Absolute angular positioning in ultrahigh vacuum

Hansjörg Schief, Vittorio Marsico, and Klaus Kern
Institut de Physique Expérimentale, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

(Received 7 November 1995; accepted for publication 10 January 1996)

Commercially available angular resolvers, which are routinely used in machine tools and robotics, are modified and adapted to be used under ultrahigh-vacuum (UHV) conditions. They provide straightforward and reliable measurements of angular positions for any kind of UHV sample manipulators. The corresponding absolute reproducibility is on the order of 0.005°, whereas the relative resolution is better than 0.001°, as demonstrated by high-resolution helium-reflectivity measurements. The mechanical setup and possible applications are discussed. © *1996 American Institute of Physics.* [S0034-6748(96)02804-2]

I. INTRODUCTION

The precise sample positioning in ultrahigh vacuum (UHV, 10^{-11} mbar$<p<10^{-9}$ mbar) is usually based on the application of commercially available (or homemade) mechanical motion feedthroughs. The corresponding resolution and reproducibility[1] is mainly determined by the design principle, the mechanical backlash, and the kind of motorization. For step-motorized rotary drives—according to the supplier specifications—the resolution and reproducibility usually amount to about 0.01° to 0.1° and 0.05° to 0.5°, respectively. But in practice these values are often not achieved and no precise control of the absolute position is provided.

The situation becomes more difficult when so-called secondary rotations, such as a second (or even third) axis of rotation at multiaxis sample manipulators are needed. In these cases, the spatial orientation of the second axis varies upon rotation about the first axis of rotation. Rather complicated and less rigid mechanical construction has to be applied in order to couple the secondary rotation inside the vacuum to the corresponding vacuum feedthrough.[2]

Although current angular resolutions and reproducibilities of UHV sample manipulators are satisfactory for most applications, there is an increasing number of experimental methods and modern technologies requiring ultrahigh precision positioning in UHV. Surface sensitive synchrotron x-ray diffraction, for example, requires angular resolutions and reproducibilities of the order of 0.001° and 0.005°,[3] respectively. This precision is routinely achieved in air with classical x-ray or neutron diffractometers consisting of very precise mechanical devices such as rotational tables, angle cradles, and linear translators.[4] Since these devices can carry large weights, they have also been used in surface sensitive x-ray scattering experiments by moving the whole UHV apparatus during a diffraction scan.[5] A second and more promising way to take advantage of these highly precise mechanical diffractometers was to couple their motion into the vacuum by a flexible metal bellows and specially designed rotational feedthroughs.[6] Both solutions require huge mechanical setups and suffer from restricted ranges of attainable angles.

In this article we present a completely different and inexpensive solution to achieve high-resolution angular positioning in UHV. The device is small in size and allows full 360° rotation. Instead of trying to reduce the mechanical backlash we *measure* in vacuum the precise angular position of the axis of rotation with a relative resolution of ~0.001° and an absolute reproducibility of the order of 0.005° (see Ref. 1). This is achieved by commercially available incremental resolvers, as they are routinely used in machine tools or robotics,[7] that we have transformed and adjusted to be used in UHV.

The development of this UHV compatible resolver was instigated by our construction of a novel He-surface triple-axis spectrometer[8] for the study of surface structure and surface dynamics. A detailed description of this apparatus, which is the direct analog to a neutron-triple-axis spectrometer, will be given in a forthcoming publication.[9] In this He-surface spectrometer, high-resolution angular scans in UHV with an absolute reproducibility better than 0.01° at the monochromator, sample, and analyzer surface are required routinely.

