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Nonlinear Reflection of a Spherically Divergent *N*-wave from a Plane Surface: Optical Interferometry Measurements in Air

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Abstract. Mach stem is a well-known structure typically observed in the process of strong (acoustic Mach numbers greater than 0.4) step-shock waves reflection from a rigid boundary. However, this phenomenon has been much less studied for weak shocks in nonlinear acoustic fields where Mach numbers are in the range from 0.001 to 0.01 and pressure waveforms have more complicated waveforms than step shocks. The goal of this work was to demonstrate experimentally how nonlinear reflection occurs in air for very weak spherically divergent acoustic spark-generated pulses resembling an *N*-wave. Measurements of reflection patterns were performed using a Mach-Zehnder interferometer. A thin laser beam with sub-millimeter cross-section was used to obtain the time resolution of 0.4 μs, which is 6 times higher than the time resolution of the condenser microphones. Pressure waveforms were reconstructed using the inverse Abel transform applied to the phase of the signal measured by the interferometer. The Mach stem formation was observed experimentally as a result of collision of the incident and reflected shock pulses. It was shown that irregular reflection of the pulse occurred in a dynamic way and the length of the Mach stem increased linearly while the pulse propagated along the surface. Since the front shock of the spark-generated pulse was steeper than the rear shock, irregular type of reflection was observed only for the front shock of the pulse while the rear shock reflection occurred in a regular regime.

INTRODUCTION

Nonlinear reflection of shock waves was first experimentally observed by Ernst Mach in 1878 and then theoretically investigated by von Neumann in 1943.[1,2] However, the three-shock theory of von Neumann conflicts with experimental results for weak shocks with values of acoustic Mach number less than 0.47,[3] which is known as von Neumann paradox. Numerous studies have been undertaken to resolve von Neumann paradox, mainly in the framework of aerodynamics covering step shock waveforms for acoustic Mach number greater than 0.035.[5-8] In nonlinear acoustics, shock waves have more complicated waveforms than step shocks and the values of acoustic Mach numbers are at least one order smaller than in aerodynamics. The reflection of such very weak, but nonetheless strongly nonlinear acoustic waves has not been reported to the same extent.[9-11]

MACH-ZEHNDER INTERFEROMETRY METHOD FOR MEASUREMENTS OF IRREGULAR REFLECTION PATTERNS

The experimental setup designed for optical measurements of reflection pattern is shown in Fig.1 and includes optical and acoustical parts. Acoustic shock pulses were produced by a 15 kV electric spark source with 20 mm gape between tungsten electrodes. The generated waves were a short duration shock acoustic pulses often called as *N*-wave due to their specific waveform.[12,13] Spherically divergent acoustic pulses were reflected from the rigid surface,

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located at a distance h_{sp} under the spark. The emerging reflection pattern was measured using the Mach-Zehnder interferometer composed of a laser source (He-Ne laser with wavelength $\lambda = 632.8$ nm), two beam splitters, two flat mirrors, three lenses (not shown in Fig. 1a), and a photodiode sensor.

In the absence of acoustic wave, light intensity I formed by the interference of the reference (I_1) and the probing (I_2) beams at the surface of the photodiode is: $I = I_1 + I_2$. When an acoustic pulse passes through the probing beam it induces the refraction index perturbation n and leads to a phase difference φ between the reference and probing beams:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\varphi. \tag{1}$$

The phase difference φ is measured by the interferometer. In our previous works[14,15] it was shown that the phase difference φ is related to the refraction index perturbation n via the direct Abel transform:

$$\varphi(R) = \frac{4\pi}{\lambda}\int_r^\infty \frac{n(r)rdr}{\sqrt{r^2 - R^2}}, \tag{2}$$

where R is the distance from the spark. In order to reconstruct pressure waveforms $p(\tau)$ one should apply the inverse Abel transform to Eq. (2) and use the Gladstone-Dale relation: $p = nc_0^2 / G$, where c_0 is a sound speed and $G = 0.000226$ m^3/kg is the Gladstone-Dale constant at 632.8 nm wavelength.

