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Review of “Passive discrete lens for broadband elastic guided wave focusing”

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^E Editor

The authors would like to thank the reviewers for their work and constructive remarks. This revised form aims at answering their comments.

1 Reviewer #1 (Anonymous)

Reviewer This paper is presenting numerical and experimental works about a passive discrete focusing lens for elastic wave. It reminds that a varying thickness region in a plate can constitute a lens and that a continuously varying thickness can be replaced by a discrete gradient. Overall, the manuscript is well written and quite pleasant to read. I don't have major remarks on the scientific content, but some questions can be answered and mistakes corrected.

Authors Thank you for these kind words. We have tried to answer the given remarks and revise the paper in accordance.

Reviewer In the literature review, two more articles may be of interest in the context of the paper. The first is “Attenuation of waves in plates and bars using a graded impedance interface at edges”, by Vemula, Norris and Cody, in JSV 196(1), 1996, mainly for historical reasons, because it describes a proto-ABH with discrete segments of varying material. The second would be “A review on acoustic black holes (abh) and the experimental and numerical study of abh-featured 3D printed beams” by Chong, Tan, Lim, Lee, in International Journal of Applied Mechanics 9 (6), 2017 where the authors study the effect of discrete steps on a varying thickness plate.

Authors The authors thank the reviewer for these new references, they have been added to the bibliography.

Reviewer In Section 2, several equations are questionable. Eq. (1) mentions $\sec()$ while Zareei (2018) mentions $\operatorname{sech}()$. The development logically yields Eq. (8) where $\cos()^2$ appears, where the use of $\operatorname{sech}()$ would yield $\cosh()^2$. Note that the first gives a maximum of thickness in beta while the latter gives a minimum in beta, which is expected! Fortunately, Figure 1(b) mentions correctly a hyperbolic secant and Figures 2 and 5 seem to have a $\cosh()^2$ profile. Moreover, if Eq. (8) comes from Eqs. (1,6,7), I would expect to see a n_0^2 appear. Please rewrite the correct equations in Section 2.

Authors The authors thank the reviewer for catching these mistakes and want to apologize for this. Indeed, the right formulation to use is the one with sech , not \sec , as represented in Figure 1(b). The missing n_0^2 term has been corrected.

Reviewer Still in Section 2, while it is often made mention of varying thickness, Eq. (3) only applies to

constant thickness plates. I understand it permits to obtain conveniently the dispersion relation that follows, but some words could be added to make things clear.

Authors The wave propagation is studied in the x -direction, and the variations for the thickness are in the y -direction, thus the thickness is constant in the direction of waves. A sentence has been added to explain this assumption: “*Wave propagation is considered in the main direction x of the plate, and the thickness is assumed to vary only in the y -direction, thus the thickness is constant along x .*”

Reviewer Section 2.1: the design is interesting. Would we obtain the lens effect by removing material to the plate instead of adding material? Or is the important added thickness at the edges playing a role, for example by preventing the waves from going sideways due to the discontinuity?

Authors Considering Equation (8) that gives the evolution of the thickness profile, removing material would require to obtain an extremely-fine profile at the center of the lens, very difficult to manufacture. A similar problem occurs in the case of ABH, leading to non-ideal truncated profile. The strategy of adding material for the lens allows avoiding this problem.

Reviewer Section 3.1, is there a low frequency limit below which the discrete lens does not have the same effect than the continuous one?

Authors Simulations have been performed for lower frequencies than the one presented in the article, and similar focusing effects are still obtained with the discrete lens and the continuous one. One major limit in reducing the frequency is that the wavelength becomes high compared to the length of the lens, and the refraction effect is not as visible for the continuous as for the discrete cases.

Reviewer Section 4: the authors mention that the segments are bonded on a host plate. How exactly and can it have an influence? I expect that welding aluminum is a delicate process, much like machining a continuously varying thickness (which should also be welded anyways).

Authors The segments are bonded on the host plate using a strong cyanoacrylate glue. This configuration has led to a good continuity between the plate and the lens to ensure that the lens affects waves. Welding has not been tested at all, as it would be a delicate process indeed. The means at our disposal did not allow machining either, even for the isolated lens profile. Feedback from companies is that it is a complex curved geometry to manufacture. That is the reason why investigations on a discrete profile have been done.

