An approach regarding some performances of a FESTO pneumatic muscle actuator

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Abstract. This paper presents some performances of a pneumatic actuated artificial muscle, manufactured by FESTO. Pneumatic muscles are novel actuators, constructed by an elastic membrane covered with a braided mesh, based on a contraction principle: inflated, it shortens its length with a certain dimension depending on the compressed air pressure. Those muscles are known for their wide application in industry and robotics, as actuators. The aim of this study is to find operational behaviour of a pneumatic muscle. Some experiments were made, in order to prove the maximum contraction of the muscle, the evolution of the contraction at different pressures and loads. The results obtained are graphically plotted. Based on the obtained results, it was made an analysis and identified the best fit equation for the data. The experimental research carried out highlighted that the pneumatic muscles offers many advantages and disadvantages in terms of their behaviour in operation.

1. Introduction

Pneumatic muscles are used in a wide range of applications. An optimal use of the pneumatic muscles is in assistive devices for disabled people or older ones. This type of actuator has a smooth movement and can obtain the desired stroke with minimal pain for the users. Others advantages over pneumatic cylinders are: higher power-to-weight ratio, smooth speed adjustment [1], and longer operating life (50 million cycles for FESTO pneumatic muscles [2].

The construction of the pneumatic muscles is simple: an inner tube covered by a braided mesh with fitting caps on both sides, which, under the action of pneumatic air, inflates and deflates, acting like a spring.

In this paper, it is presented some performances of a FESTO pneumatic muscle. The aim of the research is to obtain some real information about the maximum contraction of the muscle, in order to establish the possibility of using it as an actuator for a human leg assistive device.

The method used proposed the applying of different pressures to the pneumatic muscle and recording the contraction, in two situations: without load and with a 20 kg load. The aim is to establish the maximum possible contraction for the pneumatic muscle.

Some mathematical expressions can be developed for describing the correlation between contraction of the pneumatic muscle and the pressure.

2. Pneumatic muscle

Since their development, pneumatic muscles have been used in different applications. Nowadays, their applicability is mostly in industrial application as an alternative of the hydraulic or electric drives, as
There are many studies focused on the applicability of the pneumatic muscle in industry: industrial manipulators [3–5], robotic arms [6, 7], assistive devices [8–10] and others.

Pneumatic muscle advantages are many, an important one to be specified is the low weight and the compliant behavior, assuring safe interactions with human.

2.1. Construction
The pneumatic muscle is made by a rubber diaphragm with non-crimped fiber made of aramid yarns on the inside [2]. When internal pressure is applied, the muscle decreases its length, expanding its diameter, as it can be seen in figure 1.

Following the deformation of the tube due to the increase of the pressure, the actuator shortens by a certain amount, called stroke.

![Figure 1. Working principle of a pneumatic muscle [11].](image)

In the figure 2 it can be seen the construction of a pneumatic muscle: a rubber inner tube covered with a shell braided according to helical weaving. The braided sleeves act to constrain the expansion for maintaining the cylindrical shape.

In order to cover a wide range of applications, the pneumatic muscles can be constructed with different lengths and diameters. They are closed by two ends, one being the air input and the other the force attachment point.

![Figure 2. Construction of a pneumatic muscle [2].](image)

2.2. Advantages and disadvantages
The utilisation of the pneumatic muscle is preferred because of the advantages they have: a varying force-displacement relation at constant gas pressure, an adjustable compliance; the absence of friction and hysteresis; the ability to operate at a wide range of gas pressures, and thus to develop both very low and very high pulling forces; the possibility of direct connection to a robotic joint; cheaper to buy and install than other actuators and pneumatic cylinders; smooth and natural movement; fast -full contraction. Pneumatic muscles has many focal points for human-machine interface: low weight, high force to weight proportion, working principle same as human, safe energy [12].

