Estimation of vibration amplitude in Fourier domain optical coherence tomography interferometric signals from Doppler spectrum

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Abstract: In presented method combination of Fourier and Time domain detection enables to broaden the effective bandwidth for time dependent Doppler signal that allows for using higher-order Bessel functions to calculate unambiguously the vibration amplitudes.

OCIS codes: (110.0110) Imaging systems; (170.0170) Medical optics and biotechnology

1. Introduction

One of the most important capabilities of novel imaging techniques using Optical Coherence Tomography is ability to further enhance imaging contrast and to increase accuracy of tissue selectivity. In elastography OCT (OCE) the elastic properties of different biological samples, while applying a vibrational motion, can be extracted either from Doppler spectrum of the signal in TdOCT or by straightforward application of the phase-sensitive Fourier domain OCT technique.

The aim of this work is to propose a method of measuring the vibration amplitude in a sample, which is stimulated by a macroscopic oscillatory excitation. To measure Doppler signals we use the combination of Fourier and time domain (STdOCT) detection scheme. We believe that this scheme, which in our opinion can be more robust and advantageous over the phase-sensitive technique, should facilitate broadening the effective detection bandwidth for time dependent signals, which means that higher-order Bessel functions could be used to calculate the displacement amplitude without ambiguity.

2. Methods

Fourier-domain OCT setup detects the interference of a reference light and a light coming from a sample. In the case of OCE the sample is stimulated by a sinusoidal vibration along the optical axis by means of a piezoelectric transducer, magnetic field or acoustic radiation force. If the reference arm is considered to be static, the detected signal can be written as:

$$I(t) = A \cdot cos\big(\varphi + \theta \cdot sin(2\pi\Omega t)\big) \qquad (1)$$

where A is proportional to the optical intensities at the reference and sample arms and the photodetector responsivity and φ indicates the phase at the static reference arm. Equation 1 can be expanded as a series of Bessel functions:

$$I(t) = A\{cos(\varphi)(J_0(\theta) + 2\sum_{n=1}^{\infty} J_{2n}(\theta)cos(4\pi n\Omega t)) - sin(\varphi)(2\sum_{n=1}^{\infty} J_{2n+1}(\theta)sin(2\pi(2n+1)\Omega t))\} \qquad (2)$$

where J_n represents the n-th order Bessel function of the first kind. Basing on the theory of Bessel functions, the recurrent equation that relates subsequent Bessel function with the previous ones leads to the following estimate of the vibration amplitude:

$$\theta_n = \frac{2nJ_n(\theta)}{J_{n+1}(\theta)+J_{n-1}(\theta)} \qquad (3)$$

Basing on Eq. (2), the amplitude of the odd Bessel functions is proportional to $sin\varphi \cdot J_{2n+1}(\theta)$ and the even Bessel to $cos\varphi \cdot J_{2n}(\theta)$. To cancel the dependency on φ in Eq. (3) and to reduce possible extra source of errors, consecutive odd θ_{2n+1} and even θ_{2n} terms can be multiplied.

$$\theta_n^2 = \theta_{2n} \cdot \theta_{2n+1} = \frac{4 \cdot 2n(2n+1)J_{2n}(\theta)J_{2n+1}(\theta)}{\big(J_{2n+1}(\theta)+J_{2n-1}(\theta)\big)\big(J_{2n+2}(\theta)+J_{2n}(\theta)\big)}, n = 1,2,3, \dots L-1 \qquad (4)$$

where L represents the maximum number of detected Bessel harmonics. Fig. 1E shows exemplary Doppler spectrum of the interferometric signal with the phase modulation caused by a vibration of the sample. Each amplitude of the discreet harmonics in the Doppler spectrum corresponds to the value of consecutive order of Bessel function for vibration amplitude and the spacing between harmonics is equal to the vibration frequency.

There are two known ways of reconstructing the amplitude of object vibrations: 1. to measure value of chosen orders of Bessel functions and recalculate θ by using certain combination of ratios of amplitudes; 2. to analyze the spectral spread (or variance) of the Doppler spectrum. In this submission we propose introducing new way of measuring the vibration amplitude, using combination of modified Bessel-ratio and spectral spread techniques. To extract the Bessel harmonics the STdOCT processing scheme is used.

