DESIGN OF APPARATUS FOR EVALUATION OF TEMP-DEPENDENCE OF CREEP EFFECT IN PAM

MONIKA TROJANOVA, ALEXANDER HOSOVSKY, TOMAS CAKURDA

Technical University of Kosice, Faculty of Manufacturing Technologies with the Seat in Presov, Slovakia

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monika.trojanova@tuke.sk

The creep effect in relationship with the research of pneumatic artificial muscles represents a dynamic phenomenon characterized by slow changes in muscle displacement caused by the material's elasticity. However, the temperature of the environment in which the muscle works affects the temperature of the muscle. It also affects the creep effect itself; as a result, the process of identifying hysteresis models of muscle becomes difficult. The article contains a description and implementation of a measuring apparatus designed to measure the temperature dependence of the creep effect of fluid muscles. The apparatus was designed and constructed at the authors' workplace to analyze the creep effect and evaluate its impact on the accuracy of experimental models describing the dynamics of the drive.

KEYWORDS

Creep Effect, Fluid Muscle, Dynamics, Modeling

1 INTRODUCTION

The current trend in the industrial sphere is to solve issues and tasks related to increasing human safety in the work environment. Therefore, it is mainly the interaction of human-machine, respectively human-robot, when the perception of the machine as an element cooperating with a human on the same goal is to be achieved. In connection with this fact, special drives come to the fore in robots. These are characterized by more excellent elasticity. Fluid muscles are one such unconventional drive. However, before their possible implementation in practice, it is necessary to eliminate all undesirable properties, including hysteresis and creep effect. Moreover, their presence results in reduced accuracy in the regulation of essential muscle variables.

Modeling the hysteresis of unconventional types of drives, as well as the pneumatic artificial muscles (PAM) itself, has been of interest to many scientists for several years, as evidenced by the growing number of publications published in scientific journals and international scientific conferences. Recent works of hysteresis modeling of unconventional drives include, e.g., [Capace 2021], [Xie 2020], [Luo 2020], [Ovidiu 2020], [Xu 2019], [Zhang 2019], and many more. Interest in research into the creep effect of unconventional drives and their impact on control has grown, especially in the last decade. E.g., the investigation of the creep effect in a piezoceramic actuator is described in [Gu 2013], [Su 2021]. As another unconventional drive type, the creep effect of a dielectric elastomer actuator is described in [Gu 2017], [Zou 2017].

For this article, but especially for further research, the creep effect of fluid muscles is a priority. Therefore the related work of other authors in this field is, e.g., [Minh 2012], where a new approach to hysteresis modeling using the Maxwell-slip model is described, taking into account the creep effect of muscle. Within the muscle creep section, the authors present the results of research where they used mean force centers to monitor the creep effect and came to the following:

- The creep effect of the rubber bladder varies depending on the time and ambient temperature;
- After a while, the creep effect stabilized;
- The creep effect depends on the static pressure;
- The creep effect results in the mean force rising infinitely;
- Dependence of the future creep effect on the previous creep effect.

Furthermore, the paper presents the results of modeling, which demonstrate that the model can predict torque–angle hysteresis under isobaric conditions at any time in the creep effect. This article was preceded by similar research-oriented publications in a similar author's composition [Minh 2010], [Minh 2011], where the Maxwell-slip model represents the primary approach to hysteresis modeling. In another study [Geng 2020], the authors propose a feedforward-feedback composite control method, the task of which is to compensate for the hysteresis of pneumatic artificial muscles in the delta mechanism, which has two degrees of freedom. Part of the article is a chapter devoted to the hysteresis and creep nonlinearities of pneumatic artificial muscle, the courses of which were plotted based on measured data.

Several researchers worldwide are studying the creep effect of fluid muscles (e.g., author's team Minh, Tri Vo; Rooms, Bram; Tjahjowidodo, Tegoeh; Ramon, Herman; and Van Brussels, Hendrik). Still, not all dependencies have been investigated in the practical implementation of fluid muscle, e.g., the impact of temperature on this phenomenon has not been significantly investigated. Suppose manipulators that fluid muscles would power are to be able to withstand even more demanding operating conditions (dust, temperature, humidity). In that case, it is necessary to know the impact of these factors on muscle accuracy. In particular, the effect of elevated ambient temperature on the accuracy of hysteresis modeling.

Because of this fact, the present article focuses on designing a measuring apparatus to investigate the creep effect of fluid muscle from Festo as a function depending on temperature.