The weak points of the pneumatic muscle are: the force which can be applied is only tensile in nature; its total displacement is only about 20% to 30% of its initial length; friction between the netting and the tube leads to a substantial hysteresis in the force-length characteristics; rubber is often needed to avoid the tube from bursting; rubber deformation will lower the force output of this type of muscle up to 60% [13].
3. Experimental setup

3.1. Components of the experimental stand

The experimental setup consists of several components, as can be seen in figure 3. The pneumatic muscle used for the research is an FESTO origin pneumatic muscle of 750 mm length and 20 mm diameter. It is fixed at one side and different loads are applied at the other side. Under the pneumatic air influence, this muscle becomes pressurized and shortens with a certain stroke, of interest for the research.

Other components involved in experimental stand are: mechanical system with the support structure of the pneumatic muscle (1), pneumatic actuator system with compressor (2), compressed air preparing group, pneumatic distributors (3), transducers for determining the pressure and flow rate, interface for data acquisition (5) and computer equipment (4), loads of 20kg.

![Figure 3](image)

**Figure 3.** Experimental setup: (a) photograph and (b) diagram.

The connection scheme is presented in figure 3 (b). The pressure of the compressed air delivered by the compressor is set from the pressure regulator valve with gauge, and the 3/2-way valve switch, normally closed is actuated for the pneumatic muscle feed. The value of the compressed air debit is read at the display of the flow rate sensor. The displacement of the muscle resulted is measured after each experiment.

3.2. Parameters and method

The objective of the experiment was the study of the effects of loaded pressure on the length of the pneumatic muscle. The parameter used for this experiment is specified in table 1. The FESTO muscle used in the experiment has the nominal diameter of 20 mm and the length of 750 mm. The air pressure within the pneumatic muscle supplied by an air compressor was ranged between 0.0 bar and 6 bar (gage pressure). At the free end of the muscle, was attached a load of 20 kg.

| Parameters               | Values                  |
|--------------------------|-------------------------|
| Muscle diameter (mm)     | 20                      |
| Muscle length (mm)       | 750                     |
| Load (kg)                | 0, 20                   |
| Pressure (bar)           | 0, 1, 2, 3, 4, 5, 6     |
| Pneumatic supply         | At one end              |

Table 1. Experimental parameters.
The pneumatic muscle used is manually pressurized and the displacement resulted is measured. Next, the contraction is calculated, by reporting the measured displacement and the initial length.

The experiment is repeated using pressures between 0 and 6 bar, for 0 and 20 kg applied load at the free end of the muscle.

4. Results and discussion

The experimental results of the muscle contraction, for the considered parameters are presented in table 2, for the 0 kg load and in table 3, for the 20 kg load.

The contraction of the muscle, with no load applied ($m = 0$ kg) varies between 0 and 27.23%. The values of the contraction, with a 20 kg applied load, at the free end of the muscle varies between 0 and 25%.

**Table 2.** Experimental results of the contraction (%), $m = 0$ kg.

| Number of sample | Pressure [bar] | 1   | 2   | 3   | 4   | 5   | Average     |
|------------------|---------------|-----|-----|-----|-----|-----|-------------|
| 0                | 0             | 0   | 0   | 0   | 0   | 0   | 0           |
| 1                | 5.00          | 5.11| 5.13| 4.69| 4.89| 4.96533   |
| 2                | 15.04         | 15.27| 15.53| 14.79| 14.99| 15.1227   |
| 3                | 20.41         | 20.69| 20.85| 20.33| 20.63| 20.584     |
| 4                | 23.69         | 23.80| 24.01| 23.51| 23.69| 23.7413    |
| 5                | 25.93         | 25.84| 26.01| 25.36| 25.52| 25.7333    |
| 6                | 27.09         | 27.23| 27.16| 26.69| 26.91| 27.016     |

**Table 3.** Experimental results of the contraction (%), $m = 20$ kg.

| Number of sample | Pressure [bar] | 1   | 2   | 3   | 4   | 5   | Average     |
|------------------|---------------|-----|-----|-----|-----|-----|-------------|
| 0                | 0             | 0   | 0   | 0   | 0   | 0   | 0           |
| 1                | 2.15          | 1.93| 2.36| 2.36| 2.44| 2.248  |
| 2                | 8.12          | 7.71| 8.60| 8.68| 9.01| 8.424  |
| 3                | 15.69         | 15.21| 15.76| 16.05| 16.21| 15.7867 |
| 4                | 20.04         | 19.81| 20.32| 20.29| 20.49| 20.192  |
| 5                | 22.85         | 22.59| 23.05| 23.00| 23.21| 22.9413 |
| 6                | 24.83         | 24.64| 25.00| 24.87| 24.96| 24.8587 |

