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Reconstructing non-stationary surface normal velocity of a planar structure using pressure-velocity probes

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ABSTRACT

An acoustic method based on the time domain plane wave superposition method is proposed to reconstruct the non-stationary surface normal velocity of an impacted planar structure by measuring the normal particle velocity. In this method, the time-evolving normal particle velocity on the hologram plane is first measured by pressure-velocity probes; then, the normal particle velocity spectrum on a virtual source plane is used to establish the relationship between the time-evolving normal particle velocity on the hologram plane and the time-evolving surface normal velocity on the structural plane; finally, the normal particle velocity spectrums can be solved by an iterative solving process and are used to calculate the non-stationary surface normal velocity of the planar structure. An experiment of a planar steel plate impacted by a steel ball is presented to examine the ability of the proposed method, where the time-evolving normal particle velocity and pressure on the hologram plane measured by pressure-velocity probes are used as the inputs of the proposed method and the pressure-based reconstruction method, respectively, and a laser Doppler vibrometry is used to measure the surface normal velocity of the plate as the reference for comparisons. The comparison results demonstrate that the proposed method is effective in reconstructing the non-stationary surface normal velocity in both time and space domains and can provide more accurate results than that of the pressure-based reconstruction method.

1. Introduction

Planar structures are typically encountered in industry, and considerable work has focused on the sound radiation from an impacted planar plate [1–6]. The structural surface velocity is the important information for studying the force source identification and the fault diagnosis of industrial equipments. Therefore, it has great engineering significance to accurately measure the surface normal velocity of an impacted planar plate. Usually, Optical methods [7–10] with the characteristic of non-contact measurement are used to measure the surface normal velocity of a vibrating structure. Especially, laser Doppler vibrometry (LDV) [10] is an off-the-shelf instrument to measure the surface normal velocity of the structure. However, for measuring the surface normal velocity accurately, the optical methods require that the structure must have better reflective characteristic or the reflective paper can be easily attached on the structural surface to strengthen this characteristic. These requirements are difficult to be satisfied in the situations of a high-temperature device and a magneto-electricity device. For avoiding these requirements of optical methods, nearfield acoustic holography (NAH) [11–16] is developed to reconstruct the structural surface vibration by measuring the easily available pressure/particle velocity.

However, NAH is originally proposed for analysing harmonic fields. For a non-stationary vibration whose statistical properties fluctuate with time, it is more reasonable to reconstruct the non-stationary vibration of a planar structure at a single time instant and further analyze the vibration characteristics related to time. Time-domain acoustical holography (TDH) [17] is proposed to reconstruct the time-evolving pressure and normal velocity on the structural plane. In TDH, the Fourier transform and two-dimensional spatial Fourier transform are first applied to the measured time-evolving signals on the hologram plane for obtaining the corresponding frequency-wavenumber spectrums, then the wavenumber spectrums on the hologram plane at each frequency are introduced into NAH for reconstructing the frequency-wavenumber spectrums of the pressure and normal velocity on the reconstruction plane, finally, the inverse Fourier transform and two-dimensional spatial inverse Fourier transform are applied to the reconstructed frequency-wavenumber spectrums for obtaining the time-evolving pressure and normal velocity on the reconstruction plane. To reduce time aliasing errors caused by the Fourier transform in TDH, Blais et al. [18] introduced the Laplace transform into TDH for reconstructing the transverse acceleration and velocity, and they

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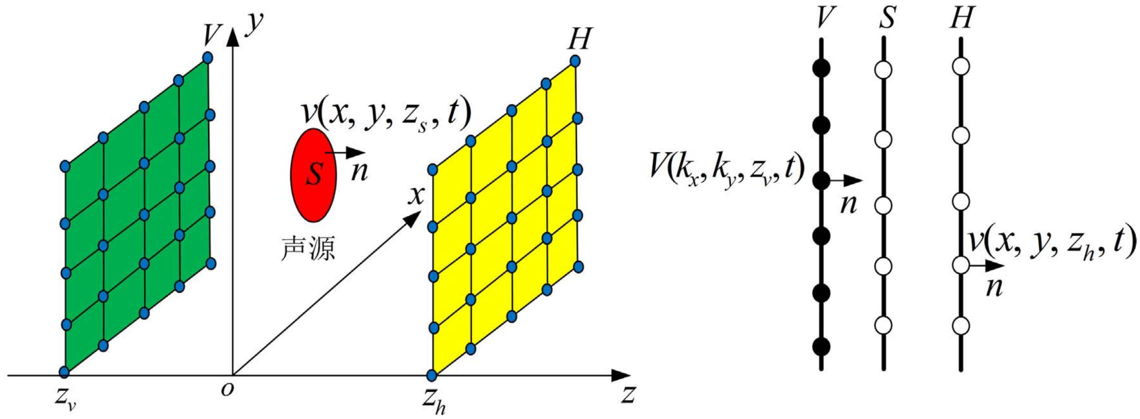

Fig. 1. Geometric description of the structural plane S, the hologram plane H and the virtual source plane V in the Cartesian coordinate system $o(x,y,z)$.

