Measuring mirrors

As part of the armoury of hardware used in steering and focusing high-energy beams in today's synchrotrons, precision mirrors are becoming increasingly important as energy levels continue to rise. This article sets out to explain some of the challenges in designing and building a metrology system to precisely map the surface of these large mirrors, for use at the new National Synchrotron Light Source II site at Brookhaven National Laboratory, Long Island, New York (USA).

In simple terms, a synchrotron consists of a large storage ring where electrons circulate at high energy levels under the control of strong magnetic fields. Each time the electrons are turned by the magnets, they emit radiation which can be directed down one of the tangential beamlines, where the collimated beams are used for a wide variety of experiments. To accurately focus and shape the beam, a series of optical components are used, including long mirrors with both plane and curved surfaces. The requirements on these mirror surfaces are extreme and, with the low incidence angles employed, the surface profiles must be precisely measured. To characterise such surfaces, the Long Trace Profilometer (LTP) was developed; see Figure 1. It's function is to scan the reflecting surface of mirrors up to 1,500 mm long, measuring their slopes to better than 0.1 microrad.

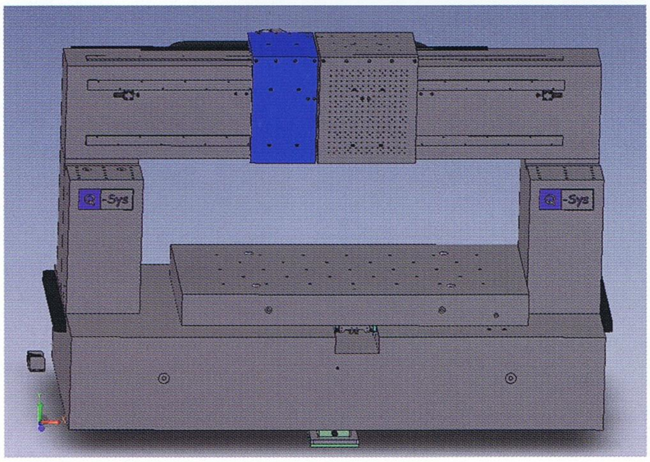
Figure 1. Design of the LTP.

Scanning options

The techniques for scanning these reflective surfaces have been developed and refined over recent years and one method involves exploring the surface with a pair of laser beams and recording the surface slope. These beams must be scanned over the entire mirror surface, generally in a raster-scan type pattern. Directed down through a pentaprism to aim them directly onto the mirror surface, the beams are moved along a straight scan path, either in step-by-step mode or in a constant speed traverse. The mirror is then indexed sideways, perpendicular to the scan path and the next line scan is performed. This is repeated across the entire area of interest and the returning data is used to create a complete computer model of the mirror surface.

Editor's note

This article was contributed by Q-Sys, based in Helmond, Netherlands. Q-Sys designs and builds precision motion and positioning systems for various markets.

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to the max

Step-by-step scanning means the motion system must be able to acquire a new target position and settle to a 'quiet' state in a reasonable time, while constant-speed sampling requires a very steady, vibration-free movement to enable good data capture on-the-fly. Generally speaking, motion systems are optimised for one or other of these two types of motion – this system, however, must be capable of excelling at both. Also, with the laser source and measuring equipment being mounted in fixed positions, the resulting optical path is very long, potentially 3 m or more. The effect of this is that an angular error of just 5 microrad can introduce an uncertainty in position of up to 15 microns. As a result the angular performances of the motion stages – particularly repeatability and stability – are of paramount importance.

Motion platform

The LTP bench designed by Q-Sys consists of a split-axes XY motion platform, with the main structure constructed from precision granite pieces; see Figures 1 and 2. The mirrors to be measured are anything up to 1,500 mm long, with a mass of up to 150 kg in their holding supports. The lower axis of the platform is used to position the mirror and hold it precisely in position during the measurement process. It needs to be stable to better than 0.15 micron during the scan and is also used to step the mirror position beneath the flying optics. The upper axis carries these optics over a travel of 1,500 mm and must have minimal angular errors over this travel range, combined with the capability to deliver point-to-point and constant speed movement profiles. A further complication is that the optics payload and associated components may be anything up to 20 kg. Mounted to the front face of the carriage, this constitutes a cantilevered load introducing unwanted angular forces that must be restrained by the bearing arrangements.

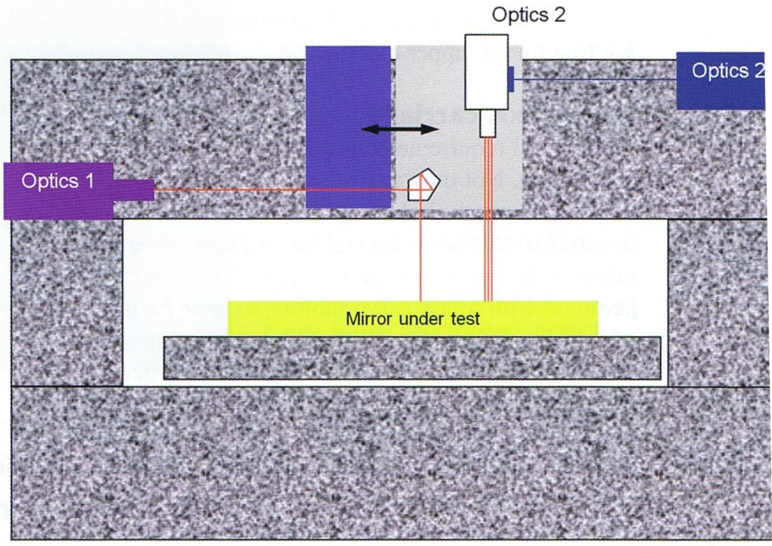

Figure 2. Set-up for scanning a mirror surface, with the lower axis carrying the mirror and the upper axis carrying the optics.

