

A flexible image fiber probe based speckle imaging for extraction of surface features with possible application in intra cavity inspection

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ABSTRACT

Non-destructive inspection and non-invasive interrogation of surface features has always been a subject of discussion owing to the rapid advances in engineering and medical fields. Measurement of surface features which are miniature in size, inaccessible and of complex shape, has always posed challenges to conventional types of imaging and metrological systems. This paper, presents a methodology and a miniature image fiber probe configuration based on speckle technology for imaging such surface features, with possible application in intra cavity inspection. In the present work, a metal pipe is used as a test sample representing an engineering cavity. The acquired images of the intra cavity were subjected to image processing for contouring and size estimation. An analysis on the variation in the average speckle intensity, when the speckle image passes through an image fiber, is also carried out in this work. The obtained results indicate that the proposed probe configuration and related methodology can be used for inspection of cavity features and profiles of diffusive surfaces.

Keywords: Fiber optic metrology, Speckle imaging, Intra cavity inspection, Non-destructive evaluation

1. INTRODUCTION

Investigation and extraction of surface features of any component or structure becomes vital to ensure standards of quality and safety^{1,2}. A considerable proportion of component or structural failures can be accounted for improper investigation and poor choice of adopted metrology³⁻⁵. For several decades, researchers have employed various technologies across different domains for the extraction of surface features, specifically adopting non-destructive methods. Common methods currently used to detect surface artefacts include the visual approach (inspection with the naked eye), the liquid penetrant method and the magnetic particle method which are either cumbersome or application specific⁶. The most widely adopted and reliable surface artefact mapping technology currently used is mechanical profilometry, such as stylus instruments which mandates surface contact for measurements⁷⁻¹⁰. More recently, optical technologies have gained importance due to their inherent ability for non-contact measurement¹¹⁻¹⁶.

Among many optical technologies used for metrological applications, speckle technology is gaining importance due to its unique ability of extracting surface feature information^{17,18}. Interference of a large number of random coherent waves scattered from a rough surface, or propagated through a medium of random refractive index fluctuations results in a granular structure known as speckle pattern¹⁹. Laser speckle metrology is extensively explored for nondestructive evaluation (NDE) of various engineering and medical parts or components²⁰⁻²⁶. Various configurations of laser speckle metrology are explored by researchers with the objective of extracting surface features and to obtain relevant parameters of different surfaces²⁷⁻³³.

Particularly, such examination becomes all the more difficult and challenging when the structure to be investigated is inaccessible or related instrumentation becomes cumbersome. There has been an exponential growth in the use of complex and miniature size components used in engineering and medical industries, which in turn demands qualitative and quantitative inspection of their structural components^{2,34,35}. From this perspective, there is still a great demand and market for a suitable and adoptable technology to meet the above mentioned needs. Such technologies are expected to be minimally invasive, non-contact and flexible to extract surface features of inaccessible intra cavities of structural

components accurately. The obvious and most probable choice of methodology is to use a flexible optical fiber probe based investigation system, which can reach hard to access intra cavities of the structure, in combination with technology recognized for surface feature extraction. Use of flexible fiber bundles for collecting speckle images and their implications on the image quality are well explored by many researchers^{36,37}. Considerable work has been carried out for medical and engineering cavity inspection where a flexible fiber bundle is considered as an alternative image conduit for traditional intra cavity inspection^{21,27,38,39}.

In the present work, a non-destructive, non-contact, whole field optical fiber probe based on speckle imaging technology is developed and demonstrated. Preliminary results are shown which illustrates the feasibility of the proposed methodology for identification of defects or artefacts in intra cavities. The results obtained by the adopted methodology are further analyzed using suitable image processing algorithms for contouring of the target site or artefact.

