Finite Simulation of Deformation Mechanism of a Perforated Plate and Applications

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Abstract. In recent years, new metamaterials emerge one after another in various fields with various functions, showing a bright future for the development of metamaterials. Negative Poisson's ratio material is one of the promising materials. It has a wide range of applications in mechanical engineering, acoustics and architecture science. This paper attempts to explore the different deformation mechanisms and possible applications of perforated plate materials with negative Poisson's ratio. Finite element analysis is used to simulate a typical perforated plate structure, which shows negative Poisson's ratio effect and abundant deformation forms in vibration condition. In addition to the existing applications in vehicle buffering and building noise reduction, this paper proposes that the perforated plate can be used as a filter screen for water treatment, as well as the filter screen of air purifier. In addition, it can also be used to cultivate precious herb seedlings. Intersects with the medical field, it can even manufacture the vascular embolization treatment device, which can ensure that the longitudinal does not contract and scratch the blood vessel when the blood vessel is opened. On the basis of this study, we can further study the special properties of metamaterials and solve the specific problems in various applications.

1. Introduction
In the study of mechanical metamaterials, there is an abnormal mechanical phenomenon - negative Poisson's ratio effect, which has the effect that the longitudinal dimension and transverse dimension can change synchronously. It is also known as auxetic materials. Metamaterials with negative Poisson's ratio effect usually show some physical properties such as light weight, high damping, sound absorption and heat insulation, and play an important role in functional materials. Negative Poisson's ratio materials are widely used in structural vibration reduction [1], vehicle buffer structure [2], building noise reduction and so on. At first, negative Poisson's ratio materials were found in nature, but in recent years, a large number of artificial negative Poisson's ratio materials have emerged, and many excellent structural designs occur, such as concave polygon structure [3], perforated plate structure [4], rotating rigid body structure [5], node fiber structure [6], etc. In the above structures, the structure form of perforated plate is relatively simple. As long as the slit is processed on the complete plate according to certain rules, it can be made quickly. In the aspect of application, there is little introduction and discussion on its application in the existing literature. In this study, in addition to the simulation of a kind of perforated plate, the idea of its application will also been put forward.

2. Selection and Simulation of Perforated Plate
There are dozens of perforated plates with different topological structures. In this study, a typical perforated plate is selected to simulate, and its negative Poisson's ratio effect is verified by static finite
element analysis under static load; In addition, the vibration characteristics are summarized by modal analysis based on perturbation principle.

2.1. Deformation of Orthogonal Slotted Perforated Plate under Static Load

Considering that the orthogonal slotted perforated plate is the most typical of all perforated plate types, the model of perforated plate is established in CAD software, as shown in figure 1. The length, width and thickness of the plate are 50 mm, 50 mm and 2 mm respectively.

![Figure 1. Model of orthogonal slotted perforated plate.](image)

The CAD model of perforated plate is imported into the finite element program to establish the finite element simulation model. The elastic modulus of the material is set at 10 GPa and the density is 600 kg/m³. The axial tensile displacement load is applied to the perforated plate in the X direction to increase its length in the X direction by 2 mm. The simulation results are shown in figure 2.

![Figure 2. Contours plot of orthogonal slotted perforated plate under tension in X direction and deformation in Z direction.](image)

It can be seen from the plot that when the tensile load is applied in the X direction, as the deformation in the X direction is 1 unit length, the deformation in the Z direction is about 0.8 unit length. Therefore, when the axial tension is applied, not only the axial size will increase, but also the transverse size will increase, reflecting the negative Poisson’s ratio effect. The Poisson’s ratio is

\[
\mu = \frac{0.79 + 0.79}{1 + 1} = -0.79
\]

In the mechanism diagram of slots deformation on the right, it can be observed that slots have obvious expansion. It can be seen that in the case of axial tension, the total area of slots of perforated plate will increase significantly. Based on this mechanism, a filtration device with flow control
function can be designed. Its key component is a perforated plate with micro slots. By changing the force on the control edge, the rate of fluid flow and the particle size through slots can be regulated.

Simulation result of axial compression load is shown in figure 3. The displacement load is applied to the perforated plate in the X direction to reduce its length. It can be seen from the figure that when the compression load is applied in the X direction, the deformation in the Z direction is very small, which is 16 orders of magnitude smaller than that in the X direction. It can be seen that the transverse deformation is almost zero under axial compression, reflecting the zero Poisson's ratio effect. It can be seen that in the case of axial compression, the total area of slots of the perforated plate can remain basically unchanged. If the perforated plate is used as the flow control unit, the lower flux limit through the plate can be ensured.

![Displacement in Z direction](image)

**Figure 3.** Z-direction displacement contours plot of orthogonal slotted perforated plate under X-direction compression.