presented an experiment with an impacted, free Plexiglas plate to prove that the Laplace transform-based TDH can improve the precision of recovering transverse time signals. However, the reconstruction procedures of TDHs based on the Fourier transform and the Laplace transform must be carried out in the frequency domain. For avoiding the reconstruction in the frequency domain, real-time nearfield acoustic holography (RT-NAH) [19–21] is developed to reconstruct the time-evolving pressure and surface normal velocity of an impacted plate directly in the time domain. The reconstruction process in RT-NAH is performed in the time-wavenumber domain by means of a discretized time convolution between the time-wavenumber spectrum and an inverse impulse response, which provides the advantage of continuously reconstructing the time-evolving signals. However, two-dimensional spatial Fourier transform in both TDH and RT-NAH leads to wrap-around errors and the limitation of the regular measurement array. To avoid these shortcomings, a time domain plane wave superposition method (TD-PWSM) [22] is developed. In TD-PWSM, the direct discretization of double infinite integral of two-dimensional spatial Fourier transform is first used to replace two-dimensional spatial Fourier transform in the wavenumber domain, and then the time-domain propagation kernels relating the pressures on the hologram (and reconstruction) planes to the pressure time-wavenumber spectrums on the virtual source plane are applied to establish the relationships, finally, the pressure time-wavenumber spectrums on the virtual source plane are obtained by an iterative solving process and are further used to calculate the time-evolving pressure on the reconstruction plane. Besides, by establishing two time domain propagation kernels relating the time-evolving pressure on the hologram plane (and the normal acceleration on the plate plane) to the normal acceleration time-wavenumber spectrum on the virtual source plane, the TD-PWSM is applied to reconstruct the normal acceleration of the plate [23]. Besides, some other time domain methods also have the capacity to reconstruct the time-evolving pressure gradient and acoustic velocity [24–31].

Usually the input quantity is the pressure rather than the particle velocity, because the particle velocity is difficult to be measured. However, in recent years, pressure-velocity (p-u) probes have been developed to measure the pressure and particle velocity [32]. The particle velocity-based NAH is less sensitive to the measurement errors than the pressure-based NAH. Especially, in the reconstruction of the stationary surface normal velocity, the former can provide the higher reconstruction accuracy than that of the latter [15,16,33]. The reason is that the condition number of the transfer matrix in the pressure-based NAH is more than that in the particle velocity-based NAH, which leads that the former matrix tends to be more ill-conditioned than that of the latter. In this present paper, an acoustic method based on the TD-PWSM and time-evolving particle velocity is proposed to reconstruct the non-stationary surface normal velocity of an impacted planar plate, and its advantage is to be proven by comparing with the time-evolving pressure-based reconstruction method.

This paper is organized as follows. In Section 2, the theories of the proposed particle velocity-based method and the pressure-based reconstruction method are described. In Section 3, an experiment of reconstructing the non-stationary surface normal velocity of an impacted planar plate is carried out to examine the performance of the proposed particle velocity-based method in both time and space domains, and to show its advantage in comparison to the pressure-based reconstruction method. Finally, conclusions are drawn in Section 4.

2. Theoretical background

Fig. 1 shows the position relations of the structural plane S, the hologram plane H and the virtual source plane V in the Cartesian coordinate system $o(x,y,z)$. There are F points, M measurement points and N virtual sources distributing on the planes S, H and V, respectively. The time-evolving normal particle velocity $v(x,y,z_h,t)$ and pressure $p(x,y,z_h,t)$ on the hologram plane H, the time-evolving normal particle velocity $v(x,y,z_v,t)$ on the virtual source plane V and the time-evolving surface normal velocity $v(x,y,z_s,t)$ on the plane S are processed by performing a two-dimensional spatial Fourier transform, respectively, and the corresponding time-wavenumber spectrums can be expressed as

$$V(k_x,k_y,z_h,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v(x,y,z_h,t)e^{j(k_x x+k_y y)}dxdy, \tag{1}$$

$$P(k_x,k_y,z_h,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} p(x,y,z_h,t)e^{j(k_x x+k_y y)}dxdy, \tag{2}$$

$$V(k_x,k_y,z_v,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v(x,y,z_v,t)e^{j(k_x x+k_y y)}dxdy, \tag{3}$$

$$V(k_x,k_y,z_s,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v(x,y,z_s,t)e^{j(k_x x+k_y y)}dxdy, \tag{4}$$

where k_x and k_y represent the wavenumber components in x and y directions, respectively.

Referring to the derivation in Appendix A and Ref. [21], the normal particle velocity time-wavenumber spectrum $V(k_x,k_y,z_v,t)$ on the virtual source plane V can be related to the normal particle velocity and pressure time-wavenumber spectrums $V(k_x,k_y,z_h,t)$ and $P(k_x,k_y,z_h,t)$ on the hologram plane H, and the surface normal velocity time-wavenumber spectrum $V(k_x,k_y,z_s,t)$ on the plane S with the following formulations:

$$V(k_x,k_y,z_h,t) = V(k_x,k_y,z_v,t)*G_{vv}(k_x,k_y,\Delta z_{hv},t), \tag{5}$$

$$P(k_x,k_y,z_h,t) = V(k_x,k_y,z_v,t)*G_{vp}(k_x,k_y,\Delta z_{hv},t), \tag{6}$$

$$V(k_x,k_y,z_s,t) = V(k_x,k_y,z_v,t)*G_{vv}(k_x,k_y,\Delta z_{sv},t), \tag{7}$$

where the analytical expression of the impulse response function $G_{vp}(k_x,k_y,\Delta z_{hv},t)$ is provided in Ref. [21].