INSTITUTE OF PHYSICS PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **16** (2005) N19–N23 doi:10.1088/0957-0233/16/7/N01

DESIGN NOTE

Design of a non-magnetic high-accuracy linear translator for use in vacuum systems

Andrew James Murray, Martyn J Hussey and Alan Venables

Schuster Laboratory, The University of Manchester, Manchester M13 9PL, UK

E-mail: Andrew.Murray@manchester.ac.uk

Received 2 March 2005, in final form 7 April 2005
Published 26 May 2005
Online at stacks.iop.org/MST/16/N19

Abstract
A linear translator which employs no bearing lubricant and which can be used inside vacuum systems is described. The translator has been designed to accurately position an electron energy analyser within a new low-energy electron spectrometer, and so is constructed completely from non-magnetic components which are also UHV compatible. The translator uses a novel design combining a two-wedge displacement bearing which drives a translator constrained by a linear bearing. As such, the design is easily modified to provide very high translational accuracy by varying the wedge angle. In the present design, the deviation from linearity as a function of displacement has been determined to be less than $\pm 4\ \mu\text{m mm}^{-1}$ using laser interferometric techniques.

Keywords: in-vacuum translator, electron spectrometer, xyz-translator, vacuum component

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1. Introduction

There is a continual need for accurate positioning of components located inside vacuum chambers. Commercial systems exist for this purpose, but these almost always use a vacuum bellows coupling the component to an xyz-translator located outside the chamber [1, 2]. Whereas this is a successful solution in many applications, these translators are expensive and the movement is restricted by the flexibility of the bellows. For many experiments, it is necessary to align internal components independently of the chamber flanges, and so these methods cannot be used. As an example, within an electron spectrometer it is often required to rotate an electron gun or electron energy analyser around a central interaction region, whilst ensuring that the gun and analyser always point towards the centre [3–5] (see figure 1). In this case, it is necessary to accurately position these components on the rotating turntables, the most flexible method employing accurate xyz-translators as shown.

Since the internal xyz-translator must be vacuum compatible, commercial translators as available for optics experiments cannot be used [6, 7]. The main restriction arises due to the lubricants used in the linear bearings of these translators, which outgas when under vacuum. A further restriction may arise due to the magnetic materials used in these commercial translators (e.g., steel ball or roller bearings). For high-resolution electron spectrometers these materials cannot be tolerated as all internal magnetic fields must be eliminated.

To provide a solution to this problem, a new xyz-translator was designed and detailed in a previous publication [8]. This translator used all non-magnetic components, thereby satisfying the exacting requirements for use in electron spectrometers. The design further solved the outgassing problems presented by commercial optical components by

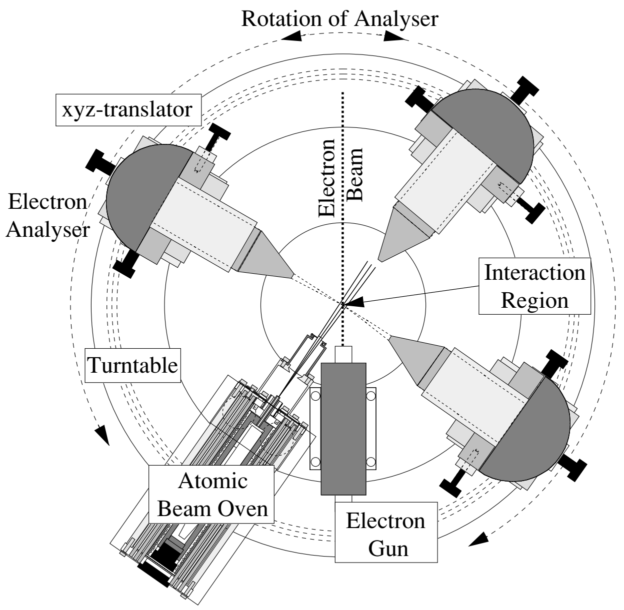

Figure 1. Requirement for accurate xyz-translation in an electron spectrometer. The figure illustrates an application of the translator to a new experiment which measures the count rate of electrons superelastically scattered from laser-excited atoms emitted from an oven. In this experiment, the electron gun and atomic beam oven are fixed, the laser is input perpendicular to the plane of rotation and the electron analyser rotates on a turntable around the interaction region. Three different positions of the analyser are shown to illustrate this movement. All components have to be directed towards the interaction region with an accuracy of ~0.1 mm.

completely eliminating any lubricants. This was accomplished by using ground and polished ceramic rods for the bearing housing [9], while adopting highly polished ruby balls with a tolerance of ± 5 μm for the bearings [10].

