euspen's 22nd International Conference & Exhibition, Geneva, CH, May/June 2022
www.euspen.eu

Compare in-plane vibration frequencies and modes of tuning fork using FEM simulation and sampling moiré method

Mona Yadi [1, 2], Yasuhiro Takaya [1], Yasuhiro Mizutani[1], Tsutomu Uenohara[1], Yoshiharu Morimoto [2, 3], Masaki Ueki [2]

[1] *Department of Mechanical Engineering, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan*
[2] *4D Sensor Inc.,579-1, Umehara, Wakayama 640-8550, Japan*
[3] *Wakayama University, 930, Sakaedani, Wakayama 640-8510, Japan*

E-mail: mona@optim.mech.eng.osaka-u.ac.jp

Abstract

Investigation of in-plane vibration modes has huge benefits in the predictive maintenance of industrial machines. Besides, this kind of study shows an interesting field of work in precision measurement. As an example, in-plane vibration modes of a quartz tuning fork (QTF) recently used for multi-frequency scanning near-field optical microscopy and the mode sensing performance of the QTF-prob is an important issue for characterizing the tip-sample interactions and achieving higher resolution microscopic imaging. However, the study of in-plane vibration mode shape was limited to using the finite element method. Recently, some optical methods were developed for vibration investigation which sampling moiré method was exclusively developed for in-plane vibration investigation. In this study, we introduced a new discussion on the capability of the sampling moiré method on the detection of in-plane vibration natural frequencies and mode shapes of a tuning fork. The reason for using a tuning fork as a specimen in this study is the appearance of two symmetrical in-plane vibration modes during its vibration. The in-plane symmetrical vibration modes of tuning forks are also audible, which made it suitable for acoustic analysis. In this study, in-plane vibration frequencies and mode shapes of an under struck tuning fork detected using an optical method named sampling moiré method. Then, extracted frequencies compared with Fast Fourier Transform (FFT) results of tuning fork's recorded sound during its vibration. Furthermore, mode shapes extracted from sampling moiré experimental results, which are phase distribution graphs in each frequency, compared with predicted natural frequencies and mode shapes using the finite element method. This study shows good potential in the newly developed optical method for in-plane vibration detection as the first in-plane vibration mode (fundamental mode) of the tuning fork and its harmonics were completely detectable. However, the second in-plane mode was not detectable due to its short amplitude which makes room for more future works.

Keywords: sampling moiré, vibration frequency, frequency mode shape, finite element method (FEM), quartz tuning fork, optical microscopy

1. Introduction

Vibration frequency mode shapes allow the evaluations of the displacement amplitude in the whole sample's surface. Besides, this kind of information is used as a maintenance factors in industrial point of view. Using mechanical or electrical devices for detecting mode shapes is expensive in terms of both money and time. In addition, it cannot provide accurate results in mode detection as they must be attached to the surface of the specimen. Optical methods, on the other hand, shows much capability and resolution as these techniques do not need any attachment to the surface of the sample. As an example, the optical method which is used recently for out of plane vibration analyzing in [1], shows one of the most powerful analyzing methods in measuring vibration frequencies and mode shapes.

The only known method for in-plane frequency mode shapes investigation of specimens is finite element method (FEM) [2,3]. The FEM is a general numerical method for solving partial differential equations in two or three space variables. It uses theoretical algorithms in finite subdivided elements of a large system and approximate the behavior of that system during vibration. Although, FEM works like a calculator in measuring mechanical behavior of variety of speciemens; however, it can be very inaccurate in the hands of the inexperienced engineer.This fact, makes scientists to think about experimental approaches as an alternative.

The author recently developed one optical method for measuring the in-plane vibration of a healing tuning fork [4] which sampling moiré method used for in-plane frequency mode shap's recognition of a tuning fork during attack by a hammer. As the tuning fork shows two symmetrical in-plane vibration modes, it uses as a popular speciemen for in-plane vibration and/or displacement studies. In this article, capability of new in-plane vibration analysing method [4] and FEM simulation of same tuning fork is studied more deeply. At first, the experimental results of frequency amounts is compared with post processing of recorded sound data. Then, the extracted frequency mode shapes of experimental data is compared with result coming from finite element method.

The outline of this paper is as follows: In section 2 we discussed the steps toward the whole in-plane vibration detection through the theory of sampling moire method, and the principle of in-plane vibration detection besides the finite element method which used for comparison, explained in detail. The experimental setup and results is addressed in section 3. The whole study is concluded in section 4.