2. EXPERIMENTAL DETAILS

3.1. Experimental setup

Figure 1 shows the schematic diagram representing the optical probe configuration and the related components/accessories used in this study. It fundamentally consists of an illumination fiber arm and a collection fiber arm which are integrated at the distal end of the probe. The illumination fiber is a single mode fiber and the collection fiber arm is made using a specialty image fiber bundle (Fujikura: FIGH-15-600N, Number of cores: 14700, NA: 0.4). An imaging lens is attached at the distal end face of the image fiber so as to collect the speckle pattern formed due to the diffusivity of the target surface. A self-contained thermally stabilized diode pumped solid state pigtailed laser (OZ optics, OZ 2000) of wavelength 635 nm and power 10 mW is used as the light source, which is coupled into the illumination single mode fiber arm. The collected speckle patterns are guided through the image fiber, which acts as the conduit and relays the speckle pattern onto the charge coupled device (CCD) camera through a microscope objective (Mitutoyo infinity corrected 20× objective) lens as well as through a zoom lens attached to the CCD camera. The speckle pattern acquired by the CCD is subjected to image processing using the associated image processing software.

3.2. Methodology

The proposed image fiber based probe system is initially used to find the effective lateral resolution. It is then used to conduct a feasibility study for imaging inside a test specimen cavity as well as to extract and contour a simulated artefact of 1.5mm diameter and 200µm thickness.

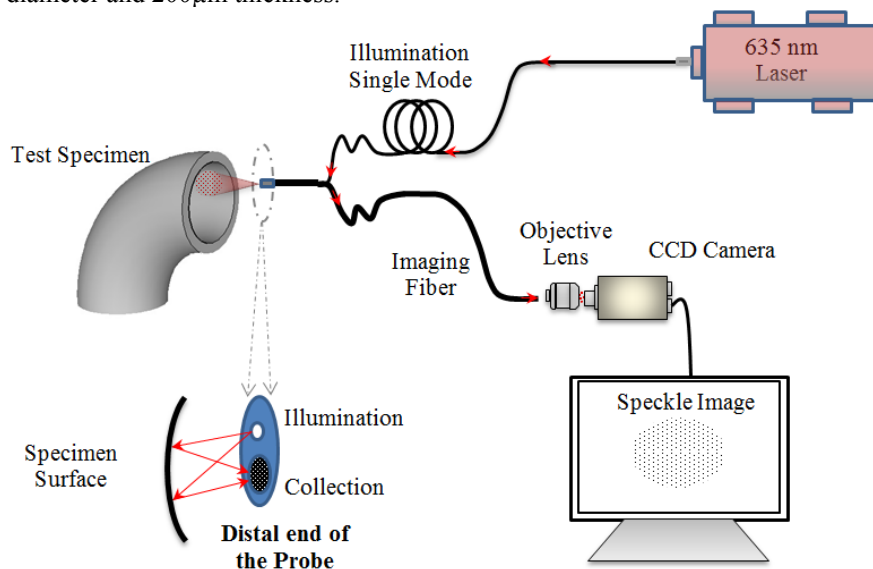


Figure 1: Proposed optical probe configuration, accessories and image processing unit. The targeted test specimen with the simulated artefact is shown next to the distal end of the probe.

As shown in figure 1, the probe distal end is kept static and the test specimen is moved along the optical axis of the probe. It is to be mentioned that the specimen can be kept static and the probe can be under locomotion, which is the subject for future study. The CCD camera captures several sequential speckle patterns representing the instantaneous position of sample surface when the probe or the specimen moves along/across the optic axis. These speckle patterns are further subjected to image processing to extract the required information.

3. RESULTS AND DISCUSSION

3.1 Calibration and characterization of intra cavity image probe configuration

Resolution is defined as the best minimum detectable separation between two definite features of a specimen, to be seen as clear and distinct objects. The spatial (lateral) resolution of the image fiber with associated imaging lenses at the distal and proximal ends are calculated using a Unites State Air Force (USAF1951) chart as the test target^{40,41}.

