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Handheld non-contact evaluation of fastener flushness and countersink surface profiles using optical coherence tomography

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ABSTRACT

We report the use of spectral domain optical coherence tomography (SD-OCT) for non-contact optical evaluation of fastener flushness and countersink surface profile. Using a handheld galvanometer scanner of only 0.5 lb in weight the SD-OCT can perform line scan surface profile measurement of fastener and countersink without demanding accurate scan center alignment. It demonstrates fast measurement of fastener flushness, radius, slant angle, as well as countersink edge radius and surface angle within 90 ms suitable for handheld operation. With the use of a broadband light source at 840 nm center wavelength and 45 nm spectral bandwidth and a lens of 60 mm focal length, the low coherence interferometry based SD-OCT measurement offers axial depth resolution of 8.5 μm, lateral resolution of 19 μm, and measurement depth of 3.65 mm in the air. Multi-line scans can yield 3D surface profiles of fastener and countersink.

1. Introduction

High speed aircrafts require precise surface profile inspection of fasteners relative to the surrounding surfaces. The fastener flushness is critical to aircraft's aerodynamic performance. The inspection of countersink surface profile and fastener flushness is traditionally performed by contact measurement using a handheld caliper and its modified version [1] and non-contact measurement using a laser line scanner [2] or a structured light [3]. The caliper measurement suffers from gauge contact positioning errors, visual gauge angular alignment errors, and measurement readout errors. It also has slow measurement speed, difficulty in translating the measurement data into a 3D surface profile, and potential surface contact damage. The measurements by laser line scanner offer non-contact non-surface damage assessment of the countersink and fastener flushness, but have limited measurement precision and 3D surface profiling ability. Recently, the structured light measurement in particular fastCHECK introduced by 8tree Inc. is offering an axial resolution of 5 μm and can impressively check the flushness of multiple fasteners at once. However, it does not provide 3D surface profiling inspection and individual measurement of fastener tilting angle, fastener radius, and countersink surface angle.

Optical coherence tomography (OCT) is a low coherence interferometry technique [4] which can perform cross-sectional imaging of biological tissues [5]. It has evolved from earlier time domain OCT with scanning reference arm length to the later spectral domain OCT (SD-OCT) with no reference arm mirror scanning [6–9]. OCT especially the SD-OCT has been developed and is now clinically used for non-invasive non-contact cross-sectional imaging of the posterior [10] and the anterior segments [11] of the eye for detecting early signs of eye diseases and for quantitatively monitoring of disease development and treatment efficacy. It has also been used for dermatological detection of skin abnormality and skin cancer [12,13] and for cardiovascular and larynx imaging [14,15].

With capability of high axial resolution and fast lateral scan imaging, SD-OCT has recently attracted significant interest in industrial measurement applications. In particular, it has been used for surface roughness evaluation [16], fingerprint acquisition [17,18], inspection of fiber coils [19], surface and coating evaluation [20], evaluation of metallic material fractures [21], non-destructive metrology of layered polymeric material [22], and diagnosis of fruit tree disease [23]. However, to the best of our knowledge, SD-OCT has not yet been explored for evaluation of fastener flushness and countersink surface profiles.

In this paper, we report the use of SD-OCT constructed in house for fast non-contact quantitative evaluation of fastener flushness and countersink surface profiles. A handheld scanner of only 0.5 lb in weight is used which is in soft contact with the fastener and countersink surrounding surface for measurement stability. Without accurate scan center alignment, the introduced *X–Y*

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perpendicular two-line scan with vector-based calculation can acquire SD-OCT image data in 44 ms, fast enough to support the handheld measurement operation, and can effectively determine the fastener's center position, radius, relative tilting angle, and its flushness with respect to the surrounding mounting surface. The same *X–Y* perpendicular two-line scan can determine the cone shape countersink's slant surface angle and its edge radius. A multi-line scan can further yield a complete 3D surface profile of the fastener or the countersink, offering high quality 3D surface inspection. The evaluation technique should benefit greatly to quality production and aerodynamic performance of high speed aircrafts.

2. Methods

SD-OCT utilizes a low coherence interferometry technique to examine the interference between two split broadband light beams based on the Michelson interferometer configuration [4,7,8]. As shown in Fig. 1, a superluminescent diode (SLD) light source sends a broadband light through an isolator to a 2×2 single mode fiber coupler that splits the light into two arms; one is the reference arm where the light is reflected back from a mirror, while the other is the sample arm that sends the light beam to the sample (fastener or countersink) through a galvanometer scanner and optical lenses. The scattered return light from the sample is collected by the fiber through the scanner and the lenses to interfere with the reference arm beam at the 2×2 fiber coupler and form spectral dependent interference fringes on the optical spectrometer. The isolator blocks the return light to the SLD to ensure SLD stability and is optional if the SLD stability is not a concern. At each lateral scanning spot position on the sample, the wavelength dependent interference fringe from the spectrometer is acquired and the fringe in the frequency domain is processed by the Fourier transform computation to extract its surface depth (Z) scattering information, which is the A-scan depth profile information. We note here that for measurement of metallic surface, the tomographic based imaging will extract only the surface depth position due to limited beam penetration into the metal. Thus, a lateral scan in X direction (B-scan) will yield a surface X–Z profile in the scanned line direction. A multi-line C-scan (multiple X scan lines at different Y positions) can produce a 3D (X–Y–Z) surface profile of the measurement sample.