Lower axis carriage

The final design for the system employs air-bearings for lift and guidance on both axes. The lower axis carriage consists of a single granite block with four air-bearing pucks for lift; see Figure 3. These in turn bear on prepared surfaces on the main granite base plate. A gully in the base plate accommodates the linear motor and optical encoder components, together with additional air-bearing pucks that restrain and guide the carriage along a straight path. The combination of the location of the linear motor and the precision of the walls of the gully ensures the motion of the lower carriage has minimal straightness and yaw errors. As the carriage is never moving during the scanning process,

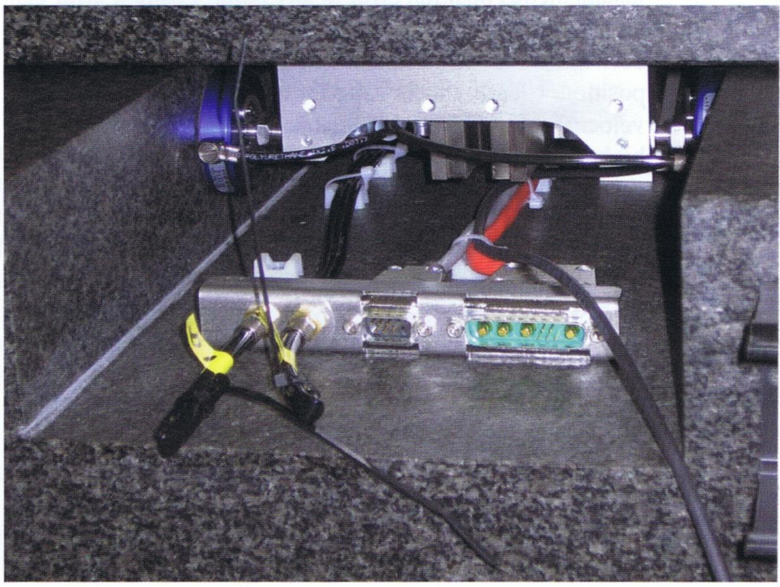

Figure 3. The underside of the lower axis carriage, with guidance air-bearing pucks mounted.

the principal requirements on its performance are for accuracy and repeatability of positioning. This of course is not true for the upper carriage.

Upper axis carriage

The motion requirements for the optics axis are particularly demanding. Not only must the linear positioning of the carriage be precisely known, but – as mentioned above – its angular stability is crucial and it must also be able to move with near-zero velocity ripple. Linear motors, in common with rotary servo motors, exhibit cogging as part of their characteristics. While the use of ironless motors reduces this, the effect is still noticeable, particularly at these levels.

While specifications for speed control are often defined in terms of velocity stability, in practice this is a very difficult parameter to define. Since velocity is a time-based variable, a measurement of variations will also be time based. However, very short or long variations in actual velocity can result in quite different results depending on the time period of averaging. In reality, a time period can always be chosen to portray the error in the manner desired, be it good or bad. Such manipulation must devalue the final answer.

For this reason, it was decided that the only meaningful definition for velocity variation is to measure the instantaneous position error at any point. Position error can be measured at any time and represents the difference between actual position and commanded or expected position. Clearly this is valid for both position control and velocity control, provided the bandwidth of the sampling is high enough to show cyclic variations. In this way, velocity ripple can be displayed and analysed to gauge its effect on the overall system.

With the optics carriage being an L-shaped construction, it is impossible to locate the centre of force from the motor in line with the centre of mass. The Q-Sys design has the motor mounted in the upper section of the carriage while the user mass, made up from various optical components in different configurations, will generally be lower down. This means the motor can introduce torques to the carriage, which are clearly undesirable for such an error-sensitive part of the system.

For this and other reasons, the moving part of the upper axis is actually designed as a split-carriage. One section carries the linear motor, velocity feedback encoder, electrical and air connections etc., while the second section is a free-running carriage with solely the guidance and lift air-bearings and their respective supply pipes. This second carriage will carry the user optics, in whatever configuration appropriate for the measurements being made. It is connected to the motor carriage by a carefully designed flexure link, which is stiff in the axis of motion but flexes under the effect of any other linear or axial forces. This link enables the two parts of the carriage to move along the axis as one but isolates the optics carriage from as many undesirable disturbances as possible. The optics carriage is fitted with its own encoder readhead, so the point of measurement is as close to the point of interest as possible.

