Expandable Tubes with Negative Poisson's Ratio and Their Application in Medicine

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Some specially designed materials exhibit a transverse expansion when stretched. This behaviour can be described by a negative Poisson's ratio, υ, that is commonly defined as the ratio between the negative transverse strain and the longitudinal strain. Some polymers found by Lake [1] have such property. In a separate paper, Lake showed a 2d version of the micro-structure of the materials consisting of honeycomb with inverted cells and the possible conversion to 3d structure with inwardly bulging cells. In this paper, we report that the same technique can be used in origami to create expandable tubes with negative Poisson's ratio based on folding patterns for flat paper and their application as deployable stents in medicine.

Many folding patterns for flat paper could lead to an overall negative Poisson's ratio. Typical examples include some map folding patterns and the well-known Miura-ori in which the pulling of the diagonal corners of a folded paper will lead to expansion of the other two corners. Through out-of-plane motion the folded flat paper can expand or contract in two orthogonal directions simultaneously.

Some of the folding patterns for flat paper can also used for folding of cylinders. Fujimoto (藤本修三) first explored this possibility. In his book published in 1982[2], he presented numerous folding patterns for flat paper and their transformation to tubes by joining together two edges of the paper. The similar concepts have also reported by other authors[3]. The reported work primarily focuses on the artistic aspect of the folding cylinders. Most of the patterns, including the one based on Miura-ori, result cylinders which are completed rigid or have little expansion, nevertheless, a few patterns enable the diameter of the tubes to alter. More importantly, some of the expandable tubes have an overall negative Poisson's ratio, i. e., both the length and diameter increase during expansion. This allows the compact packaging of tubes possible.

Many potential applications involving expandable cylindrical structures exist in medicine simply because the human body consists of extensive "pipe-work". With the advance of the minimum invasive surgery, it becomes possible to deliver these structures to the diseased sites provided that they can be packaged to a very small volume.

A few years ago, we started working on the deployable stent. It is a tubular medical device made of biocompatible materials and designed to open up a blocked site in the human body caused, for instance, by diseases such as stenosis, arteriosclerosis or cancer. To achieve foldability, the cylindrical surface is developed into a flat sheet and it is subsequently divided into a number of semi-rectangular units. Within each unit and in between two neighbouring units, folds are introduced to enable them to fold flat. The two edges of the sheet are then joined together to form a deployable cylinder, see Fig. 1. The deployment process is essentially the reverse of the folding process involving the expansion in both longitudinal and radial directions, a typical feature of the negative Poisson's ratio structure. Moreover, to synchronise expansion and increase radial stiffness after the stent is fully expanded, the two edges are shifted longitudinally by one unit so that a helical distribution of the folding patterns is created. The schematic diagram of one of the folding schemes is given in Fig. 2 in which the major folds A and B form two sets of helices orthogonal to each other.

We also adopted triangular or semi-hexagonal units and their combinations. Geometrical analysis has been conducted for various folding patterns to determine the expansion ratio and distortion of the units during expansion with the objective to find the optimum solutions which give largest expansion ratio accompanied by small distortion. One of the solutions that we found allows the stent being made from semi-rigid materials, see Fig. 3, because the distortion to the units due to geometrical incompatibility during expansion is small. At present, we are actively producing a prototype for pre-clinical tests.

The paper will discuss the general aspect of the structures with negative Poisson's ratio, folding patterns, the geometrical and structural analysis of the structures and their applications.

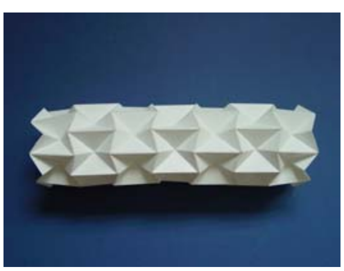

Fig. 1 A fold pattern for deployable tube.

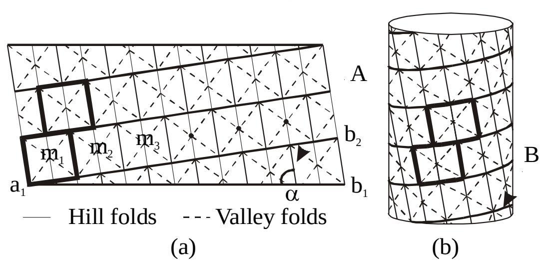

Fig. 1 A helical foldable tube.

Fig. 3. A stent made from a semi-rigid sheet.

Reference

[1] Lakes, R., Foam Structures with a Negative Poisson's Ratio, Science, Vol. 235, pp. 1038-1040, 1987
[2] 藤本修三 (Syuzou Fujimoto), 創造する折り紙遊びへの招待, 1982.
[3] Kresling, B., Plant "Design": Mechanical Simulations of Growth Patterns and Bionics, Biomimetics, 3(3), pp.105-122, 1995

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