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A negative Poisson's ratio suspension jounce bumper

Yuanlong Wang [a,b], Liangmo Wang [a,*], Zheng-dong Ma [b], Tao Wang [a,b]

[a] Department of Vehicle Engineering, School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, PR China
[b] Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, USA

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ABSTRACT

Jounce bumpers in automotive suspension can absorb impact energy and improve Noise, Vibration and Harshness (NVH) performance of entire vehicle. In this paper, a negative Poisson's ratio (NPR) structure was introduced and applied on the jounce bumper. The NPR jounce bumper can be primarily described by few parameters and is convenient for design, analysis and optimization. Three NPR jounce bumper prototypes were manufactured and tested. The test results of prototype 1 indicated that the NPR jounce bumpers had excellent viscoelasticity characteristic to absorb impact energy owing to its high damping. Compared with traditional jounce bumper, the NPR jounce bumper can achieve similar mechanical behavior but with a smoother load-displacement curve, which is beneficial to the NVH performance. Moreover, numerical calculation was conducted. Its results were fairly reliable for the prediction of mechanical behavior of NPR jounce bumper. The numerical results implied the stress concentration areas and the displacement of failure. The deformation shapes of NPR jounce bumper were also discussed. Finally, prototypes 2 and 3 manufactured from 3D printing technology were tested to explore the possibility of the application of 3D printing technology on NPR structures.

1. Introduction

Jounce bumpers play a key role in automobiles suspension system. They are typically mounted between the shock absorber and its base and located inside the suspension coil spring, as shown in Fig. 1. Moreover, jounce bumpers are commonly manufactured from hyperelastic materials like rubber or Polyurethane (PU), and they primarily serve to absorb impact energy and improve Noise, Vibration and Harshness (NVH) performance by preventing suspension components from being fully compressed during transient impacts caused by heavy loads, potholes, curbs or objects on the road [1]. Moreover, jounce bumpers may also act as an assistant compression spring when the maximum load is approached [2]. The load-displacement curve of the jounce bumper significantly affected the vehicle NVH performance [3]. Therefore it is essential to have a suitable mechanical behavior of jounce bumper. Jounce bumpers are primarily designed to retain the load-displacement curve in an ideal region defined by an upper and a lower curve. The ideal region is determined by vehicle NVH optimization. Moreover, fatigue failures may occur in jounce bumper due to long-term continuous loads. The fatigue life of jounce bumper is meaningful and should be determined, since their failure can provide discomfort during the ride and lead to the failure of other suspension components.

A large amount of variables exists in jounce bumper shape design, which affects the efficiency and enhance difficulty in design process. Dickson et al. [4,5] discussed the effects of polyurethane materials and geometry parameters on the mechanical performance of a jounce bumper. And many efforts [6–10] were conducted to use Finite Element Analysis (FEA) in jounce bumper design. Wang et al. [11] proposes a stratification method for FEA of a polyurethane jounce bumper which had different densities and mechanical properties between exterior and interior PU areas. It was proved to be reliable for small to medium strains (0–0.4). On the other hand, Schudt et al. [12] proposed a dual rate jounce bumper design, in which two bumper components with different designs were used in order to achieve a smooth load-displacement curve. Due to the hyperelasticity and inhomogeneous property [13,14] of PU and nonlinearity caused by large deformation, the FEA of PU jounce bumper is complex and requires further researches. Therefore the jounce bumper design is mainly based on experiences.

Negative Poisson's ratio (NPR) materials/structures, also called auxetic materials/structures, are impressive novel materials/structures. Poisson's ratio is defined as $\nu = -\varepsilon_t/\varepsilon_l$, where ε_t is lateral strain and ε_l represents longitudinal strain. It reflects the volume change in tensile or compression deformations. Lower Poisson's ratio leads to a higher volume change in deformation. Almost all the natural materials have a positive Poisson's ratio: Rubber nearly 0.5, Aluminum 0.33, Steel 0.27 etc. Contrarily, NPR materials/structures have opposite lateral behavior. Namely, the materials/

* Corresponding author at: Department of Vehicle Engineering, School of Mechanical Engineering, Nanjing University of Science and Technology Nanjing, Jiangsu 210094, China.
E-mail addresses: cienveryon@163.com (Y. Wang), liangmo@njust.edu.cn (L. Wang).

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structures expand laterally under tensile load, and shrink under compression load. Since Lakes [15] from Iowa University developed a PU foam with negative Poisson's ratio, many types of NPR materials/structures were investigated.

It has been researched [16–19] that NPR structures had great mechanical performances, especially fracture toughness, shear modulus etc. Wang et al. [20] researched a dual-material auxetic metamaterials using 3D printing. The auxetic metamaterials could deform without the beam or wall buckling and achieve stable negative Poisson's ratio at large strain levels. Smardzewski et al. [21] developed numerical models of auxetic compression springs suitable for seat structures of office and home furniture. Analyses were conducted on real and numerical models of different spring structures subjected to uniaxial compression.

When a concentrated compression load was applied along the longitudinal direction, NPR structures will shrink along the lateral direction, which means the material will move towards the load and improve the stiffness around load. Thus material distribution is sufficiently utilized in NPR structures, and relatively low weight can be expected under same mechanical requirements. Manufactured from specific materials, e.g. hyperelastic materials including rubber and PU, NPR structures can also have excellent performance of energy and vibration absorbing. Thus they can be applied on some key automotive components, especially engine mount, jounce bumper, tire etc.

