Measuring System for Non-Contact Oscillation Measurement

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Abstract
This paper summarizes the investigations and results of an R&D project concerning a measuring system for a non-contact amplitude and direction measurement of periodic and aperiodic lateral device oscillations. It is based on the detection and analysis of scattered light speckle patterns caused by rough surfaces and can be manufactured at low costs, qualifying it for the integration into production processes and assembly lines.

Introduction
Periodic and aperiodic lateral device oscillations cause mechanical or thermal material stress. The resulting problems are noise emissions, overstraining of tools and damages of the device surface. Another challenge is the distortion of products during a forming process.
A common oscillation measuring method is based on acceleration sensors, which are mounted to the workpiece. The measuring results are nearly independent of the environmental conditions. However, the sensor application requires mechanical modifications of the workpiece, which inevitably changes its mass or mass distribution and influences the oscillation amplitude. An inductive proximity sensor enables non-contacting oscillation measurements. Workpiece oscillations cause a high frequent electromagnetic alternating field in an LC-oscillator, which is transformed into an evaluable signal. The inductive proximity sensor operates in potentially adverse enviromontal conditions. Due to the non-contact measurement method the workpiece weight is not influenced. However, the measuring principle implies metal-based workpiece materials. A laser triangulation system enables non-contacting optical oscillation measurements. It combines all advantages of contactless measurement systems but is not applicable in polluted environments and measures only the oscillation component, which is aligned with the optical sensor axis. This measuring method is used for reference measurements within the context of the following.The electronic speckle pattern interferometry measures object deformations, from which the oscillation amplitude can be derived. Generally, this technique enables real time measurements but is very expensive.
Each of the mentioned measurement systems has certain advantages and disadvantages. Non of the non-contacting measuring methods is capable of lateral device oscillation amplitude and oscillation frequency measurements. However, in industrial manufacturing is a strong demand for competitive, fix mounted and non-contacting oscillation measuring systems, which characterise velocities (frequencies), amplitudes and directions of lateral object movements.
During the R&D project summarised in this paper an optical oscillation measuring system based on the detection and processing of stochastic scattered light speckle patterns from rough surfaces was developed. The new approach is very sensitive for lateral object movements with amplitudes up to 0,3 mm and nearly every oscillation frequency. Therefore, it has a high potential to be established in many new areas of application.

Scattered light speckle patterns
Speckle patterns occur, if a stochastically rough surface scatteres coherent light [1]. According to the Huygens principle, each point of an illuminated rough surface is the origin of a spherical secondary wavelets (Figure 1). The constructive or destructive interference of the emitted waves results in the typical speckled intensity distribution with bright and dark areas in an observation plane or a CCD array, respectively. The local intensity depends on the resulting phase difference of all contributing Huygens waves. Scattered speckle patterns emerge from almost every surface with a rms-roughness $Rq > \lambda/4$, where λ is the light wavelength.

