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Real-time nearfield acoustic holography for reconstructing the instantaneous surface normal velocity

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ABSTRACT

A pressure–velocity impulse response is deduced in this work to establish the relationship between the pressure and the particle velocity in the time-wavenumber domain. By virtue of it, real-time nearfield acoustic holography (RT-NAH) is extended to reconstruct the instantaneous surface normal velocity of a vibrating structure from the time-dependent pressure measured in the near field, which provides a non-contact and real-time method to measure and visualize the transient vibration of the structure. An experiment of an impacted steel plate is investigated, in which the surface normal velocity of the plate is measured by laser Doppler vibrometry and reconstructed by RT-NAH. The comparison of surface normal velocities obtained by using these two methods shows a satisfactory agreement not just for the time-evolving surface normal velocity signals but also for the vibration mode shapes. Accordingly, it demonstrates that RT-NAH is a viable approach for reconstructing the instantaneous surface normal velocity.

1. Introduction

Measurement and visualization of structural transient vibration are of importance to understand and describe the instantaneous phenomena associated with it, for example the transient bending wave propagation on a structural surface [1]. The traditional method with accelerometers attached to the structure is usually used for measuring the vibration. This method is economical and reliable, while the use of accelerometers will mass load the structure, and thus degrade the real vibration levels or even change the vibration modes, especially for a lightweight and thin structure. Optical methods characterized by the non-contact measurement are the alternatives to the traditional method. Among them, three-dimensional digital image correlation [2], real-time holographic interferometry [3], pulsed TV holography [4], and laser Doppler vibrometry (LDV) [5] can provide effective measurements for displaying the transient vibration. Compared to the first three, LDV is more of an off-the-shelf instrument, developed for industrial applications, but one drawback in the comparison is that it is difficult to obtain the structural transient vibration through a single measurement when the structural surface involves dozens or even hundreds of measurement points. LDV is so expensive that it is unpractical and uneconomical to organize an array formed by dozens or even hundreds of LDVs for measuring the structural transient vibration in real time. Nearfield acoustic holography (NAH) [6,7], as another type of non-contact measurement technique, can indirectly acquire the structural vibration through only a single measurement. It generally employs an easily available and economical microphone array to measure the pressure in the near field, and then reconstruct the surface normal

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velocity with the measured pressure as the input [8]. Similar to NAH, a direct inverse method based on the discretized Rayleigh integral was proposed recently [9]. In that method, the Rayleigh integral was discretized to establish the transfer relationship between surface velocity and sound pressure, and the microphones were placed close to the vibrating structure to provide a transfer matrix with a low condition number; then, the surface velocity could be calculated by directly inverting the transfer matrix. However, both NAH and the direct inverse method are often used for analyzing the harmonic vibration. When the transient vibration is desired, the relevant approaches in the time domain have to be adopted. Time domain holography (TDH) [10] with a numerical Laplace transform is the right one allowing the reconstruction of transient vibration. Blais and Ross [11] applied it to reconstruct the instantaneous transverse velocity of an impacted plate well and visualize the bending wave propagation. The disadvantage of TDH is that its reconstruction process is not real-time as a result of backward propagation at all frequencies before coming back to the time domain. Real-time nearfield acoustic holography (RT-NAH) proposed by Thomas et al. [12,13] needs no backward propagation in the frequency domain. It operates in the time-wavenumber domain by means of a discretized time convolution between the wavenumber spectrum of the pressure recorded by a microphone array and an inverse impulse response. The discretized time convolution indicates that once the wavenumber spectrum of the pressure at one time sample is obtained and given as the input, the desired pressure at the relevant time sample can be reconstructed in real time. Based on the impulse response relating the pressure on the hologram plane to the pressure on the reconstruction plane [14], RT-NAH has been used to reconstruct the instantaneous pressure. In this study, RT-NAH is further extended to reconstruct the instantaneous surface normal velocity by combining a derived impulse response that relates the pressure on the hologram plane to the normal velocity on the source plane (hereinafter referred to as pressure–velocity impulse response). Similar to the aforementioned optical methods, RT-NAH with the pressure–velocity impulse response can measure the transient vibration in a non-contact and real-time way as well, but the difference is that it is based on the sound radiation from a vibrating structure in theory and makes use of the standard acoustic measuring sensor – microphone in experiment. The use of microphones significantly eases the measurement in practical industrial applications.

2. RT-NAH with the pressure–velocity impulse response

As shown in Fig. 1, a microphone array laid in the near field takes charge of the measurement of time-dependent pressure signals $p(x, y, z_H, t)$ on the hologram plane H that will serve as the input to reconstruct the instantaneous normal velocity signals $v(x, y, z_S, t)$ on the source plane S.

The measured pressure signals $p(x, y, z_H, t)$ are first processed by performing a two-dimensional Fourier transform with respect to x and y, yielding the time-wavenumber spectrum as

$$P(k_x, k_y, z_H, t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x, y, z_H, t) e^{j(k_x x + k_y y)} dx dy. \tag{1}$$

In Appendix A, we deduced the pressure–velocity impulse response $G(k_x, k_y, \Delta z, t)$ to relate the time-wavenumber pressure spectrum $P(k_x, k_y, z_H, t)$ and the time-wavenumber velocity spectrum $V(k_x, k_y, z_S, t)$ with the time convolution formulation (A.11)

$$P(k_x, k_y, z_H, t) = V(k_x, k_y, z_S, t) * G(k_x, k_y, \Delta z, t), \tag{2}$$

where Δz is the distance between the hologram plane H and the source plane S, the asterisk denotes the convolution of two functions. Since the time-wavenumber pressure spectrum $P(k_x, k_y, z_H, t)$ and the pressure–velocity impulse response $G(k_x, k_y, \Delta z, t)$ are known, the time-wavenumber velocity spectrum $V(k_x, k_y, z_S, t)$ can be solved by deconvolving Eq. (2) as the following procedure.

First of all, the time t is discretized as $t_n (n = 1, 2, \ldots)$ to model the actual sampling. According to Eq. (A.16), the impulse response $G(k_x, k_y, \Delta z, t)$ is equal to zero for $t < \tau$. $\tau = \Delta z / c$ corresponds to the time needed for the waves to propagate from

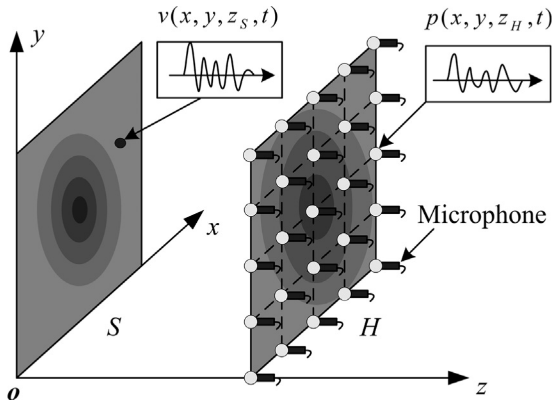

Fig. 1. Geometry of the source plane S, the hologram plane H, and the microphone array.