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Single-Shot Digital Holographic Interferometry Using a High Power Pulsed Laser for Full Field Measurement of Traveling Waves

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Abstract. In the past, interferometric holographic techniques have been used extensively to perform full-field, yet time-averaged analysis of vibrational patterns. When time-resolved information was needed, optical scanning single-point measurement techniques, such as heterodyne interferometric vibrometry, were available. Recently, stroboscopically illuminated digital holography has proven to yield both full-field and time-resolved information of vibrations with nanometer range amplitudes. In this technique, short laser pulses, synchronized to the vibration phase, are recorded. Good results have been achieved for high-frequency vibrations. However, due to the low energy in a single pulse, acquisition time increases for decreasing vibration frequency in order to receive enough energy on the camera, introducing problems such as artifacts due to slow movements of the object or electronic read-out noise.

In this work, stroboscopic holography is combined with a high power, frequency doubled pulsed Nd:YAG laser, which produces enough energy in a single pulse to perform single-shot holographic recordings. This new setup allows imaging vibrations ranging from quasi-static deformations to high-frequency vibrations (1 – 20000 Hz), while avoiding the earlier mentioned acquisition issues. The additional challenge is to synchronize the lasers flash tube and Q-switch to the image acquisition and the vibration phase of the measured object.

Results of measurements on a stretched circular latex membrane will be presented. The out-of-plane displacement of the membrane is visualized over the entire surface as a function of time, thus providing true four-dimensional information. Extracting the vibration phase map is useful, for instance to reveal travelling waves, which are invisible on time averaged images.

Keywords: Digital Holography, Time –resolved vibrometry
PACS: 42.40.Kw

INTRODUCTION

The advantages of digital holography over its analogue counterpart are versatile. One is the fact that phase information of the object wave can be accessed directly, so that interferometric measurements provide quantitative and overall more valuable information. In combination with stroboscopic illumination, a powerful technique becomes available to investigate vibrational patterns on objects with a depth resolution in the nanometer range.

In the section 'Digital holographic recording', the recording principle and limitations of the setup are addressed. Next, the introduction of high-power stroboscopic illumination to perform holographic vibrometry measurements is explained in 'Stroboscopic illumination'. A conceptual comparison with other techniques can be found in 'Comparison with other techniques'. The section 'Timing sequence' describes the microprocessor based timing sequence. Finally, results of measurements on a vibrating stretched circular rubber membrane, driven by a sound source, are presented in 'Results'.

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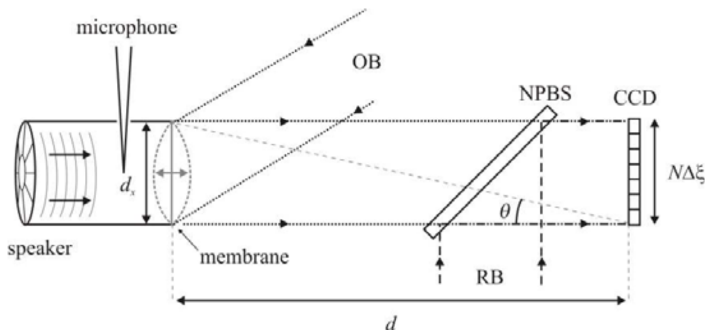

FIGURE 1. Digital holography setup. The object (in this case, a membrane) reflects the OB onto the CCD. In a non-polarizing beam splitter (NPBS) the OB is combined with the RB. To reduce the interference angles, a quasi-inline arrangement is chosen. However, even in an inline arrange there are angles between the waves. The indicated angle θ is the maximal angle between the OB and the RB. For vibration measurements the membrane is acoustically driven by a speaker. The sound pressure level is monitored by a probe microphone.

DIGITAL HOLOGRAPHIC RECORDING

Digital holography consists of recording the interference pattern of two waves, the object beam (OB) and the reference beam (RB), on a lensless digital imaging device, such as a CCD array. The larger the angle θ between these waves, the smaller the distance p between the interference fringes will be:

$$p = \frac{\lambda}{2\sin\frac{\theta}{2}}, \tag{1}$$

with λ being the wavelength of the used laser light. There are two ways to prevent us from violating the Nyquist theorem: increase the pixel density of the CCD or reduce the angle between the object and reference wave, the latter being the easiest and less expensive way. The first measure to be taken is to choose a quasi-inline arrangement (Figure 1).