### 2.2. Modal Analysis of Orthogonal Slotted Perforated Plate Fixed at both Ends

The modal analysis of the perforated plate in this study is based on the finite element analysis of the perturbation algorithm to obtain the vibration shape of a certain order under the condition that both ends of the perforated plate are fixed. In the modal analysis, first 20 modes of the perforated plate are solved. Through the finite element analysis, the vibration modes with typical characteristics are obtained, as shown in figure 4.
Figure 4. Typical modal displacement patterns in the first 20 modes.

The results of modal analysis show that the orthogonal slotted perforated plate exhibits negative Poisson's ratio effect under vibration state, and the area of the slotted plate also increases significantly. Therefore, the increase of slots area in vibration can also be used to design particle filter.

3. Potential Application of Perforated Plate

The simulation results show that under the condition of tensile load and vibration, the slots area of perforated plate will increase remarkably. Based on this discovery, a filter based on perforated plate structure can be designed. The diameter of micro particles and the flux through the fluid can be controlled by applying tensile load or high frequency vibration excitation.

3.1. Design of Filter Screen for Water Treatment and Air Purification

In human daily lives, water and air are usually polluted by various substances, such as organic matter, inorganic matter and various microorganisms. Generally, sewage can be divided into two types according to the particle size of pollutants in water: one is called coarse dispersion, which has a diameter of more than 100μm; the other kind of particles with a diameter of 1 to 100μm is called fine dispersion. Among the pollutants in the air, particles are the most harmful to human body, which can be divided into coarse particles, fine particles and ultrafine particles according to the diameter. According to the data, the amount of 2.5μm particles deposited in the lung was 83% and the amount of 10μm particles deposited in the lung was 40%. Under special circumstances, particles larger than 20μm will be suspended in the atmosphere and may deposited in human lungs. A filter with small critical size usually has good filtering effect, but the filtration resistance is large and the flux is low; However for the large critical size filter, the filtering effect will be poor. If the perforated plate structure is used to make the filter screen, the filter device with adjustable critical size can be made. As shown in figure 5, the original width of the micro slots in the perforated plate filter screen is 15μm, however the maximum width of these micro slots can exceed 50μm after being loaded. Using such a filter screen will greatly improve the controllability of the filtration process, and in the future,
environmental researchers can even develop intelligent filtration equipment based on perforated plate structure.

![Microstructure perforated plate filter without loading](image1)

![Microstructure perforated plate filter loaded with axial tension](image2)

![Microstructure perforated plate filter loaded with high frequency vibration excitation](image3)

**Figure 5.** Fluid filter screen with micro slotted perforated plate structure.

### 3.2. Application of Precious Herbs in Seedling Cultivation

In many flowers and crops planting, fertilization is a very important step. If too much fertilizer is applied, the concentration of soil nutrient solution will be higher than that of plant root hair cells, resulting in cell dehydration and death. If not enough fertilizer is applied, the growth and development of plants will be slow. In this study, a film with negative Poisson's ratio was designed to cover the soil and made of waterproof and anti-corrosion materials. When slots on the film are matched with the cultivation position of the seedling, the seedling can just pass through the pores of the film. When fertilizer is applied on such a film, the pore size of the film can be changed by adding tensile force to the film, so as to control the infiltration speed of fertilizer. By using the seedling cultivation device, the seedlings of precious herbs can be cultivated more finely. The schematic diagram of the device is shown in figure 6.

![Application of perforated plate structure film in precious herb seedling cultivation](image4)

**Figure 6.** Application of perforated plate structure film in precious herb seedling cultivation.

### 4. Conclusions

The design of negative Poisson's ratio materials provides new ideas for the development and research of new materials, and also shows great potential in various fields. Combining the cell structure design of metamaterials with ordinary materials can create many new materials with new characteristics, which provides more possibilities for material research. Through the simulation analysis in this paper, it is proved that the orthogonal slotted perforated plate structure has the property of negative Poisson's ratio in the static tensile state, and the Poisson's ratio is about - 0.8. In the case of vibration, the perforated plate also shows a certain negative Poisson's ratio under various modes of different orders. Using the phenomenon that slots area of the perforated plate can increase dramatically, the perforated plate structure with micro slots can be prepared, and the filter screen which is able to adjust the pore
size can be made. By changing the static load or high frequency vibration excitation, the critical size of the filtered pollutant particles can be adjusted, and the flux of the fluid can be controlled at the same time. The above device will greatly improve the controllability of the filtration process, and in the future, environmental researchers can even develop intelligent filtration equipment based on perforated plate structure. In addition, a film with negative Poisson's ratio can be designed to cover the soil, and the pore size of the film can be changed by adding tension to the film, so as to control the infiltration rate of fertilizer. By using the seedling cultivation device, the seedlings of precious herbs can be cultivated more finely. In medical field, it can even manufacture the vascular embolization treatment device to ensure that the longitudinal contraction of the blood vessel will not scratch the blood vessel when it is opened. The perforated plate model has been proved to have good properties in the simulation experiment, but whether it can play a good role in the practical application and whether it can achieve the expected effect still need to be studied.

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