Development of a low-cost measurement system for cutting edge profile detection

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The use of a compact disk (CD) pickup head as a displacement measurement system is described. The components contained in a pickup head are explained and how they are combined to obtain the functionality of a pickup head. The application of measuring a knife edge profile is introduced. The results reveal some insuffiencies with the current system. The cutting edge's radius of curvature can be estimated.

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When knifes are produced, a main point of interest is their sharpness of the cutting edge. A way of attempting to measure the radius of curvature of the cutting edge is to use commercially available optical pickup heads of standard compact disk (CD) drives and let them scan the distance to the knife's surface. Because of the pickup heads' disposability and the high production numbers, those pickup heads are very inexpensive, but still show a high level of accuracy.

Several different applications using an optical pickup head as a measurement system can be found[1−3]. most of those applications were relying on assumed ideal reflective properties of the specimen's surface[4].

An approach to scan a knife edge using a pickup head can be found[5]. In contrast to our work, where only a CD pickup head is required, an interferometer setup and a redirecting mirror are necessary, too.

Preliminary to the use of a CD pickup head as a sensor system, several investigations have to be carried out. These investigations ought to deliver information about the electrical and mechanical structures and characteristics of those high quality but still low cost pickup heads. Those very low costs are the main advantage when trying to use a CD pickup head as a measurement system. Main focus is given to the so-called focus error signal, conveying the sought after measurement information of a change in distance to the reflective probe surface.

With an optical pickup head as a profile measurement system, there are two different operating modes. In the first mode, the specimen is placed in the focal plane and the objective lens is kept fix. The focus error signal can then directly be calculated into the surface roughness of an object moving laterally to the sensor. In the second mode, the position of the objective lens is servoed to keep the focus error signal close to zero giving the advantage that the system is always operating in focus. The drive current or voltage respectively of the objective's actuator is then a direct though slightly non–linear indicator for the profile of the object moving along the sensor, as long as the linear range of the focus error signal is not dynamically overwhelmed. The useful working range in this mode is more than 100 times the range of the first mode and amounts to approximately 1 mm of displacement.

In this letter, we focus on the first mode, which is actually used for detecting the profile of a cutting edge. The optical setup is introduced and its functionality as well as the signals delivered by the pickup head are explained. The voice coil motors (VCMs) characteristics are investigated. The use of a pickup head as a measurement system is illustrated, followed by a measurement example and derived result.

Optical storage systems usually consist of a rotating data storage medium, an optical pickup head for reading the information and electronics for controlling the mechano-optical system and for converting the gained data. In this project, a CD pickup head (PXR-550X, Mitsumi, Japan) from a commercially available CD-drive was investigated to show its suitability in a profile measurement system.

Figure 1 shows the principle of a CD pickup head. It consists of a laser diode operating at a wavelength of 780 nm, a linearly polarizing beam splitter, a collimator, an objective lens, an anamorpholic lens in front of the detector array, and etc. Subsequently, the laser beam is polarized and collimated, it is directed via the objective

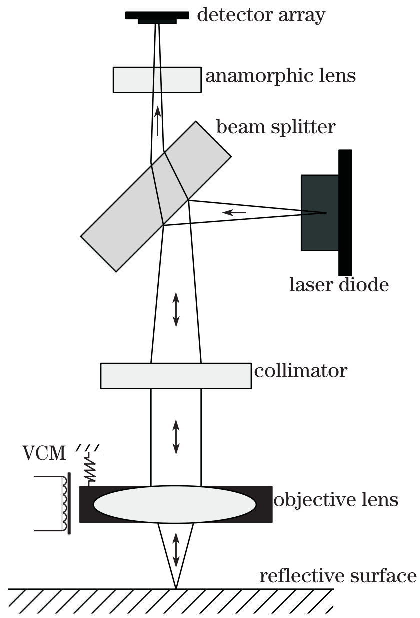

Fig. 1. Principle of a CD pickup head (beams shown for the focused case).