The article is divided into five parts:

- After the introduction (part 1), which included related current research work of other authors, follows a chapter two, explaining the drive-fluid muscle and its characteristics.
- Subsequently, the third chapter describes the apparatus's construction, describing individual parts and components. At the same time, the principle of transmission of respective signals is explained.
- The fourth chapter of the article is devoted to the description of heat spread within the temperature chamber, while it contains the results of measuring the temperature in the temperature chamber at two different places using two temperature sensors.

- The last part of the article is the conclusion, which briefly outlines future research in connection with the proposed apparatus.

2 FLUID MUSCLE AND ITS CHARACTERISTICS

Fluid muscles are a type of drive that provides more flexibility compared to conventional kinds of drives. Pneumatic artificial muscle resembles human muscle in shape and properties, so it is possible to engage it antagonistically. This property allows implementation in more complex manipulators, which subsequently have features such as operation in adverse working conditions, safer interaction between the manipulator and human, a high ratio of traction force to weight depending on the size of the muscle used, and others. These muscles use pneumatic energy to be able to exert an external tensile (mechanical) force. The muscle is filled with the working medium, which causes the muscle to contract (shorten the muscle and increase its diameter - see Fig. 1), and subsequently, a tensile force will occur. The pulling force depends on the pressure in the muscle and the already mentioned contraction (a nonlinear function).

If the muscle is clamped, as shown in Fig. 1, one end is fixed (for example, by a screw connection). At the same time, a medium is fed through it. A load is attached to the other free end, so when the muscle is pressurized and contracted, it will be possible to observe the upward displacement of the weight. However, when the muscle is released, it will return to its original position, and thus the load would shift downward. Therefore, it is an isotonic load. The weight of the load does not change, but the muscle's length and pressure change.

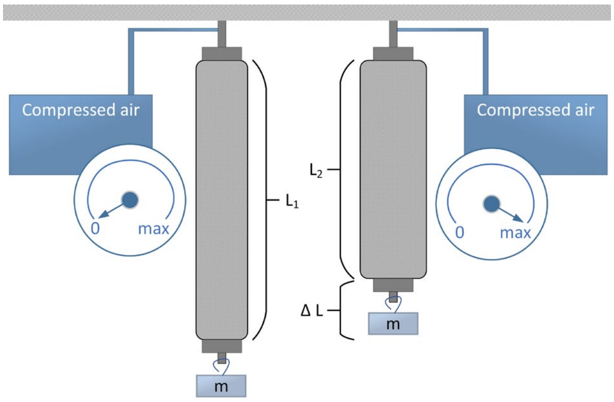

Figure 1. Isotonic loading of pneumatic artificial muscle

The first types of pneumatic artificial muscles (the most typical is McKibben artificial muscle) were composed of two layers. The outer braid and the inner tube were closed at both ends with endings. The materials used to produce individual parts of the muscle ensured gas tightness, the elasticity of the muscle, and its resistance to external influences. The disadvantages of pneumatic artificial muscles with a separate outer and inner layer were the resulting friction between the layers, nonlinear characteristics, and hysteresis presence. However, the muscle, designed for implementation in the proposed measuring apparatus, is from the manufacturer FESTO. FESTO eliminates the resulting friction by joining the outer and inner layers into one. Nevertheless, hysteresis, nonlinear characteristics, and others that must be eliminated in modeling and control remain undesirable properties.

The measuring device proposed in this article will measure the temperature dependence of the fluid muscle under isotonic loading and the same muscle engagement and load as shown in the example in Fig. 1. The input setting parameter will be the pressure in the muscle. The output monitored parameters will be temperature and displacement. The proposed measuring device uses a fluid muscle from the manufacturer FESTO, specifically type DMSP-5. The designation DMSP indicates a pneumatic muscle with a pressed connection intended for a screw connection, where the adapters are already integrated. In Fig. 2. the working range of the DPSM-5 muscle with a theoretical force of 140 N is shown. The graph shows a total of 6 dependences of the resulting tensile force *F* of this type of muscle depending on the contraction *h* at a certain muscle pressure *p* (0-6 bar).

The graph shows three limit values:

- limit 1 (left vertical) - determines the maximum possible preload of the given muscle type,
- limit 2 (right vertical) - determines the maximum possible contraction of the given muscle type,
- limit 3 (upper horizontal) - determines the theoretical force at maximum operating pressure; for this case, the value of the theoretical force is 140 N.

