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MD-LUFFY: Massively Deformed Linearly-elongation-actuator Using Flexible Fiber and Yarn - Fundamental Characteristics on Elongation/contraction and Expansion rate

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***Abstract*—This paper presents a pneumatic actuator utilizing a cylindrical rubber structure achieving an axial elongation of more than 520 % from its original length while maintaining a thin wall thickness and minimal radial expansion of less than 20 %. This study aims to develop an actuator providing a great axial elongation, small radial expansion and thin wall thickness which has a high power-to-weight ratio of pneumatic drive to perform in the narrow spaces. The cylindrical pneumatically driven elongation actuators developed in the other studies include bellows types utilizing material bending property and rubber type utilizing material extension property. These actuators have thick wall thicknesses or expand greatly in the radial direction when driven, and their application environment is limited because they interfered in narrow environments. We develop a cylindrical pneumatically driven elongation actuator compositely restrained by a flexible long yarn and short-oriented fibers that are compatible with rubber. The actuator is structured as a rubber tube helically wound around by the yarn. The actuator deforms in the axial direction and the rubber between one pitch of the helically wrapping yarn expands in the radial direction by air pressure. Then, the rubber is bent, and thrust into the yarn, causing the actuator to break due to stress concentration in the rubber around the yarn. An actuator helically wound around by the yarn many times has a small length of rubber between one pitch of the helically wrapping yarn because the proportion of the thickness of the yarn is dominant in one pitch. Under the above conditions, the deformation rate of the rubber is higher than that of the actuator. Therefore, strong stress acts on the rubber, leading to the actuator breakage. To solve these issues, we develop MD-LUFFY: Massively Deformed Linearly-elongation-actuator Using Flexible Fiber and Yarn that is an actuator reducing the radial expansion of the rubber between one pitch of the helically wrapping yarn to relieve the stress concentration in the rubber around the yarn. MD-LUFFY, a rubber tube compositely reinforced by short-oriented fibers and yarn, can elongate to 520 % within an expansion rate of 20 %. Considering the results, realizing the significant elongation and contraction while a high power-to-weight ratio in narrow environments is expected by applying MD-LUFFY.**

Keywords— ***Hydraulic/Pneumatic Actuators, Soft Sensors and Actuators, Soft Robot Materials and Design***

I. Introduction

Flexible linearly elongation and contraction actuators, such as pneumatic artificial muscles [1][2][3], have been the subject of many studies due to their high output-to-weight ratio and compliance [4][5]. The main shape of the actuator is a cylinder, and its inner space is used as a chamber, which is elongated or contracted when the actuator is pressurized or depressurized.

To generate larger displacements, some of these actuators use bending deformation and radial expansion of the material [6][7], the other actuators utilize the elongating deformation of the rubber material [8]. The difference between the inner and outer diameters of the actuators, which uses bending deformation of the material is large, therefore, they have the thick wall thickness. In contrast, if the material expands during driving, radial wide space is required. Thus, the range of application of these actuators is narrow. For example, these actuators might interfere with other parts or the environment when they applied to the mechanism such as antagonistic drive mechanism that drives near the human body [9] or a robot that moves in small pipe [10][11][12]. In the case of using the rubber elongation, a significant axial elongation and contraction deformation can be obtained in a narrow space by designing to control the direction of rubber expansion. Therefore, the method using the rubber elongation is capable of elongation making use of the rubber axial extension in a smaller radial space by radially binding the rubber expansion reaching over 600-800 %, and has a wider range of adaptability.

Conventional studies on cylindrical pneumatically driven elongation actuators include McKibben-type artificial muscles that generate axial deformation of rubber by a braided sleeve [2][13], Straight-Fiber-Type artificial muscles that axially contract by applying axial fiber constraint to a rubber tube [14][15], bellows type actuators that axially elongate by the material bending property [6][7][16][17], actuators consisting of a cylindrical sleeve and rubber tube [8][18][19], and actuators that expand and contract axially by providing helical fiber binding to a cylindrical rubber tube [20][21]. However, If we define the elongation and expansion rate as shown in Fig. 1, as shown in Fig. 2, these actuators require a large expansion or wall

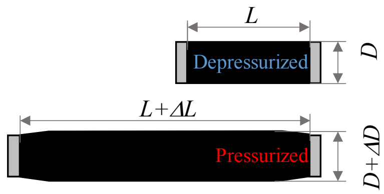


Fig. 1 Definition of elongation/extension rate of linearly-elongation-actuators.

