Towards 3D Confocal Imaging with Laser-Machined Micro-Scanner [†]

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Abstract: A micro-scanner made of stainless-steel is fabricated via laser cutting technology for 3D Lissajous confocal imaging. The multi-gimbaled structure of the device provides two orthogonal torsional modes and three different out-of-plane modes. Torsional modes can be used to achieve 2D scan and all of the out-of-plane modes can be used in changing the focus of the micro-scanner to achieve a 3D scanning pattern. One of the out-of-plane modes along with two orthogonal torsional modes can be employed for scanning a large depth-stack in sparse fashion while another out-of-plane mode can satisfy a much higher scan fill-rate with less field of view (FOV). Simulations of the micro-scanner are obtained using finite element method (FEM) software and compared with the characterization data gathered from Laser Doppler Vibrometer (LDV). Using various out-of-plane modes, the constructed fill patterns are simulated on MATLAB and fill rates compared.

Keywords: laser-machined; confocal microscopy; micro-scanner; magnetic actuation; 3D imaging; Lissajous scan; stainless steel

1. Introduction

Among various optical imaging techniques, confocal microscopy draws attention as it provides high optical resolution and increased contrast [1]. Scanning the surface of the sample point by point with laser source while collecting the reflected light as out-of-focus light is eliminated with the help of a pinhole is called laser scanning confocal microscopy (LSCM). The scanner of the LSCM system plays a crucial role as the field of view (FOV), resolution and the frame rate are mainly defined by the structural material and topology of the scanner as well as the actuation technique. Stainless-steel scanner is previously fabricated with laser cutter [2] and 3D operation of a MEMS mirror is realized by using Lorentz force principle [3].

In this study we are focusing on 3D scanning micro-scanner fabricated out of stainless steel with high relative magnetic permeability (grade: 430) which can work in different out-of-plane modes. Laser cutting technology is preferred as fabrication technique since it provides rapid production, high resolution and high accuracy. The proposed scanner generates Lissajous scan pattern satisfying high fill rate. The mode frequencies of the micro-scanner are found using finite element simulations and verified using Laser Doppler Vibrometer. After comparison of simulation and LDV results, a detailed study is provided for different out-of-plane modes in simulation environment using MATLAB.

2. Mechanical Design

Multi-gimbaled scanner is designed to work in different out-of-plane modes along with two orthogonal torsional modes for 3D scan (Figure 1a). In order to demonstrate the operation of the proposed device with different out-of-plane modes, the frequency of the first out-of-plane mode is made as low as possible by playing with the width of the outer flexures. Moreover, the displacement of this mode is also considered and increased to scan the whole sample area. The areas of the gimbals adjusted in a fashion that slow and fast scan modes are separated from the first out-of-plane mode. While the outer flexures controls the slow scan movement of the device, central flexures determines the fast scan. Moreover, inside flexures creates an additional out-of-plane mode with higher frequency to be used to scan a specified location on the sample. On the other hand, second out-of-plane mode is designed to have higher frequency to provide better fill ratio; hence, a more detailed scan. The dimensions and material properties of the proposed scanner are given in Table 1. In order to actuate the scanner, two permanent magnets are fixed close to the mirror with an inclination of 45 degrees to the fast axis scan to get maximum displacement for both slow and fast scan (Figure 1b).

Figure 1. (a) Designed multi-gimbaled scanner. (b) The magnetic actuation principle of the scanner in terms of the interaction of the DC B-field generated by the permanent magnets and the AC flux induced by the external coil.

Table 1. Dimensions and material properties of the fabricated stainless-steel micro-scanner.

Parameter	Symbol	Value
Radius of the mirror	R1	9 mm
Radius of the first gimbal	R2	12.5 mm
Radius of the second gimbal	R3	16.5 mm
Width of the inner flexures	W1	0.14 mm
Width of the center flexures	W2	0.32 mm
Width of the outer flexures	W3	0.41 mm
Length of the inner flexures	L1	5 mm
Length of the center flexures	L2	1.5 mm
Length of the outer flexures	L3	2.8 mm
Thickness of the device	t	0.4 mm
Young's modulus	E	200 GPa
Density	r	7740 kg/m ³
Poisson's ratio	n	0.28