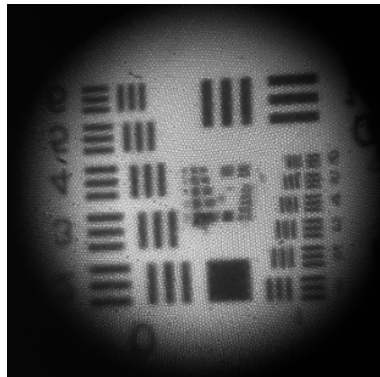


Figure 2 shows the USAF resolution chart comprising several groups and elements, imaging of which can lead to the calculation of the resolution.

Figure 2 shows the image comprising several groups and elements of the USAF chart, which can lead to calculation of the resolution. The mathematical formula used for the calculation of lateral resolution expressed as line pairs per millimeter (lp/mm) of the intra cavity image probe system from the USAF chart is as below

$$Resolution (lp/mm) = 2^{Group+(element-1)/6} \quad (1)$$

It is found that using the developed image fiber probe system, group 6 and element 1 of the of the imaged USAF chart can be best resolved. Hence, the lateral resolution is calculated as 64 lp/mm or 15 μ m.

3.2 Identification and contouring of the artefact

Speckle pattern images obtained using the proposed intra cavity image fiber system are analyzed using codes written with the MATLAB[®] image processing toolbox. Several algorithms such as dilatation, erosion and edge detection are sequentially carried out and analyzed before selecting the precise and suitable scheme of image processing. Figure 3 shows the flow chart depicting the image processing scheme adopted to contour and extract dimensional features of the artefact from the speckle pattern.

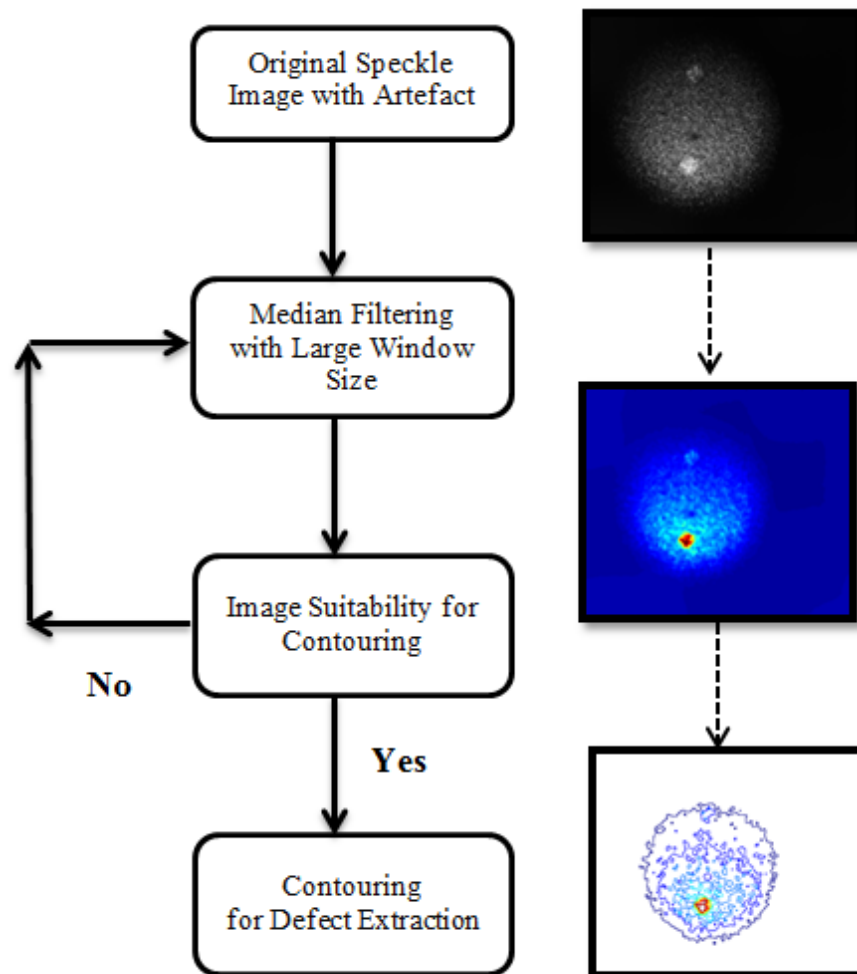


Figure 3. Image processing flow chart adopted for extraction of dimensional features of artefact.