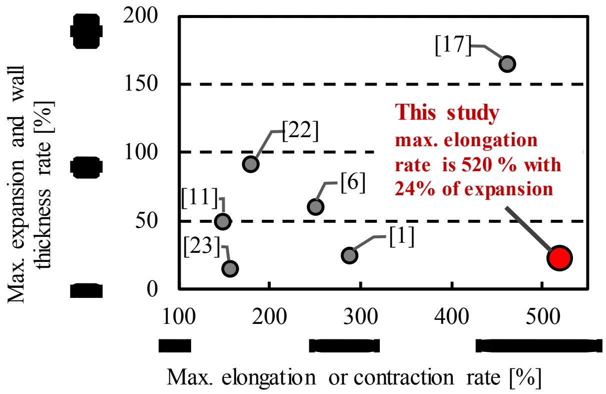


Fig. 2 Relationship between radial expansion or wall thickness and axial elongation/contraction ratio of linearly-elongation-actuators.

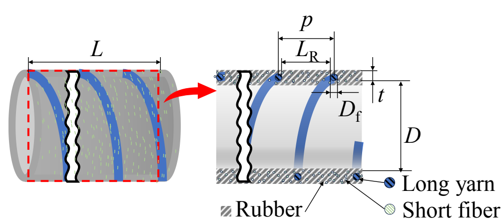


Fig. 3 Concept of the MD-LUFFY. The left figure is an image of the external appearance of the MD-LUFFY. The right figure is the axial cross section of the MD-LUFFY.

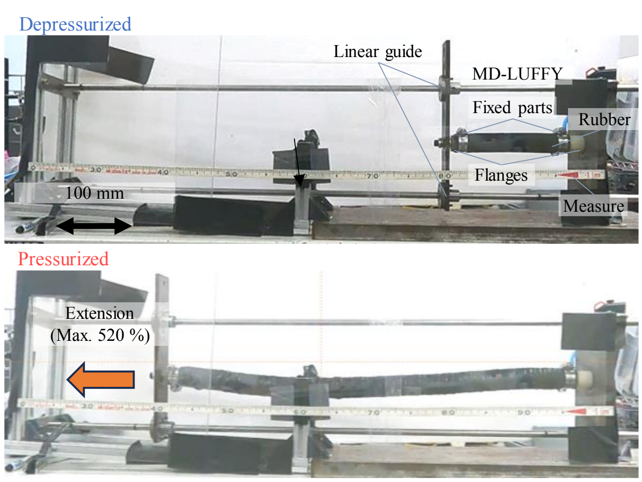


Fig. 4 Appearance of the elongation/contraction of the MD-LUFFY.

thickness in the radial direction to obtain a substantial elongation and contraction in the axial direction. For example, the actuators consisting of a cylindrical sleeve and rubber tube provide long elongation utilizing the rubber extension, however, its max. elongation rate is only approximately 250 % when the natural length is 100 %. Actuators using bellows also have been reported to have a max. elongation rate of 350 %, however, they have thick wall thickness. Considering that the max. strain of natural rubber is generally 600-800 %, there are no actuators have been developed that enable longer elongation and contraction in the axial direction by appropriate constraint in the radial direction. Therefore, the application range of cylindrical pneumatically driven elongation actuators was narrow.