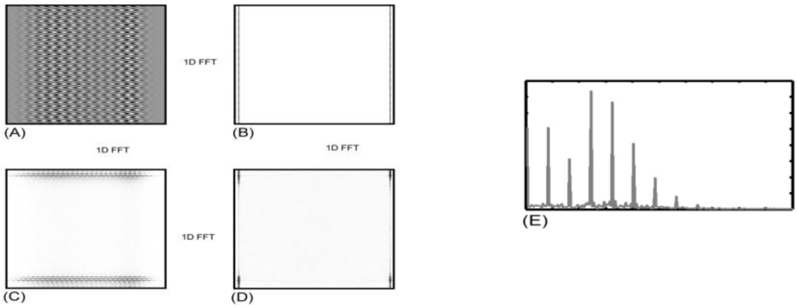
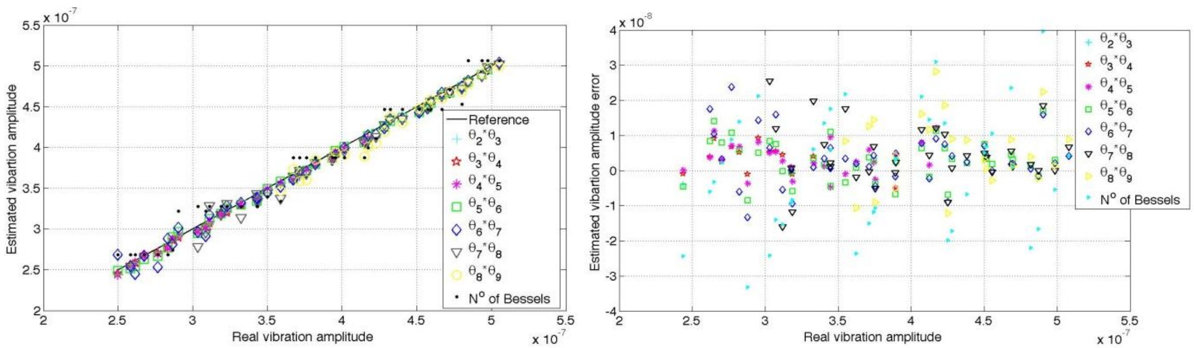


Fig. 1. Joint Spectral and Time domain OCT analysis of interferometric signal with oscillatory phase modulation

Let's consider a set of spectral fringes dependent on time, which are acquired at the same location of a vibration sample. The spectral fringes are arranged into a two-dimensional array where they are positioned along the x-axis (Fig. 1A). A Doppler frequency arising from the movement of the sample is visible along the y-axis, whereas the information about the sample location (depth) is encoded along the x-axis. Therefore, a fast Fourier transform (FFT) performed on the x-axis will provide the information of the depth/location (Fig. 1B) and a FFT on the y-axis - the information of the velocity (Fig. 1C). Finally, a second FFT of the obtained data along the x-axis will produce a combined structural and velocity image (Fig. 1D). From this data we can obtain a Doppler spectrum which contains the set of L Bessel harmonics that are related to the vibration amplitude. The Bessel function peaks can be detected, extracted and labeled (Fig. 1E). Once the values of Bessel functions are obtained, a set of candidate amplitudes can be extracted by using Eq. (4). By using the criterion of the three consecutive values the correct amplitude of vibration can be calculated.

3. Results

The method was experimentally validated on a Fourier-domain OCT system. A vibration of mirror mounted on piezo actuator was mounted in the object arm. The vibration amplitude was set 40 times from 250 nm to 500nm at 800 Hz, this value was calculated form piezo actuator response using the um/V ratio given by manufacturer and verified experimentally by the phase-sensitive technique. Single A-scans were collected with repetition time of 80 μs. Each experiment was repeated 10 times. Fig. 2 shows results of vibration amplitude measurement using different combinations of Bessels harmonics – each index corresponds to three Bessel harmonics starting from indexing number (Eq. 4): $\theta_n \rightarrow J_n, J_{n+1}, J_{n+2}$.



Fi. 2. Experimental results for 800Hz frequency vibrations with variable amplitudes between 250nm and 500nm (mean values). Left: results of measurement of vibration amplitude. Right: error of measured amplitude for different combinations of four consecutive Bessel harmonics. Reference measurement was performed with the phase sensitive method. No. of pixels represents the measurement of the spectral spread.

4. Conclusions

A method of estimation of vibration amplitude using OCT has been proposed and demonstrated. The approach uses STdOCT processing scheme to extract the Bessel harmonics and a practical methodology to extract information about the vibration amplitude in a sample, which is under certain motion. Simulation and experimental results using a Fourier-domain OCT, both further proof the method. The proposed method appears to be robust preserve its performance under low SNR, in the simulation and experiment carried out for this manuscript the method shows error within a 5% interval. This approach demonstrated with interferometric type signals can be also applied to a variety of techniques and applications.