In the new vacuum compatible translator detailed in this paper, a combination of double-wedge drive system and linear bearing is adopted as shown in figure 2. This more complex drive mechanism provides two advantages over the previous design. Firstly, the axis of the adjustment screw no longer lies along the direction of the translator's motion, but rather lies orthogonal to this direction. This has the advantage that the adjusting screw does not impinge on the component fixed to the translation table. The second advantage is that the sensitivity of the drive mechanism to rotation of the adjustment drive screw can be varied by changing the wedge angle. In the design presented here, the wedge angle has been chosen to be $\tan^{-1}(1/3) = 18.43°$. Hence, for every 1 mm displacement of the wedge, the linear translation table moves 0.33 mm. The adjustment screw has a pitch of 40 threads per inch, and so the resolution limit of the translator table as a function of the screw rotation angle is 0.59 μm/degree. This is equivalent to a direct drive pitch of 120 threads per inch. The novel combination of wedge and linear bearing ensures that the resolution of this translator exceeds all current commercial designs used in optics, which use actuators with 40–100 threads per inch.

2. Design of the translator

As with the previous design of an in-vacuum translator [8], the range of materials that can be used for construction of the present design is restricted. 310-grade stainless steel was adopted for the translator housing and table, as this has the lowest magnetic susceptibility of all 300-series stainless steels. A further advantage of this grade of steel is that the surface does not oxidize after repeated exposure to air, and so remains conductive when electrons within an electron spectrometer impact onto the surface. Surface contamination of the steel will create uncontrolled electric fields within the spectrometer due to these stray electrons, and so contaminants are removed by adopting clean working practices when the system is open to air, and by baking the chamber when under vacuum.

Other materials used in construction of the translator are phosphor-bronze for the bearing race, beryllium–copper wire for the springs, ceramic and ruby. Phosphor-bronze is used as it is non-magnetic and is hard wearing, whereas beryllium–copper can be used to manufacture non-magnetic springs with simple preparation in an oven, as detailed in [8] (*it should be noted that in this reference the springs were incorrectly stated as being manufactured from phosphor-bronze*). The bearings are constructed using ground and polished ceramic rods [9] together with ruby balls [10]. These materials are used as their hardness and finish allow the bearings to operate without lubrication. Ruby balls manufactured to exacting tolerances are available in a range of diameters from different manufacturers, whereas ground ceramic rods come in a range of lengths and diameters and are available widely. All materials used in the translator are UHV compatible, with outgassing rates less than 5×10^{-12} Torr l s^{-1} cm^{-2}.

The design of the new translator is shown in figure 2. The translator is based on the proven design detailed previously [8], and which has been operating inside a number of spectrometers in Manchester for more than two years. The L-shaped baseplate of the translator (A) is machined from 310-grade stainless steel which can be secured to the vacuum chamber via a number of M3 counter-bored clearance holes in the bottom of the plate. A 10 mm diameter hole is located 14 mm from the top side of the baseplate to allow light from an alignment laser beam to pass, should this be required. The top side of the baseplate is machined to allow the spring guides and retaining plate to be centrally located.

310-grade stainless steel side arms (B) are secured to the baseplate using three M2 screws. One of the side arms uses clearance slots so as to firmly secure the bearings upon assembly, whereas the other side arm is accurately positioned onto the baseplate using phosphor-bronze dowel pins. Within the side arms are located two ground ceramic rods (C) which act as the stationary bearing cage. Ground and polished ceramic rods are used as the primary bearing surface since this eliminates the need to grind the internal section of the side arms. The hardness of the ceramic rods also makes them resilient against wear from the 5 mm ruby balls (D) used in the linear bearings.

The translator table (E) is also constructed of 310-grade stainless steel, and is machined to have a 1 mm clearance gap from the baseplate. The sides of the slide are constructed in the same way as the side arms, so that ceramic rods again act as the primary bearing surface. Eleven M3-tapped holes are arranged in an array on the table so that components can be secured to the slide. A 10 mm diameter hole is also located in the slide to allow laser beams to pass through both the baseplate and slide, should this be necessary.