At each height h above the surface, 140 waveforms were recorded in order to allow statistical analysis of the data. “Average” waveform was selected from these 140 waveforms as a waveform with the arrival time, duration, and peak positive and peak negative pressures closest to their averaged values over all waveforms. Here we present results of waveforms obtained at distance $h_{sp} = 21$ mm and at distance $l = 25$ cm along the surface (see Fig. 1b). The time resolution of the interferometric method is 0.4 μs.[14]

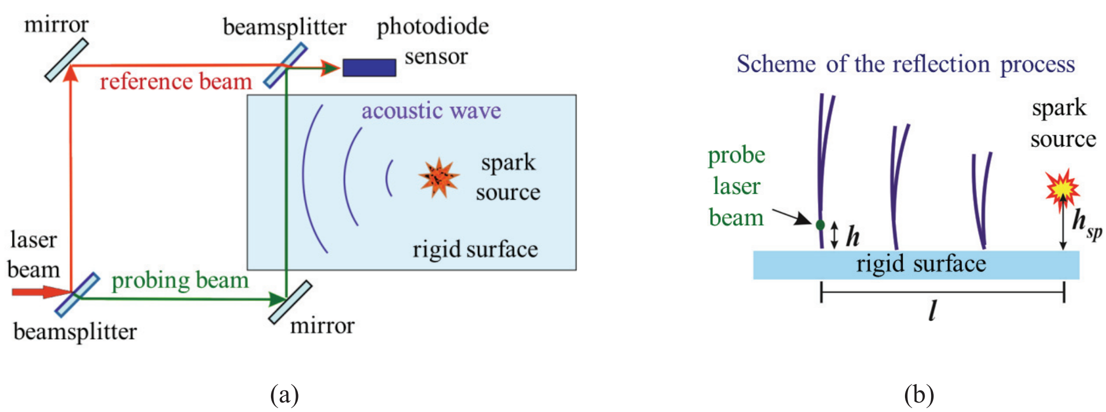

FIGURE 1. Illustration of the experimental setup: (a) the top view, (b) the side view on the reflecting surface.

DYNAMICAL IRREGULAR REFLECTION OF *N*-WAVES

A reflection pattern measured using the Mach-Zehnder interferometer is shown in Fig. 2a for the case $l = 25$ cm. This pattern represents the results of measured waveforms obtained at distances h from the rigid surface in the range from 2 mm up to 30 mm with increments of 2 mm. Pressure levels are indicated by colors. The formation of the Mach stem occurs as a result of collision of the incident and reflected shock pulses and observed in Fig. 2a for the front shock of the pulse (area with highest pressure levels). The detailed structure of the front shock of the pulse is shown in Fig. 2b. At distance $h = 6$ mm the waveform contains only one front further dividing into two fronts (waveforms at $h = 8$ mm and $h = 10$ mm). The first single front is the Mach stem, dividing at the triple point on the incident and reflected fronts.