Yet there are still angles between some parts of the beams, setting a lower limit to the distance d between the CCD and the object. For each dimension x and y, this distance has to obey (see chapter 'Digital Recording and Numerical Reconstruction of Wave Fields' in [1]):

$$d > \Delta\xi \frac{(d_x + N\Delta\xi)}{\lambda}, \tag{2}$$

with $\Delta\xi$ being the pixel center-to-center distance, N the number of pixels and d_x the object size.

The used reconstruction algorithm in this work is based on the Fresnel propagation of light waves. A computational consequence is that, after reconstruction, only one half of the pixels contain the actual real image of the object (Figure 2). The size of the field of view (FOV) is fixed in this method and given by:

$$S_x \times S_y = \frac{d\lambda}{\Delta\xi} \times \frac{d\lambda}{\Delta\eta}, \tag{3}$$

with $\Delta\eta$ being the pixel center-to-center distance in the second dimension. This reconstruction algorithm produces different diffraction orders, similar to light diffraction in non-virtual optical experiments. The 0^{th} order beam is called the DC-term, the two 1^{st} order beams are called real and virtual images. Although they contain the exact same information, only one of them can be reconstructed sharply and in-focus at the same time. In order to separate the real image from the disturbing influences of the other beams, a slight off-axis arrangement is to be used, hence the

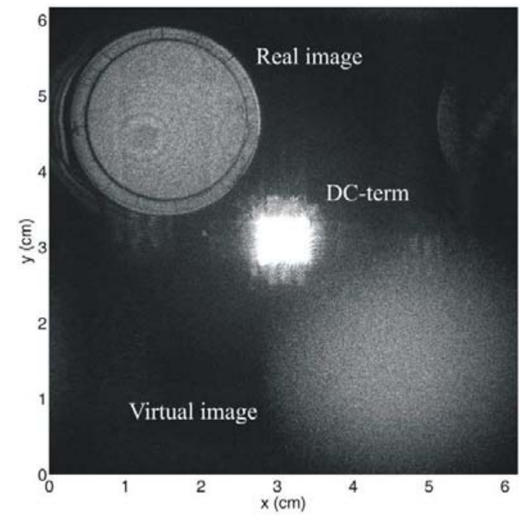

FIGURE 2. Example of a Fresnel reconstruction of a digital hologram of a circular membrane. The complex modulus or intensity of the reconstruction is shown. Due to an off-axis setup, the three main components, DC-term, virtual and real images, are separated. The disadvantage is that only half of all pixels are used for the real image.

term *quasi*-inline arrangement. For clarity considerations, this off-axis aspect is not made visible on the setup in Fig. 1. Because of this necessity, only a part of the image can be used for the real image.

STROBOSCOPIC ILLUMINATION

Using a frequency-doubled high-power pulsed Nd:YAG laser, we realize stroboscopic illumination with pulses of 8 ns containing an energy of approximately 5 mJ in every pulse, or a power of ≈ 600 kW in Q-switched mode. This is amply sufficient to record holograms with a single pulse, bringing along some advantages over continuous illuminated holography, especially in the field of vibrational analysis. The conventional way to perform vibrational research using holography uses an exposure time that is long compared to the vibration period, resulting in a time average hologram containing all the vibrational information in one image [2]. Of course, using this method, a considerable amount of information is lost such as possible asymmetric motions and the vibration phase. Since phase information is lost, it is impossible to distinguish standing from traveling waves on time average holograms.

Stroboscopic digital holography allows an intensive yet more valuable vibration measurement method. First, a hologram is recorded of the object in rest state. Then a single pulse hologram is recorded in vibrational state, where the laser pulse illuminates only one particular phase within the vibration period, since the pulse length is much shorter than the vibration period. Combining this with the hologram of the object in rest, a full field displacement map of the object on that particular instance in the vibration period can be calculated. By cycling the illumination pulse through the entire vibration period and recording one pulse per camera exposure, the complete motion of the object can be reconstructed as a function of time, making this a four dimensional imaging technique, as three spatial coordinates and time are measured. In fact, we use the periodicity of the signal to construct a very high-speed holographic interferometric imaging device.