Our new type of UHV sample position control has not only substantially increased the quality of He-surface-scattering experiments but could also have a certain impact on any surface science technique requiring high angular resolutions, such as angle-resolved electron spectroscopies or ion scattering. Among the wide range of its potential applications the exact absolute control of synchrotron x-ray monochromator positions is certainly one of the most promising candidates.[10] One might even think about industrial applications such as x-ray lithography at synchrotron radiation facilities.[11]

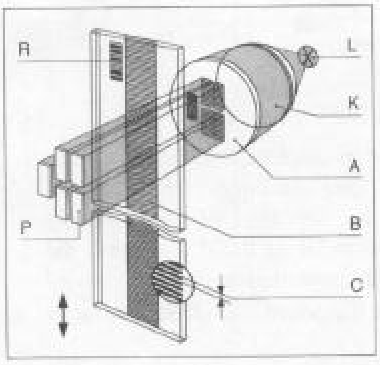
II. THE ELECTRO-OPTICAL POSITION MEASURING TECHNIQUE

Among the various options that can be found on the market, we gave preference to the electro-optical measuring system over methods using light diffraction or induction phenomena because it provides higher resolution combined with greater reliability.[7]

The basic scheme of this method is shown in Fig. 1(a). A detailed description of the method can be found in Ref. 7. A parallel light beam furnished by a special bulb (L) and a condenser lens (K) is directed towards a glass plate (A). This glass plate supports four identical arrays of parallel 1:1 absorption line gratings made by metal evaporation. They pro-

 0034-6748/96/67(5)/2026/4/$10.00

a)



b)

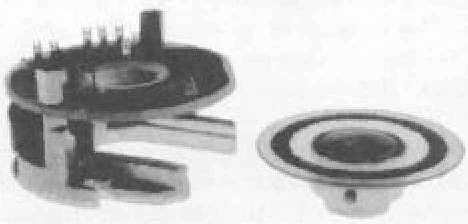


FIG. 1. (a) Schematic design of commercially available resolvers based on the electro-optical principle, (b) photo of the ERO1251 resolver bought from Heidenhain GmbH (Ref. 13). The rotating glass disk is shown off-axis for the sake of better visibility.

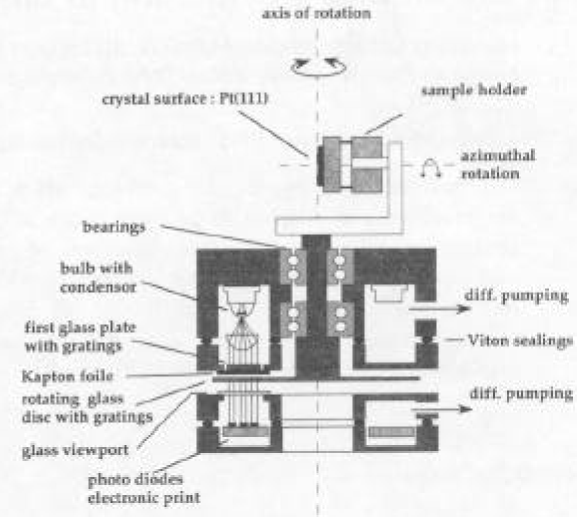


FIG. 2. Section view of our mechanical setup containing the modified resolver encapsulated by two differentially pumped housings.

vide the *relative* angular position measurement (the fifth nonperiodic grating on the left-hand side of the glass-plate A provides the *absolute* angular position measurement and is discussed below). A second glass plate (B), which is attached to the moving object, is installed in front of the first glass plate (A) at a distance of about 100 μm. It supports the same periodic line grating [see the zoom (C) in Fig. 1(a)]. When sliding the second glass plate with respect to the first one the light transmission through both glass plates varies periodically giving rise to a stripe pattern or so-called Moiré pattern.[7] These transmission changes are detected for each of the four arrays independently by four different photodiodes (P). The measured signal at each diode consists of a periodically varying portion upon which is superimposed an almost constant signal originating primarily from alignment errors. Since the four grating areas on the glass plate A are phase shifted by 90° with respect to each other, subtracting the signals from two arrays with a phase shift of 180° eliminates the constant signal background and provides a pure periodical signal. This can be done for two grating pairs leading to two periodical signals with 90° phase difference. Both signals are converted to rectangular signals and read by a counter leading to four count events per grating period. Thus, the corresponding resolution is 1/4 times the grating periodicity. It is also possible to take into account the phase information of the measured signals, which can increase the resolution by a factor up to 100 by an interpolation process also described in Ref. 7. Modern microstructuring techniques nowadays allow for grating periodicities down to 4 μm and therefore for resolutions in the submicron regime.[12] In our case, 2500 lines are arranged at the outer border of a turning glass disk (∅=42 mm) giving rise to an theoretical *relative* angular resolution of the order of 0.0004°.