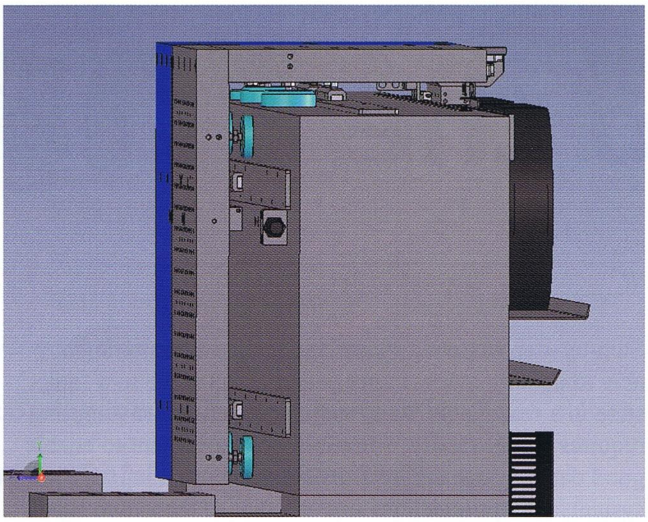

Figure 4. Sideview of the upper axis carriage, showing the guidance air-bearing pucks.

Both parts of the upper axis carriage are supported and guided by air-bearing pucks, with the lapped granite beam providing the flat bearing surfaces; see Figure 4. These bearings use magnetic pre-load to maintain them at the correct flying height. Pre-loading the bearings in this way provides a high stiffness support that introduces no cyclic disturbances as the carriage moves – which is essential. This is further complemented by the use of linear amplifiers to drive the system axes, ensuring no undesirable harmonics are injected into the system.

Result

The final result, see Figure 5, is an excellent demonstration of the benefits of custom system design and build – a bench capable of positioning a large, 150kg payload precisely beneath a set of flying optics and completing high-accuracy measurements reliably and repeatably. Previous systems in this family have yielded measurements of slope error down to 50 nanorad with a noise level of just 15 nanorad – this latest bench is expected to at least reproduce this level of performance.

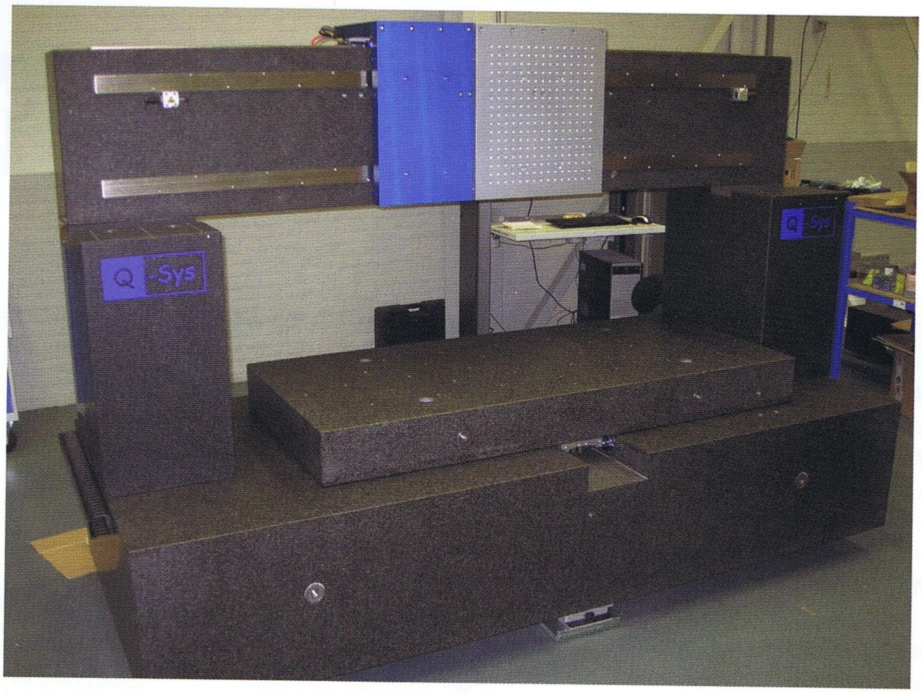

Figure 5. The optical bench nearing completion.

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Leidse Instrumentmakers School (LiS) in search of new

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The Leidse Instrumentmakers School (LiS, www.lis-mbo.nl) is inviting applications for a senior engineering teacher to take over from the current incumbent who is retiring.

Anticipated starting date: 1 January 2013

Professional Profile:

Knowledge, skills and background:
- Educational level at least Bachelor of Engineering, preferably Master level
- Proven capability to conceive, design and build high tech precision instruments, and broad understanding of disciplines related to engineering
- Familiarity with sensors, actuators, electronics (digital and analogue) and photonics
- Has education degree (at least second degree) or will achieve this within two years
- An education degree to teach bachelor level engineering is preferable, must at least have demonstrable willingness to pursue this

Required competences:
- Very good communication capabilities, at least in the Dutch and English language
- Results orientated
- Analytical mind ; capable of combining applied science and engineering with practical instrument building
- Has an extensive personal network that is aligned to the professional needs of the LiS