Studying parameters and quality of thread by optical light field recorder

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Abstract. The work suggests a method to inspect the profile and micro-relief of thread surface using a light-field optoelectronic system based on a digital camera with a collection of micro-lenses. The authors have developed an optical scheme to record 3D images of the profile and micro-relief of the controlled thread surface. The system involves computer technologies of National Instruments Company (NI, USA) to elaborate the algorithms for determination of thread profile geometry and micro-relief parameters. The results demonstrate that the implementation of the algorithms of morphological image layer analysis derived from the light field file specifying the depth of field allows increasing multiple times the accuracy of thread profile determination using the profile height. The article was prepared according to the State task (the project's number № 9.10520.2018/11.12)

1. Introduction
The shape and quality of thread joints in all industrial products are determined by strength characteristics and joint reliability. Currently, many new threading technologies are developed what increase the quality of thread joints.

As of today, absolute thread quality assurance, which includes the inspection of profile geometry and working surface micro-relief, is a labor-intensive operation that requires special instruments. Partial inspection of parameters does not determine all thread quality characteristics. On the other hand, the complexity of such inspection is conditioned by compound volumetric properties of the thread profile, from the other hand, by limited access of inspection instruments to the thread working surface. Currently used instruments are limited in terms of the dimensions of inspected products.

In practice, the thread parameters are measured by measuring rulers, thread calipers, thread gages, profilographs and other instruments. Optical instruments for surface micro-relief measurement (roughness) are based on surface profile conversion principles. The standard sets the following list of instruments allowed for such control: shadow-type inspection tools, light-section inspection tools, single-lens moiré microscopes, interference microscopes (based on two-beam light interference), interference profilograph microscopes (based on light interference with generation of fringes of equal chromatic order).

All optical methods are highly accurate and high-performance contact-less means to control the quality of many industrial products. However, their implementation does not provide simultaneous control of all necessary parameters of complex three-dimensional geometries and surface quality
parameters. More accurate methods and instruments (holographic correlators) demand much effort and mechanical stability of an object under control.

Today, there are light field recorders developed by Raytrix (Germany) and Lytro Inc. (USA) that can be effectively used to determine product and surface geometry and quality (patent of Apple Inc. (USA) no. US 2016/0063691A1 Plenoptic cameras in manufacturing systems). Such recorders for studying thread surface parameters were never used before. They will allow recording by single camera with single exposition a fragment of the thread surface and analyze it qualitatively and quantitatively, which will increase accuracy and performance of thread control in products. Since such off-the-shelf recorders emerged in the market not so far ago, they have not been used yet for thread surface study. Implementation of light field recorders may several times increase the performance and accuracy of thread quality control.

During the development of technologies for threading in products, one needs determining the deviations in thread profile geometry and parameters of its working surface micro-relief.

2. Purpose of research
The aim of the research is to determine the capabilities of light field recording method for accurate determination of geometrical profile and micro-relief of internal thread surface. The work involves the development of such control method and main algorithms to determine the geometrical profile shape and parameters of the thread surface relief.

3. Materials and Methods
The light field recording method of a focused image, unlike photorecording, is known to record a series of coordinates and direction of beams from surface points of a controlled product [1]. This allows controlling both geometrical parameters of complex products and peculiarities of the surface relief along the height [2]. In addition, it yields images of a set of sharp layers of the recorded space, which allows recording under conditions of a number of uncontrollable parameters and performing morphological analysis of the image layers. This approach is known to extend the capabilities of the industrial control of complex products [3–5].

The main issues is the control of internal thread, which is connected with impeded optical access to all controlled fragments of the surface. With due regard to the main properties of the light field recorder [1], to record the direction of incoming rays, we may consequently apply algorithmic processing of signals from matrix photoreceiver to get a specific depth of field, on the one hand, while on the other, we can distinguish the structure of the reflecting surface along the height (along the viewing direction). Hence, the work suggests the optical scheme for registration of an internal thread surface fragment at viewing angle $\alpha$ to the thread profile surface that enables the recording of the field of view of thread fragment under control $I$ by digital light field camera 2 (Fig. 2). Light source 3 and its orientation should provide uniform lighting of all thread profile surface elements. The study has shown that optimally the light source should generate heliocentric divergent bundle of rays illuminating the digital camera field of view, which is achieved by its distancing from the surface under control. The profile image contract is ensured by direction of light rays reflected from the surface. The dissipation indicatrix of lighting rays from the surface micro-relief points forms in the image a lighting structure that determines the shape and micro-relief parameters. The analysis of illumination distribution in the image gives geometrical parameters of the profile and the thread surface relief. However, according to the experiments, the effect of shadowing of certain thread profile surface parts by beams necessitates the usage of separate light sources located at different access sides of the surface under control.
The experimental specimens were represented by threads in metal done by taps with and without magnet-abrasive treatment [5], which allowed comparing the relief of surfaces depending on the quality of the instrument used. The thread surface images (Fig. 1) were recorded by Lytro ILLUM (Lytro Inc., USA) light field digital camera [2, 5]. To record the internal thread surface, one should use optical recording scheme at viewing angle $\alpha$ to the normal of the thread surface tangent. We need to take into account that this optical recording scheme introduces perspective [6] and changes the display scale for different thread surface parts. These spatial distortions are eliminated by spatial transformations of obtained 2D-images [7, 8]. The distortion of the light field digital camera is corrected by its calibration [2, 9]. In practice, it is difficult to determine the viewing angle of the digital camera at the thread surface fragment. Therefore, to compare the experimental measurement results, we have used simplified recording scheme perpendicularly to the thread axis ($\alpha=0$) using halves of the metal billets threaded by different taps [5]. In this case, there is no change in the scale of visualization along the image field (perspective). Necessary depth of field is determined by the thread diameter and the size of recorded specimen fragment. As mentioned before, the parameters and orientation of light sources play a significant role in this case. Taking into account the appreciable role of mirror component of section surface 1 and thread surface 2 during recording, a complex illumination structure formed in the light field image file.