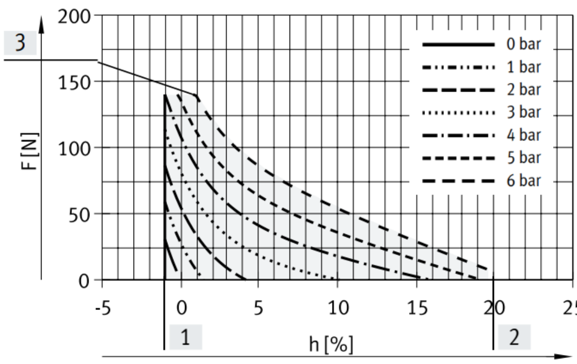

Figure 2. Operating range of DMSP-5-100N FESTO fluid muscle [FESTO 2017]

The presence of nonlinear characteristics of fluid muscles results from their design - the use of material with elasticity, as they are made of rubber tube and braid of aramid fibers. In terms of application, the ambient temperature of fluid muscles should range from -5 °C to 60 °C. Exceeding this ambient temperature limit in practice can significantly affect the accuracy of the manipulator position control. The creep effect as an undesirable phenomenon in fluid muscles is understood as the material's relaxation, depending on ambient temperature and time. It is a slow phenomenon whose time constant reaches the order of tens of seconds. Given this fact, the authors decided to investigate the effect of temperature on the creep effect of fluid muscle.

3 CONSTRUCTION OF THE APPARATUS

The proposed apparatus for measuring the temperature dependence of the creep effect of fluid muscles constructed at the authors' workplace is shown in Fig. 3, where the most basic preparation components are indicated. A detailed diagram of the preparation is shown in Fig. 4, where the individual components can be divided into several groups:

- Construction elements - Main frame (2), Temperature chamber (3), L-shaped profile (4), Mounting plate (8), and Transverse profile (9)
- Electrical elements - Proportional pressure regulator (1), Optical displacement sensor (7), Heating element (10), Temperature sensor (11), Digital thermostat (12)

- Elements enabling signal transmission and processing - Input/output device (14), Computer (15)
- Other elements - Fluid muscle Festo (5), Load (6), Power supply (13)

The stabile supporting part of the apparatus structure is the Main frame, on which most other components are mounted. The object of investigation - Fluid muscle FESTO is a screw joint attached to an L-shaped profile attached to the Main frame. At the free end of the muscle, a mechanical Load is also connected by a screw connection. Precise regulation of muscle pressure is ensured by a Proportional pressure regulator, which is controlled by an analog signal fed from the Computer to the Input/output device and then to the regulator.

A proportional-pressure regulator with pressure range 0-6 bars (0-600 kPa) from FESTO, type VEAB-L-26-D9-Q4-V1-1R1, was applied. This type of sensor was chosen because it has features such as high accuracy, short switching times, quiet operation, low power consumption, integrated pressure sensor, H-rail mounting, and more. To ensure proper sensor operation, the ambient temperature must be in the range of 0 °C to 50 °C. By filling muscle with compressed air occurs to a contraction. It is manifested by the displacement of the muscle with the Load.

The muscle displacement is sensed by an Optical displacement sensor mounted on a mounting plate located on the Transverse profile. A Laser Displacement sensor from Panasonic type HL-G112-A-C5 was implemented, which meets the expected measurement range and accuracy: the measuring range is ± 60 mm, the resolution is 8 µm, and the ambient temperature is required for its correct operation from -10 °C to 45 °C. If measurements are made in this temperature range, then the temperature change should not affect the accuracy and results of the measurement. The scanned position is transmitted in the form of a signal to the Input/output device and then processed in the Computer. An orange dashed line in the scheme indicates signals routed within the apparatus, either for Proportional pressure regulator control or as an Optical displacement signal output. The solid blue line indicates the power supply of electrical elements from the Power supply.

The task of the measuring apparatus is to monitor the creep effect of fluid muscle depending on the change in a temperature chamber. The chamber was created around the muscle, which is made of plexiglass. The chamber has two walls designed to be opened if necessary for easier handling of individual components located inside. In addition, the chamber ensures that the space around the muscle is thermally insulated and thermally regulated. The temperature in the chamber is sensed by a temperature sensor, which is connected to a Digital thermostat. Its task is to control the temperature by switching the connected Heating element. A heating module from COBI ELECTRONIC type CV-R20 was used, whose power is 20W, surface temperature 85 °C, and supply voltage 230V. A heat source was chosen to ensure the propagation of heat by radiation. The individual sensors and the muscle were placed as close to each other as possible to avoid influencing the measurement results.