The aim of this research is to study how the contraction varies at different input pressures and at different applied loads. It can be observed that while the pressure increases, the contraction is also increasing. Also, it can be seen that, with no loads applied the values of the contraction are higher that the values obtained with a 20 kg considered load.

Figure 4 shows the average of contraction percentage obtained versus applied pressure with values between 0 and 6 bar. As seen in the graph, the maximum contraction of the pneumatic muscle is obtained...
in the situation of zero load \((m = 0 \text{ kg})\) with the value of 27\%. This value deviates from the technical specifications of the pneumatic muscle analysed, providing a relative contraction of only 20\%. The real possibility of pneumatic muscle to shorten more than the value from specifications is an advantage for obtaining larger strokes.

![Figure 4. Contraction percentage versus pressure.](image)

In figure 5, using CurveExpert software, is presented the evolution of the pneumatic muscle contraction, for the case without load. The values of the contraction percentages obtained by measurement are represented by points, and the solid line shows the polynomial regression curve suggested by the considered software.

![Figure 5. The evolution of the contraction percentage versus pressure.](image)

![Figure 6. Residual values of the function for \(m=0 \text{ kg}\).](image)

The function that most accurately describes the evolution of contractions in case of no load and for pressures between 0 ... 6 bar, is:

\[
F(x) = -0.72 + 7.92 \cdot x - 0.16 \cdot x^2 - 0.06 \cdot x^3
\]  

(1)

A function is suitable as a pattern if correlation coefficient \(r\) value is close to 1. The best model is considered the one with a high correlation coefficient, between 0.8 and 0.9. The determination coefficient \(r^2\) offers a percentage interpretation of the obtained curve for the experimental dates.
For the considered function, the correlation coefficient (r) is 0.994 and the coefficient of determination (r²) is 0.988. The obtained values show that the function is the best model for the analyzed situation.

Another method of validation of the function is by graphical form of the residual values. The residual values represent the difference between the experimental values and the ones obtained through mathematical calculation.

For the function determined to be validated residuals chart must follow the two conditions:
- Residual values are independent (there is no particular pattern of these, they are arranged at random);
- Residual values are normally distributed (Gaussian) with mean 0 (negative values are equal with positive values).

In this case, those conditions are respected and the method validates the function obtained, as can be seen in figure 7.

![Figure 7. The evolution of the contraction percentage versus pressure.](image)

![Figure 8. Residual values of the function for m=20 kg.](image)

The function that most accurately describes the evolution of contractions in case of a 20 kg load and for pressures between 0...6 bar (figure 7), is:

$$F(x) = -0.39 + 2.1 \cdot x + 1.6 \cdot x^2 - 0.21 \cdot x^3$$

(2)

The correlation coefficient (r) is 0.997 and the coefficient of determination (r²) is 0.994, meaning an accepted function. The graph from figure 8 validates the obtained function.

5. Conclusion

The aim of the experiments presented in this paper was to test the functioning of a FESTO origin pneumatic muscle under the action of pressures of 6, 5, 4, 3, 2, 1 and 0 bar, with different loads applied.

The contraction of the muscle increases as the different amount of loads and pressure applied increases. Based on the obtained results, it was made an analysis and identified the best fit equation for the data. The equations developed presents the correlation between the pressure applied and the contraction of the pneumatic muscle.

The results confirms the fact that, the considered pneumatic muscle, FESTO branded, has the possibility of performing higher contractions than those proposed in technical specifications. In practice, a contraction of 27% can be obtained. The obtained results gave a concrete and effective description to understand the real possibilities of the pneumatic muscle.
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