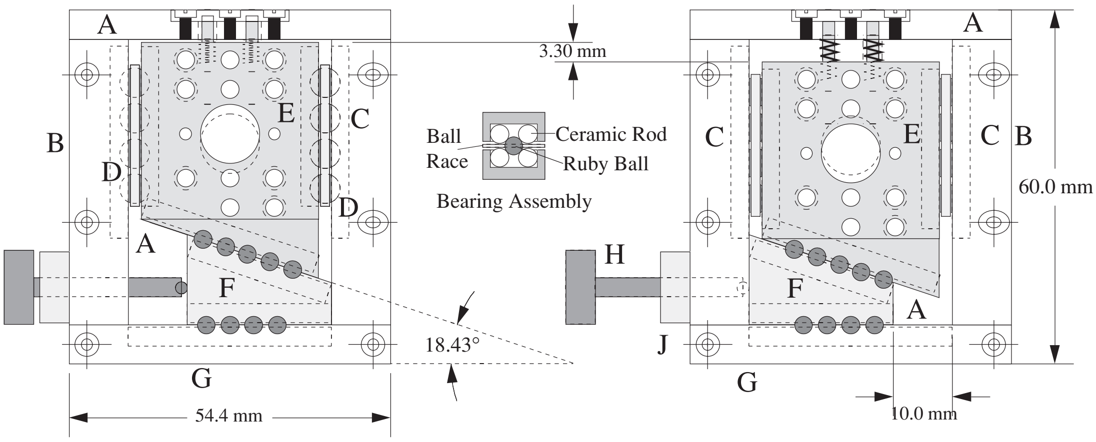

Figure 2. The new translator which uses a combined wedge drive assembly and linear bearing. The two extreme positions of the wedge and sliding table which drives in the $\pm z$ direction are illustrated. The inset shows the bearing assembly constructed from four ground and polished ceramic rods together with highly polished ruby balls. For details, see the text.

The slide is machined to have end plates so that the $1/8''$ ceramic rods are secured within the slide once the translator is assembled. This is necessary to ensure the rods remain stationary relative to the slide during translation. The top section of the slide is machined orthogonal to the sides, whereas the bottom of the slide is machined at an angle of 18.43° as shown. The bottom of the slide is further machined to locate and secure two additional $1/8''$ ceramic rods which act as the cage for the top bearing of the wedge assembly (F).

Centrally located blind holes of diameter 3.3 mm are machined 9.75 mm into the top of the slide to locate two beryllium–copper springs. These springs are axially constrained by two 2 mm diameter phosphor-bronze guides secured by the baseplate as noted above. The springs provide the restoring force to the translator table as it moves, and are constructed from 0.5 mm diameter wire as detailed in [8].

The wedge drive mechanism (F) is again constructed from 310-grade stainless steel, and is machined to retain four $1/8''$ ceramic rods which act as lower and upper bearing surfaces for the wedge bearings. Both bearings of the wedge are constructed using 3 mm diameter ruby balls which are separated by a phosphor-bronze ball cage. Five ruby balls separated by 1 mm are used for the top bearing, whereas four ruby balls separated by 1.33 mm are used for the bottom bearing. This ball separation ensures that the load from the wedge to the slide is distributed evenly as the wedge moves horizontally.

A guide plate (G) for the lower wedge bearing is fixed to the baseplate via 3 mm screws, the guide plate being accurately located again using phosphor-bronze dowels. The drive screw (H) is constructed from 310-grade stainless steel which is coated with graphite [11] before being screwed into the phosphor-bronze nut (J). The nut is fixed to the dowelled side plate using a 1.6 mm A4-grade stainless steel grub-screw. The drive screw (H) has a 2 mm ruby ball inserted into its end so that only a single point of contact is made between the ball and the wedge. Dissimilar metals are used for the drive screw and nut to prevent vacuum welding at the interface. The screw and nut use a fine pitch of 40 threads per inch to allow accurate movement of the wedge and slide when the screw is rotated. The use of graphite helps the screw to drive more smoothly, however if graphite cannot be tolerated in the vacuum chamber, this can be eliminated without any reduction in the capability of the translator.