lens to the specimen. The objective lens is actuated by the VCMs, their characteristics will be discussed. The specimen scatters back the beam through the objective lens to the beam splitter, where it is directed via the anamorphic lens onto the detector array. The detector array is a four-quadrant photo diode, whose arrangement is shown in Fig. 2. Because of the characteristics of the anamorpholic lens, the beam shape at the detector array is either elliptic or circular. The circular shape occurs only if the reflective surface of the specimen is placed exactly at the focal plane of the optical path. The laser beam in this case has a diameter of less than 1 μm. The ellpitic shape occurs when the beam reflection takes place out of focus. The orientation and size of the elliptic beam pattern depend on the location and distance from the focal plane, respectively. The detector array has four areas, named A, B, C, and D. They deliver photocurrents, depending on the illuminance integrated over their area, which are subsequently linearly converted into voltages. From these voltages the so-called focus error (FE) signal can be derived as

$$\mathrm{FE} = (A + C) - (B + D). \quad (1)$$

The FE signal has an s-shape when a reflecting object is in certain range of the focal plane. The relations between the FE signal and the specimen's travel distance (z) are shown in Fig. 2. The FE signal has been obtained by keeping the objective lens at a fixed position and then moving a mirror like specimen towards the pickup head. The mirror's velocity was approximately $v_z = 10\,\mu$m/s. The s-curve is approximately linear over an input range of 6 μm.

Beside the FE signal also the total illumination integrated over all four photodiodes, called RF signal, is

$$\mathrm{RF} = A + B + C + D. \quad (2)$$

The RF signal is plotted together with the FE signal in Fig. 2.

To move the objective lens in a two-dimensional (2D)-space or to keep it at a certain position, there are two VCMs available, included in the pickup head and they are able to move the objective lens orthogonally and

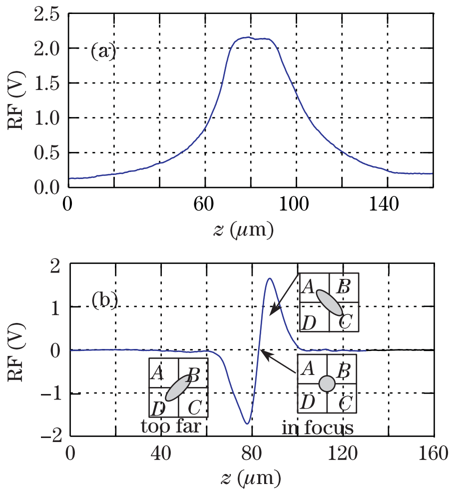

Fig. 2. (a) RF signal associated with the FE signal. (b) FE signal's characteristic s-curve with corresponding beam shapes at the detector array.

radially to the CD-surface. To investigate the static behaviour of the two voice coil motors, excitation voltages are applied and the relation between the applied voltage and the travel distance is measured. A laser vibrometer (OFV-505, Polytec, Germany) has been used to obtain the travelled displacement. As Fig. 3 shows, the VCM in focus direction features a linear excitation range of $u_\mathrm{o} = \pm 0.5$ V, corresponding to a travelled distance of $z = \pm 0.54 \times 10^{-3}$ m. These two values yield to a sensitivity of the VCM in focus direction over the nominal range of

$$\frac{z}{u_\mathrm{o}} = 1.1 \text{ mm/V}. \quad (3)$$

The linear excitation range of the VCM in radial direction also ends at $u_\mathrm{r} = \pm 0.5$ V but it exhibits less sensitivity:

$$\frac{x}{u_\mathrm{r}} = 0.8 \text{ mm/V}. \quad (4)$$

The dynamics of each VCM is determined by measuring its Bode-plot with amplitudes limited to the linear range of input voltages. The resolved magnitude responses for both, the radial and the orthogonal VCM respectively, are displayed in Fig. 4. The resonance frequencies (f) for both directions are found to be slightly above 50 Hz.