The corresponding *absolute* reproducibility is about 1/20 times the grating periodicity,[13] thus ~0.007° in our case. It is achieved with the help of the fifth grating area on the glass plate (A) and its counterpart (R) on the rotating disk [see Fig. 1(a)]. Both gratings are nonperiodic but consist of a special sequence of lines with varying widths. Sliding these two gratings against each other gives rise to a well defined sharply peaked detector signal. Its maximum is associated with a freely choosable reference value. Thus, the whole measuring unit can be turned off at any time without loss of the precalibrated absolute position.

III. MECHANICAL DESIGN

Figure 1(b) shows a photo from the ready-to-use angle measuring system ERO1251 obtainable from Heidenhain GmbH.[13] It consists of the light source including the condenser lens and the first glass plate, the detector circuit board, and the rotating glass disk. Initially, all parts are perfectly aligned by the manufacturer. Since the light source and the detector circuit board cannot be used in UHV due to strongly degassing components, they have to be separated from the rotating glass disk and independently encapsulated, whereas the rotating glass disk has to be mounted in UHV onto the axis of rotation. The crucial point is to maintain the tiny distance of 100 μm between the two glass plates, since any increase of this distance will smear out the light signal.

We solved this problem by inserting an almost transparent 25-μm-thick KAPTON foil between the two glass plates. This can be seen in Fig. 2 from the section view of our mechanical setup. The KAPTON foil is attached to the metallic housing of the light source by a UHV compatible polyester glue.[14] Although the measured leak rate of this glue connection was smaller than 1.0×10^{-9} mbar ℓ/s, the light source housing has to be pumped differentially in order to avoid damage to the 25-μm-thin KAPTON foil by the pressure differences between the housing and the surrounding UHV. A second metal housing contains the detector circuit board and has a 0.5-mm-thick glass viewport in front of the photodiodes. Both housings can be opened to access the light source and detector, respectively. They are sealed by outgassed VITON O-rings. The rotating glass disk is rigidly mounted in UHV on the axis of rotation, which is guided by two bearings before being attached to the crystal holder. The rotation is driven by a spring loaded metal cable assembly via a step-motorized translational feedtrough (not shown). Its computer control is done by means of a numeric feedback algorithm taking into account the difference between the nominal value and the actual value for each scan step. Data acquisition takes place when the difference is smaller than a chosen tolerance value. The data points consist of the real measured angular position rather than the nominal one. The apparatus bakeout has to be performed at temperatures below 130 °C to avoid damage to the measuring unit.[15] Nevertheless after two days of bake out and half a week of additional pumping time the base pressure routinely drops into the low 10^{-10} mbar range.

IV. RESULTS AND DISCUSSION

We will now demonstrate the high performance of the above-described device for the measurement of *absolute* angular positions. For this purpose we have performed successive high-resolution helium-reflectivity measurements from a atomically flat Pt(111) surface.[16] The corresponding scattering geometry is schematically shown in Fig. 3(a). A highly collimated ($\Delta\phi\sim0.01°$) thermal helium beam furnished by a standard nozzle source is specularly scattered from the Pt(111) surface and detected by a quadrupole mass detector with an opening angle of ~0.1°. The scans have been performed at a fixed total scattering angle by simultaneously varying the angle of incidence ϑ_i and the outgoing angle ϑ_f through sample rotation about an axis normal to the scattering plane.

After initializing the absolute reference signal we first measured the specular He reflectivity by a scan with a nominal step width of 0.005° shown by the open circles in Fig. 3(b) (note, that the time needed to adjust the different angular positions is of the order of 10 s and thus corresponds to the time scale of most experiments). We then turned off the measuring unit and performed arbitrary angle movements larger than 30°. Next, we turned on the resolver and again initialized the absolute reference signal. We then repeated the first scan but this time offset its data points by 0.0025° with respect to the first scan [filled circles in Fig. 3(b)]. As can be seen from Fig. 3(b), the two scans are indeed shifted by 0.0025° and the open and filled circles are almost perfectly alternating. Therefore the absolute reproducibility is better than 0.005° and, thus, corresponds to the theoretical limit.