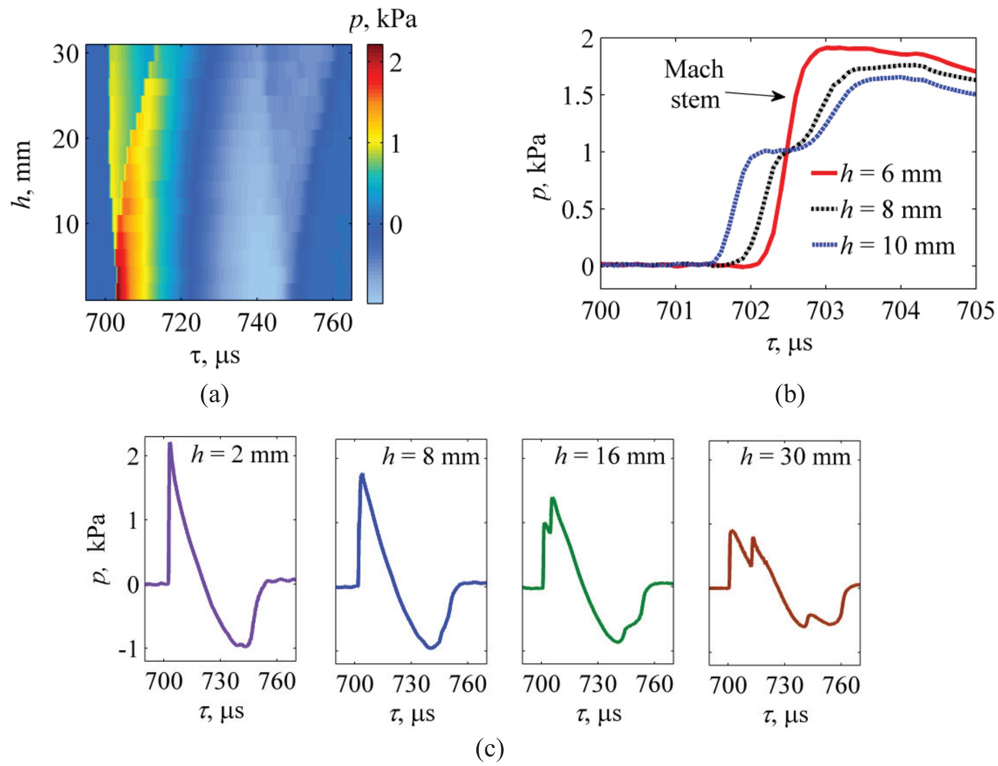

FIGURE 2. (a) Irregular reflection pattern obtained at distance l = 25 cm. (b) The zoom of the front shock structure for waveforms measured at different height h above the surface. (c) Waveforms at different height h from the surface.

The evolution of the pulse waveform with the height h is depicted in Fig. 2c. It is clearly seen that the rear "shock" of the pulse is smoother than the front shock. This fact is crucial for the nonlinear effects and the reflection of the rear shock occurs in a regular regime (area $740 < \tau < 760$ in Fig. 2a).

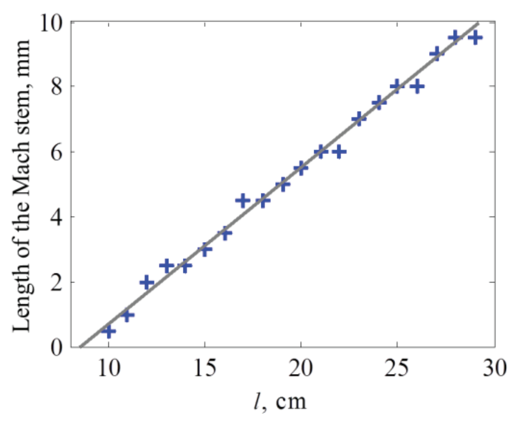

FIGURE 3. The trajectory of the triple point. Experimental points are shown by marker and a linear fit is shown by a solid line.

One of the main features distinguishing the step shock reflection from the reflection of acoustic waves is a dynamical character of the irregular reflection for the last case.[9-11] In experiment, irregular reflection of the pulse did occur in a dynamic way and the length of the Mach stem was increased linearly while the pulse propagated along the surface (Fig.3). The linear interpolation of the triple point trajectory to the surface predicts that for current geometry configuration the transition between regular and irregular reflection occurs at $l = 8.5$ cm. Note that theoretical investigation of the plane N-wave reflection from the rigid boundary[9] predicts complicated nonlinear trajectory of the triple point. Here we suppose that this linear dependence is a result of the wavefront sphericity and thus of a faster decrease of the energy on the front shock. In our future work we will study greater distances of propagation to analyze the evolution of the length of the Mach stem and its possible decrease.

CONCLUSIONS

In this work, the Mach-Zehnder interferometry method was used to measure nonlinear reflection pattern of spherically divergent spark-generated pulses reflected from the rigid surface in air. Pressure waveforms were reconstructed applying the inverse Abel transform to the phase of the signal measured by the interferometer. It was shown that irregular reflection of the pulses occurred in a dynamic way and that the trajectory of the triple point is linear within distances available in the experiment.

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