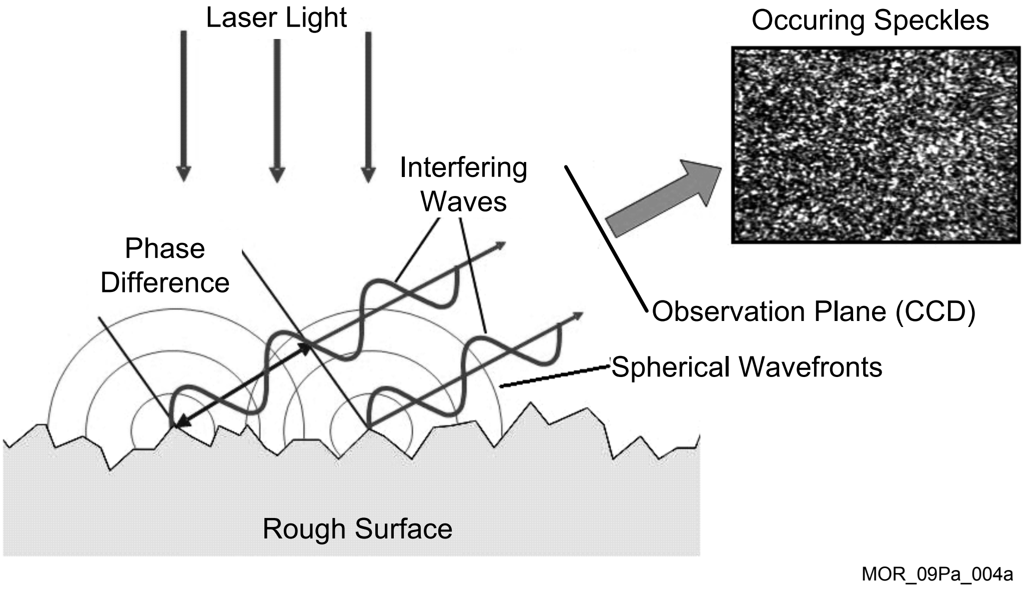

Figure 1: The interference of scattered waves from a rough surface produces a speckle pattern.

A movement of the workpiece may cause speckle shifts in different directions, depending on the geometrical shape of the incident wavefront [2]. A divergent laser beam or a convex wavefront shape (Figure 2.a) generates a speckle movement, which is aligned with the surface movement. A convergent laser beam or concave wavefront produces a speckle shift opposite to the surface movement (Figure 2.c). The distance of the speckle movement depends on the path length of the surface movement and on the distance between the CCD array in the observation plane and the surface.

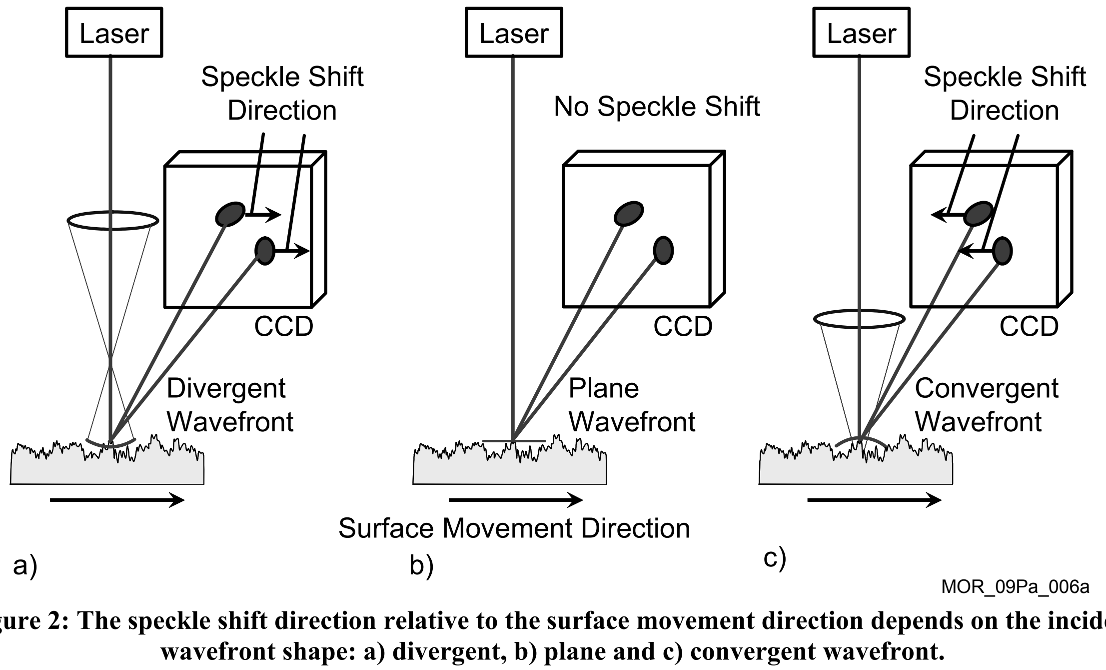

Figure 2: The speckle shift direction relative to the surface movement direction depends on the incident wavefront shape: a) divergent, b) plane and c) convergent wavefront.