2. Method

2.1. In-plane vibration analysing using sampling moire method

In sampling moiré method, a cross grating is attached to the specimen surface and a camera would take the images and transfer them to a computer for post-processing. Then down-sampling is performed on the captured image, i.e. every N-pixel (in this figure1, N = 1) from the first column of camera pixel is chosen and recorded as first moiré fringe pattern (figure 1(c)). Then, sampling is shifted to the second column of camera pixels, and the second moiré fringe which has 2π/N phase shift appears (figure 1(d)).

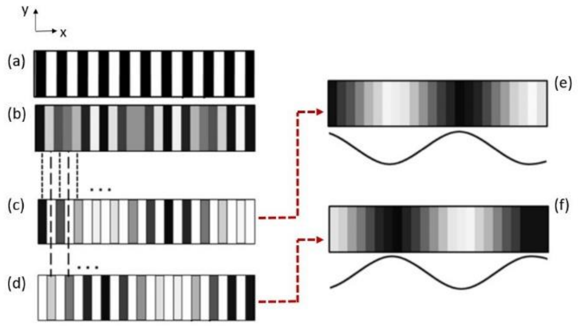


Figure 1. Principle of sampling moiré method: (a) attached grating on the surface of specimen; (b) intensity of recorded image by camera; (c, d) down-sampled intensity; (e, f) moiré fringes

As [4] completely explain, using the intensities of sampling moiré fringes, the phase of moiré fringes can be calculated, as shows in equation (1) and (2).

$$\mathrm{I}_d(j,j) = \mathrm{I}_a(j,j)\cos\left[\emptyset_m(i,j) + 2\pi\frac{d}{N}\right] + \mathrm{I}_b(i,j) \qquad (1)$$

$$d = 0,1,\ldots,N-1$$

$$\emptyset_m(i,j) = -\tan^{-1}\frac{\sum_{d=0}^{N-1}\mathrm{I}_d(i,j)\sin\left(\mathrm{d}\frac{2\pi}{N}\right)}{\sum_{d=0}^{N-1}\mathrm{I}_d(i,j)\cos\left(\mathrm{d}\frac{2\pi}{N}\right)} \qquad (2)$$

Using equation (2) and subtract phase data before and after displacement will give the accurate amount of displacement which uses for measuring in-plane vibration. A software is developed based on LABVIEW software for post processing of the recorded images.

2.2. FEM analysis

The finite element (FE) technique is a numerical technique in which a continuous elastic structure, or continuum, is discretized into small but finite substructures, known as elements. Elements are interconnected at nodes. In this way, a continuum with infinite number of degrees of freedom can be modeled with a set of elements having a finite number of degrees of freedom. It is noted that while each finite element represents a continuous system by itself possessing infinite number of DOF, we can choose the size of the element to be small enough, so that the deformation within the finite element can be approximated (interpolated) by relatively low-order polynomials.

In this study SolidWorks software is used for analyzing FEM of a tuning fork as can be seen from figure 2.

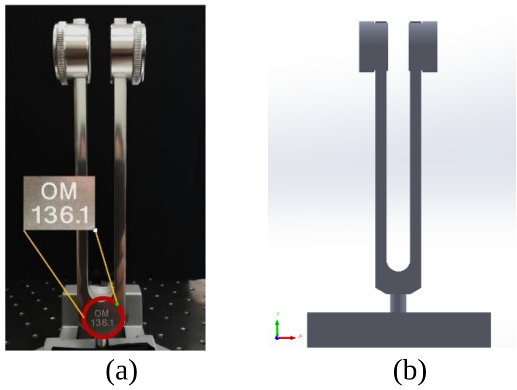


Figure 2. Experimental devices: Under experiment tuning fork (a) and CAD design of the tuning fork (b)

3. Experiment and results

3.1. Acoustic analysis of tuning fork's recorded sound

Russell et al [5] study shows that, when a tuning fork struck softly, the resulting sound is a pure tone at the frequency of the fundamental symmetrical mode of the tines. But, when this same fork is given a slightly harder impact at the tip of the tine, both the fundamental and also the second modes are excited. The second mode called the "clang" mode, wich has a frequency of slightly more than six times the frequency of the fundamental (when both end of the fork be free). The 136.1 Hz tuning fork which is shown in figure2(a) hitted hard enough that signal analysing of its recorded sound showed the two fundamental and clang frequency modes in 140 Hz and 1324.3 Hz, respectively (figure 3). The fundamental frequency has less than 3% error compare with fork's real frequency. The clang mode appeared in a different frequency compaered by what Russel et al claimed which is because in this experiment the stem of the fork is fixed by some fixture. This frequency results shows the vibration frequencies (most audible frequencies) that a tuning fork shows during the vibration. In the following, frequency mode shapes come from the finite element analysis is investigated.