Having demonstrated the performance of the absolute positioning we will now discuss the performance of the relative position measurement. For this purpose we did the same measurements as above but without interrupting the measuring unit in between the two scans. As it can be seen in Fig. 3(c) the first scan (open circles) and the second scan (filled circles) are again exactly shifted by 0.0025° and the open and filled circles are strictly alternating indicating an relative resolution better than 0.005°.

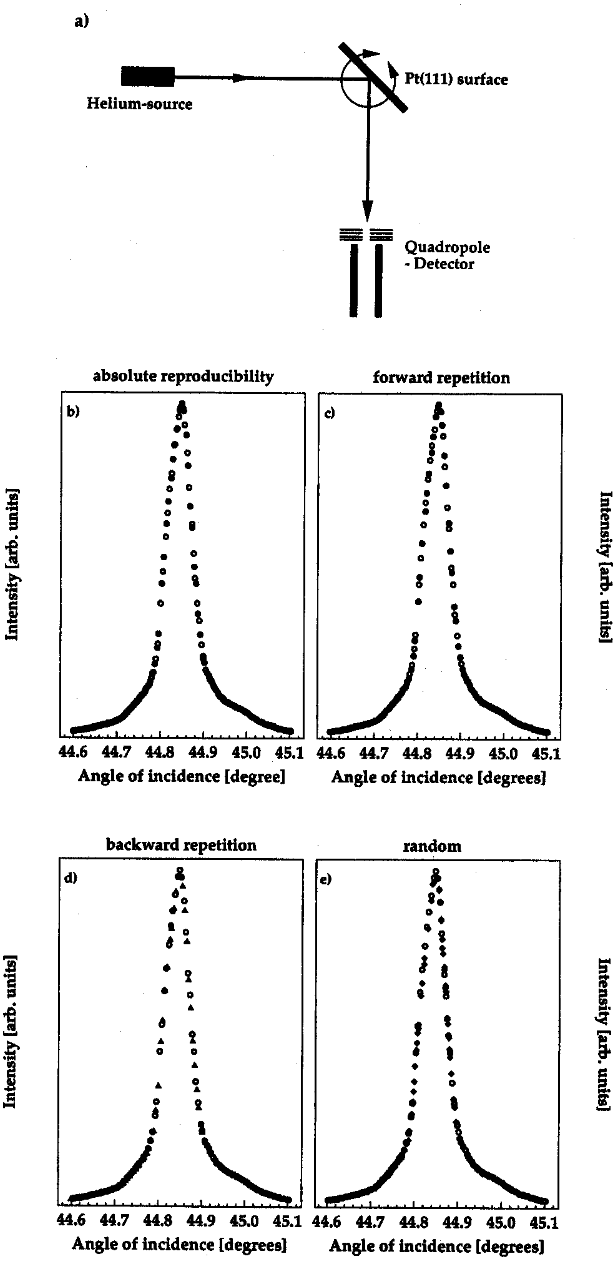


FIG. 3. (a) Scattering geometry of the high-resolution helium-reflectivity measurements, (b) reflectivity scans demonstrating the ±0.0025° absolute reproducibility of angular positions, (c) reflectivity scans demonstrating the ±0.0025° relative resolutions of angular scans in forward repetition, and (d) backward repetition, (e) random scan demonstrating the possibility to adjust angular positions within an error of ±0.001°.

The significant increase of the relative resolution without dramatic increase of the time needed to adjust each angular position was hindered by the "softness" of our spring-loaded mechanical drive for the axis of rotation. This can be seen from Fig. 3(d), where the first scan of Fig. 3(c) (open circles) has been repeated in the opposite scanning direction (filled triangles) with the nominal data points again shifted by 0.0025°. In this scanning direction small angular changes during the data acquisition (2 s) can occur due to relaxation within the cable assembly (note, that a change of the scanning directions requires about 500 step-motor steps before any change of the scanning direction is indicated by the resolver, i.e., a large mechanical backlash is present). This gives rise to the minimal data spread of Fig. 3(d). We can avoid this effect by working with tolerances far below 0.001°. We then achieve relative reproducibilities better than 0.001°, but the time necessary to adjust the angular position for one data point exceeds 2 min. Improvements of both the mechanical drive and its computer control will certainly overcome this problem making also possible *fast* scans with relative resolutions better than 0.001°.