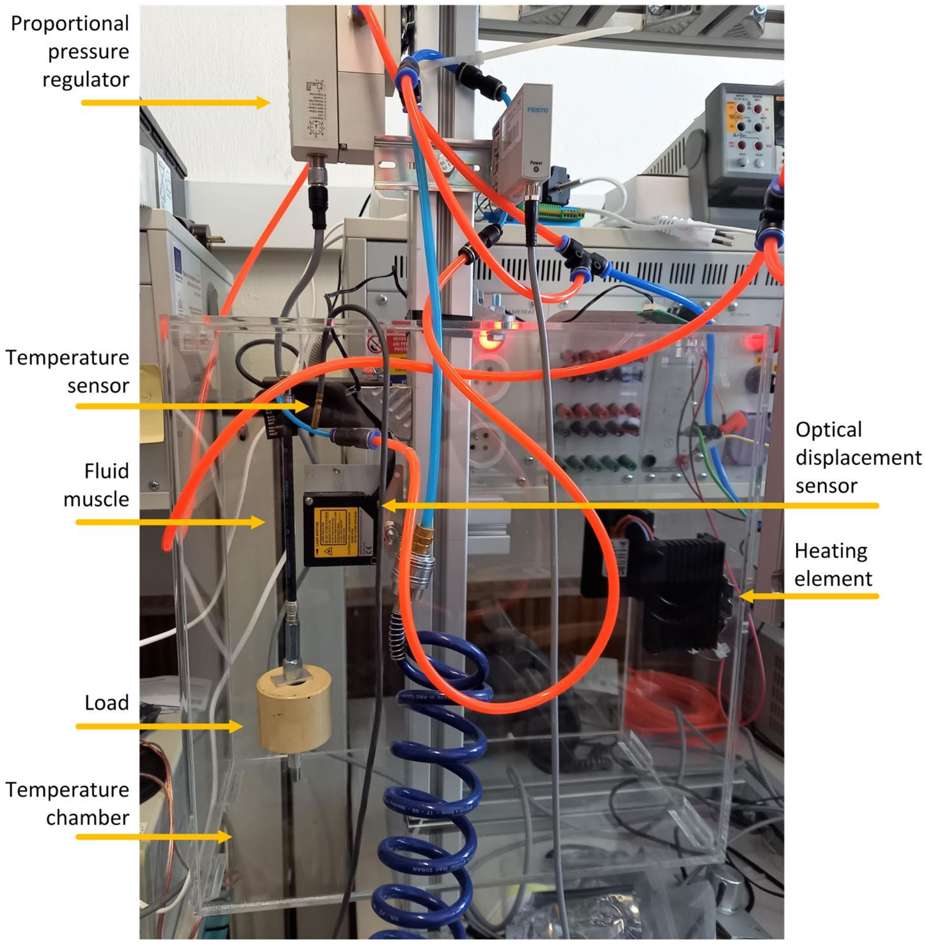

Figure 3. Apparatus for measuring the temperature dependence of the creep effect of fluid muscles