Adjustment of the position of the translator slide is accomplished by rotating the drive screw, thereby driving the wedge in the horizontal direction. As the wedge moves horizontally a given distance x, the translation table is constrained by the linear bearing to move vertically a distance $x/3$. The wedge can move a distance of 10 mm in the present design, and so the translator table moves a distance of ~3.3 mm.

The translator side bearings comprise two sets of four 5 mm diameter ruby balls (D) which are separated from each other by 1 mm using a phosphor-bronze ball race. Since the balls rotate on the ceramic rods located in both the side plate and slide, the ball-race assembly moves half the distance of the slide. By using four equally spaced 5 mm diameter balls on either side, the slide travels its full displacement while maintaining continuous and uniform contact between the balls and ceramic rods.

The load which the translator can bear has been tested by hanging a 15 kg weight from the slide while translating the slide using the adjustment screw. The load was applied in five different directions ($\pm x$, $\pm y$ and $-z$ as shown in figure 2), and the translator was found to operate smoothly under all conditions. The $+z$ direction was not tested as this would have dis-engaged the translator table from the wedge. The translator will operate with higher loads, however it is unlikely that any instrument requiring accurate adjustment inside the vacuum chamber will exceed this weight.

The translator is designed so that it can be used individually, or assembled as an xy- or xyz-translator using two or three translators together. M2 clearance holes in the baseplate allow one translator to be secured orthogonally to the slide of a second translator, making an xy-assembly. A third translator can then be secured in the z-direction using screws which pass up through the slide in the y-translator to locate into the tapped holes in the bottom bearing guide plate (G).

3. Assembly of the translator

Although the translator is quite complex, assembly is relatively straightforward. After cleaning in an ultrasonic bath, all components are inspected to ensure no residue remains on the ceramic rods and ruby balls that make up the bearings. The fixed side arm is then attached to the baseplate, the spring guides are inserted and the springs located into the slide. The baseplate is turned onto its side, the ceramic rods, ruby balls and ball race are located into the fixed side plate and the slide positioned so as to hold the ruby balls in place. The second set of ruby balls, ball race and ceramic rods are positioned in the opposite side of the slide and the adjustable side arm located to constrain this bearing assembly. The translator is then placed horizontally and the adjustable side arm is fixed to the baseplate. The slide is then moved to its top position (maximum compression of the springs) and the ceramic rods and ruby balls adjusted so as to locate correctly within the slide and side arms, ensuring free movement of the bearing. The adjustable side arm is re-positioned to eliminate any sideways movement in the slide, and is finally secured to the baseplate.

With the slide firmly held in its top position the translator is positioned so as to locate the ceramic rods, ruby balls and ball race into the bottom slide bearing. The four ceramic rods in the wedge are secured to the wedge using thin wire, and the wedge is positioned so as to hold the upper bearing assembly between translator and wedge. The balls and ball race for the lower bearing are then positioned, the ceramic rods in the bottom plate are secured to the plate again using thin wire, and the bottom plate is placed against the lower bearing ruby balls so as to secure them. The wires holding the ceramic rods in the bottom plate are removed, whilst ensuring that the balls and ceramic rods do not fall out. The bottom plate is then secured to the baseplate using 2 mm screws. Finally, the wire holding the ceramic rods within the wedge are removed (this is possible as the wedge sits 1 mm from the baseplate), and the slide is released from its upper position so as to thrust onto the wedge. The drive screw is then screwed into the nut and the mechanism checked to ensure that both the wedge and the slide move freely back and forth along their respective bearings.

It should be noted that all tapped holes in the translator are through holes, and all screws used in the assembly of the translator are filed flat on one side. This ensures that no trapped gas volumes are left in the assembly once the translator is installed inside the vacuum system.

4. Accuracy of translation

To test the accuracy of the translator a Michelson interferometer was built with one of the mirrors in the interferometer fixed to the moving slide. The drive screw was then rotated using a synchronous dc motor and fringes from a helium–neon laser ($\lambda = 632.8$ nm) were counted as a function of the angle of rotation. The displacement was determined by counting the laser fringes as a function of the drive screw angle, which was measured by a rotary encoder connected directly to the drive shaft. The encoder produced 256 TTL pulses for each 360° of rotation, these pulses being fitted to a linear function between consecutive pulses to determine the angle between encoder pulses. The interferometer fringes were detected using a photodiode and amplifier of high gain so that the fringe pattern was approximately a square wave. This signal was then connected to an analogue to digital card inside a PC, and the signal was accumulated as the drive screw rotated. The position of the fringe was ascertained by differentiating the measured signal to determine the slope of the waveform, the positive slopes being counted. An increment of 1 fringe was equivalent to a displacement of $\lambda/2 = 316.4$ nm, allowing the total displacement to be determined.