3. Experimental Results

Laser machining technology makes small patterns for a given material easier with high accuracy within a short amount of time. Fabrication process starts with the scanner design in a computer-aided-design software. The proposed design is imported to the software of our custom laser-cutter which directs the focused beam on to the stainless-steel substrate and this process gives the structure its final shape via burning the edges. In order to generate a DC magnetic field, two permanent

magnets are fixed close to the mirror with an inclination of 45 degrees to get maximum deflection for both slow and fast scan axes. As the frequency of the coil drive current is swept between 200–2600 Hz the deflection of the mirror is observed using a Laser-Doppler-Vibrometer (LDV) as given in Figure 2b. Resonance frequencies of the scanner are found by finite-element-method simulations and LDV results, show in good agreement and provided in Table 2.

Figure 2. (a) Fabricated stainless-steel scanner. (b) Frequency response of the device. Exact frequency values of the corresponding modes are provided in Table 2.

Table 2. Comparison of mode frequencies (all in Hz).

	FEM Results	LDV Results
Slow Scan	197	190
Out-of-plane 1	315	313
Fast Scan	337	329
Out-of-plane 2	1357	1296
Out-of-plane 3	2196	2192

4. 3D Scan Analysis

3D scan analysis is performed to observe three dimensional scan performance of the designed scanner. For that purpose, out-of-plane 1 (slow) and out-of-plane 3 (fast) modes, given in Table 2, are chosen to investigate fill rates of considered volumes for slow and fast out-of-plane modes, respectively. A spherical solid with a radius of 15 μm is considered as a target within a volume of 100 $\mu\text{m} \times 100 \mu\text{m} \times 100 \mu\text{m}$. Firstly, the whole volume is scanned with slow out-of-plane mode which has better displacement (Figure 2b). Scanned volume is considered as a 3D matrix (36, 36, 36) which results in 36 slices along the z-direction. Scan duration is set to 0.15 s for demonstration purpose, and fill rate of the target is found as 8% (Figure 3a). The corresponding axial slices for five different axial positions are given in Figure 3b. There are three different color seen on the slices such as white, blue and red. They represents unscanned, scanned and sphere unit cells, respectively. Then, intersection of blue and red unit cells is gathered to construct scanned unit cells of the sphere. The corresponding slices of constructed sphere is shown in Figure 3c. Thus, rough image of the target is detected by the scanner that operates in slow out-of-plane mode as shown in Figure 3d. Since the rough image of the sample obtained, this time the sample is scanned within a volume of 50 $\mu\text{m} \times 50 \mu\text{m} \times 50 \mu\text{m}$ with fast out-of-plane mode which has better fill ratio. As expected, fill rate of the target is increased to 25.7% for 70 the same scan duration as shown in Figure 3e. The corresponding axial slices for five different axial position are found as in Figure 3f,g and the reconstructed image is shown in Figure 3h. The axial positions are chosen as close as possible to the slow out-of-plane mode case. Furthermore, for a scan duration of 0.5 s, 24% and 69% fill rates are found for slow and fast out-of-plane mode, respectively.

Figure 3. 3D Lissajous scan of a spherical solid with a radius of $15\ \mu\text{m}$ within a volume of $100\ \mu\text{m} \times 100\ \mu\text{m} \times 100\ \mu\text{m}$ for slow scan (a) and within a volume of $50\ \mu\text{m} \times 50\ \mu\text{m} \times 50\ \mu\text{m}$ for fast scan (e). Demonstration of z axis slices for slow (b) and fast scan (f). Detected pixels of five different slices for slow (c) and fast scan (g). Reconstructed image for slow (d) and fast scan (h).

5. Conclusions

A laser-machined stainless steel micro scanner is designed and manufactured to work in different out-of-plane modes for confocal microscopy. The proposed device accomplish a 3D Lissajous scan in a volume of $100\ \mu\text{m} \times 100\ \mu\text{m} \times 100\ \mu\text{m}$ to detect the sample by using its lowest out-of-plane mode along with the torsional modes then it scans a reduced volume of $50\ \mu\text{m} \times 50\ \mu\text{m} \times 50\ \mu\text{m}$ with its highest frequency out-of-plane to get a sharper image. The main purpose of this work is to produce a low cost micro-scanner to be used in confocal microscopy setup for 3D imaging.

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Conflicts of Interest: The authors declare no conflict of interest.

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