The mean objective speckle diameter as well as the mean distance between two objective speckles in the observation plane depend on the laser wavelength λ, the observation distance between surface and CCD array, and the diameter of the illumination spot on the surface. Therefore, using the same optical and mechanical parameters for the measuring set-up leads to stochastically equivalent speckle patterns. This is a fundamental precondition to achieve measuring results, which are independent of individual surface topography within the illuminated area.

Amplitude and direction measurement

The correlation between the direction of the linear surface movement and the speckle movement discribed in the previous section in combination with appropriate algorithms can be used for a non-contact frequency, amplitude and direction measurement of oscillating surfaces. Figure 3 shows time exposure speckle patterns for a stationary and a lateral oscillating surface.

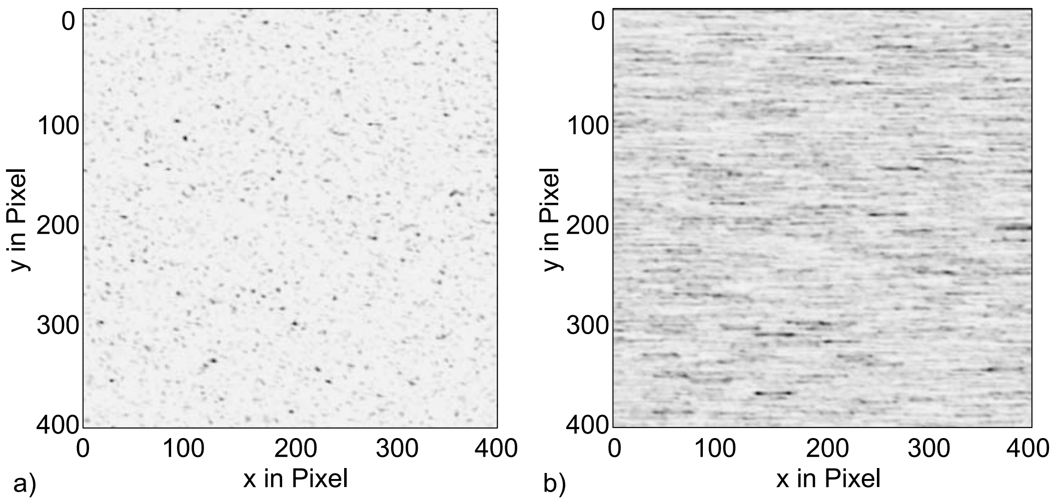

Figure 3: Time exposure speckle patterns (negatives) for a) a stationary and b) a lateral oscillating surface.

The oscillation amplitude as well as the oscillation direction can be derived from the autocorrelation function (ACF) of the speckle intensity distribution [3]. Figure 4 shows autocorrelation functions of the speckle patterns in Figure 3. The narrow ACF corresponds to a stationary object. The wide spread ACF reflects the elongated speckles occurring in the long term exposure of an oscillating object. The spread direction corresponds to the linear movement of the surface. The angle of the speckle elongation with respect to an axis of the coordinate system can be determined by a Radon Transformation of the camera image or the ACF, respectively. The oscillation amplitude follows from the distance of two distinctive points of the ACF graph, e.g. the most left and right inflexion points (Figure 7).

