AIP Applied Physics Letters

# Response to “Comment on ‘Disentangling longitudinal and shear elastic waves by neo-Hookean soft devices’” [Appl. Phys. Lett. 107, 056101 (2015)]

Zheng Chang, Hao-Yuan Guo, Bo Li, and Xi-Qiao Feng

Citation: Applied Physics Letters **107**, 056102 (2015); doi: 10.1063/1.4928393
View online: http://dx.doi.org/10.1063/1.4928393
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/5?ver=pdfcov
Published by the AIP Publishing

# Response to "Comment on 'Disentangling longitudinal and shear elastic waves by neo-Hookean soft devices'" [Appl. Phys. Lett. 107, 056101 (2015)]

Zheng Chang, Hao-Yuan Guo, Bo Li, and Xi-Qiao Feng[a)]
*Department of Engineering Mechanics, Institute of Biomechanics and Medical Engineering, Tsinghua University, Beijing 100084, China*

(Received 25 June 2015; accepted 29 July 2015; published online 6 August 2015)

[http://dx.doi.org/10.1063/1.4928393]

In a recent letter, we demonstrated, through both theoretical derivation and numerical simulations, that neo-Hookean materials can behave like smart elastodynamic metamaterials and may be used to make full control of S-waves.[1] This finding enables us to design soft devices that can disentangle P- and S-waves by introducing pre-deformation in neo-Hookean materials. On the basis of incomplete understanding of the above work, Galich and Rudykh made the Comment,[2] which is wrong in the following three aspects.

First, there are numerous kinds of hyperelastic materials, e.g., rubber, hydrogel, and various soft biological tissues, which possess greatly different constitutive relations.[3] Therefore, a number of models have been established to describe their hyperelastic mechanical behaviors. A few examples are the neo-Hookean model, Mooney-Rivlin model, Fung model, and Arruda-Boyce model.[4] Among them, the neo-Hookean model is most widely used because it has a simple form, clear physical meanings, and can well express the stress–strain relations of many materials in a wide range of deformation. Of course, none of these models can well describe the mechanical responses of all hyperelastic materials. Therefore, it is inappropriate to state, through comparison with one experimental curve of a specific material,[2] that the neo-Hookean model cannot properly predict the response of soft isotropic materials. The Lopez-Pamies (LP) model[5] mentioned by Galich and Rudykh[2] is, in fact, a modified version of the neo-Hookean model. The LP model contains four more fitting parameters, $\alpha_1$, $\alpha_2$, $\mu_1$, and, $\mu_2$, which are unclear in physical meaning and difficult to be determined from experiments.

Second, we proved that neo-Hookean materials satisfy the condition $A^h_{ijkl} = \partial^2 W^h / \partial F_{ji} \partial F_{lk} =$ constant and, therefore, can be used to perfectly control S-waves.[1] Here, $A^h_{ijkl}$ is the hybrid part of the effective elastic tensor. The path of an S-wave propagating in a neo-Hookean solid always attaches in the material coordinates and deforms along with material deformation. Both in-plane and anti-plane S-waves can be manipulated by a deformed neo-Hookean material, and the material compressibility does not interfere with this salient property. Actually, the control of S-wave in a neo-Hookean material directly relies on its linear relation between shear stresses and shear strains, i.e., $A^h_{ijkl} = \mu \delta_{ik} \delta_{jl}$. However, hyperelastic materials with the Lopez-Pamies constitutive relation[5] violate the aforementioned condition and thus are difficult to perfectly control S-waves according to hyperelastic transformation theory.

Using the method proposed in the letter,[1] Galich and Rudykh[2] showed that in the case of horizontal incidence, an incompressible Lopez-Pamies material subjected to simple shear deformation has the same wave-mode separation effect as its neo-Hookean counterpart. However, it can be seen from Fig. 4 in the Comment[2] that for compressible Lopez-Pamies materials, the divergence angle $\Delta\theta$ between P- and S-waves dramatically decreases with the increase in the material compressibility. In case of the shear angle $\gamma = \arctan(1/3)$, for example, $\Delta\theta$ will reduce to 0 when $\eta = \mu/(\lambda + 2\mu)$ approaches 0.2. Therefore, it is evident that neo-Hookean materials will have better performance than Lopez-Pamies materials when they are used to separate P- and S-waves.

Third, it is well known that simple shear is not simple in the strain and stress fields, especially along the free boundaries and in the vicinity of the corners of the deformed body. On one hand, no constitutive model has been established on the basis of simple shear experiments. In practical devices, on the other hand, the simple shear deformation of a soft material can be easily achieved by specifying the corresponding displacement boundary conditions on the two parallel material surfaces of a cubic body. In this case, the material in the central region will undergo pure shear strains. To illustrate the efficiency of the proposed technique, therefore, we simulated the propagation of a P-wave and an S-wave in a simple-sheared neo-Hookean material, as shown in the main text and the supplemental material of our letter,[1] The results demonstrate that the neo-Hookean material in a simple-shear deformation state can well achieve the function of wave-mode separation.

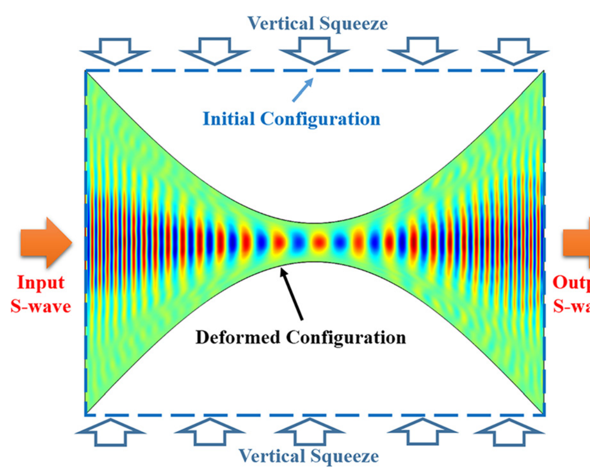


FIG. 1. Wave guide of shear elastic wave realized by vertically squeezing a rectangular neo-Hookean material.

[a)]Author to whom correspondence should be addressed. Electronic mail: fengxq@mail.tsinghua.edu.cn

 

Additionally, it is worth to emphasize that S-wave control can also be accomplished by neo-Hookean materials in other pre-deformation states. Another example is given in Fig. 1, where the upper and lower surfaces of a neo-Hookean material of cuboid shape are squeezed into a biconcave shape while the left and right surfaces are fixed. An in-plane harmonic Gaussian S-wave beam in the horizontal direction is imported on the left boundary of the device. Our numerical simulation shows that, in such a complicated deformation state, the S-wave still propagates along with material deformation and passes through the neck without loss of energy.

In summary, both theoretical analysis and numerical simulations reveal that neo-Hookean hyperelastic materials are an ideal candidate not only to manipulate S-waves but also to realize the wave-mode separation function.

[1] Z. Chang, H. Y. Guo, B. Li, and X. Q. Feng, Appl. Phys. Lett. **106**, 161903 (2015).
[2] P. I. Galich and S. Rudykh, Comment on "Disentangling longitudinal and shear elastic waves by neo-Hookean soft devices," Appl. Phys. Lett. **107**, 056101 (2015).
[3] R. W. Ogden, *Non-linear Elastic Deformations* (Dover Publications, 1997).
[4] M. G. Zhang, Y. P. Cao, G. Y. Li, and X. Q. Feng, Biomech. Model Mechanobiol. **13**, 1 (2014).
[5] O. Lopez-Pamies, C. R. Mec. **338**, 3 (2010).