From Fig. 4, one can infer that the VCMs together with the objective lens can be modelled as a forced second order system:

$$m \cdot \ddot{x}(t) + d \cdot \dot{x}(t) + c \cdot x(t) = f(t), \quad (5)$$

where m represents the accumulated mass of the moving parts (windings of the VCMs, objective lens, and lens

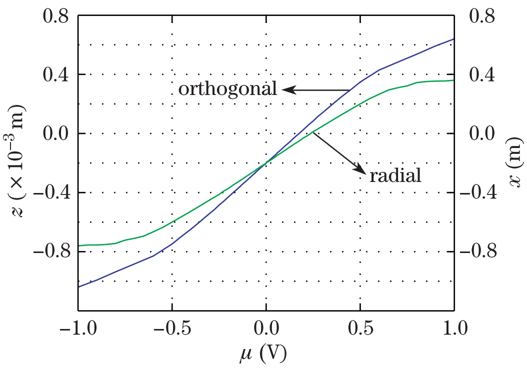

Fig. 3. Relation between VCM movement and supplied voltage (u).

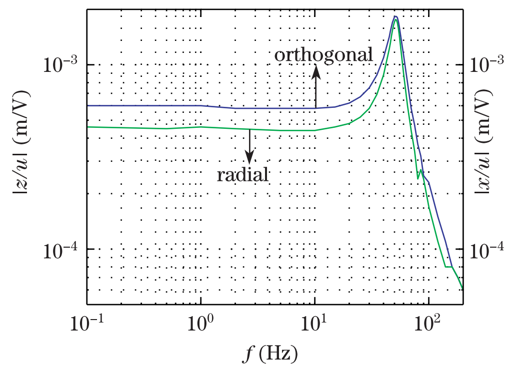

Fig. 4. VCM's magnitude response of the Bode–diagramm for a peak excitation voltage of $U_{o,r} = 0.1$ V.

holder), d and c mark the damping coefficient and the spring stiffness of the system, respectively. The external force $f(t)$ is moving the mentioned mass m, and the travelled distance is represented by the time-depending variable $x(t)$. Figure 5 is a mechanical model of a VCM/lens system, including all described coefficients and variables[1]. The wires connecting the VCMs act as springs and have equal stiffnesses in each moving direction. The damping coefficient is derived from the magnitude response of very small amount. The weight of the moving parts amounts to $m = 385 \times 10^{-6}$ kg. The spring stiffness is identified and amounts to $c = 27.06$ N/m (see below). The damping coefficient is estimated to $d = 0.01\,\text{Ns/m}$. Using Laplace transformation the equation of motion can be expressed as a transfer function

$$G_{x/f} = \frac{X(s)}{F(s)} = \frac{1}{m \cdot s^2 + d \cdot s + c}, \tag{6}$$

where $X(s) = \pounds[x(t)]$ is the Laplace transformed of $x(t)$ with a complex argument $s = \sigma + \mathrm{j}\omega$; $F(s) = \pounds[f(t)]$.

Actually, a transfer function $G_{x/u}$ is of interest which describes the objective lens' travel $x(t)$ as a result of an excitation voltage $u(t)$ applied to the VCM:

$$G_{x/u} = \frac{X(s)}{U(s)} = \frac{k}{m \cdot s^2 + d \cdot s + c}, \tag{7}$$
$$U(s) = \pounds[u(t)].$$

Here, the motor factor k specifies the f/u characteristic of the VCM in the linear range. Due to the electric system shows a time constant much shorter than the mechanical systems, it suffices to use the factor k. A simple test is used to determine this factor: measure the lens displacement at a certain excitation voltage and repeat the test with an extra mass applied to the moved parts. This test lets us compute the spring stiffness c and the motor factor k, which amounts to $k = 49.104 \times 10^{-3}$ N/V. Figure 6 depicts the resulting bode–diagram of the transfer function $G_{x/u}$.