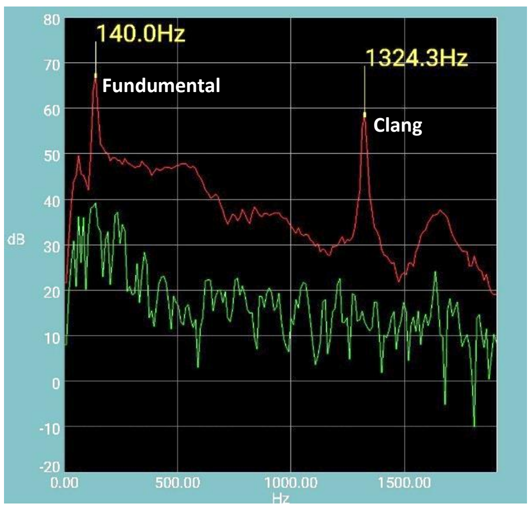
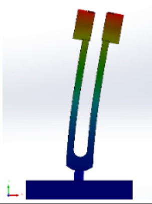
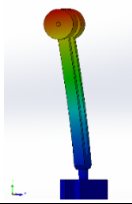


Figure 3. Frequency spectra resulting from a hard blow at the tip of the tines. Green signal is the recorded sound and the red one is the FFT of the recorded signal.

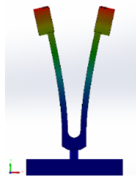
3.2. FEM results of tuning fork vibration modes



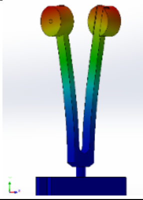
(a) Mode1, 101.62Hz



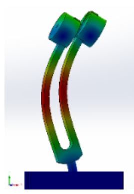
(b) Mode2, 127.71 Hz



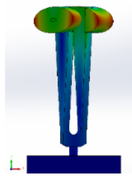
(c) Mode3, 135.45 Hz



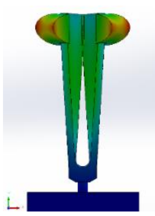
(d) Mode 4, 206.08 Hz



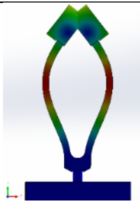
(e) Mode5, 900.92 Hz



(f) Mode6, 1067 Hz



(g) Mode7, 1133.8 Hz



(h) Mode8, 1303.6 Hz

Figure 4. FEM mode shapes of tuning fork. (a) and (e) nonsymmetrical in-plane modes; (b) and (d) out of plane modes; (c) fundamental mode; (f) and (g) tortional mode; (h) clang mode

Accurate CAD design of tuning fork is used for finite elements frequency analysis. The tuning fork is simulated using aluminum alloy (7079) as its material. Two solid plate plus rubber is simulated as a fixture of the fork and high quality curvature-based mesh with total elemnt numbers of 97099 is used in frequency analysing of the fork.The extracted frequency modes are shown in Figure 4.

When the fork is held at the stem, the normally observed vibrational mode shapes, the shapes that give rise to the sound of the fork, are symmetrical modes in which the tines move in opposite directions (figure 4(c) and (h)). Using FEM, the fundamental and clange modes are 135.45 Hz and 1303.6 Hz, respectively. FEM shows a good match with signal processd data (section 3.2), in formation of two in-plane frequency modes. Besides, the frequency amounts have less than 4% difference and less than 1% error compare to fork's real frequency. In the following, experimental results using sampling moire method is compared with section 3.1 and 3.2 results.