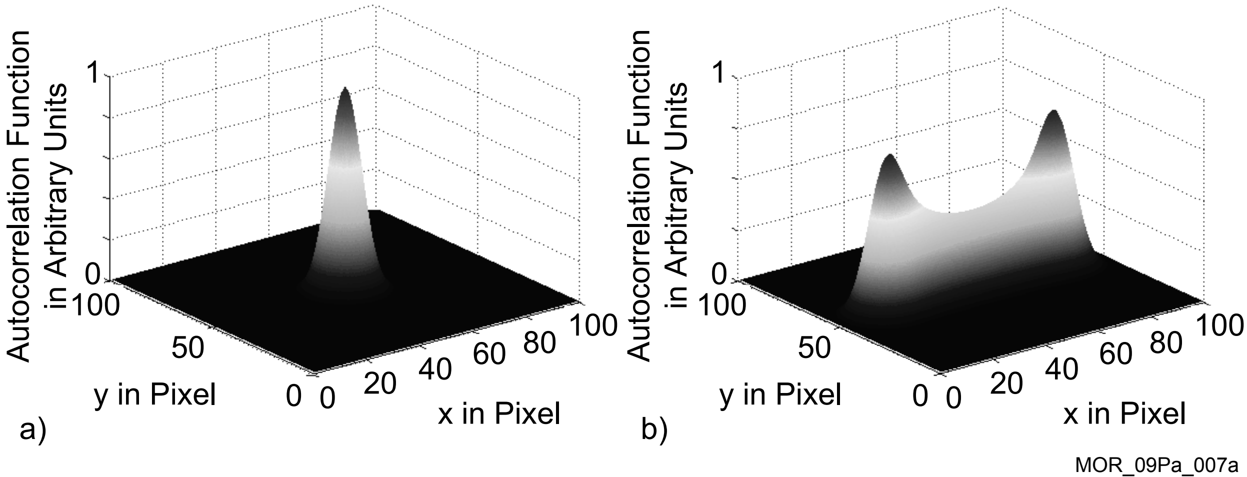

Figure 4: Autocorrelation function of the speckle intensity distribution according to a) Figure 3.a and b) Figure 3.b.

Frequency measurement

In a first approach frequency measurements are performed with a photodiode in the back focal plane of a Fourier transforming lens (Figure 5). Due to the stochastical speckle intensity distribution and the deterministic mean speckle diameter the light sensitive sensor measures intensity variations, which are proportional to the lateral displacement of the oscillating surface within certain limits. Therefore, the oscillation frequency can be derived from the nearly sinusoidal output signal of the photodiode. In connection with the described investigations the measured frequency values are in accordance with the preset oscillation frequency of the workpiece. However, this kind of frequency measuring method requires further investigations concering the mutual dependencies between the properties of the individual photodiode, the parameters of the speckle pattern and the oscillation parameters.

Measuring system

The sensor prototype consists of a cost efficient standard laser diode, optical elements, a photodiode and a digital CCD camera with a frame rate of *fr* = 30 frms/sec (Figure 5). A plano-convex lens produces a slightly divergent laser beam that forms a convex shaped wavefront on the oscillating object surface. The distance between the surface and the laser diode is chosen to produce an illumination spot diameter of about 1 mm. The digital CCD camera detects the scattered speckle intensity distribution emerging from the illuminated surface area.

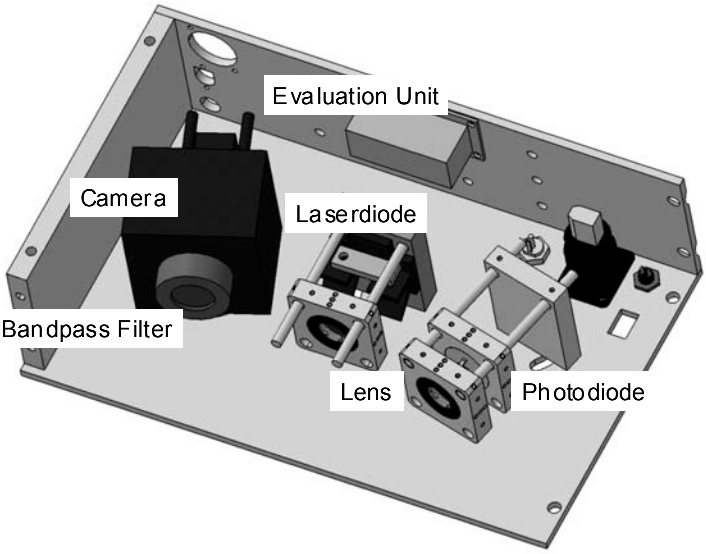

Figure 5: Set-up of the oscillation sensor prototype.

Appropriate image processing algorithms analyse the speckle patterns in order to quantify the oscillation amplitude and the oscillation direction. The speckle shape and the speckle oscillation amplitude change with respect of the observation angle. This effect may be eliminated by calibrating the sensor. A possible calibration method implies a quantification of the mean direction dependent speckle diameters of the assymetric speckles based on reference measuring results and the calculation of a corresponding correction factor for the image evaluation process.