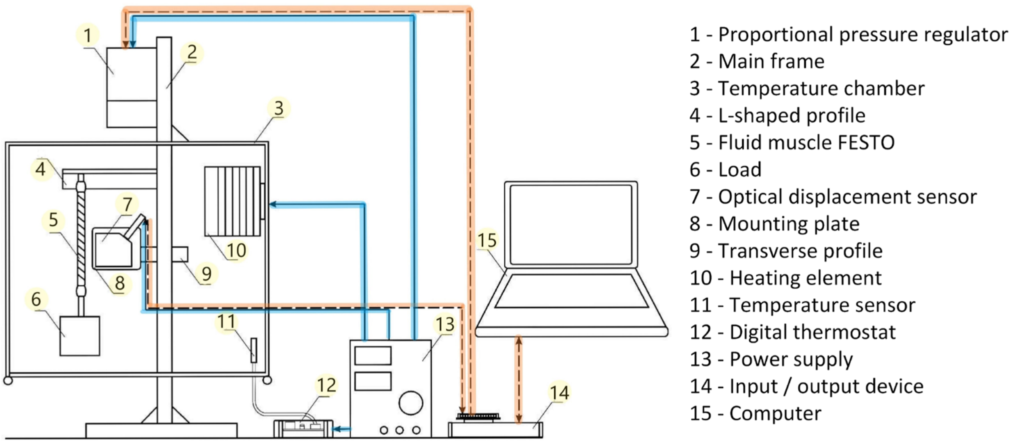

Figure 4. Scheme of measuring apparatus

4 PRINCIPLE OF MEASURING THE TEMPERATURE IN THE CHAMBER

A temperature chamber is an enclosed space that allows studying the effects of temperature on the tested object - fluid muscle. Thus, during the study, it is possible to create conditions that could artificially affect the muscle during use and thus influence its activity. However, to examine the dependence of the creep effect on the temperature around the muscle, it is useful to know the temperature distribution in the chamber. For example, how long it takes for the desired temperature to be reached at different points in the chamber; or how the temperature in the heat source area differs from the temperature in the muscle area at the same time. Therefore, two temperature sensors were integrated to sense the temperature distribution in the chamber. One sensor is located near the muscle; the other sensor is located near the heating element. The sensors used are of the same type and therefore have the same accuracy and sensitivity. Before examining the above dependence, it is necessary to identify the properties of the temperature chamber.

Measurements were performed with the following steps:

- Measurements were performed at three different supply voltages of the heating elements ($u1$ = 100V, $u2$ = 150V, $u3$ = 200V).
- Muscle was not activated during measurements.
- The required achievement of the internal ambient temperature in the chamber was selected at T= 30°C and ensured by a digital thermostat that switched the heating elements. A total of two identical were used.
- The temperature was measured around the muscle (the temperature of the working medium inside the muscle was not measured).
- Data collection from temperature sensors was realized using transducers, the outputs of which were fed to the analog inputs of the input/output device (measuring card).
- The total measurement time was 4500 seconds, and the sampling was 1 ms.
- The processing of the measured values and their subsequent interpretation took place on a computer using the MATLAB program.

In Fig. 5-7, it is possible to see the measurement results at three different supply voltages. These are time dependences of measured temperatures from sensors. The blue curve represents the temperatures sensed by the sensor located near the heating elements. The red curve represents the temperatures sensed by the sensor near the muscle. At the beginning of the measurement, the thermostat connected the source to the heating elements by switching. The temperature in the chamber began to rise to the maximum value and then oscillated over time around the desired temperature. The fluctuation of values is caused by the type of control, as a thermostat with a simple two-position temperature control was used. The graphs also show the initial temperatures around the muscle and heat sources, where the difference between these temperatures was around ΔT=1°C. The difference between the initial temperatures can be influenced by the organization of the individual elements within the chamber.

However, differences in dynamics are more pronounced when normalized data are available, respectively, time waveforms. Therefore, the measured data were further adjusted by normalization, and their time dependences according to the magnitude of the supply voltage are shown in Fig. 8-10. When switching the thermostat, it is possible to monitor the system delay - the time required for the interior of the chamber to start warming/cooling (Fig. 8-10). Also, in all measurements, it can be observed that the values of temperatures measured around the muscle lag behind the values of temperatures measured in heating elements. However, since the muscle and the heating elements are at a certain distance from each other, the propagation of heat from one end of the chamber to the other end requires a specific time depending on the actual ambient temperature and the supply voltage of the heating elements. However, it can be seen from the diagram itself (Fig. 4), but especially from the real photograph of the realized measuring apparatus (Fig. 3), that the heat propagation in the chamber from the heating body to the muscle is also influenced by the disposition of individual components. While other elements are absent around the heat source, most parts are located around the muscle.

The most significant difference between the measured temperature around the heat source and the muscle is at a supply voltage of 150V (Fig.9). On the contrary, the slightest difference can be observed at a supply voltage of 100V (Fig.8). It follows from these measurements that when modeling a muscle under the conditions mentioned above, it is necessary to take into account, among other things, the magnitude of the supply voltage of the heating elements, as well as the setting of the thermostat hysteresis.