In this study, we propose the MD-LUFFY: Massively Deformed Linearly-elongation-actuator Using Flexible Fiber and Yarn, which reduces the rubber expansion utilizing a long yarn and short-oriented fibers, and reducing the stress concentration on rubber, enables significant axial elongation and contraction. This study focuses on the actuators that expand and contract axially by providing helical yarn binding to a cylindrical rubber tube [20][21]and the short fiber oriented methods [24][25][24]. In general, the rubber between one pitch of the yarn of the actuator with the long yarn helically wound around a rubber tube to expand radially when driving. Then, the rubber between one pitch of the yarn bends, and stress concentration occurs on the rubber around the long yarn, leading to rupture. Conversely, if the long yarn is wound around the actuator many times, the ratio of rubber length between the one pitch of the yarn is small. Hence, the elongation rate of the rubber is longer than that of the actuator, and the increase in stress acting on the rubber leads to rupture at a small elongation rate of the actuators. Meanwhile, the short-oriented fibers reduce the expansion of the rubber between one pitch of the helically wrapping yarn, thereby reducing the stress concentration on the rubber around the long yarn and achieving substantial axial expansion and contraction with a small radial expansion rate.

This paper describes the development of the MD-LUFFY. This study aims to develop a pneumatic actuator with a max. expansion rate of less than 20 % when the expansion rate at the natural length is 0 % and a max. elongation rate of over 500 % when the natural length is 100 %, as an example of application to an in-pipe inspection robot [12] that requires to generate a strong force and axial elongation in a narrow pipe. In the following sections, the structure of the MD-LUFFY is described first. Next, we describe the measurement experiments of elongation/contraction and expansion characteristics of the MD-LUFFY when the pitch of the long yarn is changed to design the ratio of the pitch of the long yarn. Finally, based on the results of the experiments with different winding pitches of the yarn, the experiment regarding the composite of the long yarn and short-oriented fibers are described.

II. MD-LUFFY

A. Outline of MD-LUFFY

As shown in Fig. 3, MD-LUFFY: Massively Deformed Linearly-elongation-actuator Using Flexible Fiber and Yarn consists of a cylindrical rubber tube, two flanges, and a part to fix the rubber tube to the flanges. The cylindrical rubber tube contains short-oriented fibers, and is helically wound by a long yarn. The dimension definition of the MD-LUFFY is shown in Table 1.

If the long yarn is wound many times around the rubber tube, the elongation rate in the axial direction becomes large while the expansion rate in the radial direction is small. However, as shown in Fig. 3, since the long yarn has a thickness D_f, when the pitch p of the long yarn is reduced, the ratio of D_f to p increases. Then, the elongation of the rubber increases against that of the

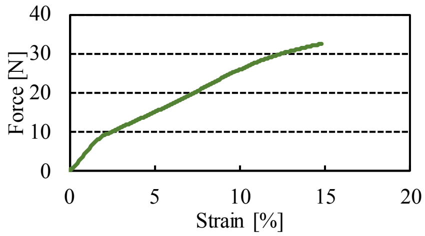
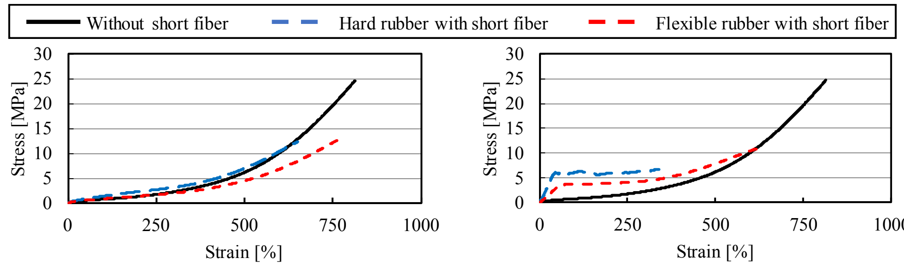


Fig. 5 Tensile properties of the long yarn.



(a) Short-oriented fibers splitting direction. (b) Short-oriented fibers parallel direction.

Fig. 6 Tensile properties of rubber and flexible and hard rubber with short-oriented fibers.

Table 1 Symbols, definition of MD-LUFFY. The value in the initial state are shown in this table. Unit is [mm].