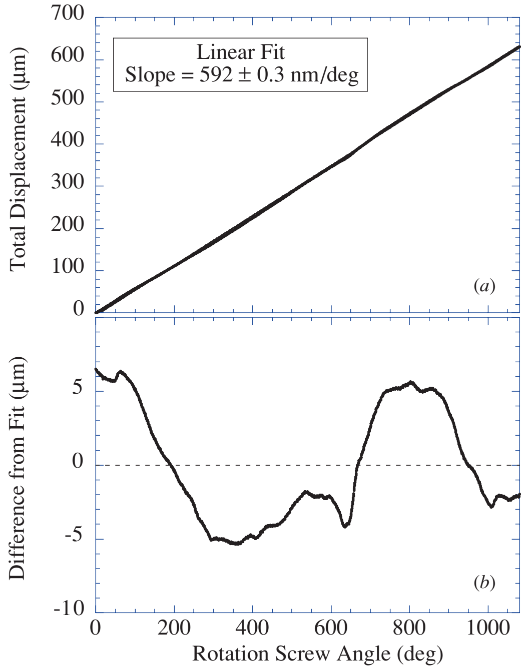

Figure 3. Results from movement of the translator slide within a Michelson interferometer using a helium–neon laser. The angle of the drive screw was measured using a digital rotary encoder, whereas fringes were counted using an edge detector. The displacement was determined to be 0.592 μm/degree of rotation of the drive screw using a linear fit to the data (*a*). The deviation from linearity is also shown over the displacement of 0.64 mm, equivalent to 1080° rotation of the drive screw (*b*).

The results of these measurements are shown in figure 3, where both the total displacement as a function of drive screw angle (*a*) and the deviation from linearity (*b*) are shown. A linear slope fitted to the data indicates that the translator moves 0.592 μm/degree, which is in excellent agreement with the expected value discussed above. The deviation from linearity is seen to be less than ± 5 μm over the displacement of $\sim$0.64 mm (three turns of the drive screw) which was measured. The standard deviation for this variation is ± 3.75 μm over this distance, equivalent to an uncertainty of less than $\pm 0.6\%$ from linearity with respect to the drive screw rotation angle.

The variation from linearity which is observed is probably due to inaccuracies in manufacture of the drive screw, as well as small variations in the linear bearing between the wedge drive and the translator table. Clearly for displacements over small angles, the translator is capable of very high accuracy. For larger displacements the distance that the slide moves can be determined directly from the drive angle with an uncertainty in the position of less than $\pm 0.6\%$.

5. Conclusion

A new high-accuracy linear translator has been built to position internal components inside vacuum systems. The translator uses a novel design which combines a linear bearing displaced by an adjustable twin-wedge drive. The assembly uses non-magnetic materials which are readily obtainable, does not require high-accuracy machining or grinding of parts and can be made in any standard mechanical workshop. The bearings use ground ceramic rods and ruby balls to ensure smooth operation without the need for lubrication. The translator has been tested at vacuum pressures down to 2×10^{-8} Torr, and is expected to operate equally well under UHV conditions since it can be baked at temperatures up to 200 °C. Movement of the translator as a function of the drive screw rotation angle has been determined using laser interferometer techniques to be 0.592 μm/degree.

It is expected that this translator will find many applications inside vacuum chambers ranging from electron spectroscopy through to surface science experiments, where accurate and reproducible alignment of internal components in the vacuum chamber is essential. The novel design of the translator should also find applications in many other fields where accurate displacement is required, since the combination of wedge drive and linear bearing allows greater accuracy than any commercial direct drive system currently available.

A complete set of CAD drawings are available for the translator as a pdf file by linking to the electronic version of this article.

Acknowledgments

The Engineering and Physical Science Research Council, UK, is gratefully acknowledged for providing funding for this work. Mr John Rowcroft is thanked for supplying the full CAD drawing and Mr John O'Hara in the mechanical workshop of the Schuster Laboratory is thanked for manufacturing the components.

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