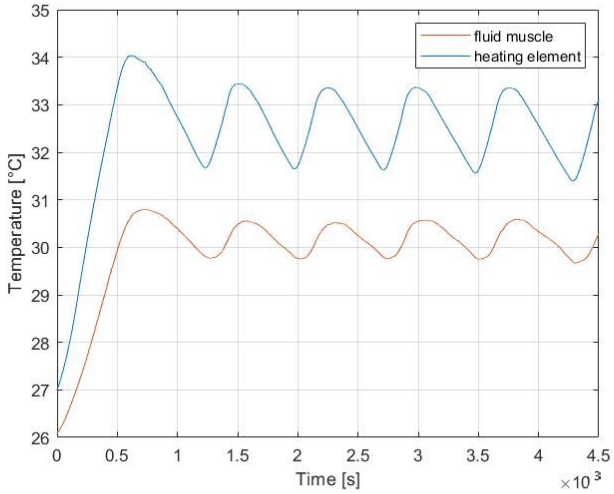

Figure 5. Time dependence of temperature at a supply voltage of 100V

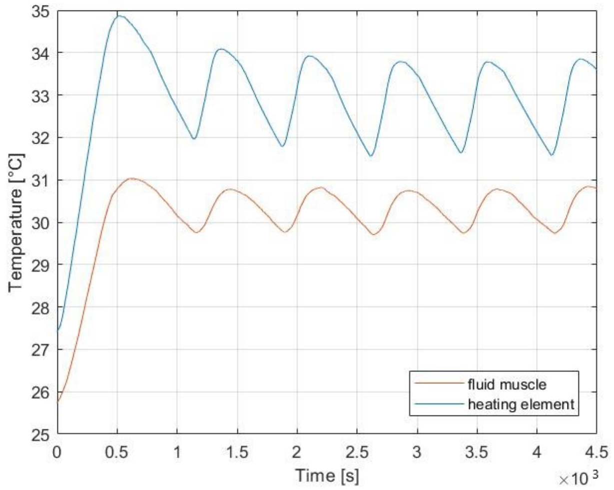

Figure 6. Time dependence of temperature at a supply voltage of 150V

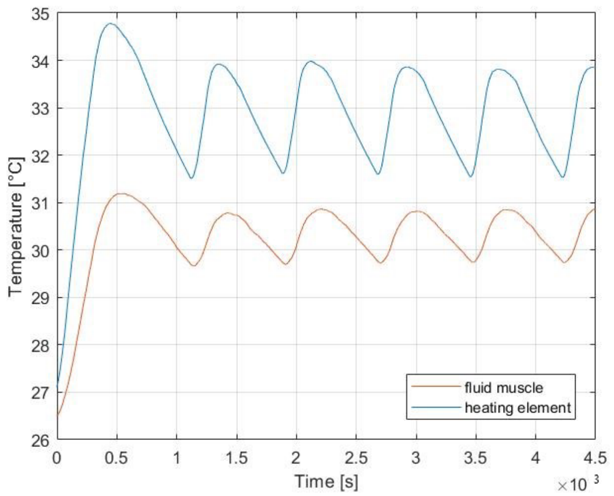

Figure 7. Time dependence of temperature at a supply voltage of 200V

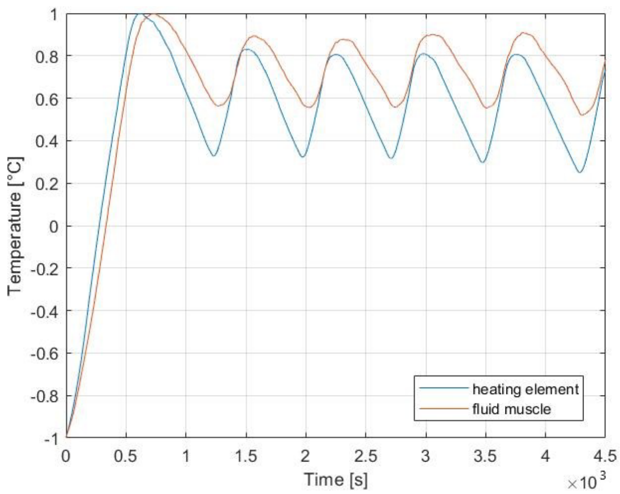

Figure 8. Time dependence of normalized temperature at a supply voltage of 100V

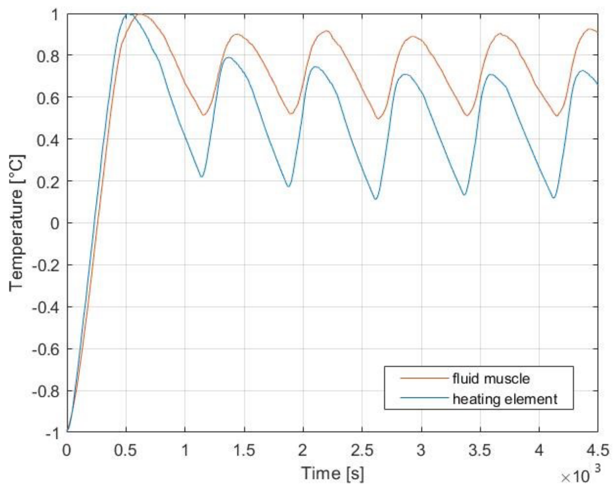

Figure 9. Time dependence of normalized temperature at a supply voltage of 150V

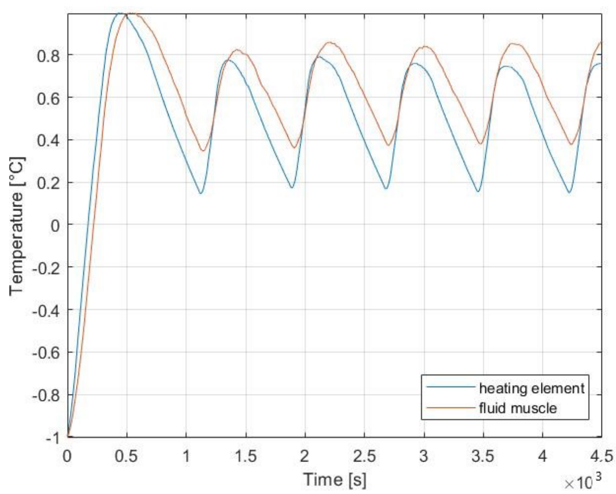

Figure 10. Time dependence of normalized temperature at a supply voltage of 200V

Tab. 1 shows an overview of the time to reach the maximum temperature for individual measurements when the maximum ambient temperature was reached for both heating elements and fluid muscle. The table shows that the fastest reaching the maximum temperature at the heat source and muscle was achieved at a supply voltage of 200V, where the difference between the maximum temperatures reached was the lowest. Furthermore, with an increasing supply voltage of the heating elements, the time was shortened when the maximum temperatures around the heat sources and muscle reached.

	Heating element		Fluidic muscle	
Supply voltage	Max temperature [°C]	Time [s]	Max temperature [°C]	Time [s]
100V	34.0373	605	30.8053	742.4
150V	34.8724	511.9	31.0387	639.7
200V	34.7836	448.5	31.1949	542.6

Table 1. Time to reach maximum temperature

From Fig. 8-10 and Tab. 1, it follows that in the process of investigating the influence and properties of phenomena with slow dynamics of fluid muscles on the accuracy of their modeling, it is necessary to monitor, among other things:

- effect of thermostat hysteresis,
- influence of supply voltage of heating elements,