Sym.	Def.	Val.
L	Length of the actuator.	117
D	Diameter of the actuator.	24
p	Pitch of the yarn wound around the actuator.	-
t	Thickness of the actuator.	2
L_R	Width between the yarn wound around the actuator.	-
D_f	Yarn's thickness.	2.7

Table 2 Tensile Testing of the yarn.

Method of the test	JIS L1017
Test piece	Test with one twisted cord
Tension rate	300 mm/min
Distance between initial grips	250 mm
Definition of elongation	(Distance between gripping fixtures after extension - distance between initial gripping fixtures)/distance between initial gripping fixtures * 100 [%]
Definition of force	Force with one twisted cord [N]

Table 3 Rubber tensile test conditions.

Method of the test	JIS K6251
Test piece	JIS-3 dumbbell test piece
Tension rate	500 mm/min
Gauge length	20 mm
Definition of elongation	(Distance between gauge lines after extension - Initial distance between gauge lines)/Initial gauge distance*100 [%]
Definition of stress	Nominal stress (Force/initial cross-sectional area) [MPa]

actuator. Therefore, the actuators with the long yarn wound many times around the rubber tube make it difficult to obtain a longer elongation rate. Hence, to reduce the expansion between one pitch of the long yarn, the proposed elongation actuator MD-LUFFY has short-oriented fibers.

B. *Configuration of MD-LUFFY*

This study aims to a develop cylindrical pneumatically driven elongation actuator driven at a max. radial expansion rate of 25 % in a pipe with an inner diameter of 35.5 mm to apply an in-pipe robot [12] as an example. Therefore, we prototype the actuator with an axial length is 117.0 mm, an inner diameter is 24.0 mm, and a rubber thickness was 2 mm to develop the strategy for designing the MD-LUFFY. Fig. 4 shows the pressurized state of the prototype.

The rubber used in the prototype MD-LUFFY is composed of cylindrical natural rubber and a PET yarn containing short-oriented fibers. The PET yarn is spirally wound around an unvulcanized natural rubber containing short-oriented fibers and integrated during vulcanization. Fig. 5 and Fig. 6 show the elongation characteristics of the PET yarn used in MD-LUFFY and the stress-strain curve of the rubber. The test methods are shown in 0 and 0, respectively. However, Fig. 6 shows the stress-strain curve (S-S curve) of the rubber for the orientation of the short fibers. Fig. 6 (a) shows the S-S curve in the direction perpendicular to the fiber orientation (fiber tearing direction), and Fig. 6 (b) shows the S-S curve in the direction parallel to the fiber orientation. From Fig. 6, due to the orientation of the short fibers, the elastic modulus of the rubber is small when pulled in the direction perpendicular to the fiber direction as shown in Fig. 6 (a). In contrast, the elastic modulus of the rubber is high when pulled in the parallel direction to the fiber orientation as shown in Fig. 6 (b). The rubber in the parallel direction to the fiber orientation yields in the elongation range of 45-70 %, and in the greater elongation range, the S-S curve is asymptotic to that of rubber without short fibers.

III. Long Yarn Pitch and Elongation Rate of MD-LUFFY

To estimate the effect of the long yarn pitch wound around the rubber tube on the axial elongation/contraction and radial expansion rate of the MD-LUFFY, which do not contain short-oriented fibers are measured.

A. *Experimental conditions/environment*

As shown in Fig. 4, one end of the actuator is fixed, and the other end is fixed to the plate which is allowed to move freely in the axial direction. In this state, air pressure is applied to the MD-LUFFY, which does not contain short-oriented fibers, and the length is measured. For measurements, the calipers are used.

