Dynamic-speckle profilometer for online measurements of coating thickness

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Abstract. Online control of thickness of as-deposited coatings is of great importance because it directly affects the quality of protective coatings. We present a novel approach that enables online, real-time and non-contact measurements thickness of thermally sprayed coatings. The proposed technique uses dynamic speckles generated by rapidly deflecting laser beam. Within 10 ms the system can scan 500 times a small area of the deposited layer thus resulting in measurement accuracy of 5 microns irrespectively of the layer roughness. In comparison with traditional optical triangulation technique of distance measurements, our system has following advantages: (i) much simpler optical scheme that includes conventional photodiode to measure the scattered light, (ii) much simpler electronics for real-time data processing, (iii) much higher speed of measurements.

1. Introduction
Fast non-contact distance sensor with micron accuracy is called by many industrial applications where mechanical sensors (or even manual solutions) are now in use. Wide area of possible applications includes control of fast moving parts of machinery, on-line monitoring of production lines where the thickness of materials should be controlled in real time (rolled metals, paper production lines), evaporation of thin films, vibration detection etc. Among these applications on-line measurements of as-deposited coatings is a challenging task. The coatings are typically quite rough (with roughness of 20 µm or even higher) but their thickness has to be measured with accuracy of few microns. Natural approach to solve this problem is averaging the measured distance. Conventional optical triangulation technique for non-contact distance measurements takes tens of seconds to achieve the required resolution with such rough surfaces [1]. Alternative optical method for z-distance measurements is the technique of dynamic speckles [2-4]. The main advantage of this technique is its very short response time, which is inversely proportional to the speed of laser-beam scanning over the surface under study. With scanning speed of hundreds m/s, the response time is about tens of microseconds only [5]. However, stochastic nature of dynamic speckles does not allow achievement of high accuracy in z-measurements during single scan. Nevertheless, providing multiple scanning of the surface under study with subsequent averaging of the data one can significantly improve the measurement accuracy. Since measurement of as-deposited coatings also requires averaging, the technique of dynamic speckles is very suitable for on-line measurements of coating thickness. In this paper we report
experimental results of thickness measurements of thin layers by using dynamic-speckle profilometer. Special attention is paid to analysis of conditions at which data averaging does result in accuracy improvement.

2. Dynamic speckles for distance measurements
Possibility of applying dynamic speckles [6,7] for distance measurements is based on the fact that in case when divergent/convergent beam illuminates the moving surface, velocity of speckles depends on the distance between the optical head and moving object [2]. This is also true when the object is static but the laser beam scans over the surface [5,8]. Therefore, to estimate distance to the object it is enough to measure speckles velocity. The fastest technique for speckle-velocity measurement is spatial filtering [9] where the speckle pattern is filtered in the simplest case by Ronchi rulings. After spatial filter, the light power is modulated at a frequency defined by the velocity of dynamic speckles. By measuring this frequency one can estimate \(z\)-distance to the object. In the geometry of divergent beam, the modulation frequency, \(f_{SP}\), approximately depends on \(z\)-coordinate as

\[
f_{SP}(z) = \frac{V_{SP}(z)}{\Lambda} = \frac{V_{OS} D_S}{\Lambda N_{SP}}. \tag{1}
\]

Here distance \(z\) is measured from the beam-waist position; \(V_{OS}\) is speed of the object surface in respect to the laser beam; \(V_{SP}\) is the velocity of dynamic speckles; \(\Lambda\) is the period of the spatial filter; \(D_S\) is distance between illuminating spot on the object surface and point of observation. By providing scanning over the object surface we control the velocity \(V_{OS}\). Therefore, with measured modulation frequency and known scanning speed \(V_{OS}\) one can calculate the distance between the focal plane of the illuminating beam and the object surface:

\[
z = \frac{D_S V_{OS}}{\Lambda N_{SP}}. \tag{2}
\]

Typical application for distance measurements implies slow (in respect to the scanning speed) motion of the object under study. It can be motion of production line (rolled metals, paper etc.), moving machinery parts, rotating rolls and rills etc. During the coatings deposition either object surface is moving or the spray gun is moving over the surface. In the latter case a profilometer can be attached to the spray gun to be moved together and monitor growth of the deposited coating. Anyway, the speed of the object movement does not usually exceed few m/s which is more than order of value smaller than typical scanning speed. Therefore, object speed can be neglected in the calculations using equation (2) especially when it is orthogonal to the scanning speed.