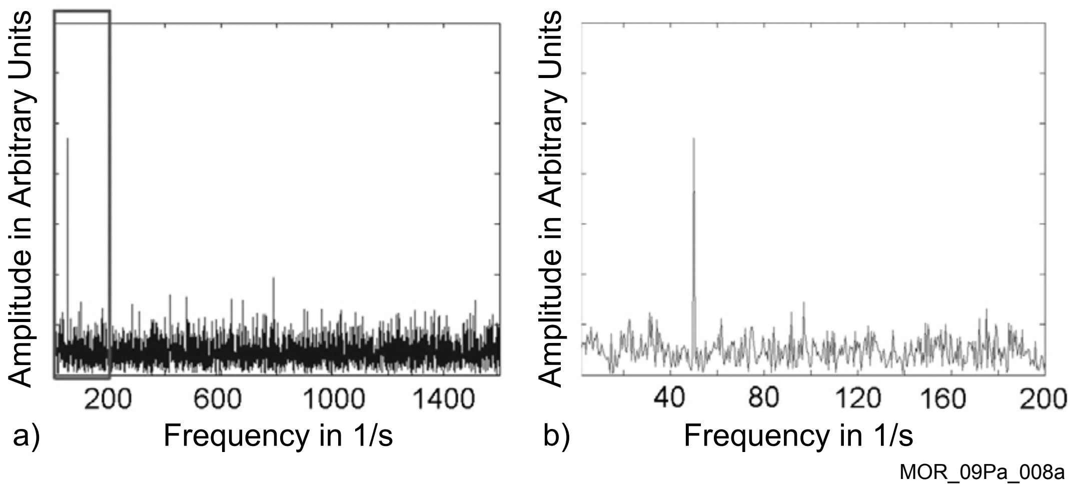

Figure 6: Frequency spectrum for a) the input signal *f* = 50Hz and the sample rate sr = 3200 samples / sec and b) a detail of Figure a.

The photodiode measures the resulting far-field intensity, which changes proportional to the elongation of the oscillating workpiece surface. A data aquisition card measures the photodiode output voltage. The oscillation frequency follows from a FFT analysis of the output signal. Figure 6 shows the frequency spectrum of an amplitude with the excitation frequency *f* = 50Hz. The shown spectrum was obtained by Fourier transformation of the noisy sinusoidal photodiode voltage signal. The enlarged detail in Figure 6.b shows a significant peak for the frequency *f* = 50 Hz, which excellently meets the excitation frequency.

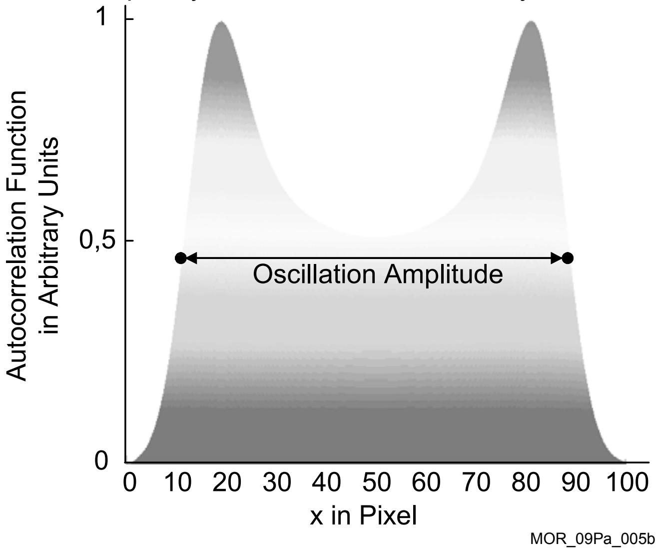

Figure 7: A measure for the oscillation amplitude can be derived from the two-dimensional intersection along the x-axis of the normalised intensity autocorrelation function according to Figure 4.b.