Reviewer What does the experimental result in case 4 mean?

Authors The experimental result in case 4 does not mean a specific thing. It corresponds to a screenshot at one fixed time, and the result does depend a lot on the chosen plot time. Time chosen for the plots in the article correspond to times at which the amplitude is maximal at the focal point. The reviewer is right to note that an unclear propagative behavior was presented for case 4 at 5300 Hz, but this is an effect of the time plot. In order to clarify this point, another plot is now proposed, slightly different from the layout presented in the original version – $\Delta t = 8 \times 10^{-6}$ s). Oscillations more similar to those obtained for the other frequencies are now visible.

2 Reviewer #2 (Anonymous)

Reviewer This article concerns the use of passive lenses for the focusing of waves in elastic plates. Considering the Kirchhoff-Love model, focusing can be achieved in the framework of the so-called GRADIENT-INDEX (GRIN) devices such as a lens with a varying thickness profile bonded to a plate. The efficiency of such devices has been evidenced in the literature and it is illustrated numerically in the present article for a continuous thickness profile. Despite these positive results, the Authors point to the difficulty to manufacture desired profiles in practice and explore the possibility to achieve comparable behaviors by approximating the continuous lens thickness profile by a piecewise-constant profile that can be manufactured more easily and with a greater precision. This question is investigated here both numerically and experimentally. This article is well written overall and the presented results are convincing. The introduction presents the motivations and the bibliographical context in a comprehensive manner.

- Authors** Thank you for these encouraging remarks.
- Reviewer** Yet, there are a number of questions (listed below) that should be addressed before I can recommend this article for publication in JTCAM. The starting point of the study is a given continuous profile. Yet, one might wonder about the possibility to assume from the very beginning that the lens profile is piecewise constant and determine (using, e.g., optimization methods) the corresponding segment sizes and heights to achieve desired properties. Could the Authors comment on this?
- Authors** Indeed, the initial goal of the research was to design a mechanical lens with a continuous profile. Once the hyperbolic secant profile established, several companies have been contacted for the manufacturing process, and it became that this presented many difficulties with the machining dimensions, the precision for instance. That is the reason why a piecewise profile has been chosen, to simplify the manufacture. From that point, the purpose has not been to define the optimal piecewise profile, but to demonstrate the focusing effect with a simplified geometry. Only a parametric study has been conducted, with the intention to find a feasible set-up configuration and observe the focusing effect. The reviewer is totally right to propose an optimization study, this would have been the better way to define an optimal piecewise configuration by comparison with the continuous profile. As the purpose of the authors was just to demonstrate the focusing property, and that this property was visible with an arbitrarily chosen number of segments, no specific optimization study has been done. To clarify this point in the paper, the following sentence has been added: *“It is possible to use optimization methods to identify a one-sided discrete distribution that achieves focusing effects similar to the symmetric configuration. Such an approach has not been adopted here as an objective was to define a design easy to manufacture: in this context, a strategy with so few segments of the same size has been retained.”*
- Reviewer** To my opinion, Section 2 should provide a little more introductory details on passive GRIN lenses: what is the lens geometry? How is it bonded to the plate and what is the effect of this bonding? For example using a figure with a zoom on the top Figure 3 to show the lens bonded to the plate. How are the constitutive properties of the lens chosen? What is the relation between the location of the focal point and the lens geometry? What about reflexion/transmission phenomena possibly occurring at the lens/plate interfaces?
- Authors** The authors agree that the GRIN lens has been introduced a little quickly in Section 2. For a better description, the following sentences have been added: *“The host plate is 5 mm thick, 1.9 m long and 0.65 m wide. It is made of aluminum with properties $E = 70$ GPa for the Young’s modulus, $\nu = 0.3$ for the Poisson’s ratio, $\rho = 7800$ kg · m⁻³ for the density. The lens consists in an aluminum plate with the same properties as the host plate. It is 0.65 m wide as the host plate, and 0.35 m long. The gradient coefficient α is chosen for the focal length to be equal to 0.35 cm meaning that the focal point should be at the exit of the lens. The thickness of the lens follows the profile defined by Eq (3). It is bonded to the plate with an assumption of perfect continuity of displacements between the two structures.”*
- Reviewer** As highlighted on p. 5, focusing effects are more pronounced at high-frequency despite the fact that they are supposed to be frequency-independent. Any explanation why? Overall, how to explain the frequency-dependent variability observed in amplitude in Figures 4, 6, 10, 11 and 12?
- Authors** Focusing effects are supposed to be frequency-independent in the sense that they occur for a wide range of frequency and not only at a given one. However, the way the propagation of waves is modified to make them converge at the focal point does depend on the frequency. As the frequency increases, the wavelength reduces and the impact of the geometry changes on the wave propagation increases. For this reason, the GRIN lens does affect more high frequency waves than low frequency ones, but it is noticeable that the focusing effect is even visible at low frequencies.
- Reviewer** Considering the discrete lens profile, the segments are assumed to all have the same thickness with an average height but no explanation is given as to why this choice was made. Other choices could be more “optimal” (in a sense to be defined) and I think this should be discussed.