3. Experimental setup
The object we used in our experiment is metallic tube with diameter of 160 mm and length of 200 mm. During protective layer deposition it was rotating around its axis to achieve uniformity of deposited layer. Dynamic-speckle profilometer is installed so that the direction of laser-beam scanning is parallel to the tube axis as shown in the figure 1. Optical scheme of the profilometer is very simple and does not include any sophisticated parts. The laser beam generated by a laser-diode at the wavelength of 806 nm is deflected by acousto-optical deflector (AOD) to scan rapidly and repeatedly over the tube surface. Typical scanning speed achieved in our experiments is from 50 to 150 m/s, which is much faster than the speed of the surface movement during the layer deposition. The light scattered from the tube surface is filtered by spatial filter (Ronchi Rulings) and then collected into the photodiode by using conventional lens. The power of scattered light is modulated at the frequency of several MHz after spatial filtering by Ronchi Rulings with spatial period \(\Lambda\) of 50 \(\mu\)m. The signal from the photodiode is either stored in the digital oscilloscope or processed in real time in a laboratory-made digital frequency-meter.
Typical signals from the photodiode are shown in the figure 2. As one can see the light power after spatial filtering is modulated at a well-defined frequency. The mean frequency of the signals was estimated either by fast Fourier transfer (FFT) or by zero-crossing technique. As we demonstrated earlier [8], the accuracy of the distance measurements using single scan is about 100 µm, which is not enough for application to coating-thickness measurements. However, AOD naturally provides multiple scanning of the surface with period of 20 µs for our particular deflector. One can expect to achieve much higher accuracy by averaging the frequencies from multiple scans still within quite short time-window. The necessary condition for accuracy improvement by means of averaging is that the averaged data must be statistically independent. Therefore, the question, how far we should displace a subsequent scan to get statistically independent signals, becomes very important.

4. Correlation of the filtered speckle pattern
According to the theory of dynamic speckles [7], the correlation time, $\tau_c$, for the speckle pattern generated when the Gaussian beam illuminates the surface moving with the speed $V$ and scattered light propagates in a free space (which is exactly the situation used in our experiments) is given by the following equation:

$$\frac{1}{\tau_c} = \sqrt{\frac{1}{r_s^2} \left( 1 + \frac{D_s}{\rho} \right)^2 + \frac{1}{w^2}},$$

(3)

where $r_s$ is average speckle size in the observation plane (the plane of spatial filter), $D_s$ is the distance between the object plane and the observation plane, $\rho$ is the radius of the wavefront incident on the object surface (which is equal to the distance $z$, if $z$ is larger than the Rayleigh range), and $w$ is the radius of the illuminating spot on the object surface. Our aim is to calculate the displacement $L_c$ of the object surface at which new speckle pattern is non-correlated with the previous one. At any speed $V$ of the object surface, this displacement will be $L_c = |V|\tau_c$ or:
\[
\frac{1}{L_C^2} = \frac{1}{r_S^2} \left( 1 + \frac{D_S}{\rho} \right)^2 + \frac{1}{w^2}.
\]

(4)

According to the geometry of the experimental setup we have \(\rho = 8\) mm, \(D_S = 50\) mm, \(r_S = 24.5\) \(\mu\)m, and \(w = 30\) \(\mu\)m. For given geometrical parameters the equation (4) yields \(L_C = 3.5\) \(\mu\)m, which is quite small displacement.

Figure 2. Oscilloscope traces of the signal from the photodiode at different displacement of the object surface perpendicular to the direction of the laser-beam scanning.

5. Experimental results

To check abovementioned estimations we carried out experiments devoted to measurements of the correlation length \(L_C\). To this end the surface was displaced orthogonal to the direction of the beam scanning with steps of 2 \(\mu\)m and corresponding signals from the photodiode were stored in the computer. Figure 2 shows typical oscilloscope traces obtained in this case. As one can see the correlation between signals (a) and (b) is quite high while the signal (c) does not correlate with both previous.

Figure 3. The maximum of cross-correlation function calculated for randomly chosen central scan and the set of displaced scans.

