held stationary during the experiment. The alignment stages align the sample to the x-ray beam and detector. These stages can have three to six axes of motion, depending on the type of experiment. In most tomography experiments, these alignment stages perform an initial alignment and then must remain stationary during the imaging process.

A rotation stage sits on top of the alignment stages. This rotation stage rotates the sample being imaged as the detector creates two-dimensional images at each of the rotation stage's angular positions. These two-dimensional images are then combined in software to create a full three-dimensional image of the sample.

Additional stages, typically used for centering and aligning the complete sample to the axis of rotation, are located on top of the rotation stage. Motion in X, Z and occasionally tip/tilt are used for this type of alignment. Once the sample is aligned to the axis of rotation, these stages are held stationary during the imaging process.

Alignment Stage Requirements

The alignment stages perform an initial alignment of the sample relative to the x-ray beam and detector. Mechanical resolutions on the order of 100's of nanometers or single-digit micrometers are generally sufficient to perform this alignment. However, once aligned, these stages must hold that position to a very high level of stability (single-digit nanometers) while the experiment is performed.

As discussed in the paper *Minimum Incremental Motion and Holding Stability in Beamline Positioning*, direct-drive and screw-driven servo and stepper motor stages can achieve nm-level in-position jitter and holding stability. However, care must be taken to ensure the heat produced by the motor does not adversely affect performance over longer (minute-level) time periods. Even though the holding currents in stepper motors can be reduced to zero once the axis is aligned, the high-current levels used during the alignment motion may cause thermal drift during the experiment. Linear and rotary servo motors with modern digital amplifiers generally perform the best in terms of both short-term (seconds) and long-term (minutes or hours) stability.

In addition to the stages' holding stability, high mechanical static and dynamic stiffness are crucial to achieving nm-level imaging performance. Therefore, it's necessary to implement good design practices like minimizing the number of stages stacked together; using larger and stiffer stages at the bottom of a stack; minimizing stage weight and height; and/or using parallel kinematic designs.

Figure 2 shows an example of a 6-axis hybrid parallel and serial structure used for sample manipulation in a beamline application. The three alignment motions are Y, Z and a rotation about the Z-axis (roll). Roll motion can be accomplished by controlling Y1 and Y2 differentially. Synchronizing commanded motion to Y1 and Y2 causes the sample to move in the y-direction. This approach results in a compact design with high-stiffness.

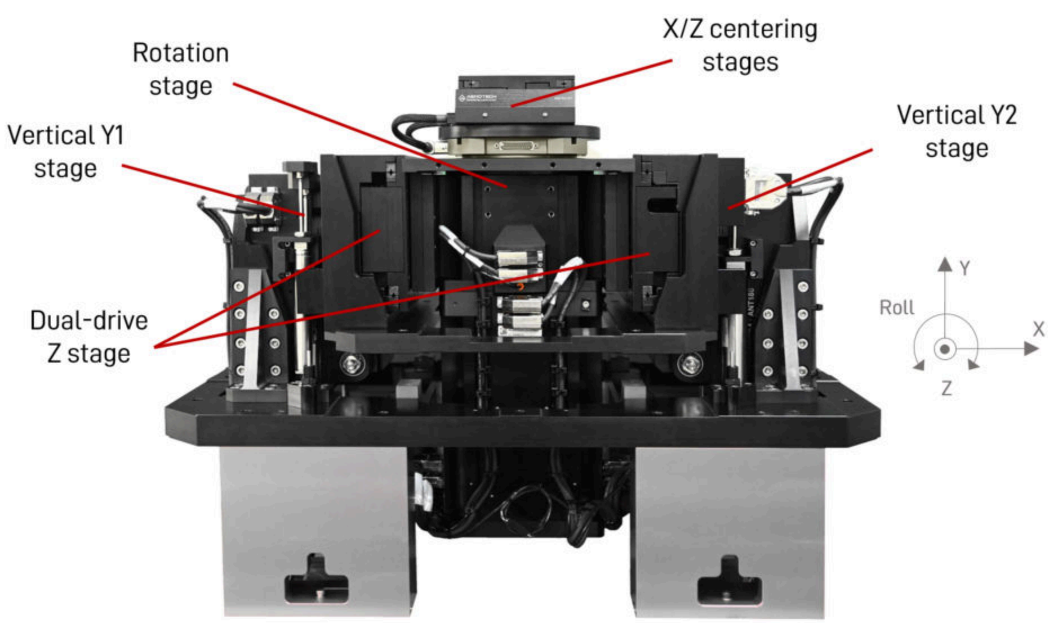

Figure 2. *6-axis hybrid parallel and serial kinematic structure used for beamline sample manipulation.*

Alternatively, a hexapod can be used for the alignment axes. The advantage of this approach is that it accomplishes alignment motion in all six-degrees of freedom and in a compact system package. However, travels are typically limited to 10's of mm's of linear motion and 10's of degrees of rotational motion. Figure 3 shows a hexapod with a rotation stage positioned on top.

