International Journal of Impact Engineering 64 (2014) 20–29

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Blast-wave impact mitigation using negative effective mass density concept of elastic metamaterials

K.T. Tan [a,*], H.H. Huang [b], C.T. Sun [a]

[a] *School of Aeronautics and Astronautics, Purdue University, West Lafayette, IN 47907, USA*
[b] *Department of Engineering Science and Ocean Engineering, National Taiwan University, Taipei 10617, Taiwan*

ARTICLE INFO

Article history:
Received 13 April 2013
Received in revised form
4 September 2013
Accepted 23 September 2013
Available online 3 October 2013

Keywords:
Blast-wave
Negative effective mass density
Elastic metamaterials
Wave propagation
Wave attenuation

ABSTRACT

This paper presents the use of elastic metamaterials for impact attenuation and blast-wave mitigation. Metamaterials represent a novel and emerging research area where materials exhibit exceptional properties not commonly found in natural materials. These unique properties are enacted by specifically designed microstructures. In this study, a single-resonator model and a dual-resonator microstructural design are proposed to exhibit negative effective mass density. The effect of negative effective mass density is explicitly confirmed by analysis of wave propagation using numerical simulations. Results evidently show that impact stress wave attenuation occurs over a wider frequency spectrum for the dual-resonator model as compared to the narrow band gap of a single-resonator design. Parametric studies of blast-wave simulation reveal that the mass and number of internal resonators have significant influence over the frequency range of blast-wave attenuation. The effectiveness and performance of the single-resonator and dual-resonator models on blast-wave mitigation are examined and discussed. Finally, practical ways to design and manufacture elastic metamaterials with negative effective mass density are presented and explored.

1. Introduction

As advanced body armor and head protection gears greatly reduced soldier fatalities from explosive and ballistic attacks, the problem of blast-related traumatic brain injury (TBI) in the attack survivors has become a more severe issue [1]. The impact of blast-wave propagation is so lethal to human health that although no external physical injuries are detected in the affected soldiers, serious damages are inflicted internally, particularly to the brain where neurological effects can be slow to appear [2]. It has been postulated that blast waves ripple through the victim's torso up into the brain through major blood vessels [3]. The increasing use of improvised explosive devices (IEDs) poses a very serious threat in military conflicts. Moreover, in recent times, the exposure to blast threat extends beyond war zones. Civilians now encounter the increased risk to terrorist attack by the use of explosive bombs, dangerous detonation, as well as IEDs. As such, it is important to develop materials that would absorb or reflect the full range of blast-wave frequencies generated by an explosion. It is critical to find ways for a material, not only to stop projectiles like shrapnel or bullets, but also to effectively attenuate the injurious effects of incoming blast and shock wave.

Researchers have been investigating ways to mitigate shock and blast waves by using different forms of materials and structures. Nesterenko [4] considered the applications of "soft" condensed matter for blast mitigation using simplified approach, based on the material's ability to absorb significant energy. Christou et al. [5] developed a fluid-structure interaction computational continuum model to investigate the attenuation properties of foam-specimens containing filler materials under shock loading. Dawson [6] designed a blast mitigation and protection infrastructure consisting of a steel plate backed by a layer of low-density, reticulated, flexible, fluid-filled foam. Wadley et al. [7] explored the feasibility of cellular materials concepts for active mitigation of blast overpressures, in which a deployable, precompressed, cellular medium is released just prior to the arrival of the blast-created impulse. This accelerates an attached buffer toward the blast and creates momentum opposing that acquired from the blast. Su et al. [8] proposed a blast wave mitigation device, which makes use of the repeated reflection of the shock wave within the blast mitigation device to significantly increase the duration of the force on the base of the cylinder over that of the blast wave. Grujicic et al. [9] investigated the blast-wave impact-mitigation ability of polyurea when used as a helmet suspension-pad material and compared

* Corresponding author. Tel.: +1 765 494 6237; fax: +1 765 494 0307.
E-mail addresses: kttan@purdue.edu, kwektze@hotmail.com (K.T. Tan).

0734-743X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.09.003

with the case of a conventional foam suspension-pad material. Grujicic et al. [10] also studied the effect of the prior processing and the resulting microstructure on the blast performance of all-metal sandwich-structures with an auxetic-hexagonal core. By far, the principal of blast-wave mitigation is either using deformation of materials to absorb energy, which results in vast material damage, or using anti-momentum principle to oppose the incoming blast-wave, which requires somewhat complex structures. Moreover, these concepts cannot be designed to tailor attenuation of specific frequency ranges, or cover the full range of blast-wave frequencies.