- time to reach maximum temperature.

5 CONCLUSIONS

Research in the field of fluid muscle creep (excluding hysteresis) is relatively limited, so this area is becoming more attractive for further investigation. Not all dependencies have been investigated in the practical implementation of fluid muscle, e.g., the impact of temperature on this phenomenon has not been significantly investigated. Because of this fact, the present article focuses on designing a measuring apparatus to investigate the creep effect of fluid muscle from Festo as a function depending on temperature.

From the measurements presented in section 4, it is clear that the rate of heat propagation in the temperature chamber and the time taken to reach the desired temperature in the chamber and around the muscle also depend on the supply voltage. Therefore, it needs to be taken into account in further research. It was also found from the presented measurement results that for the following process of investigating the effects and phenomena with slow fluid muscle dynamics on the accuracy of fluid muscle modeling, for example, the impact of thermostat hysteresis must be monitored.

The following study will aim to analyze the creep effect, examine its dependence on the temperature in the temperature chamber, and evaluate its influence on the accuracy of experimental models describing the dynamics of the drive. Specifically, this process will consist of the following stages:

1. Implementation of measurements to obtain a representative set of data that will characterize the dynamic properties of the drive with respect to nonlinearity. The result will be models suitable for simulation.
2. Analysis and application of methods suitable for drive modeling.
3. Validation of models based on experimentally obtained data.

