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Short Communication

A novel compliant-body pump with a high volumetric efficiency

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ABSTRACT

The article introduces a novel compliant-body pump, with a high volumetric efficiency: A flexible-matrix-composite hyperboloid structure. The high volumetric efficiency is attributed to the geometry of the pump's structure (hyperboloid) and the high negative effective Poisson's ratio of the 3-layer flexible-matrix-composite laminate adopted for the compliant body of the pump. The pumping potential, introduced as a measure of the volumetric efficiency, was determined both analytically, using the finite element method, and experimentally, using a built-in prototype. The results indicate that the proposed pump has a very high volumetric efficiency.

1. Introduction

Pumps are vital components in machines. Most pumps may be classified under "rigid-body pumps", where the pumping action is generated by a reciprocating (piston and rod) or rotary (centrifugal) mechanism. Compliant or flexible body pumps, on the other hand, have a compliant body or membrane for generating the pumping action. The diaphragm pumps, the jellyfish-inspired flexible pump [1], and the heart are examples of compliant-body pumps. They enjoy a more gentle pumping action, and they forgo the need for bearings and their associated problems.

The Pumping Potential (PP) of a compliant-body pump may be defined as "the relative volume reduction due to a relative input stroke" [2,3]; that is:

$$PP = \frac{\Delta V/V_0}{\Delta L/L_0}, \tag{1}$$

where ΔV, V_0, ΔL, and L_0 are the volume reduction (ejected volume), the initial volume, the change in an input characteristic length, and the initial input characteristic length, respectively. The PP is introduced as a measure of the volumetric efficiency of the pump. Ghoneim el al. investigated, analytically and experimentally, the PP of two compliant-body (flexible-body) structures: a barrel-shaped flexible-matrix-composite (FMC) structure [2], and a hyperbolic FMC one [3]. The barrel-shaped compliant body is based on the principle that angle-ply FMC laminates can exhibit a very high effective in-plane Poisson's ratio. This high ratio implies that upon axially stretching an axisymmetric shell-of-revolution structure made of this material, it would experience a high reduction in its diameter and volume, and consequently a high PP. The barrel-shaped FMC structure achieved a PP of approximately 10 (the PP of a typical human heart is approximately 4 [4]); however, a very high axial force is needed for stretching the structure, which limits its practicability. The hyperbolic structure, on the other hand, is made of a single lamina and is based on a geometric principle, which suggests that a single lamina hyperboloid structure produces a high volumetric change upon twisting [3]. A PP of 2.59 was achieved for this hyperbolic structure. It should be mentioned also that inspired by the left ventricle, Chanda and Ghoneim [5] introduced a left-ventricle-like FMC structure, made by twisting and looping a flat FMC band in accordance with the Helical Ventricular Myocardial Band hypothesis [6,7]. A PP $\approx$ 2.85 was reported.

For most natural materials the Poisson's ratio has a positive value. In an attempt to acquire a negative in-plane Poisson's ratio effect (lateral contraction under compression), artificial engineering materials with negative effective Poisson's ratio have been introduced, including foams with re-entrant structures, hierarchical laminates, polymeric foams and micro-porous polymers [8–10]. Miller et al. [11,12] developed a negative Poisson's ratio fiber composite with double-helix yarn reinforcements. The negative effective Poisson's ratio of fibrous composite laminates was first predicted by Herakovich [13]. Chen et al. [14] built a FMC laminate with a negative effective Poisson's ratio close to -1, and predicted the possibility of having a FMC laminate with a larger negative effective Poisson's ratio if its fiber angle-orientation is set properly.

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The present work adopts the hyperboloid FMC structure [3] with a simple modification. The hyperboloid FMC structure was modified by employing a 3-layer FMC symmetric laminate, with a negative effective Poisson's ratio, for the body of the structure, instead of the single-ply lamina [3]. This modification was surmised to substantially improve its PP. An axisymmetric shell-of-revolution made of an isotropic material with a positive in-plane Poisson's ratio would radially expand under axial compression. The same shell, made of a material with a negative effective Poisson's ratio, would radially contract under compression rendering a considerable volume reduction. The hyperboloid FMC structure enjoys a couple of advantages. Since a hyperboloid surface can be generated by rotating a straight line about a skew axis, a hyperboloid continuous fibrous laminate structure can be built by simply laying up the fibers in straight lines at a specific wrapping angle. In addition, to generate the necessary twist for pumping, only a moderate torque, in the direction of the fiber angle-orientation, is needed.

The objective of the current work is to estimate, analytically and experimentally, the volumetric efficiency (PP) of the proposed FMC compliant-body pump, with the negative effective Poisson's ratio, and therefore, validate the suggested hypothesis of the negative Poisson's ratio effect on improving the PP. First, the analytical work for determining the optimum design parameters and the PP of the optimum pump are presented. The experimental work (building and testing a prototype) is given next. Finally, discussion of the results and conclusion are presented.