Nevertheless the current manipulator setup already now allows for a precise (±0.001°) adjustment of angular positions. This can be seen from the measurement in Fig. 3(e), where the first measurement of Fig. 3(c) (open circles) has been repeated by a random scan with 0.001° tolerance (filled squares). Instead of making a standard angular scan the nominal angular positions of this scan have been created with the computer random generator and transferred to the control program. Despite the permanent movement direction changes occurring in this scanning mode no significant deviations from the original spectrum can be observed.

In conclusion we have realized a UHV compatible angular position measuring device based on commercially available resolvers. It operates in the low 10^{-10} mbar range and can be baked out at 130 °C. Its absolute reproducibility is better than 0.005° whereas the relative resolution amounts to 0.001°. Since the relative resolution is not limited by the resolver characteristics but by the performance of our mechanical setup, further improvements of the mechanical drive will certainly allow fast scans with a relative resolution far below 0.001°. The development of a three-axis sample manipulator, where each axis is equipped with a UHV compatible resolver, is in progress.

ACKNOWLEDGMENTS

The technical support by M. Scherz (Heidenhain GmbH), P. Cordey, and C. Blanc is gratefully acknowledged.

[1] Here we use the terms relative resolution (or relative angular position measurement) and absolute reproducibility (or absolute angular position measurement) in order to make the distinction between two different working modes of our UHV compatible position measuring device. In mode 1 the measuring unit remains permanently on duty registering all position changes (relative resolution). In mode 2, it can be interrupted without loss of the precalibrated absolute position providing absolute reproducibility.

[2] R. David, K. Kern, P. Zeppenfeld, and G. Comsa, Rev. Sci. Instrum. **57**, 2771 (1986).

[3] I. K. Robinson, in *Handbook on Synchrotron Radiation*, edited by G. S. Brown and D. E. Moncton (North Holland, Amsterdam, 1991), Vol. 3.

[4] D. E. Moncton and G. S. Brown, Nucl. Instrum. Methods **208**, 579 (1983).

[5] S. Brennan and P. Eisenberger, Nucl. Instrum. Methods **222A**, 164 (1984).

[6] P. H. Fuoss and I. K. Robinson, Nucl. Instrum. Methods **222**, 171 (1984).

[7] A. Ernst, *Digitale Längen-und Windkelmesstechnik* (Verlag Moderne Industrie, 1993).

[8] K. Kuhnke, E. Hahn, R. David, P. Zeppenfeld, and K. Kern, Surf. Sci. **272**, 118 (1992).

[9] H. Schief, V. Marsico, and K. Kern (unpublished).

[10] Relative monochromator angular positions are measured in UHV with microradian resolution by sophisticated laser light diffraction methods. J. C. Rife, Nucl. Instrum. Methods **222**, 279 (1984).

[11] A. Heuberger, Z. Phys. B. Condensed Matter **61**, 473 (1985).

[12] Coincidentally the Moirée-principle brakes down at smaller grating periodicities due to diffraction effects.

[13] Dr. J. Heidenhain GmbH, D-8225 Traunreut Germany. The technical support by M. Scherz is gratefully acknowledged.

[14] Leitpaste PC860005, Heraeus GmbH, D-6450 Hanau, Germany.

[15] According to the supplier specifications the maximum working and storage temperature in air is 85 °C. Our detailed investigation of the corresponding heat resistance under vacuum conditions ($p<10^{-3}$ mbar) revealed no damages at temperatures below 150 °C.

[16] *Helium Atom Scattering from Surfaces*, edited by E. Hulpke, Springer Series in Surface Science 27 (Springer, Berlin, 1992).