In comparison to the measured system from Fig. 4, the resonance frequency can be found at a lower frequency of $f = 42$ Hz. The gain at frequencies $f < 10\,\text{Hz}$ originally amounts to $|z/u| = 0.6 \times 10^{-3}\,\text{m/V}$ but is now

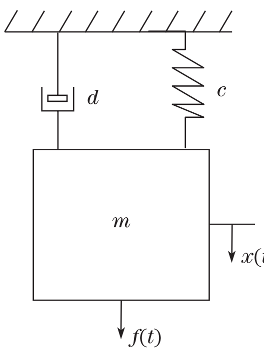

Fig. 5. A forced second order system modelling a pickup head's mechanical system containing the moving parts (objective lens, the lens holder, and the windings of the VCMs), a spring, and a damping.

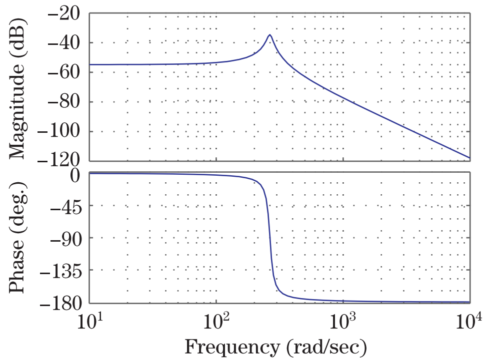

Fig. 6. Bode–diagram of the identified system $G_{x/u}$. The resonance frequency is at 42 Hz, the gain amounts to 1.82×10^{-3} m/V for frequencies $f < 10\,\text{Hz}$.

$|z/u| = 1.82 \times 10^{-3}\,\text{m/V}$. These errors occuring with the identified model have to be investigated before the VCMs are controlled to servo the focal plane and the laser beam position, respectively. A possible source of error is the test setup which is used to identify the factors k and c. This setup has to be improved by using a laser vibrometer instead of now calculating the displacement relations obtained by macro photography.

The detailed investigation of the dynamic characteristics of the VCM is used for future work, where the VCM moves the objective lens in horizontal direction to scan across a knife edge. Hence the VCMs then have to be controlled, an exact equation of motion is necessary.

Ensuming the information about the pickup head's electrical and mechanical characteristics, two different ways of using such a pickup head as a profile measurement system will be described in the following.

Two different modes of using the pickup head as a profile measurement system can be distinguished. In the first mode, the specimen is positioned at the focal plane. Meanwhile, the objective lens is fixed at its rest position. Subsequently, the pickup scans across the surface and the obtained FE signal gives information about the surface roughness. The measurement range in this mode amounts to $\pm 3\,\mu$m as already explained with Fig. 2.

As a test specimen a standard blade of a Stanley knife is used. In Fig. 7, a magnified picture of such a Stanley knife, taken with a microscope can be seen. The knife is clamped tightly to a 2D motion controlled micro translation stage (Oriel Encoder Mike) and can be moved orthogonally and radially. The pickup head as well as the motion control with the clamped knife are all assembled to an active vibration absorber (Micro 40, Halcyonics, Germany) so that the measurement system is somewhat less affected by external mechanical disturbances. After the knife edge is placed into the focal plane, the motion control moves the knife edge horizontally along the pickup head. The output voltages A to D are acquired with a digital storage oscilloscope (TDS 2024, Tektronix, USA), the data is sent to (via general purpose interface bus) and evaluated on a computer.

The FE signal which is expected when a circularly rounded tip of a knife edge is scanned, is shown in Fig. 8. The RF signal will strongly decrease when the laser beam leaves the focal plane, because the beam is no longer properly reflected in the orthongonal direction. This fact prohibits the FE signal's transformation into an exact information of the knife's edge profile. But the broadness of the knife edge in the focal plane can be estimated, which still gives information about the quality.

The measured RF and FE signals are shown in Fig. 9 (color online), where the red area marks the estimated broadness of the knife edge, beginning at the minimum of the FE signal. For finding the estimated area's end, one has to act another assumption: when the RF signal falls below a certain limit (RF = 0.4 V) while the FE signal is still not yet zero, one can assume that the laser beam's main part is reflected into another direction. This implies the beam has already left the circular part of the profile. With these assumptions, one can estimate the width of the knife edge to be 12×10^{-6} m, according to the measurement from Fig. 9.