Figure 4 (a) shows the comparison between the speckle pattern of the targeted site with a simulated artefact and the figure 4 (b) shows the image contours representing the simulated defect more prominently after applying the image processing algorithms. The difference in diffusivity and stress distribution of the normal surface and the simulated has contributed to the observed results which helped in easy identification and contouring of the artefact. Figure 4 (b) represents the image contours of the speckle pattern with the simulated artifact which is extracted from the original speckle pattern image. From figure 2, the information on size of each pixel is obtained and used for size estimation of the extracted artefact. Figure 4(b) indicates that the artefact covers about 67 pixels in both x and y axis which is estimated to be around 1.47 mm square sized artefact. This correlates well with the actual size of the simulated artefact which is 1.5 mm with an error margin of <2% in size. This result validates the adopted scheme of image processing algorithm along with feasibility of the developed intra cavity image fiber probe.

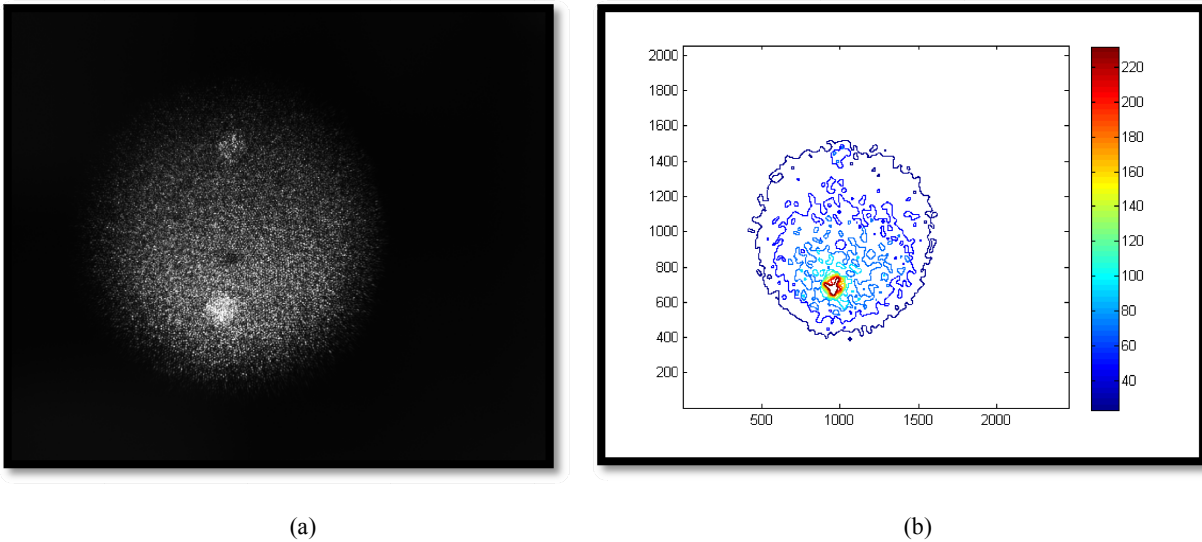


Figure 4. (a) Speckle image of the artefact collected using the intra cavity image probe, (b) Contouring of the speckle image for features extraction of the artefact

4. CONCLUSION

An image fiber based probe and related system is proposed for imaging and contouring of artefacts inside cavities. The proposed methodology is illustrated by taking a curved specimen as the test target. An artefact was simulated at the inner surface of the cavity for experimental validation of the proposed methodology. Appropriate image processing routines were adopted for processing the acquired speckle patterns representing the object surface. The speckle pattern images are subjected to further processing for contouring and the obtained results found to correlate well with the original size of the simulated artefact. It is envisaged that the proposed methodology can be extended with additional features for developing a variant of the same that can be used for micro size cavities for extracting surface features, profiling and for determination of surface roughness parameters.

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