CALIBRATION MACHINE FOR LINEAR SCALES

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Abstract: In this paper we describe the retrofitting of a length measuring machine for the calibration of linear scales, with a scale division of a few micrometers. The new system consists of optics, equipped with a CCD camera with a built-in computer, for capturing the line width and the scale division, an illumination system. The motion stage carrying the scale provides linear motion with a resolution of approximately 20nm. A simple and robust algorithm able to correct for the various disturbances of the pitch distance is given. The effect of non-linearity and diffraction, is eliminated to a large extend by using appropriate optics and illumination. The displacement is measured by an HP laser interferometer.

Keywords: Linear scales, calibration scale division, length measuring, laser interferometer.

Introduction: The increasing application of micro- and nanotechnologies emphasizes the importance of precise measurement, which in turn, increases the demand for calibrated standards with submicron structures. Many kind of calibration systems for line scales have been built in various laboratories.

One of the earliest paper[2] describes the NIST length scale interferometer for measuring graduated length scales. It discusses in detail not only the machine and its operation, but elaborates also on it's uncertainty and the required environmental conditions.

Barakauskas and his co-authors investigate in their paper the effect of systematic and random component errors on the resulting accuracy of the calibration system. Design methods are introduced to increase motion accuracy. Also computational and active methods of geometric error compensation are described [1][4][5]. Kaušinis paper addresses errors specific to dynamic line scale calibration caused by geometric and thermal deviations of the various system components [4]. A 3D finite element model was used in his investigation.

Meli's paper [8] presents a different approach, based on laser diffractrometry, according to Littrow principle, resulting in picometer measuring uncertainty

Scanning probe microscopy is a new technique to capture the distance between subsequent grating lines [9]. Atomic force microscope is one appropriate instrument for this purpose. If the scale is covered, then this method is not applicable. Peng Xi etc. [10] solve this problem by applying noncontact near field microscope for the detection of the measuring points.

The Nanometer Comparator[6] provide traceable measurements of incremental systems, line scales and photomasks with measurement uncertainty of a few nanometers. The equipment has the following key features: the iodine-stabilized Nd:YAG laser based interferometers operate in vacuum, the length of the measurement loop is minimal and is constructed from material with low thermal expansion coefficient, angular interferometers are used to correct the angular deviation of the slide, z-piezos are used to focus the microscope. The Nanometer Comparator was designed to achieve an uncertainty of 2 nm.

The paper by Lassila describes the line scale interferometer of MIKES[7] having four metrological loops to compensate the environmental influences as far as possible.

Druzuvec and his co-authors [3] discuss the effect of contamination in the calibration uncertainty model. Significant influence in calibration uncertainty budget is represented by the uncertainty of the line centre detection. The paper discusses different types of line scale contamination like dirt spot, scratches, line edge incorrectness and line intensity variations.

Requirements: Graduated scales are made of various materials including steel, invar, glass, glass-ceramics, silicon and fused silica. The cross sectional shape can be rectangular, H or U-form, or modified X called Tresca. The machine should be able to accommodate and calibrate all these linear scales types up to a length of 400 mm, with a minimal scale division of 1µm. The resolution of the measuring system has to be better 0,02 µm.

The image of the lines should be captured optically. The structure has to be equipped with the appropriate number of high precision temperature sensors to collect enough data for determining the thermal distribution and compensating the effect of the resulting deformation.

To meet the requirements given in the subsequent paragraph, we have designed an additional carriage for the measuring machine and added a novel optical system with automatic line recognition capability. Hereby we have extended the measuring machine's capabilities for semi-automatic calibration of linear scales.

Various definition of scale division: The scale division can be defined on three ways given in the subsequent picture.

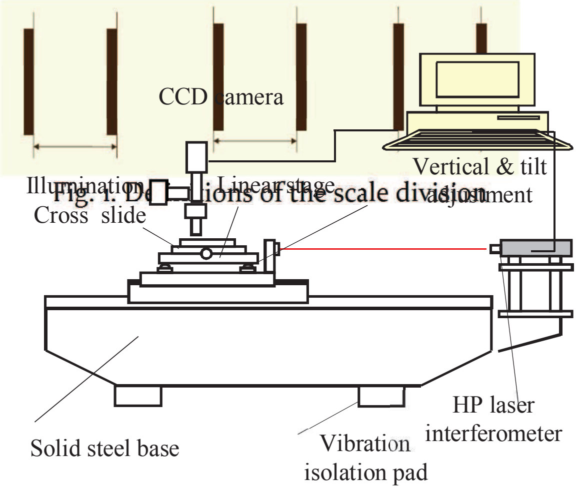

Fig. 1. De[illegible]ions of the scale division

Fig. 2. The overall construction of the calibration system

The construction of the linear scale calibration system consists of three physically separated parts: the solid steel bed of the measuring machine and the carriage module, the optical microscope and image capturing module and the measuring system.

The motion and the image evaluation is executed and coordinated by a personal computer. The carriage's position is determined by an HP heterodyne laser interferometer. It is of vital importance that the distance between the microscope and the laser interferometers remain fixed during the scale measurement, because any relative motion between them will be seen as part of measured scale length, thus resulting in additional uncertainties.