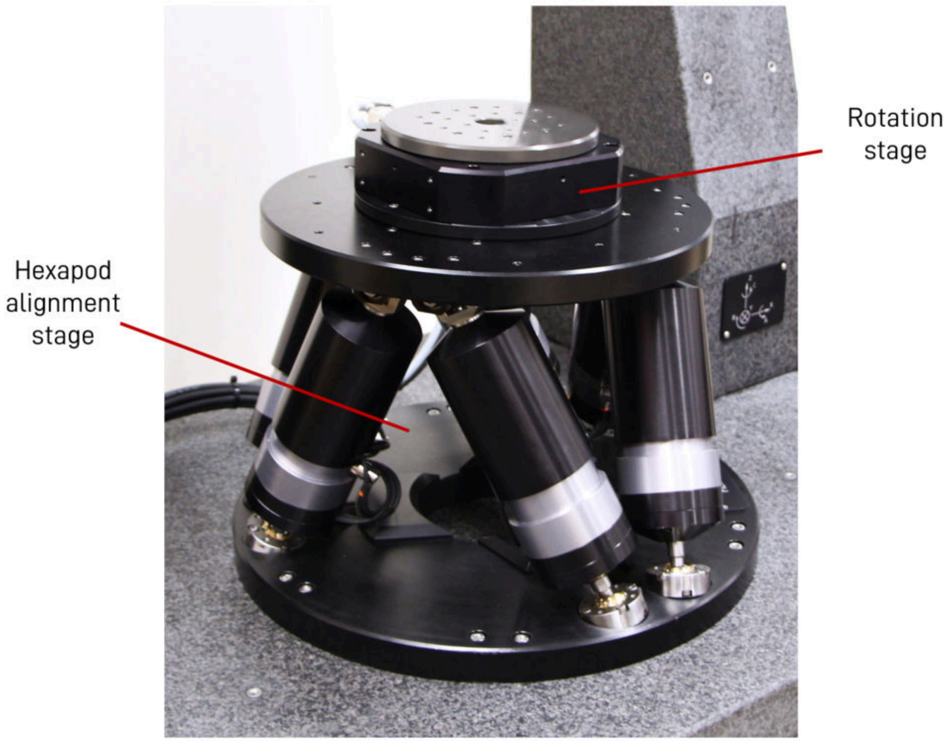

Figure 3. *Aerotech's HEX500 hexapod with a precision rotation stage mounted to the moving platform.*

Rotation Stage Requirements

A rotation stage that has good error motion performance is absolutely critical to obtaining high image quality in nanotomography applications. In most cases, the rotary stage is an air bearing design, which minimizes synchronous (repeatable error motions from revolution to revolution) and asynchronous error motions (error motions that do not repeat from revolution to revolution).

To characterize the error motions of the rotation stage, a precision-lapped spherical artifact with a roundness of < 5 nm is mounted to the rotation stage. A high-resolution capacitance sensor targets the artifact as the stage rotates over multiple revolutions. Data are collected and post-processed to determine the radial and axial error motion performance of the rotation stage.

Figure 4 shows axial and radial error motions measured on an Aerotech ABRX250 stage at 60 rpm at a height of 65 mm above the tabletop. A high-quality air bearing rotary stage like the ABRX-series can achieve sub-25 nm error motions and is commonly used for ultra-high resolution tomography experiments.

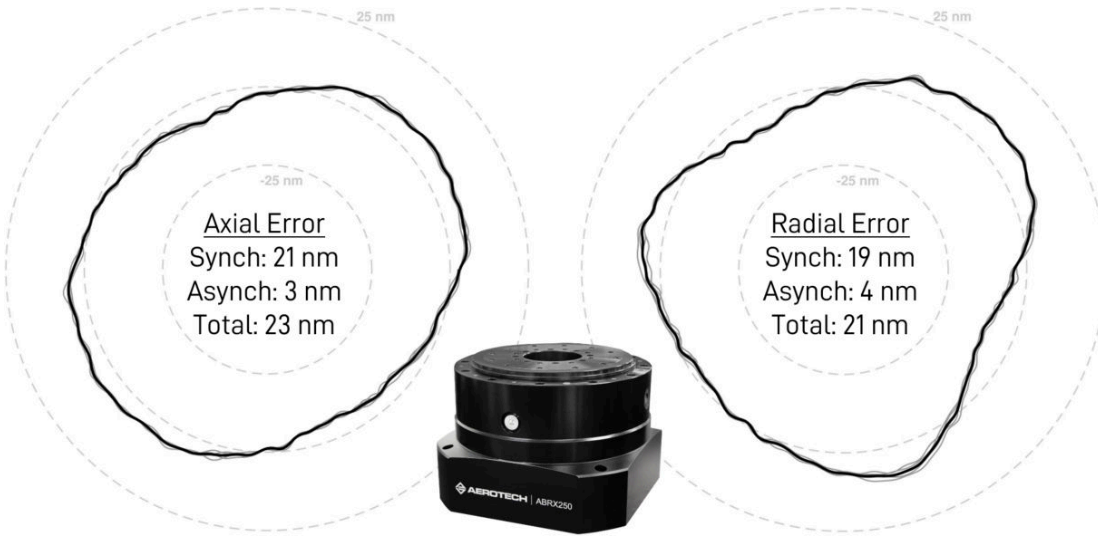

Figure 4. *Axial and radial error motion plots measured on an ABRX250 rotary air bearing stage at a height of 65 mm above the tabletop and at 60 rpm.*