COMPARISON WITH OTHER TECHNIQUES

As mentioned earlier, the stroboscopic illumination in our setup is realized by a high energy pulsed laser. Similar setups have been used in the past, using an acousto-optic modulator (AOM) assisted shuttered continuous wave (CW) laser or a pulsed laser diode [3]. However, both these methods have some problems that are solved by the implementation of a high energy pulsed laser in our setup.

The main disadvantage of the use of a laser diode is that the energy and length of the pulses are relatively low and fixed. This makes it necessary to integrate the light of a certain number of pulses N in order to receive enough energy on the CCD. This causes the exposure time of the camera to increase linearly with the vibration period, introducing problems in the lower frequency range (below 1 kHz). Electronic noise then becomes a major concern. To increase the signal-to-noise ratio (SNR), one could average over several recordings, but then the total acquisition time also increases, introducing other problems such as higher acoustic stability and overall vibration stability requirements.

Another option is to use a CW laser and shutter it by the use of an AOM or Bragg cell. The advantage then is that the length and therefore energy of the pulses can be chosen to scale with the vibration period. For example, one could choose to illuminate 2% of the vibration period. The needed CCD exposure time then is constant for all vibration frequencies, allowing the measurement of a larger frequency range. However, this also means a relatively long exposure time for high frequency vibrations compared to the method using a laser diode, where exposure times decreases with increasing frequencies. The underlying cause for this is that with a shuttered CW laser, 98% of the produced light energy is lost (in the case of 2% illumination), while a laser diodes bundles all of its energy into very short pulses. Other problems with the AOM based setup have more practical nature. Experience teaches that the polarization of the outgoing light is not unaffected by the AOM**.** Furthermore, the temperature of the AOM is affected by the length of the pulses and the intensity profile of the outgoing light beam is altered significantly by this temperature variations. This obviously means that an important property of the reference wave, its homogeneity, is more difficult to control.

Summarized, both of these methods bring along a number of limiting and complicating factors, justifying the introduction of a high energy laser into our setup. The combination of this with a fast microprocessor based timing sequence reduces the total time needed to record an entire dataset in our setup strongly. The maximal pulse rate of the laser is 20 Hz, so if the camera is also able to reach this rate, 20 vibration frames on different phases can be recorded in only 1 second, minimalizing the influence of low frequency variations. Furthermore, the exposure time of the camera can be chosen to be extremely short, since the length of the pulses is in the order of nanoseconds.

The advantage of this time-resolved full field technique over time-average holography is obvious, since the latter provides no time-resolved information at all. Another optical measurement technique does provide time-resolved data with a very good time and depth resolution, namely laser Doppler vibrometry (LDV). The drawback here is that only one point at a time can be measured per LDV. The technique can be used to scan a number of points on a surface [4], but then the phase relation between different object points becomes difficult to track. Our stroboscopic digital holography setup allows the measurement of 100s by 100s of points on the object at once.

TIMING SEQUENCE

The timing is crucial in this setup: if the vibration frequency is 20 kHz and we want 50 frames at uniformly distributed phases in the period, the pulses need to have a precision below 1 μs. To achieve this, we introduced a microprocessor in the setup. The timing sequence is shown in Fig. 3. The camera passes its exposure state to the microprocessor, acting as the first input. This signal is high when the camera is open and low when it is closed. A function generator is used to drive the vibration. In our case, the vibration was induced by a sound source, connected to the generator. Another output channel of the generator produces short trigger pulses synchronized to the sound frequency, with period P. These pulses act as second input of the microprocessor.