- Authors** As explained in a previous question, the purpose was not to determine a piecewise profile optimally corresponding to a continuous one, but to show that it was possible to design a mechanical lens by locally changing the thickness. Finally, the discrete profile of the lens proved to be an asset as it is easier to manufacture. To clarify this point in the paper, the following sentence has been added: *“It is possible to use optimization methods to identify a one-sided discrete distribution that achieves focusing effects similar to the symmetric configuration. Such an approach has not been adopted here as an objective was to define a design easy to manufacture: in this context, a strategy with so few segments of the same size has been retained.”*
- Reviewer** I think that the results of Figure 8 could be summarized by reporting in a table the errors between a given curve and the reference one using, e.g., the L^2 -norm in a subdomain of interest. Overall, it might not be entirely clear what is the main issue under investigation here. Indeed, what is the most important characteristic to achieve here (e.g. local focusing or overall matching of the waveforms)?
- Authors** The most important characteristic to achieve here was the focusing at one point that was expected on a wide range of frequency. In order to quantify the error about this characteristic, a table giving the error on the mean quadratic transverse velocity around the expected focal point between a reference case (continuous profile) and the different discrete profile has been added to the paper.
- Reviewer** This article investigates the question of approximating a GRIN device with a discrete lens profile but only one continuous profile has been studied. How are the results dependent of the chosen continuous profile?
- Authors** The analytical study of the thickness variation necessary to obtain the desired refractive effect showed that the necessary profile was a hyperbolic secant profile, which is how the continuous profile has been chosen. A parabolic solution as a first-order Taylor series approximation could have been tested to generate focusing.
- Reviewer** I find Section 3 a bit confusing as the symmetrical continuous profile is used as a reference whereas it seems that it is the unsymmetrical continuous profile that is approximated by the discrete lens. This should be clarified.
- Authors** The symmetrical continuous profile is the theoretical profile which effectively leads to the localization phenomenon, and which must therefore be reproduced. That is the reason why it is used as the reference. To precise this point, the following sentence has been added: The symmetrical continuous profile is always used as a reference as this configuration corresponds to the optimal case.
- Reviewer** I might be confused but it seems to me that the x and y labels are inverted on the Figures 4, 6, 10, 11 and 12.
- Authors** The reviewer is totally right, axes have been changed on all figures to homogenize the notations. The x -axis is along the length of the plate, the y -axis corresponds to the width and the z -axis to the thickness.
- Reviewer** In Figure 8, the x -domain does not coincides with this of Figure 4. The x -axes should be defined consistently throughout the article (by, e.g., defining $x = 0$ as the lens “upper” boundary).
- Authors** Axes have been changed to clarify the reading, the plate is 1.9 m long between $x = -0.8$ m and 0.8 m, then the PML is between 1.6 m and 1.9 m for the experimental case. The lens is exactly between $x = -0.63$ m and $x = 0.28$ m.
- Reviewer** The objective of Section 4 are not quite clear to me as the comparison of numerics with experiments do not seem to be the main concern of this work. Please clarify what is intended to be shown in this section.
- Authors** The objective of Section 4 is to validate the design, and demonstrate that the focusing effects predicted by the simulation did effectively occur on a real case. The actual observation of focusing by vibrometric measurements is convincing evidence that the design is appropriate.