The relationship between pressure and elongation rate was measured when the pitch of the helical yarn wound around the rubber tube was changed to 2.9 mm, 2.4 mm, 1.2 mm, 0.8 mm, and 0.4 mm. From Fig. 1, the definitions of elongation rate and expansion rate is explained. Eq. (1) as the elongation rate L_{Change} [%] and Eq. (2) as the expansion rate D_{Change} [%] are applied.

$$L_{\mathrm{Change}}\ [\%] = \frac{L + \Delta L}{L} \times 100 \tag{1}$$

$$D_{\mathrm{Change}}\ [\%] = \frac{\Delta D}{D} \times 100 \tag{2}$$

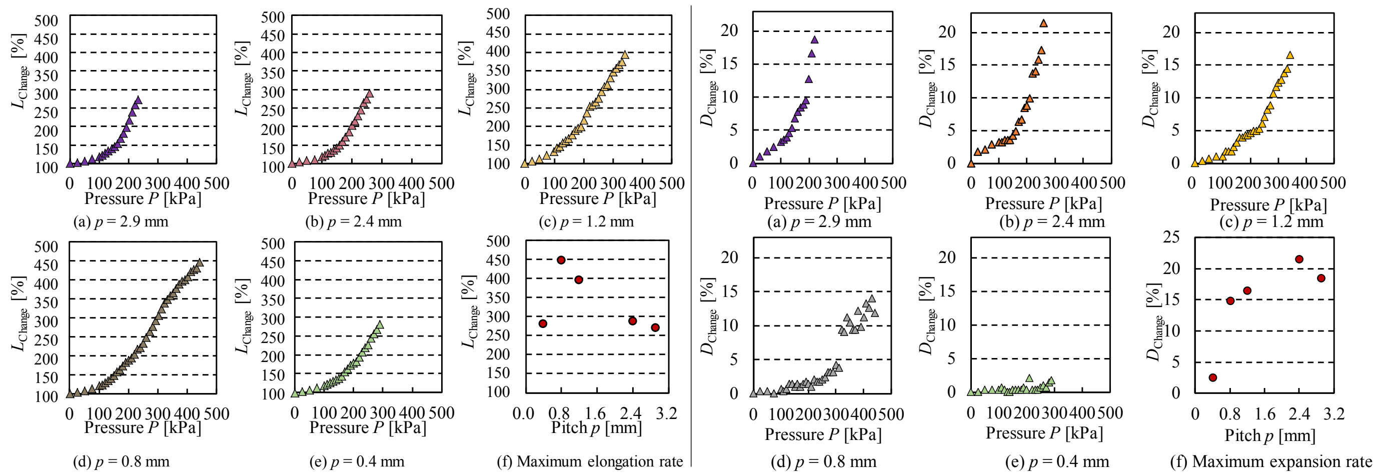
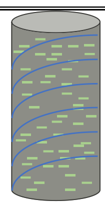
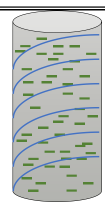
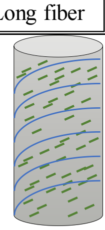
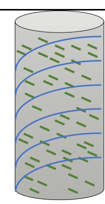


Fig. 7 Relationship between pressure and elongation/expansion rates regarding the actuators restrained by long yarn pitch.

Fig. 8 Broken condition of the actuators. When p = 2.9, 2.4, 1.2, and 0.8 mm, yarn breakage occurred, and the rubber expanded at the point where it was no yarn constrained, and after deflating, the yarn was exposed from the rubber. At p = 0.4 mm, a small hole appeared in the rubber.

Table 4 Comparative of the direction regarding short-oriented fiber and rubber hardness.

	Short fiber		Long fiber	
Image of MD-LUFFY	 (a)	 (b-1)	 (b-2)	 (b-3)
Direction of short fiber	Circumferential direction		Parallel to long yarn	Axial symmetry to long yarn
Rubber property	Hard	Flexible		

B. Experimental results and discussion

The measurement results are shown in Fig. 7. Furthermore, the expansion rate of the MD-LUFFY at all pitches was less than 25 %. Fig. 8 shows the state of the MD-LUFFY at the breakage. From the above results, the max. elongation rate was 450 % at pitch p = 0.8 mm, which exceeded the previously reported max. elongation rate of 350 % [16] for an extendable pneumatic actuator with small radial expansion. The elongation rate under the same pressure decreases as the pitch decreases.