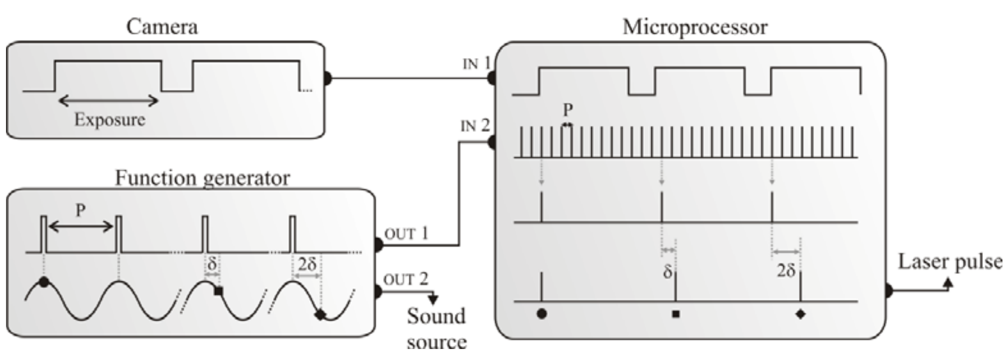

FIGURE 3. Microprocessor controlled timing sequence. Not all time axes are on the same scale. The figure is a schematic overview and is constructed to support the algorithm explanation, not to be perfectly scientifically correct.

The program on the chip selects exactly one of these pulses per camera exposure. Finally, every outgoing pulse is delayed an integer multiple of a certain amount of time (δ). Between each successive camera exposure the delay time is increased by δ so that holograms are recorded stepwise through the entire vibration period. In Fig. 3, we have indicated the time points at which holograms are recorded. The first selected pulse will have no delay and will illuminate the object at moment ●. The second will be delayed with δ and will illuminate the object at moment ■, the third 2δ and moment ◆, and so on.

After recording the holograms, they are reconstructed and the phase difference maps between the vibrational holograms and the hologram at rest state are calculated. From this, the full field displacement maps of the object over the entire vibration period can be constructed, by phase-unwrapping the phase difference maps and converting the phase into displacement for every recorded vibration state.

RESULTS

The technique results in a large amount of information which can be visualized in different ways. One way is to construct a movie of the different displacement maps. Because it is impossible to include this in a text, a selection of 6 frames uniformly distributed within the vibration period is shown in Fig. 4, for the vibration frequency of 1040 Hz and a root-mean-square (rms) sound pressure level (SPL) of 85 dB. This SPL was measured using a Brüel & Kjær probe microphone, placed directly behind the object (see Fig. 1). The vibrating object was a stretched circular rubber membrane with a diameter of 2.1 cm.

This is a rather extensive way to visualize the data. A more compact way is to calculate maps of both vibration magnitude and phase. To this purpose, the temporal Fourier spectrum of each object point is calculated. The vibration magnitude is given by the maximal complex modulus of this spectrum. The vibration phase can be found by calculating the complex phase of the spectrum and selecting the one that belongs to the frequency with maximal magnitude. The results of these operations can be seen in Fig. 5 for the same vibration of 1040 Hz.

The combination of the magnitude and phase maps offer a lot of information, condensed in two images. When two points have a phase difference of π, they are mutually out of phase. A continuous phase change along a certain path on the object indicates the existence of a travelling wave instead of a standing wave.

CONCLUSION

Building on an existing method, we realized a very fast stroboscopic holographic vibrometry setup, using a high power pulsed Nd:YAG laser and a microprocessor. It is applicable for the frequency range of 1 Hz to 20 kHz. For all these frequencies, a four dimensional dataset can be recorded, imaging the full field displacement maps as a function of time over the entire vibration period. Condensed information can be extracted in the form of magnitude and phase maps. The main advantage over time-averaged holographic vibrometry is that travelling waves can be discovered, which are very important in the transfer of energy over the membrane.