Ideally, a single SD-OCT line scan should yield the fastener flushness information, namely the height difference between the fastener and the surrounding mounting surface. If the fastener is tilted at an angle, the two-side of the scan line should show height difference as indicated in Fig. 2.

In a practical measurement operation, the handheld scanner as shown in Fig. 3 will have the circular ring in soft contact (using a mounted plastic or rubber ring) with the surrounding surface to ensure near normal beam scanning while the scan measurement center by visual alignment may be off with respect to the fastener center. We have thus developed an X–Y perpendicular two-line scan pattern to determine the center position of the fastener and the related fastener tilt information without demanding good scanner alignment. As schematically illustrated in Fig. 2, the off center X–Y scan can extract X and Y scan images of the fastener. The measured positions and fastener flushness (height h respect to surrounding surface) information on the scanner coordinate are $(x_1, 0, h_{x1})$, $(x_2, 0, h_{x2})$, $(0, y_1, h_{y1})$, and $(0, y_2, h_{y2})$. For typical small fastener tile angle, the center of the fastener is (x_0, y_0) where

$$x_0 = \frac{x_1 + x_2}{2} \text{ and } y_0 = \frac{y_1 + y_2}{2}. \tag{1}$$

The virtual fastener surface center height h_0 (ignoring the cross-hole used for tightening the fastener) is

$$h_0 = \frac{h_{x1} + h_{x2}}{2} + \frac{h_{y2} - h_{y1}}{y_2 - y_1} y_0. \tag{2}$$

This can be used to obtain the radius R of the fastener

$$R = \sqrt{\left(\frac{x_2 - x_1}{2}\right)^2 + {y_0}^2 + \left(h_0 - h_{x1}\right)^2}. \tag{3}$$

To determine the fastener surface tilting, we first obtain the two fastener surface vectors along the red scan lines $\vec{V}_{f1}$ and $\vec{V}_{f2}$ as

$$\vec{V}_{f1} = (x_2 - x_1)\hat{x} + (h_{x2} - h_{x1})\hat{z} \tag{4}$$

$$\vec{V}_{f2} = (y_2 - y_1)\hat{y} + (h_{y2} - h_{y1})\hat{z} \tag{5}$$

where the $\hat{x}$, $\hat{y}$, and $\hat{z}$ are coordinate unit vectors. The cross-

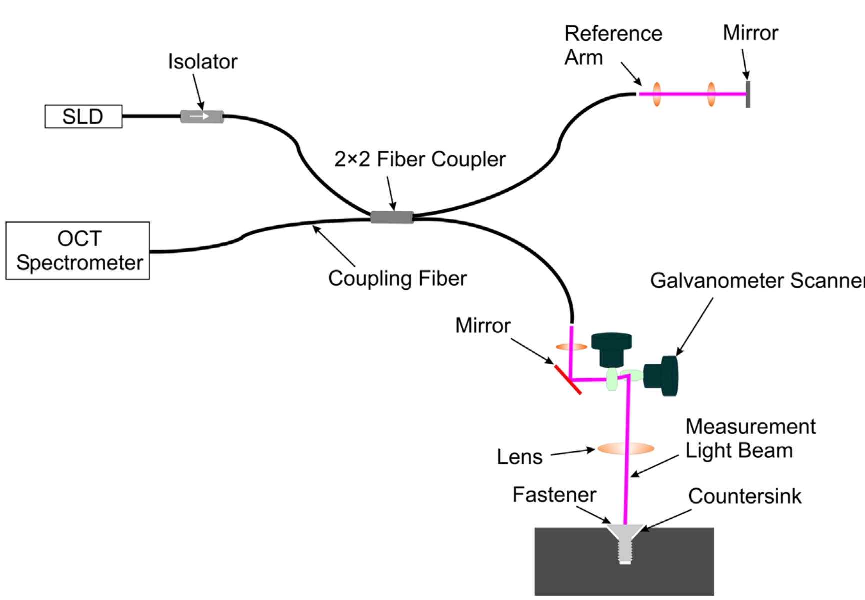

Fig. 1. Schematic of spectral domain optical coherence tomography system for evaluation of fastener flushness and countersink surface profile.