4. Experimental results and discussion

Two-dimensional images for measurement of geometry were generated from the light-field file (3D) using LytroDesktop application [2] with necessary depth of field, which provided the sharpness of the whole threaded surface. The converted image of halved threaded specimen from light-field file is given in Fig. 2. The image shows the whole internal thread profile in section 1, thread surface edge 2, brightness structure of the image of halved metal billet 3 corresponding to its micro-relief. The figure shows that internal thread surfaces have significant illumination nonuniformity, in the left part of which, the angular filtration of the light source light additionally highlights weakly localized curves 4 of the contrast gradient corresponding to the thread profile. In the right part of the inner surface, there is a light elongated periodic structure of illumination contrast change 5 which was formed by the interaction of rays with the thread surface profile. These effects are determined by the parameters and orientation of light sources and provide additional feature: by setting the parameters of the light source, one can form in the image the illumination information structure determined by the thread profile shape, i.e. one can control the profile in several radial sections.
To analyze the images and make necessary measurements, the work used virtual instruments of National Instruments company (USA) [10] with NI IMAQ Vision artificial vision module [11]. The processing and measurement algorithm was developed in NI Vision Assistant application using IMAQ-Vision functions.

To distinguish the curves of thread profile contours, different algorithms of 2D image processing were used (Fig. 3), including filtration of contrast gradient 3 [1], function of image morphological quality enhancement 5, frequency filtration 6. To determine and give unique identification of the surface relief shape structure, the segmentation function 7 was used [13]. These algorithm functions allow producing new image which distinguishes the shape and character of the thread elements (Fig. 4).

Figure 2. Two-dimensional image of thread specimens

Figure 3. Thread specimens obtained by light field digital camera

Figure 4. Thread specimens obtained by light field digital camera

Figure 4 demonstrates that along with the shape of thread profile, the filtration function distinguishes the micro-relief structure of the halved billet surface 4 and thread 5 (Fig. 4). The geometry of the relief shape was measured by determining the coordinates of contrast curves in the section profile lines of their image [14] in the given geometric region. The algorithms of contrast curve digitization [15] use the method of search and determination of curve maxima coordinates of coefficients of continuous wavelet transformation [16] of the illumination distribution in the image profile lines. This method considers weakly localized character of profile curves in the image and noise factors. Then, the digital camera viewing angle was considered and 3D reconstruction of the thread surface profile.

The image with the relief shape was obtained by the correlation of several image layers [5], located at different distance $z$ along depth $\Delta z$ of the space (along axis Z). The correlation of layers on the basis of chose morphological functions ($M$) determined the geometrical structure and local defects along the height of thread profile surface.
\[ \therefore (\text{Im}_1, \text{Im}_2) = \mathcal{R}_1 \text{Im}_1(z_1, \Delta z_1) \bigotimes \mathcal{R}_2 \text{Im}_2(z_2, \Delta z_2), \]

where \( \therefore \) is the image of correlation of image layers, \( \mathcal{R} \) additionally set transformations of image layers (histogram, shift, scale, rotation).

The layer images were generated by the signal summation algorithm from receiver photo diodes under microlenses which distinguished the combination of rays \( L_i \) that build the surface image by optical system of the light field digital camera \( \Xi \):

\[ \text{Im}(z, \Delta z) = \bigcup_{z \in \mathbb{R}, \mathbb{N} \in \mathbb{M}} L_i \left( \begin{array}{c} x \\ y \\ \varphi \end{array} \right), \]

where \( z \) is the focusing distance of the optical system, \( D_V \) is the virtual aperture of the optical system preset in the conversion software.

The digitization of the image fragments in the near the thread profile edge has demonstrated their shape to correspond to the profile of the taps[5] and increased surface quality in the case of taps with treated surface; they also demonstrated appreciable reduction in the thread working surface roughness (Figs. 2 and 4).

The study results allow concluding that the image recording by light field method forms the information file with geometric shape and relief of the thread surface. Methods for 2D image processing ensure the accuracy of thread profile shape determination close to that of methods of geometric gages and profilographs. The morphological analysis of image layers from the light field file grants the contact-less highly accurate estimation of the height and character of the thread surface micro-relief, which plays crucial role in the determination of thread joint quality.

5. Conclusions

The study has shown the ability to accurately control the geometric parameters of profile shape, micro- and macro-relief of the thread surface by single light field camera with one exposition, which will ensure the industrial application of suggested thread joint control method. Presumably, light field recorders can be the basis for compact mobile instruments for control and diagnosis of qualitative thread parameters.

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