In this paper, an engineering NPR structure was applied on the jounce bumper. The NPR structure has an opposite lateral behavior other than normal material, which was ideal for jounce bumper. The structure would shrink laterally under compression which obviously enhanced the stiffness of entire structure. Thus the cup and reinforcement rings for traditional jounce bumper can be removed from the suspension assembly. The NPR jounce bumper can be defined by few structure parameters. Through further parameter analysis and optimization, the ideal load-displacement curve may be obtained. Hence the design procedure of jounce bumper can be simplified, boosted and optimized. The NPR jounce bumper can also be used in other applications in which specific stiffness and damping were required. This study primarily focuses on the load-displacement performance of NPR jounce bumper through experimental and numerical method. The stress and strain analyses and fatigue life prediction of NPR jounce bumper were not conducted here and require further researches.

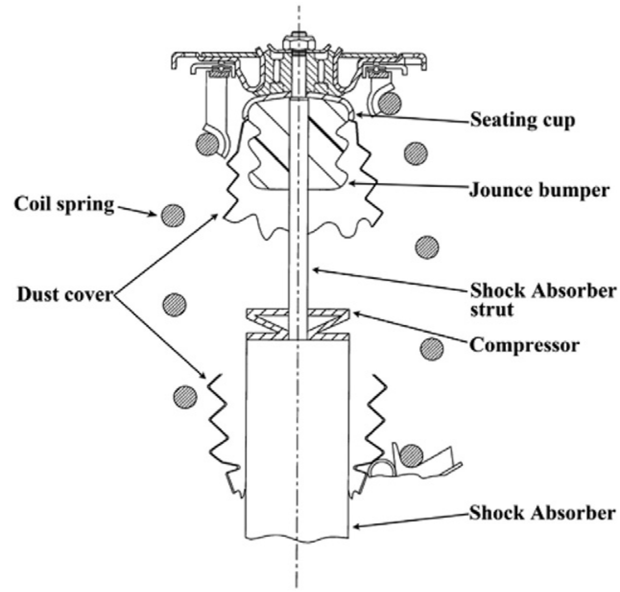

Fig. 1. Location of jounce bumper in suspension.

2. Materials and methods

2.1. 2D engineering NPR structures

Larsen et al. [22] fabricated a NPR structure through a topology optimization process. Base on Larsen's work, Ma, Liu and Zhang et al. [23–25] investigated an engineered NPR structure as shown in Fig. 2. The low inclined layers are called tendon. They are mainly bearing tensile stress. While the high inclined layers are named as stuffer. Compression and bending are the primary deformations exist in stuffer.

The 2D NPR cell has 3 main parameters: stuffer angle ϕ, tendon angle θ and layer height H, as shown in Fig. 3. Stuffer angle ϕ is the angle between stuffer cell wall and vertical axis, while tendon angle θ is the angle between tendon cell wall and vertical axis. It is evident that $0<\phi<\theta<90°$. The effective layer height H is the distant between stuffer bottom hinge and tendon bottom hinge. Moreover, the sectional property and material of stuffer and tendon can vary depending on the engineering requirements.

Liu et al. [24] conducted specific researches on this type of NPR structures. It came to a conclusion that different parameters lead to different mechanical performance and deformation behavior. The effective Poisson's ratio can even reach -60 theoretically. And the mechanical performance of structure can cover a large region with variable parameters and materials. Fig. 4 shows the deformation shapes of two NPR structure cases with same dimension in height but different cell angles. In case 1, $\phi=30°$ and $\theta=60°$. While $\phi=15°$ and $\theta=30°$ in case 2. These two cases were both loaded with a 200 MPa uniform pressure on the top surfaces. The dashed lines represent the original structures, and the real lines are the deformed shapes. Distinct compression behaviors can be observed between these 2 cases. Case 2 has larger lateral displacements than case 1. After calculation, the effective Poisson ratio is -0.94 in case 1 and -7.4 in case 2. The effective Young's modulus is 1.4 GPa in case 1 and 2.7 GPa in case 2. Hence a relative lower effective Poisson ratio leads to a higher Young's modulus. In conclusion, applying NPR structure, a large range of mechanical performance can be achieved with same material using different structure parameters.

Zhang et al. [25] developed a theoretical analytical model of NPR structure cell, as shown in Fig. 5. It is a 1D beam model, and the thicknesses of cell walls shown in Fig. 5 were only for the purpose of better understanding. L and M are the lengths of inclined cell walls respectively in stuffer and tendon. The length of horizontal cell wall is defined as $N=\beta L$, where β is horizontal cell wall length to inclined cell wall length ratio. T_L and T_M are the thicknesses of inclined cell walls respectively in stuffer and tendon. If the cell wall thickness to length ratios α are the same both in stuffer and tendon, there are $T_L=\alpha L$ and $T_M=\alpha M$. M can be calculated by other parameters according to geometry requirements, let $M=KL$, where K is a length ratio.

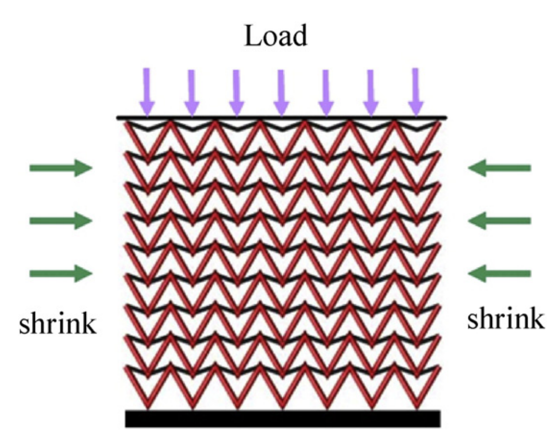

Fig. 2. A 2D NPR structure.