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REFERENCES

[Capace 2021] Capace, A. et al. Modelling and identification of the asymmetric hysteresis in the viscoelastic response of the fingertip under indentation: A multistate friction model with switching parameters. Mechatronics, 2021, Vol. 77, pp 1-11, ISSN 0957-4158

[FESTO 2017] Fluidic muscle DMSP [online]. June 2017 [date of citing 2021-10-07]. https://www. https://www.festo.com/cat/sk_sk/data/doc_engb/ PDF/EN/DMSP_EN.PDF

[Geng 2020] Geng, P. et al. Direct Inverse Hysteresis Compensation of a Pneumatic Artificial Muscles Actuated Delta Mechanism. In: 2020 10th Institute of Electrical and Electronics Engineers International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER), Xi'an, China, 10-13 October, 2020. Danvers: IEEE, pp 18-23, ISBN 978-1-7281-9010-5

[Gu 2013] Gu, G. and Zhu, L. Motion control of piezoceramic actuators with creep, hysteresis and vibration compensation. Sensors and Actuators A: Physical, 2013, Vol. 197, pp 76-87, ISSN 0924-4247

[Gu 2017] Gu, G. et al. Modeling of Viscoelastic Electromechanical Behavior in a Soft Dielectric Elastomer Actuator. IEEE Transactions on Robotics, 2017, Vol. 33, no. 5, pp 1263-1271, ISSN 1941-0468

[Luo 2020] Luo, X. et al. Hysteresis modeling and compensation of a pneumatic end-effector based on Gaussian process regression. Sensors and Actuators A: Physical, 2020, Vol. 315, pp 1-11, ISSN 0924-4247

[Minh 2010] Minh. T. V. et al. Characterization of Hysteresis in a Pneumatic Muscle Manipulator with Accounting for the Creep Effect. IFAC Proceedings Volumes, 2010, Vol. 43, no. 21, pp 296-302, ISSN 1474-6670

[Minh 2011] Minh. T. V. et al. A New Approach to Modeling Hysteresis in a Pneumatic Artificial Muscle Using The Maxwell-Slip Model. IEEE/ASME Transactions on Mechatronics, 2011, Vol. 16, no. 1, pp 177-186, ISSN 1941-014X

[Minh 2012] Minh. T. V. et al. Modeling and control of a pneumatic artificial muscle manipulator joint – Part I: Modeling of a pneumatic artificial muscle manipulator joint with accounting for creep effect. Mechatronics, 2012, Vol. 22, no. 7, pp 923-933, ISSN 0957-4158

[Ovidiu 2020] Ovidiu, F. et al. Experimental Research on the Hysteretic Behaviour of Pressurized Artificial Muscles Made from Elastomers with Aramid Fibre

Insertions. Actuators, 2020, Vol. 9, no. 3, pp 1-14, ISSN 2076-0825

[Su 2021] Su, Q. et al. A 3-DOF sandwich piezoelectric manipulator with low hysteresis effect: Design, modeling and experimental evaluation. Mechanical Systems and Signal Processing, 2021, Vol. 158, ISSN 0888-3270

[Xie 2020] Xie, S. et al. A modified asymmetric generalized Prandtl–Ishlinskii model for characterizing the irregular asymmetric hysteresis of self-made pneumatic muscle actuators. Mechanism and Machine Theory, 2020, Vol. 147, pp 1-20, ISSN 0094-114X

[Xu 2019] Xu, J. et al. Modeling and compensation of hysteresis for pneumatic artificial muscles based on Gaussian mixture models. Science China-Technological Sciences, 2019, Vol. 62, no. 7, pp 1094-1102, ISSN 1674-7321

[Zhang 2019] Zhang, Y. et al. A novel hysteresis modelling method with improved generalization capability for pneumatic artificial muscles. Smart Materials and Structures, 2019, Vol. 28, no. 10, pp 105014, ISSN 0964-1726

[Zou 2017] Zou, J. et al. Open-Loop Control of Creep and Vibration in Dielectric Elastomer Actuators With Phenomenological Models. IEEE/ASME Transactions on Mechatronics, 2017, Vol. 22, no. 1, pp 51-58, ISSN 1941-014X

CONTACTS:

Ing. Monika Trojanova, PhD., Assoc. Prof. Ing. Alexander Hosovsky, PhD., Ing. Tomas Cakurda

Technical University of Kosice, Faculty of Manufacturing Technologies with the Seat in Presov, Department of Industrial Engineering and Informatics, Bayerova 1, 080 01 Presov, Slovakia +421 055 602 6420, monika.trojanova@tuke.sk, alexander.hosovsky@tuke.sk, tomas.cakurda@tuke.sk, http://www.fvt.tuke.sk