Conference Proceedings of the Society for Experimental Mechanics Series

Cosme Furlong · Chi-Hung Hwang · Gordon Shaw ·
Ryan Berke · Garrett Pataky · Shelby Hutchens *Editors*

Advancement of Optical Methods and Fracture and Fatigue, Volume 3

Proceedings of the 2023 Annual Conference on Experimental and Applied Mechanics

SEM

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Conference Proceedings of the Society for Experimental Mechanics Series

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Society for Experimental Mechanics, Inc.,
Bethel, USA

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ISSN 2191-5644 ISSN 2191-5652 (electronic)
Conference Proceedings of the Society for Experimental Mechanics Series
ISBN 978-3-031-50498-3 ISBN 978-3-031-50499-0 (eBook)
https://doi.org/10.1007/978-3-031-50499-0

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Advancement of Optical Methods and Fracture and Fatigue represents one of the five volumes of technical papers presented at the 2023 SEM Annual Conference & Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics scheduled on June 5–8, 2023. The complete proceedings also include volumes on: *Additive and Advanced Manufacturing, Dynamic Behavior of Materials, Inverse Problem Methodologies, Machine Learning and Data Science, Mechanics of Biological Systems and Materials, Mechanics of Composite and Multifunctional Materials, Residual Stress, Thermomechanics and Infrared Imaging, and Time-Dependent Materials.*

Each collection presents early findings from experimental and computational investigations on an important area within Experimental Mechanics, Fracture, and Fatigue being one of these areas.

Fracture and fatigue are two of the most critical considerations in engineering design. Understanding and characterizing fatigue and fracture has remained as one of the primary focus areas of experimental mechanics for several decades. Advances in experimental techniques, such as digital image correlation, acoustic emissions, and electron microscopy, have allowed for deeper study of phenomena related to fatigue and fracture. This volume contains the results of investigations of several aspects of fatigue and fracture such as microstructural effects, the behavior of interfaces, the behavior of different and/or complex materials such as composites, and environmental and loading effects. The collection of experimental mechanics research included here represents another step toward solving the long-term challenges associated with fatigue and fracture.

With the advancement in imaging instrumentation, lighting resources, computational power, and data storage, optical methods have gained wide applications across the experimental mechanics society during the past decades. These methods have been applied for measurements over a wide range of spatial domain and temporal resolution. Optical methods have utilized a full-range of wavelengths from X-Ray to visible lights and infrared. They have been developed not only to make two-dimensional and three-dimensional deformation measurements on the surface but also to make volumetric measurements throughout the interior of a material body.

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Contents

Blast Production by a Shock Tube for Use in Studies of Exposure of the Tympanic Membrane to High-Intensity Sounds

Anahita Alipanahi, Jonathan Oliveira Luiz, Jeffrey Tao Cheng, John J. Rosowski, and Cosme Furlong-Vazquez

Abstract Blast exposure can result in tympanic membrane (TM) rupture and middle ear and inner ear damage. However, the dynamics of the blast-induced TM rupture are unclear, leaving questions about how the blast-induced stresses and strains on the TM surface produce TM rupture unanswered. Our group is developing quantitative high-speed optical techniques for real-time characterization of the fracture mechanics of the TM. Here we describe our efforts to produce a shock tube acoustic loading device that produces repeatable and accurate supersonic blasts with peak pressures capable of rupturing TM samples. The design of the shock tube was decided through structural analysis, and the pressures produced by the blast waves were verified with multiple high-speed pressure sensors. Schlieren imaging combined with a high-speed camera is used to "visualize" blast waves emitted from the shock tube opening and analyze how they propagate and interact with testing samples. This information is necessary to understand the influence of these waves on the dynamic behavior of the TM and how they induce damage of the TM.

Keywords Blast · DIC · Schlieren imaging · Shock tube · Tympanic membrane

Introduction

The mechanics of the human ear for hearing are complex. Of the multiple components within the ear, the tympanic membrane (TM, or the eardrum) is both crucial to hearing and highly vulnerable to damage. However, our understanding of the real-time mechanics of TM fracture is limited. Fractures of the TM can be caused by exposure to intense sound pressure, resulting in moderate to severe conductive hearing loss [1, 2]. Until the fracture mechanics of the TM are better understood and more effective hearing protective devices are developed, hearing loss will continue to impact significantly the lives of those exposed to blast [1]. While previous studies have shown cracks on the TM surface after blast exposure [2, 3], no measurement has been done to quantify the effects of crack initiation and propagation, as well as changes in the frequency response and the mechanical properties of TMs exposed to sub-fracture level blasts.