The optical system :. Linear scales are calibrated by moving the carriage and measuring it's displacement by interferometers. The determining factor to this correspondence is the line centering process. The scale structures are captured optically. The optical

Whereas the first two versions given in the picture can be measured directly, the third one requires more processing. The difficulty is generated by line thickness variation and the straightness error of the edges.

Overall construction:

system is assembled together from various commercially available modules. The microscope consists of an objective, a manual control element for focusing, a tube lens, and a camera connection module. The microscope with the CMOS camera is mounted on a beam fixed to the steel base. Digital measuring microscope enables precise estimation of the line edge quality and precise location of lines.

To process the image data captured to different approach had been followed in the subsequent paragraphs. In the first approach each horizontal line profile within the region of interest in the image is analysed. The centre of the left and the right edge is used and the edge locations are determined with a moment based edge operator. A line is fitted through all these centres using only points within 2σ. The intersection of this fitted line with the reference line is used as the scale line position.

Another way is, to calculate directly the line centres. The first step in processing image delivered by the camera attached to the microscope is to restrict the picture plane area to immediate neighbourhood of the graduation line. That means that subsequent processing will be performed only on the pixels inside the window. Hereby we exclude the influence of contamination and damages not in the centre of "gravity" of the gray values of the individual pixels:

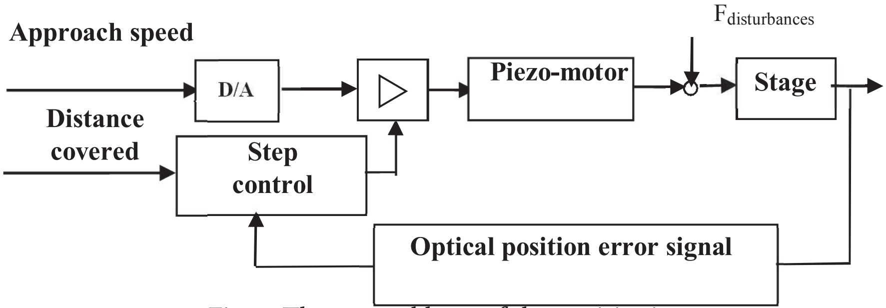

Fig. 3. The control loop of the positioning system

$$r_{centre} = \frac{\sum_i \sum_j g_{i,j} r_{i,j}}{\sum_i \sum_j g_{i,j}}$$

where r is the distance from the origin of the coordinate system and $g_{i,j}$-s are the gray scales values of the different pixels.

The centreline detection algorithm was tested with different deteriorated scales. First the centreline of the original image was calculated and after that the line was "repaired" either by filling the white spots or cutting of the bulges and repeating the calculation again. It was found that the displacement of the centre line due to these distortions was in our cases less than one pixel resulting in centreline shift less than 20 nm.

The system will be equipped with both ring- and backlight illumination. The white LED ring light is positioned around the objective. Telecentric backlight directs light emitted from a green LED source onto the object with very small deviation angles. This results in a high contrast image. The intensity of both illuminations can be adjusted under computer control.

The motion system: The motion system consists of two linear stages mounted on top of each other. The lower carriage is moved on high precision miniature profile guide-ways by linear piezomotor using friction drive. When the AB2 driver operates in gate mode the motor is driven at resonant frequency with periodic on/off pulses. Here steps were found to be uneven. To overcome this problem sliding mode control was implemented, where the friction index was estimated from the velocity variation of the previous and the present steps. In this mode the stage moves close to its destination and the remaining portion is covered in DC mode, where the motor works as a piezo-actuator with a range of 300 nm.

The cross stage is moved also on high precision miniature profile guide-ways by ultrasonic piezomotors. From the point of measuring uncertainty it is vital that the scale remains in focus measurement, because any relative motion results in measurement error. Therefore a flat surface made of glass is linked to the stage by flexures providing small frictionless linear motion. The distance between the two, are regulated by piezo actuators, resulting in a highly dynamic system. The entire equipment rests on a vibration isolated concrete block and is housed in an environment where the temperature is kept 20°C±0,2C°.

The motion control system consists of the following components: Nanomotion ultrasonic motor, AB2 driver box, Advantest D/A converter, Position controller in software, Interferometer. The motion controller, implemented in software runs on a microcontroller working in dual mode. The driver box is switched into gate mode and a point 200 nm from the target position is approached with constant velocity. The stationary velocity, and the step size (the distance to be covered) can be introduced as control system parameters. The last 200 nm is covered in DC mode. In this range the friction coefficient could be assumed constant.

While the carriage is in motion angular errors can appear. The pitch error will be corrected by tilting the transparent table using piezo actuators. The yaw error, due to the precision profile rail guides, is negligible. The roll error doesn't influence the measuring accuracy.

The measuring system: The scale division is the sum of the carriage displacement measured by the laser interferometer and the difference between the optical axis of the camera and the detected line centre position in the camera coordinate system.

Environmental parameter values of air temperature, barometric pressure and relative humidity and are measured and used to compute the refractive index of the air in the optical path. The short term stability of the He-Ne laser wavelength is $1x10^{-9}$. The laser beam is in line of the scale in order to eliminate the Abbe error. The scale is clamped to the table by soft springs. The sources of measurement uncertainty can be divided into five groups: stage positioning and interferometric measure-ment related uncertainty, optical and scale related uncertainties, and repeatability. Taking into account the contribution of all these parameters the estimated extended uncertainty amounts 50 nm.

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