One of the main problems appearing while measuring is the uncertainty about the exact profile shape. Due to the bevel of the knife at its edge, the laser beam is no longer reflected into the middle of the detector array but rather onto one side of the array. These facts lead to measurement results which can only be interpreted but not transformed into an exact profile. Another problem appears in the slightly inproper alignment of the laser-beam and the knife. In Fig. 10, another possible source of error can be seen: the picture of the detector array with the four areas A, B, C, and D can be spotted and it strikes out, that there is a slight deviation in angle of about 6°. This deviation has to be investigated in future work like each of the other mentioned uncertainties.

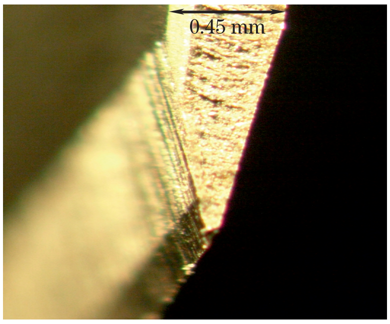

Fig. 7. Picture of a Stanley knife's cutting edge, taken with a microscope. Because of Stanley knifes are broken for renewing, the first part of the blade is bent.

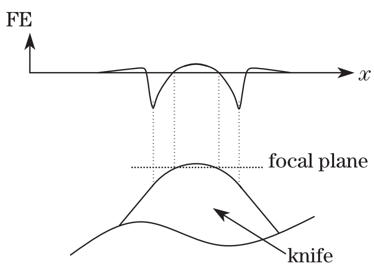

Fig. 8. Expected FE signal when scanning the knife's edge. The leftmost vertical dashed line marks the begin of the FE signal's linear range. The reflection on the detector array appears as an elliptic shape. The two vertical lines in the middle mark the points where the reflection takes place in the focal plane. In between these two lines, the scanned surface is in the positive defocus to the lens, so the FE signal becomes positive. The rightmost line marks the end of the scanable surface because the FE signal leaves its linear range.

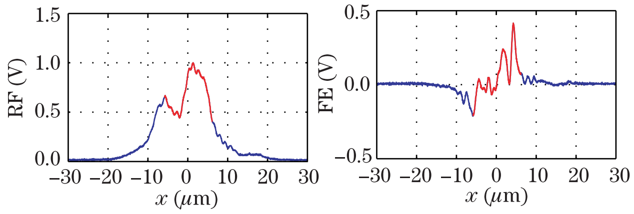

Fig. 9. (Color online) Measured RF and FE signals while scanning a knife edge. The red area marks the estimated broadness of the knife edge.

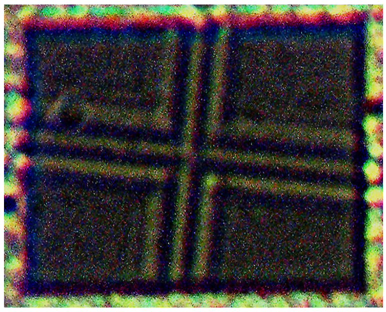

Fig. 10. Picture of the detector array (width $w = 120\,\mu$m, height $h = 75\,\mu$m), taken via a microscope. The deviation in angle of the four areas A to D can be indentified . Artefacts (increased noise) appear due to sharpening filters.

In conclusion, the adaptability of a CD pickup head as a measurement system for characterizing a knife's edge profile is shown. The optical and mechanical characteristics of such a pickup head is introduced. For pickup heads, there are two different ways to use them for profile detection. Firstly by controlling the objective lens and keeping the focus error to zero, and secondly by placing the object at the focal plane and then scanning across the object. This second option is used for the work descibed in this letter. The experienced uncertainties prohibit an exact conclusion about the measured edge profile. Future work will mainly focus on developing several strategies to avoid the mentioned uncertainties and errors so that the measurement results provide information about the scanned edge profile. Subsequently these investigations will focus on using the VCMs instead of the micro stages.

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