If p is small, the ratio of the yarn thickness D_f to the rubber length L_R between the one pitch increases. The elongation ratio of the rubber increases relative to that of the actuator. Therefore, the elastic force of the rubber increases, and the elongation ratio when the pressure is equalized decreases at a small p. Additionally, as the pitch became smaller, the withstand pressure improved and the max. elongation rate also increased. However, at p = 0.4 mm, the withstand pressure is small compared to other pitches.

Here, we consider the low withstand pressure at p = 0.4 mm, from the MD-LUFFY. In the MD-LUFFY with a pitch longer than p = 0.8 mm, the yarn break when high pressure is applied, leading to the breakage. At p = 0.4 mm, there are cracks on the rubber. From this state, we measured the extension of another MD-LUFFY with p = 0.4 mm. However, the MD-LUFFY occurs cracks and the characteristics are the same as the described data with a low-pressure resistance of 150 kPa and a max. elongation rate of 250 %. Considering that as the pitch becomes smaller, the volume occupied by the yarn increases. If the amount of rubber is small, the adhesive strength between the yarn and rubber will decrease. Therefore, the weakening of the bond between the yarn and the rubber made it easier for cracks to occur in the rubber between the yarn, leading to breakage at the low-pressure. In the future, we will discuss the cracks at the pitch p = 0.4 mm of the helical yarn based on theoretical models.

IV. Elongation/Contraction and Expansion Rate of MD-LUFFY Considering Short-Oriented Fibers Direction

In this section, the relationship between the elongation rate and the applied pressure of MD-LUFFY, which was constrained by short-oriented fibers and a long yarn is experimentally measured.

A. Experimental conditions

From the experiment described in section III, we obtained a max. elongation rate of 450 % at p = 0.8 mm by applying restraint by long yarn spirally to a cylindrical rubber. Therefore, in this experiment, we added a restriction using short-oriented fibers to the rubber tube, which was set at p = 0.8 mm. However, the inclusion of short-oriented fibers increases the rubber hardness in the axial and radial directions. Therefore, we developed MD-LUFFY, which has a lower and the same rubber hardness as shown in Table 4 and compared its elongation and expansion ratio. Furthermore, the relationship with the direction of the short-oriented fibers and the long yarn wound spirally around the rubber tube affects the elongation characteristics of the actuator. Hence, we changed the oriented direction of the short-oriented fibers into three patterns and experimentally verified their effects. The rubber tubes used for comparison were the four patterns shown in Table 4.

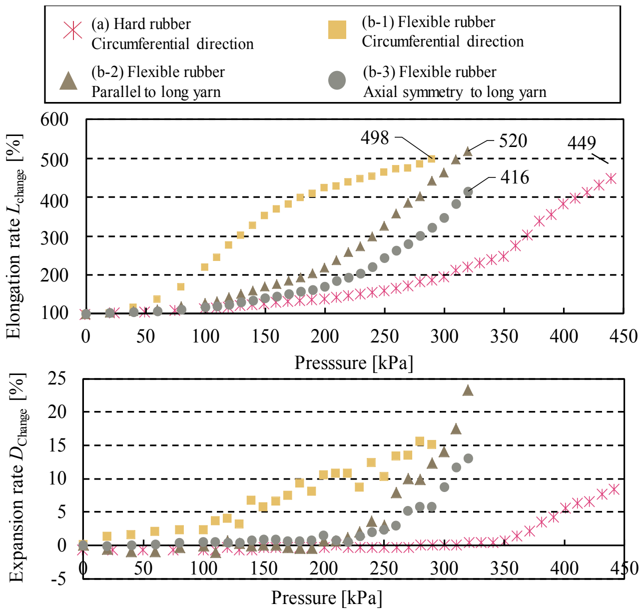


Fig. 9 Relationship between pressure and elongation/expansion rate of MD-LUFFY when changing the orientation direction of short fibers and the rubber hardness.