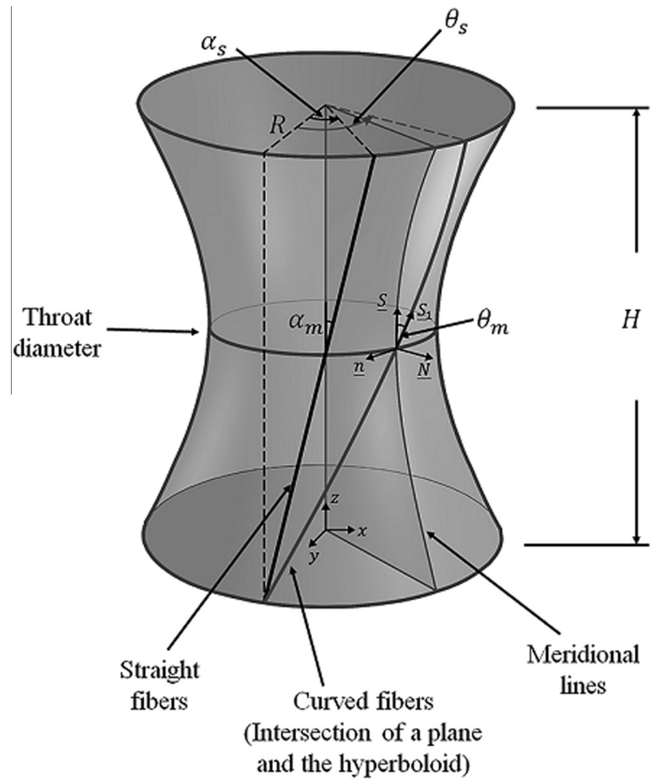

Fig. 1. Basic geometric parameters.

2. Analytical work

The analytical work was conducted to estimate some of the design parameters for best performance (highest PP) of the proposed hyperboloid compliant-body pump. The design parameters were applied to build the prototype of the proposed pump used for performing the experimental work. The analytical work was also conducted to compare the PP analytical results with the corresponding PP of the experimental results using the prototype, and consequently to assess the validity of the analytical and experimental work as well as the viability of the proposed novel pump's idea.

The design parameters of the proposed hyperboloid flexible matrix composite pump (Fig. 1) are the height, H, the end radii, R, the thickness of each layer, h, the constituents' materials (fiber and matrix), the stacking order, and the wrap angle of each layer (lamina), $\alpha_{s,}$ and θ_s. For consistency with the previous work of the other FMC structures (Barrel-shaped [2], and the single lamina hyperboloid [3]), the same material (carbon/polyurethane) was adopted. The corresponding material properties are given in Table 1. Also for simplicity and to allow for a meaningful direct comparison between the PP of the single lamina hyperboloid [3] and the proposed multi-layer with the negative effective Poisson's ratio hyperboloid structure, the geometric parameters H, R, and h were kept the same; that is, $H = 11.43$, $R = 5.08$ and $h = 0.127$ cm ($H = 4.5$, $R_I = 2$ and $h = 0.05$ inches).

Chen et al. [14] suggested a 4-layer $[\alpha/\theta]_s$ laminate for achieving a high negative effective Poisson's ratio. In the present work a 3-layer $[\alpha/\theta/\alpha]$ laminate was adopted instead. The 3-layer is a special case of the 4-layer one, where the thickness of the θ-layer is halved. The three-layer laminate saves computation time for the analytical work as well as construction time and material's cost for the experimental work. With the stacking order specified, the laminate parameters to be determined were the fiber orientation angles α and θ. First, the optimum fiber orientation angles, α and θ, were determined using a cylindrical FMC tube model. Then, guided by these results, a hyperboloid FMC structure model was created and analyzed to estimate the PP of the proposed structure.

Table 1
Material properties of carbon/polyurethane.

Property	E_1 (GPa)	E_2 (MPa)	ν_{12}	ν_{23}	G_{12} (MPa)	G_{23} (MPa)
Value	139	345	0.32	0.58	82.7	138

2.1. Analysis of the cylindrical tube model

A preliminary analysis was conducted to determine the optimum fiber orientation angles α and θ, which achieve the highest negative effective Poisson's ratio. An analysis, based on the classical lamination theory, was performed for an infinitely long cylindrical tube [15]. A MATLAB program was written and applied for the analysis. For the tube, the effective Poisson's ratio is defined as, $\overline{\nu}_{x\theta} = -\frac{w_I}{\varepsilon_x^0 R_I}$, where w_I is the radial displacement at the inner radius, R_I, and ε_x^0 is the axial strain. Fig. 2 displays a map plot of $\overline{\nu}_{x\theta}$, for $R_I = 5.08$ cm and $h = 0.127$ cm, as a function of the fiber angles α and θ. Clearly, a high negative Poisson's ratio can be achieved. The Figure shows that a negative value as high as -5 in the vicinity of [40/5/40] and [5/40/5] is attainable.

In order to determine the optimum fiber orientation angles α and θ, which achieve the highest PP, including the effect of the length and the boundary conditions, a parametric FE analysis using ANSYS was performed for a cylindrical tube. As stated before, the following geometric parameters were considered: $H = 11.43$, $R = 5.08$ and $h = 0.127$ cm. For the boundary conditions, one end was completely fixed, and the other was fixed in the radial direction, set free in the tangential direction (free to rotate), and was subjected to a 1% compressive axial-displacement. The Solid 185 element was used for the analysis, and a mesh with $100 \times 80 \times 1$ elements, along the length, circumference, and the thickness, respectively, was adopted for each layer. Fig. 3 shows a mesh plot of the PP for different values of α and θ. The graph indicates that a fiber angle orientation close to [10/40/10] achieves the highest PP