The final goal of our research is to quantitatively describe the transient responses of the TM to high-intensity sounds, such as the blast, and the dynamics of the TM fracture by the blast in real time. For this purpose, we created a shock tube as an

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C. Furlong et al. (eds.), *Advancement of Optical Methods and Fracture and Fatigue, Volume 3*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-031-50499-0_1

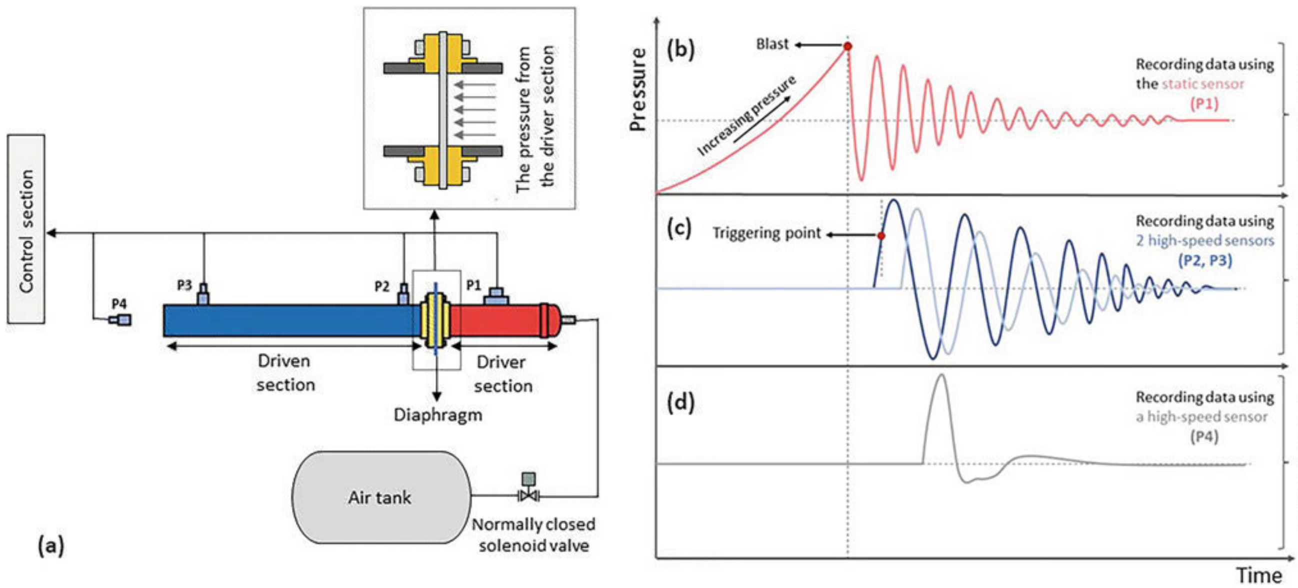

Fig. 1 Schematics of shock tube and corresponding collected signals: (**a**) overall schematic of the shock tube showing sensors for monitoring the conditions of the tube shown in driver and driven sections, including the inset that shows a thin diaphragm that separates the driver and driven sections; (**b**) pressure before and after the initiation of the blast at P1; (**c**) pressure in the driven section after initiation of the blast at P2 and P3; (**d**) pressure recorded by P4 at a distal location from the end of the tube matching a Friedlander waveform [6]

acoustic loading apparatus that delivers transient acoustic forces similar to those encountered in real conditions. The shock tube is combined with a high-speed Schlieren system designed to visualize and quantify the blast wave. In the future, 3D high-speed digital image correlation and high-speed holography will be integrated with this loading apparatus to perform full-field measurements of the TM's dynamic response to the blast wave.

Methodology

Shock Tube

A shock tube is a scientific instrument for creating high-speed gas flows, shock waves, and other related phenomena [1, 3, 4]. Our instrument, shown in Fig. 1a, consists of a 1.3-m-long tube divided into two sections by a thin metallic diaphragm. The section behind the diaphragm is filled with high-pressure air (the driver section), and the other section (the driven section) has air at ambient pressure before the blast. When the diaphragm bursts, a shock wave is created as the air from the high-pressure driver rushes into the low-pressure-driven section. Since the average pressure value for rupturing the TM is around 197 dB SPL (141 kPa) [5], the shock tube needs to produce such pressures to study the rupture dynamics of the TM.

Figure 1a is a schematic of the shock tube equipped with four pressure sensors. The sensors mounted at different locations within the device characterize the system. The static pressure sensor (P1) records the low-speed buildup of pressure in the driver section, as shown in Fig. 1b. The other sensors (P2, P3, and P4) are high-speed pressure sensors. In Fig. 1c, P2 and P3 measure the pressure inside the tube. P4 monitors the pressure at a distal location from the end of the driven section, capturing the generated shock wave, as in Fig. 1d.