Reviewer In the conclusion, it is stated that "focusing properties do not depend on the frequency", a statement which is not supported by the numerical and experimental results. This should be amended.

Authors The purpose of the work was to show that wave focusing did occur not only for one, but for several different frequencies. This does not mean that the focusing effect is obtained the same way for all the frequencies, but that focusing at a focal point always occur. That was the meaning on the sentence. In order to clarify this point, the sentence has been changed to "*focusing effects resulting in a concentration of elastic waves at one point of the structure are obtained on a wide range of frequencies.*"

Reviewer Typo: "doesn't" -> "does not".

Authors The correction has been done.

3 Reviewer #3 (Anonymous)

Reviewer Overall, this paper is well-constructed, well-written and present interesting results on an up-to-date topic: manipulation of material structure to achieve adequate wave propagation properties.

Authors Thank you for these kind remarks.

Reviewer Nevertheless, there is some points to modify or to clarify before accept it for publication. Page 3, Equations (1) and (8): Please change the notation of the hyperbolic functions to standard ones: Equation (1): "sec" to "sech" and Equation (8): "cos" to "cosh"

Authors The notations have been changed, there was a confusion in the document and the authors want to thank the reviewer for catching these mistakes.

Reviewer Page 5, paragraph 2.2 - unsymmetrical GRIN lenses. The model is based on a Kirchhoff thin plate symmetrical with respect to the middle plane. In case of unsymmetrical GRIN lens, this symmetry is locally broken. Is there any consequence of this asymmetry on the wave propagation or refractive index? The question is the same for the added PML.

Authors The reviewer is right to point out that the unsymmetrical GRIN lens breaks the symmetry of the structure with respect to the middle plane. That is the reason why the initial studied profile studied in Section 2.1 was symmetrical. The problem with such a profile was the space needed for it, which is the reason why investigations have been done on the unsymmetrical profile. The added GRIN lens acts as an obstacle to the wave propagation, which is a symmetrical obstacle in one case, and an unsymmetrical in the other. This generates an asymmetry in the waves to focalize. In order to evaluate the impact of this asymmetry on the efficiency of the lens, comparisons can be done between Figures 4 and 6. It seems that the asymmetry does not affect consistently the focusing effect of the lens. There was a desire to propose a configuration where only one side of the structure was impacted by the integration of the lens and the PML layer, to allow vibrometric measurements over a large surface, and to propose a configuration where the control strategy is hidden. Again, as the introduction of a single layer of PML was sufficient to attenuate the waves, it was not considered necessary to introduce a symmetric added layer.

Reviewer Page 8, paragraph 3.1 - discretization of the curved profile and page 11, Figure 8; I have numerous questions about the results presented:

- Why choosing test frequencies different from those used in the rest of the paper?
- Correct the legend "to 1000 Hz (case f)" to "to 10 000 Hz (case f)"

Authors Frequencies were different because numerical tests about this point had been done before the experiments, and not actualized then. New plots are proposed for the same frequencies as for the rest of the paper.

Reviewer I do not understand the dimension and coordinate presented: in sub-figures 8(a) to 8(f), the axis is given as " x (m)" and ranges from 0 to 1.2 m. However, if I understand well, x is the transverse coordinate and sizes 0.5 m while y sizes 1.9 m. Then, none of the characteristic presented in

Figure 8 corresponds to what is used in the rest of the paper.