B. Experimental results and discussion

Fig. 9 is the relationship between the applied pressure and elongation/contraction and expansion rate of MD-LUFFY by changing the rubber hardness and short-oriented fiber direction. The developed MD-LUFFY can elongate up to 520 % at a low expansion rate of less than 25 % by short fibers oriented in the same direction as the long yarn. The MD-LUFFY with high-hardness rubber generates a small elongation/contraction ratio under the same pressure and the max. elongation ratio compared to the MD-LUFFY with low-hardness rubber. Furthermore, when comparing the elongation ratio in the direction of the short-oriented fibers, when the short fibers are oriented in the same direction as the long fibers (b-1) shown in Table 4, the expansion/contraction ratio is the highest, 520 %. When the short fibers (b-3) shown in Table 4 were oriented axially symmetrically with the long yarn, the smallest elongation ratio was 416 %. When the short fibers are oriented in the axisymmetric direction with respect to the long yarn (b-1) shown in Table 4, as the MD-LUFFY elongates and contracts, the rubber tube expands and contracts in a direction parallel to the orientation direction of the short fibers. Therefore, the elongation rate under the same pressure decreased, leading to a decrease in the max. elongation rate.

When the short fibers are oriented in the same direction as the long yarn (b-3) shown in Table 4, the orientation direction of the rubber short fibers and the constraint direction of the long yarn are the same direction. Therefore, when MD-LUFFY elongates and contracts, the rubber elongation is perpendicular to the orientation direction of the short fibers, which is a wider expansion and contraction. On the other hand, when short fibers (b-2) shown in Table 4 are oriented in the radial direction, the direction of restraint by the long yarn and short fibers is the direction of axial symmetry. Therefore, concentrated stress was generated in MD-LUFFY, and the max. elongation rate decreased. When the short fibers are oriented in the same direction as the long yarn (b-3) shown in Table 4, the orientation direction of the rubber short fibers and the constraint direction of the long yarn is the same direction. Therefore, MD-LUFFY elongates and contracts, the rubber The elongation is perpendicular to the oriented direction of the short fibers, which is considered to be a greater expansion and contraction. Finally, when short fibers (b-2) shown in Table 4 are oriented in the radial direction, the direction of restraint by the long yarn and short fibers is the direction of the axial symmetry. Therefore, concentrated stress was generated in MD-LUFFY, and the max. elongation rate decreased. The elongation of MD-LUFFY is produced by the elongation of the direction perpendicular to the short fiber orientation direction of the rubber. From this consideration, we believe that the MD-LUFFY greatly elongated due to the elongation characteristics of easy elongation in the direction perpendicular to the oriented-short fibers.

As described above, the proposed MD-LUFFY has a low expansion of less than 25 % and a max. elongation rate of 520 % with a thin wall thickness of 2 mm. Therefore, we expect that MD-LUFFY will exhibit great elasticity and elasticity in narrow spaces.

V. CONCLUSIONS

This paper proposes an actuator named MD-LUFFY: Massively Deformed Linearly-elongation-actuator Using Flexible Fiber and Yarn, which has low radial expansion of less than 25 % and axial elongation of up to 520 % with a thin wall thickness, and the axial elongation/contraction and radial expansion ratio against applied pressure of MD-LUFFY. are describes. The cylindrical pneumatically driven elongation actuators that do not contain short-oriented fibers developed in this study achieved a maximum axial elongation rate of 450 % at a pitch of helical long yarn $p = 0.8$ mm. Furthermore, MD-LUFFY with short-oriented fibers and the long yarn achieves an elongation ratio of 520 % with an expansion rate of less than 25 % when the short-fiber oriented parallelly in the direction of the yarn. As shown in Fig. 2, the above results exceeded the maximum expansion rate of 350 % of the conventional elongation-type pneumatic actuator, with a low expansion rate. From these results, we can expect that the M.D.LUUFY will expand the range of the applications of the actuator by allowing it elongate in the narrow space.

In the future, we will reveal the cause of the low-pressure resistance of the actuator when the pitch of the helical yarn is set to $p = 0.4$ mm. Moreover, a theoretical model including force and response of an MD-LUFFY in which short-oriented fibers and a long yarn act compositely will be constructed.

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