As previously discussed, it is common for the rotation stage to carry centering and alignment stages for aligning the sample to the axis of rotation. Since continuous rotation is necessary, the centering stage motor power and feedback signals are typically transferred through a slip ring located inside of the rotation stage. The rotary stage design and slip ring interface must be optimized specifically to minimize radial forces that would cause an increase in error motions.

In tomography applications, it is also quite common to have the measurement point located at distances of 100 mm or more above the rotation stage tabletop due to the need to provide other instrumentation and process control mechanisms at the sample (e.g. cryogenic cooling). While these larger distances become necessary for packaging, they can have an adverse effect on the error motion (or sphere-of-confusion) tolerance due to the tilt error motion of the rotation stage.

Finally, higher rotation speeds are critical in ultra-high resolution tomography experiments in order to achieve the desired experimental throughput.

Table 1 shows the results of error motion testing on a custom ABRX250 rotary stage with a slip ring at various speeds and heights above the tabletop.

Table 1. *Total axial and radial error motion results from an ABRX250 rotary stage with a slip ring at 60 rpm, 120 rpm, 350 rpm and two different measurement heights (65 mm and 230 mm).*

Speed	Total axial error motion	Total radial error motion @ 65 mm height	Total radial error motion @ 230 mm height
60 rpm	19 nm	26 nm	26 nm
120 rpm	19 nm	26 nm	28 nm
350 rpm	21 nm	36 nm	41 nm

The results in Table 1 illustrate the very low error motion capabilities of a well-designed, ultra-high resolution tomography rotation stage. In this particular example, a sphere-of-confusion of <50 nm is achieved at a height of 230 mm above the rotation stage table. Lower tomography measurement heights would result in an even lower sphere-of-confusion.

Centering and Aligning Stage Requirements

The centering and alignment stages are used to align the sample on the rotary stage axis of rotation. These stages must have minimum incremental motion capabilities below 50 nanometers. Once the sample is centered and aligned, the stages must hold that position to a few nanometers while rotation occurs, as any motion will cause imaging errors. Finally, maintaining a small overall height keeps the sample as close to the rotary stage tabletop as possible for the reasons discussed above.

Structural Design

The structural path, or structural loop, in a beamline tomography experiment is typically quite long. Any unwanted relative motion that occurs between the beam, sample and detector will show up as an image error. The following design practices will minimize this relative motion:

- Minimize motion stage stack heights;
- Keep the overall design path length as short as possible;
- Design high-stiffness fixturing for the detector, sample and other instrumentation;
- Minimize and/or isolate vibrations where possible; and
- Select high-quality motion equipment with high static and dynamic stiffness.

Data Acquisition and Control

Since rotation stages must rotate continuously and at high speeds, it is critical to have a motion control system that can synchronize data collection of the image while continuously scanning. Ideally, these triggering events will occur off the position feedback of the rotation stage or other motion axes with low-latency to allow easier image recreation in post-processing. Tools like Aerotech's Position Synchronized Output enable this type of data collection while maintaining high image fidelity.

Summary

Precision motion control for sample manipulation is critical to achieving good imaging results in ultra-high resolution tomography applications. While selecting good motion control components is essential, other aspects like good structural design and high-speed, synchronized data acquisition are also required. By taking a system-level design approach to all elements – including precision motion – experimental success is more readily achieved.

About the Authors

Brian O'Connor is the vice president of marketing at Aerotech, where he oversees global business development, product management and marketing communications. In nearly 20 years with Aerotech, Brian has held multiple technical and business leadership roles and holds three patents for designs used in Aerotech products. He is also an active member of the American Society for Precision Engineering (ASPE), serving on the executive committee from 2019-2021 and as president in 2020.

Chris Charlesworth, Aerotech's European control systems specialist, manages the control systems business and provides application support for controls components. Chris previously worked in a variety of automation roles, including 4.5 years working at the UK's synchrotron where he was responsible for the design and implementation of beamline control systems with a specific focus on beamlines using tomography and diffraction techniques.

Darrell Paul is an Aerotech business development manager with 20+ years of expertise in automation and motion control. At Aerotech, he focuses on key precision automation industries such as semiconductor, test and inspection, optics and photonics, aerospace, and advanced sciences.