3.3. Sampling moire analysing for investigation of in-plane frequency modes

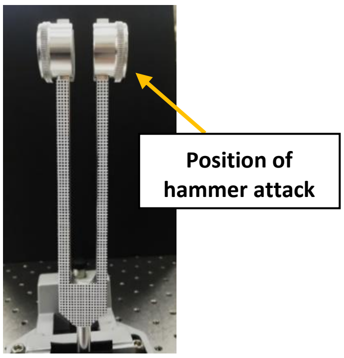
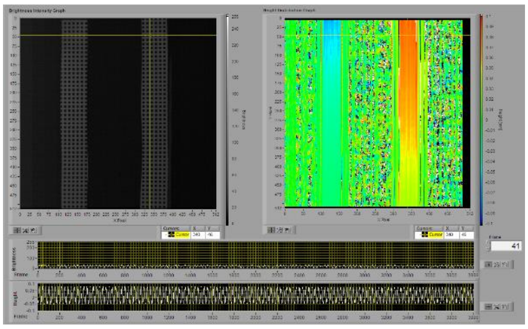


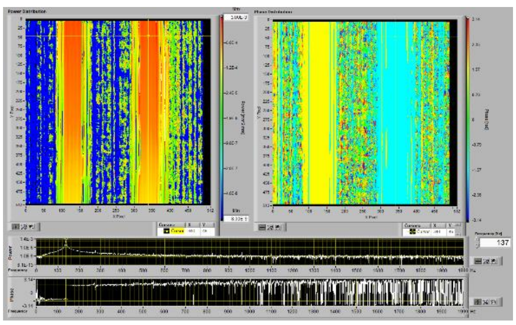
Figure 5. Specimen with attached grating on the surface

In this section accuracy of new developed method for in-plane vibration analyzing is checked. The same tuning fork as what studied in [4] is used in this experiment.

A cross grating with the pitch of 1 mm attached to the surface of tuning fork. The in-plane displacement can be measured with the accuracy corresponding to 1/1000 of grating pitch [7,8] so in this experiment the displacement accuracy using sampling moire method would be 1 micron. A high-speed camera captured images of tuning fork after being struck by hammer for 1 second. The camera captures 4000 images per second.

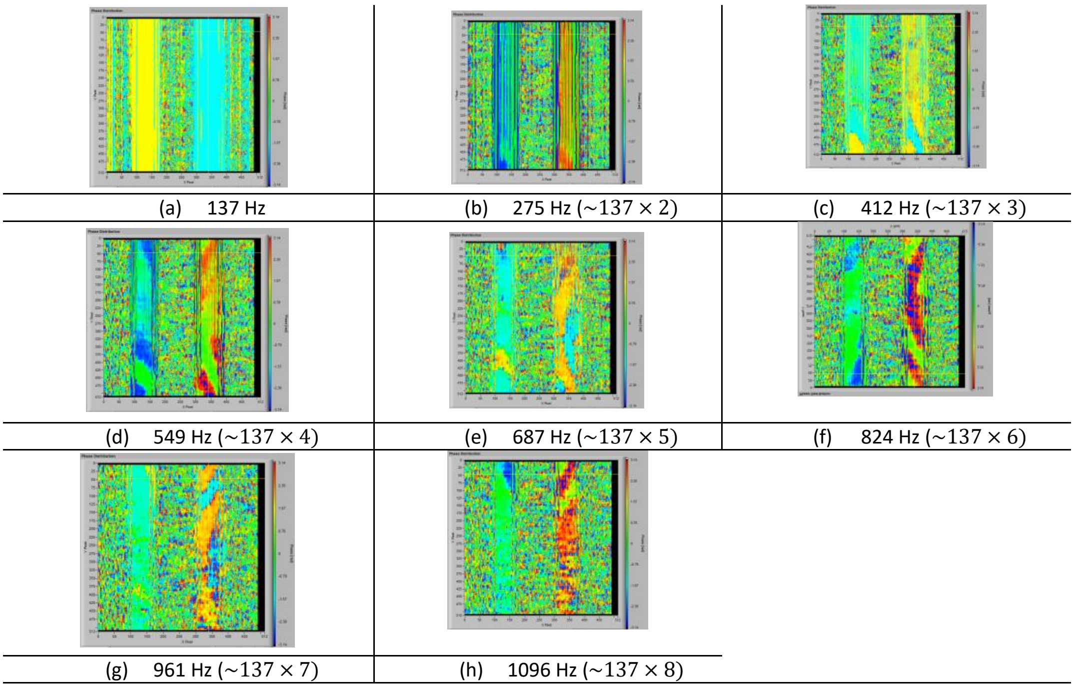


(a) brightness intensity/displacement graphs and waveform for all captured images