In this paper, we investigate the use of elastic metamaterials to mitigate blast-wave and attenuate stress wave propagation. Metamaterials represent a novel and emerging field in materials engineering, and are characterized by the fact that they possess exceptional material properties not commonly found in natural materials. These material properties are enacted, not due to chemical composition, but by specially designed man-made microstructures. Metamaterials originally started in the field of electromagnetic waves where researchers investigated negative electrical permittivity, negative magnetic permeability and negative refractive index [11,12]. Motivated by the mathematical analogy between acoustic and electromagnetic waves, the counterpart acoustic metamaterials are recently explored [13–16]. This new branch of acoustic metamaterials, also known as mechanical or elastic metamaterials, consists of tailored microstructures that exhibit unusual mechanical properties such as negative effective modulus and/or negative effective mass density [13–16]. This paper aims to employ the effective negative mass density concept of acoustic/elastic metamaterials for blast-wave impact mitigation. The original single mass-in-mass resonator model, which offers negative mass property over a specific frequency range, is first introduced. A newer dual-resonator model is then described. This model maximizes the negative mass density over a wider frequency range, and aptly corresponds to the wide frequency nature of blast-wave problem. The transient and dynamic response of the metamaterial is then analyzed by examining a lattice system model that consists of mass-in-mass units to exhibit negative effective mass density. The effectiveness of the negative mass models on impact wave attenuation is demonstrated by computational simulation using numerical analysis. The use of elastic metamaterials for blast-wave mitigation is further presented and discussed by understanding how different internal resonator parameters affect stress wave propagation.

2. Analytical negative mass models

2.1. Single-resonator model

The concept of negative effective mass density can be achieved by using a mass-in-mass unit microstructure [15,17]. Fig. 1 shows the microstructure of a single-resonator spring-mass system. The outer unit cell has a mass m_1 and displacement u_1, while the internal resonator has a mass m_2 and displacement u_2. The internal resonator is coupled to the outer mass by a linear spring of stiffness k_2. By considering the free body diagrams of the masses m_1 and m_2, we can obtain the equations of forces as

$$m_1\ddot{u}_1 = F + k_2(u_2 - u_1) \tag{1}$$

$$m_2\ddot{u}_2 = k_2(u_1 - u_2) \tag{2}$$

Assuming that the displacement of masses follow harmonic wave behavior, similar to that of the applied force F, we have

$$F(t) = F_O e^{-i\omega t} \tag{3}$$

$$u_\gamma(x,t) = \hat{u}_\gamma e^{-i\omega t} \tag{4}$$

whereby $\gamma = 1, 2$ in this case.

By solving the above equations, we can simplify the relation to

$$0 = F_O + \left(m_1 + \frac{\omega_2^2 m_2}{\omega_2^2 - \omega^2}\right)\omega^2 \hat{u}_1 \tag{5}$$

where $\omega_2 = \sqrt{k_2/m_2}$ is the local resonance frequency of the internal resonator mass m_2.

To obtain an effective mass behavior of the microstructure, the following equation must be satisfied.

$$F_O = -m_{eff}\omega^2 \hat{u}_1 \tag{6}$$

Physically, this means that the motion of outer mass, m_1 is similar to that of an equivalent effective mass, m_{eff}, depicted schematically in Fig. 1. Solving Equations (5) and (6), we attain the effective mass of the microstructure as

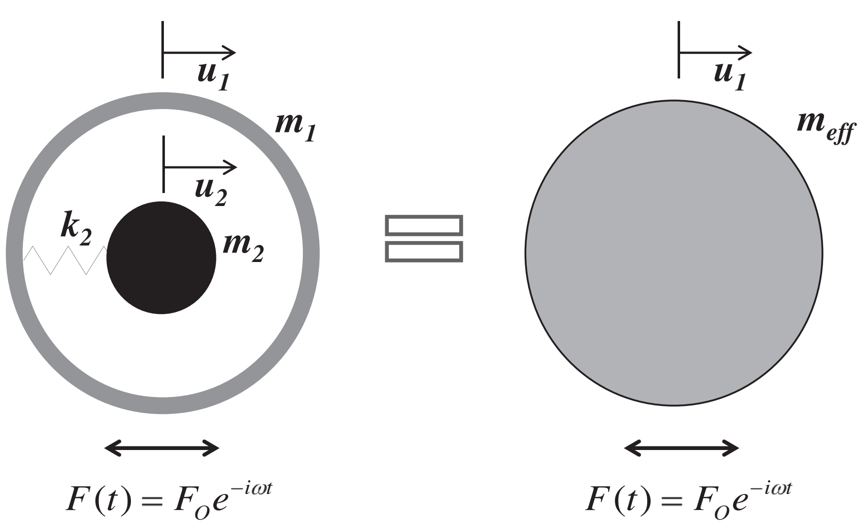

Fig. 1. Microstructure of single-resonator spring-mass system and its effective mass; the motion of outer mass m_1 equals to that of the effective mass m_{eff}.