We have recorded 2300 oscilloscope traces by displacing sequentially the object surface in respect to the scanning beam. Thereafter, the cross-correlation function of a selected signal with all others has been calculated. Typical result for one of the scan in the middle of the set is shown in the figure 3. Average width of the correlation peak is about 30 \(\mu\)m. Therefore, the sought correlation length is 15 \(\mu\)m for the beam radius of 30 \(\mu\)m in the direction perpendicular to the direction of scanning, which is almost order of value larger than that expected from the theory. Second experiment was carried out for
the beam radius of 200 µm. With this beam the correlation length was even larger, about 100 µm. Observed discrepancy with the theory is not surprising because the theory considers correlation properties of the speckle pattern itself but in our experiments we deal with the spatially filtered speckle pattern. The experiment shows that the displacement of the surface by the quarter of the illuminating beam diameter on the surface is enough to obtain uncorrelated signal. Note that the beam size in the direction perpendicular to the scanning direction is changed by means of the cylindrical lens that does not affect the wavefront radius parallel to the scan responsible for formation of the signal. Therefore, one can choose any desirable step of surface displacement for optimal data averaging without affecting parameters of the spatially filtered speckle pattern.

We also carried out measurements of the correlation properties of our signal in the case of longitudinal displacement of the surface in respect to the laser-beam scanning. This geometry was practically useful for us because at the same time we were able to measure the profile of the tube in the laboratory conditions. The protective layer of this particular tube was intentionally done of different thickness with two steps: by 90 and 30 µm. The tube was fixed in the translation stage enable computer controlled movement of the tube along its axis. Laser-beam scanning was implemented along the tube motion direction. The total number of scans covering whole length of the tube was 51,000 meaning that each scan was shifted along the tube axis in respect to previous scan by 3.5 µm. Each scan was 1.1 mm length and included about 100 oscillations at averaged frequency of about 4.5 MHz. All the signals were recorded and thereafter processed to estimate the correlation length and the profile of the tube.

For estimations of the correlation length in this experiment we have used the technique allowing us to calculate the instant frequency of the signal during the time of the single scan. The instant frequency of each single scan was centered on about 4.5 MHz and it varies in the range of 300 kHz. Figure 4 shows collection of 400 sequential scans (which correspond to longitudinal displacement of 17 mm) along the tube where in the x-axis we put the scan number and the y-axis is the current time of the scan. The instant frequency of the signal is coded by pseudo-colors. One can clearly see the tilted color lines at approximately the same angle to the x-axis. We interpret them as repeated signatures of instant frequency distribution, which is shifted in time domain because of the displacement of the scanning beam in the space. Average number of adjacent scans correlating each other was found to be about 80. Remembering that the longitudinal shift between the adjacent scans is 3.5 µm and the correlation length is the half of the full width of the correlation peak, we obtain $L_C = 140$ µm, which is a half of the beam radius in the direction of the scan in this experiment. Therefore, to obtain statistically independent signals after spatial filtering of the dynamic speckle pattern, one should provide displacement of the surface by at least a half of the illuminating-beam radius on the surface in respective direction.

![Figure 4. Instant frequency of the photodiode signal as a function of the current time and its variation for sequential scans recorded with longitudinal step of 3.5 µm. Right picture shows coding of the modulation frequency with pseudo-colors.](image.png)
independent signals from our set of 51,000 scans (only one scan from 40 was considered for averaging). The results are shown in the figure 5. Each point on the graph was obtained after averaging 36 independent scans that correspond to the longitudinal displacement of the tube by 5 mm. When the modulation frequency is measured in real time, the time required to get one measurements is 0.72 ms, while only 24 ms (1200 scans) is needed to measure whole profile of the tube. After this averaging the accuracy of z-distance measurements is 15 µm. Much higher accuracy can be obtained after averaging of more scans. As one can see from the figure 5, the steps of the coating thickness are clearly distinguishable. Solid line in the figure 5 shows the profile of the tube measured by the conventional contact profilometer. Here we used longitudinal displacement of the surface for the data averaging just to estimate parameters of the technique. It is clear that much better results could be obtained using optimal transverse displacement, which provides data averaging over surface area, which has the shape approaching to a square.

Figure 5. Object under study: metallic tube with evaporated layer. (b) The thickness of the layer along the tube measured by conventional contact profilometer (solid line) and by dynamic-speckle (squares).

6. Conclusion

We have demonstrated that a novel technique based on dynamic speckles generated with rapidly scanning laser beam is very suitable for on-line non-contact measurements of as-deposited coating thickness. Fast response time of the technique allows increasing the measurement accuracy by averaging large amount of data. We have shown that accuracy of 15 µm can be achieved within the time window of 0.72 ms. Analysis of the correlation properties of spatially filtered speckle pattern allows us to find the optimal geometry for measurements of z-distance with high accuracy.

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