The oscillation amplitude results from an analysis of a statistically sufficient number of CCD images, which are superimposed in order to get a long term exposure equivalent image with a movement blurred speckle pattern. The speckle pattern in Figure 3.b ermerges from an oscillating surface with an oscillation amplitude larger than the mean speckle diameter. Figure 7 shows the two-dimensional intersection along the x-axis of the corresponding normalised speckle intensity autocorrelation function in Figure 4.b. The distance between the first and the last inflexion points reflects the oscillation amplitude. A special image processing algorithm enables a confident determination of the inflexion point coordinates. The algorithm is independent of the individual shape of the ACF. Figure 8 shows the measuring results according to linear oscillations with different amplitudes and different frequencies. Obviously, the measured values show a good linear correlation with the reference oscillation amplitude of the surface.

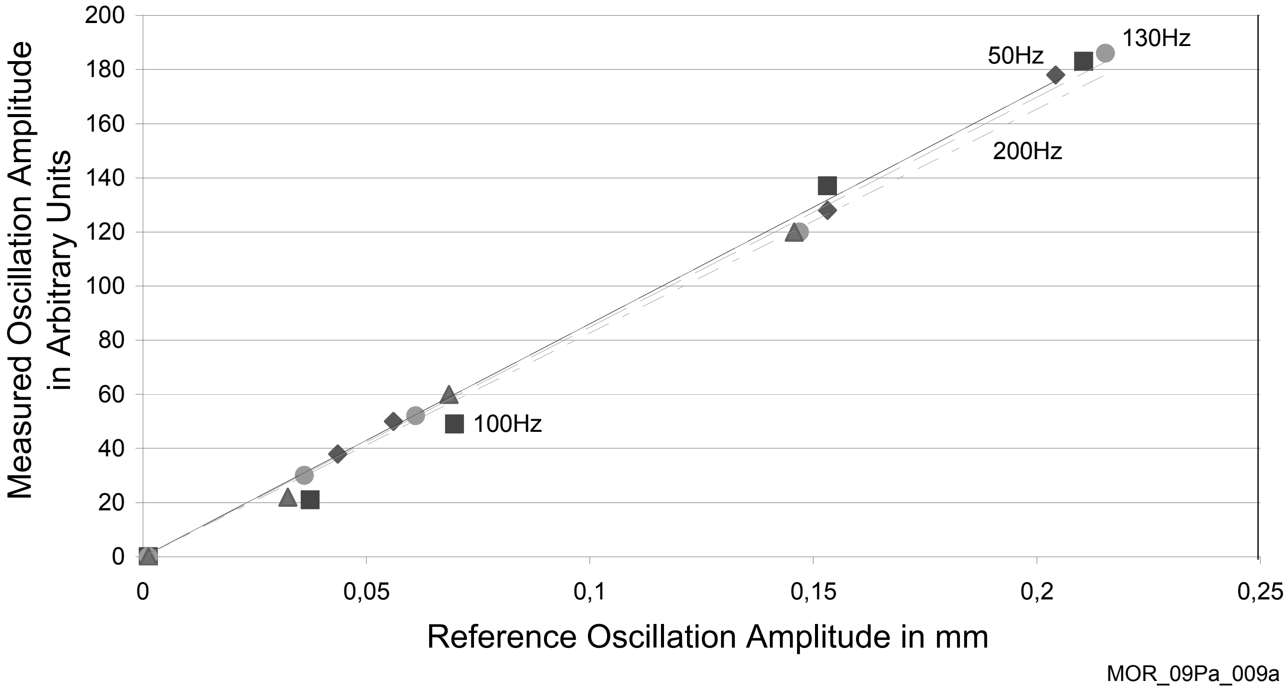

Figure 8: Measuring results of object oscillations with different amplitudes and different frequencies.

Conclusions

A non-contact measurement system for the characterisation of linear oscillation amplitudes and oscillation frequencies based on the analysis of scattered light speckle patterns from rough surfaces is described. The measuring results show a good linear correlation with the reference oscillations and are independent of the oscillation frequency. By analysing the main orientation of the ACF the oscillation direction can be calculated as well. Further research in surface dependencies and measurement resolutions has to be done to integrate the new sensor prototype into production machines and assembly lines.

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