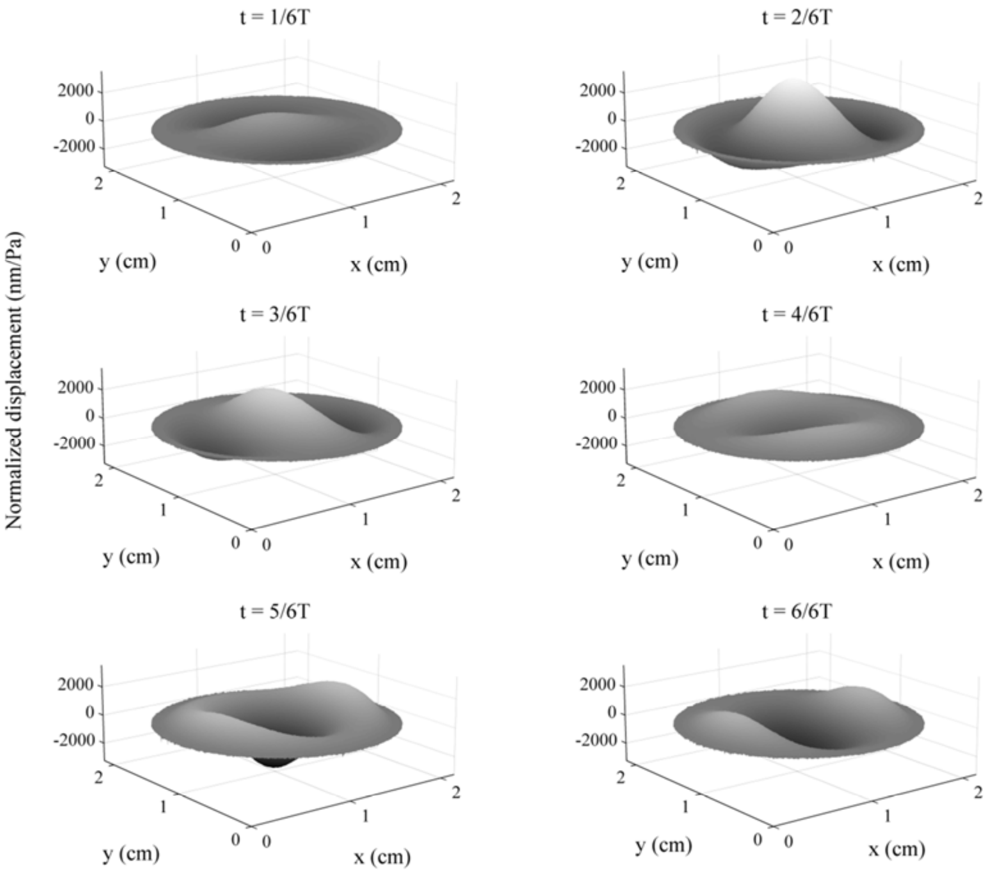

FIGURE 4. Displacement maps at 6 moments in the vibration phase of the stretched membrane vibrating at 1040 Hz.

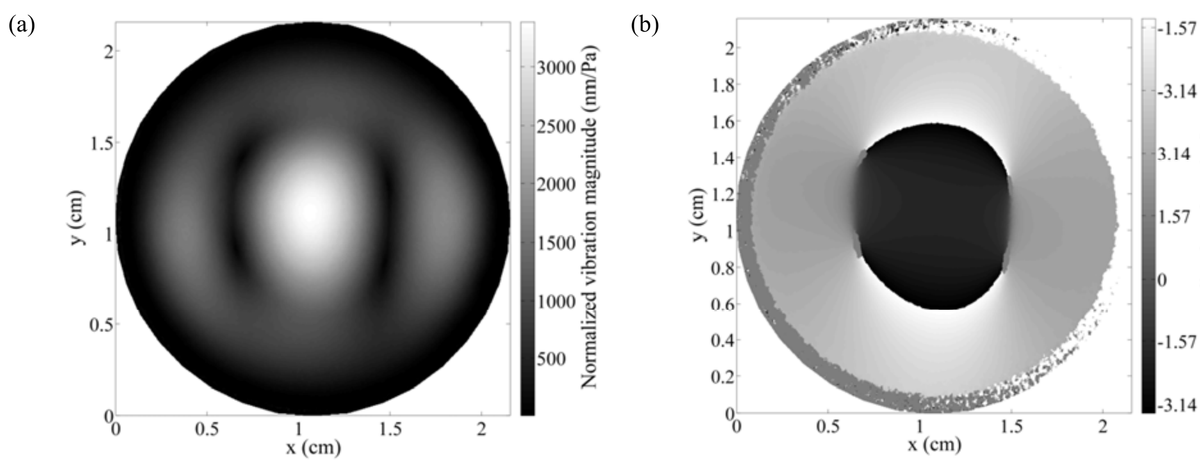

FIGURE 5. Vibration magnitude (a) and phase (b) maps of the membrane vibrating at 1040 Hz. Notice that the phase is wrapped in an interval *[-π,π]*, so a black-to-white transition is in fact continuous.

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