The ideal pressure versus time graph of the shock wave, shown in Fig. 1d, is a Friedlander waveform, where the pressure is initially at ambient conditions. At the initiation of the blast, there is a sudden surge in pressure when the shock wave hits the high-frequency sensor outside the tube. Next, the pressure decreases until it reaches ambient pressure. This is the positive duration of the shock wave. After the initial peak, the pressure drops to less than ambient air pressure for a period known as the negative duration and lasts until it returns to ambient conditions [6].

For a shock tube with a circular cross section, the diaphragm can be modeled as a thin, circular disk in order to estimate the rupture pressure of the diaphragm. Careful consideration of the diaphragm's material and thickness helps select a diaphragm that ruptures when the pressure in the driver section reaches a predetermined level. Besides the material and thickness of the

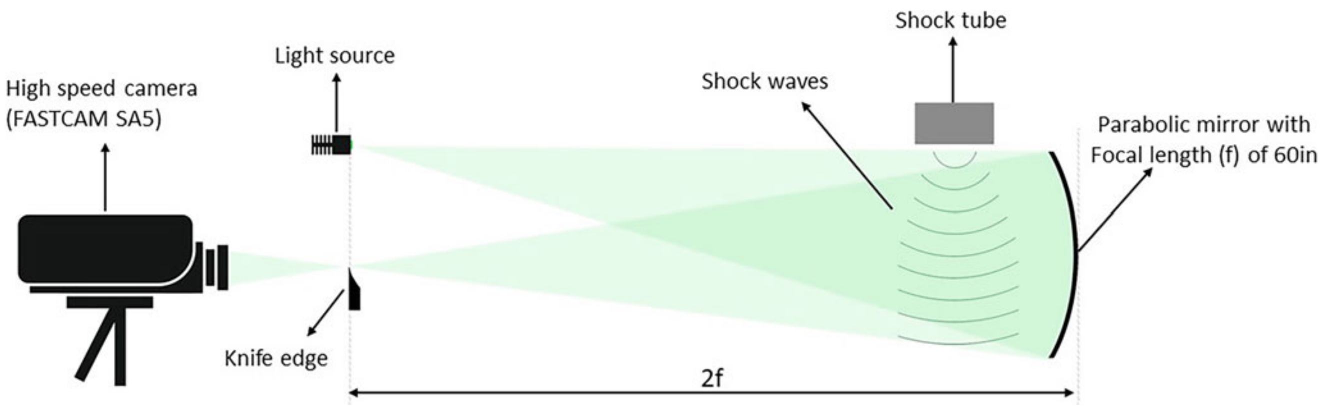

Fig. 2 Schlieren imaging setup consisting of a 530 nm, 32.5 mW, LED, directed through the volume of interest and reaching a parabolic mirror with a focal length *f*. The reflected light is focused at a distance *2f*, passing through a knife edge, and detected by a high-speed camera

diaphragm, other critical parameters to the tube's performance include the length of the shock tube, its radius, the materials used in its structure, as well as the length ratio (length of the driven section/length of the driver section) [7].

High-Speed Schlieren Imaging

We use high-speed Schlieren imaging to characterize the propagating shock waves we produce. Schlieren imaging visualizes variations in the refractive index of a transparent medium. The method relies on the fact that light is refracted differently by regions of varying density and pressure, such as those found in shock waves [8]. The result is images that capture spatial variations in the density of the medium being studied, with regions of high and low density appearing as bright and dark regions.

A single-mirror Schlieren setup (as pictured in Fig. 2) comprises four primary components: a point light source, a circular parabolic mirror, a knife edge (or razor blade), and a camera. The point light source is positioned at a distance of twice the mirror's focal length and directed toward the mirror, which reflects and focuses the light onto the camera's light sensor. A razor blocks half of the focused light from reaching the camera's sensor in order to enhance the contrast of the Schlieren image.

Integration of the Shock Tube and the Schlieren Imaging System

Figure 3 shows the current realization of the shock tube combined with the high-speed Schlieren imaging system. The pressure released within the driver section of the tube is recorded using the static pressure sensor Omega PX181B (P1 of Fig. 1a). When the pressure is large enough, the diaphragm ruptures, and pressurized air is released to the driven section of the tube. The sound pressures within the driven section are sensed using the high-speed sensors PCB102B06 (P2 and P3 of Fig. 1a) and PCB102B16 (P4 of Fig. 1a) and recorded using a data acquisition system (National Instruments). The output of the sensor P3 is used to trigger the camera just in time to record the shockwave using Schlieren imaging.

Figure 4 illustrates the expected setup (under development) for using the shock tube as a loading apparatus to rupture the tympanic membrane and a 3D optical quantitative measurement system (in this case, digital image correlation (DIC)) to record and analyze the rupture and the dynamic response of the TM. Inset shows a human TM sample prepared with a random pattern for quantitative high-speed DIC.