- Authors** Figure 8 corresponds to a plot along the central line in the x -direction. It goes from -0.8 to 1.1 (length of the plate = 1.9 m). The x -axis has been modified to clarify the notations.
- Reviewer** More generally, as the six segments are bonded on the plate, what is the influence of the discontinuity at the interface between two adjacent segments and have you any idea of the influence of the bonding (such as added stiffness or damping)?
- Authors** For the initial set-up the bonding had been done using a fine VHB patch in order to easily remove the lens from the support plate. The focusing effect was not observed with this configuration, meaning that the waves did manage to propagate through the patch, without being affected by the lens. So the segments have been finally bonded with a strong cyanoacrylate adhesive to ensure the continuity between the plate and the lens.
- Reviewer** I have a question about results presented in Figures 10, 11 and 12 (comparison c_1 , c_2 , c_3 , c_4 , c_5 and c_6). There is an apparent difference between the quadratic velocities of the longitudinal cut along the central line showed in these figure and the ones presented in Figure 8. In Figures 10 to 12, it seems that the amplitude of the wave decreases rapidly (a few wavelength) after exiting the GRIN, while in Figure 8 this is not the case. Also, in Figures 10 to 12, the maximum amplitude of the waves arises at the exit of the GRIN while this is not the case in Figure 8.
- Authors** The quadratic velocities presented in the article correspond to two different simulations:
- In Figures 8, they are obtained from a frequency simulation, thus corresponding to a stationary behavior in the whole structure
 - In Figures 10 to 12, they are obtained from a time simulation, and the proposed plot corresponds to the time at which the level at the focal point is maximum. For these cases, there was no propagation in the area behind the lens and thus the amplitude of the wave decreases.
- The reviewer is right to note that the position of the maximum was not clear for all the configurations; this was linked to problems in the definitions of axis. New results are proposed in the revised version: it can be seen that the focal point arises at the exit of the GRIN lens, and the focalization at the expected focal point is better obtained for high frequencies.
- Reviewer** There is a maximum amplitude achieved at the exit of the GRIN for each frequency as shown in Figures 10 to 12. Is this a consequence of the particular geometry under consideration? Does this depends on the GRIN longitudinal extension?
- Authors** The maximum amplitude is achieved at the focal point that correspond to the exit of the design lens, which is the reason of the observations in Figures 10 to 12. The position of the focal point depends on the gradient coefficient α that is chosen here for a focal length equal to 0.35 m.
- Reviewer** If my estimates are correct, for a uniform plate with same parameters, there is about 900 modes below $10\,000$ Hz with a mean differences between two consecutive modes of about 11.5 Hz. For the plate under consideration, this should be similar. Then for such a system, the modal density is very high and each chosen frequency is likely to correspond to a resonance frequency of the plate. Do you think that coincidence of the chosen frequency with a plate resonance changes the wave localization induced by the GRIN?
- Authors** Frequencies for the study have been chosen independently of the eigenfrequencies of the host plate. In Figure 1 is shown a simulation for a resonance frequency (4953 Hz), the coincidence phenomena does not prevent the wave localization induced by the GRIN.

4 Editor' assessment (O. Thomas)

The paper presents an innovative design of a gradient index acoustic lens, used for focusing a guided wave in an elastic plate, based on the discretization of a continuous profile of varying thickness on a localized region of the plate. The main interest of this design is its easiness of manufacturing, since the paper proves numerically and experimentally that the discretization of the continuous profile does not significantly alter the properties of the focusing lens on a broad

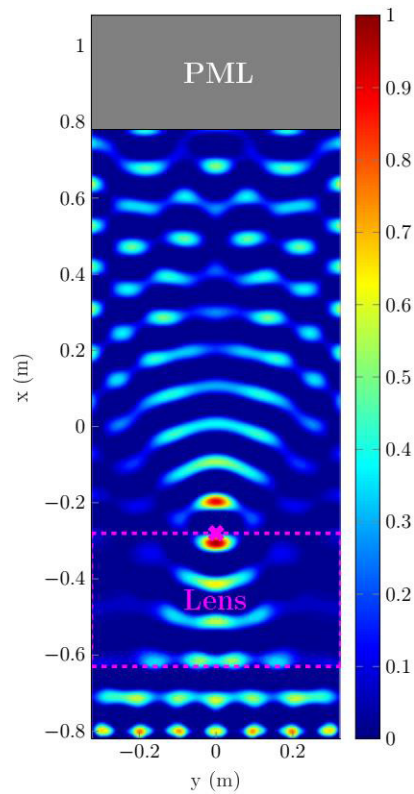


Figure 1 Simulation for a resonance frequency 4953 Hz

frequency band. Three reviewers expertized the manuscript and proposed minor changes and clarifications to the first version of the manuscript. The authors satisfyingly addressed all the reviewers' comments, leading to the acceptance of the paper for publication in JTCAM.

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