(b) power/phase distribution graphs and waveforms

Figure 6. Front panel of developed Labview software



(a) 137 Hz
(b) 275 Hz ($\sim 137 \times 2$)
(c) 412 Hz ($\sim 137 \times 3$)
(d) 549 Hz ($\sim 137 \times 4$)
(e) 687 Hz ($\sim 137 \times 5$)
(f) 824 Hz ($\sim 137 \times 6$)
(g) 961 Hz ($\sim 137 \times 7$)
(h) 1096 Hz ($\sim 137 \times 8$)

Figure 7. sampling moire method, phase distribution graph; (a)fundamental frequency mode; (b-h) harmonics caused from non-linear behavior of tuning fork

Recorded images possed processed using method mentioned in section 2.1. Figure 6 shows the LabVIEW software front panel developed for in-plane vibration measurement.

Detection of frequency modes is possible using both power and phase distribution graphs. In Figure 7, extracted phase distribution data in frequency range of 0-2000Hz is shown.

Regarding figure 7 results, using sampling moire, fundamental frequency mode of tuning for is clearly detected in 137 Hz (figure7(a)) which has less than 1% error compare to the fork's reall frequency. Also, the non-linear behavior of the tuning fork is also detected as some random patterns in phase distribution graph. When the fork is struck vigorously. In that case, the elastic restoring forces become non-linear and the resulting radiated sound contains clearly audible integer multiples of the fundamental which are not frequency modes [5]. In this experiment, eight harmonics was detectable which FEM is not capabale for detecting this harmonics. The clang mode was not detectable due to the small amplitude amount of this frequency which should be around 1300 Hz.

4. Conclusion

The in-plane vibration analysing method described has been shown to have the same accuracy with FEM in detecting fundamental frequency mode of a tuning fork. This method showed capability in detection of non-linear behaviour of tuning fork during the vibration which is not detectable in finite element method. The second in-plane frequency mode was not detectable using sampling moire method due to its small amplitude. This will be a good topic in future analysing of the vibration using proposed method. Also, accuracy of FEM is highly related to the accuracy of the user in simulation of speciemen. But sampling moire method which has been explained in this article is a powerful optical method which doesn't need any data of speciemen like it's mass, material ,etc. This facts makes analysing much faster, cheaper and also accurate. Study of in-plane vibration of a tuning fork opend doors on investigation of vibration behaviour of mechanical vehicels due the predictive maintenance of them. Besides, this kind of study shows an interesting field of work in precision measurement. As an example, in-plane vibration modes of a quartz tuning fork (QTF) recently used for multi-frequency scanning near-field optical microscopy and the mode sensing performance of the QTF-prob is an important issue for characterizing the tip-sample interactions and achieving higher resolution microscopic imaging.

References

[1] Morimoto, Y., 2020. High-Speed Measurement of Shape and Vibration: Whole-Field Systems for Motion Capture and Vibration Modal Analysis by OPPA Method. Sensors, 20(15), p.4263.

[2] Hwang, Y.F. and Suzuki, H., 2016. A finite-element analysis on the free vibration of Japanese drum wood barrels under material property uncertainty. Acoustical Science and Technology, 37(3), pp.115-122.

[3] Killgore, J.P., Tung, R.C. and Hurley, D.C., 2014. Characterizing the free and surface-coupled vibrations of heated-tip atomic force microscope cantilevers. Nanotechnology, 25(34), p.345701.

[4] Yadi, M., Morimoto, Y., Ueki, M. and Takaya, Y., 2021. In-plane vibration detection using sampling moiré method. Journal of Physics: Photonics, 3(2), p.024005.

[5] Russell, D.A., 2020. The Tuning Fork: An Amazing Acoustics Apparatus.

[6] Rossing, T.D., Russell, D.A. and Brown, D.E., 1992. On the acoustics of tuning forks. American journal of physics, 60(7), pp.620-626.

[7] Ri, S., Fujigaki, M. and Morimoto, Y., 2010. Sampling moiré method for accurate small deformation distribution measurement. Experimental mechanics, 50(4), pp.501-508.

[8] Ri, S. and Muramatsu, T., 2012. Theoretical error analysis of the sampling moiré method and phase compensation methodology for single-shot phase analysis. Applied optics, 51(16), pp.3214-3223.