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New Actuator Type Using Magnetically Controlled Rheological Properties of Fluids

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Abstract *The paper presents the concept of new type of actuator that uses the specific properties of a magneto rheological fluid. The proposed actuator allows controlling the speed of a mechanical element and its positioning. The paper gives details about the structure of the actuator and functions of elements, ongoing program of experiments and results obtained.*

Keywords: *Magneto rheological fluids, actuator, magnetic control*

1. Introduction

Based on space researches, the research field concerning on magnetic controllable fluids is widened from laboratory curiosity to the production of ferro-fluid components with that can be used in industrial application.
The first publications about ferro-fluids are made by Knight, Bitter, Elmore, Neuringer, and Rosensweig, founded the American company "Ferro fluidics Corporation", the first company who managed the industrial production of magnetic fluids. Studies made on magnetic fluids showed a series of sensational fluid-mechanical phenomena that make possible new settlements of the problems of science and technology. There are two scientific papers [1] and [2] who present the first technical achievements obtained using magnetic properties of ferro-fluids.
According to [3] and [4; 5; 6] magnetically controllable fluid scan be classified into two classes: ferro-fluids and magneto rheological fluids. They are characterized by the fact that the IR energy is performed by means of an external magnetic field.
Both types of liquid scan are classified as smart fluids. Magnetic fluids are colloidal suspensions of magnetic particles in different liquids. These fluids, in addition to an obvious magnetic behaviour, preserve and exhibit characteristics of liquids.
As shown by [6], ferro-fluids are colloidal suspensions of ultra-stable magnetic nanoparticles (whose order of magnitude is up to hundreds of Armstrong) dispersed in a liquid base. They are characterized by the following basic properties: the sedimentation is zero even in the presence of magnetic field, are quasi-homogenous magnetisable fluids and their magnetic behaviour are of Langevin type. From the point of view of viscosity, their behaviour is approximately Newtonian even in the presence of a magnetic field and have a reduced magneto-viscous effect.
The magnetically controllable fluids viscosity [7] is subject to the base liquid viscosity, to the shape of particles, to the dispersed phase volume and the degree of salvation. Einstein elaborated a formula that is being used in the study of spherical-colloidal liquid solutions $\eta_s = \eta_0 (1 + k_\varepsilon)$, where η_s is the liquid solution's viscosity, η_0 is the base liquid viscosity, ε is the overall volume of colloidal particles dispersed within the unit of volume, whereas k is a constant.
Magneto rheological fluids [8] comprise magnetisable solid particles, a prevailing liquid environment whose role is of carrier fluid, a surfactant whose role is to prevent the separation of the two constituents. The dimensions of the particles may vary between 0.1 to 500 µm. The solid content within the liquid varies between 31 and 90% (weight ratio).
Magneto rheological fluids are characterized by the fact that their energy derives from an external magnetic field. These liquids fall within the category of non-Newtonian fluids - Bingham type plastic fluids [9] and [10]
Magneto rheological fluids modify their apparent viscosity much faster and more dramatically by comparison to ferro fluids.

Thixotropic magneto rheological fluids [11] (www.liquidsresearch.com) are capable of providing high shear stress when subjected to comparatively weak magnetic fields. That class of magneto rheological fluids is conducive to major changes in the rheology of fluids when subjected to a relatively weak external magnetic field.
Considering the complexity of magnetically controllable fluid systems, it is difficult to achieve a thorough investigation of the latter.
The scientific literature is offering calculation models for the flow of non-Newtonian fluids.
The Herschel-Bulkley model is allowing for the calculation of τ stress for positive values of the magnetic induction.
For the laminar flow [12], is suggesting a model for the calculation of pressure drop. For the turbulent flow, the authors are proposing a method which requires that the wall shear stress is known, yet they do not provide a formula for the respective calculation. The latter model was completed by Hathoot. The Buckingham-Reiner model is giving a formula for calculating magneto-rheological fluids flow rate through circular pipes.
The size of magnetic particles distributed throughout the magnetic fluid [13] is of crucial importance for the case when the liquid is subjected to shear stress under the influence of an applied magnetic field.
For the analysis of magnetically controllable fluid systems, one should utilize notions and calculation formulae specific to ferromagnetism.
The dynamic viscosity η for a magneto-rheological fluid has two components, a η_0 component, in the absence of the magnetic field, and a η_c component respectively, which depend on the intensity of the magnetic field, H.
Experimental studies that have been undertaken [12], on various shear stresses have shown that an increase in the intensity of the magnetic field causes a rise in the fluid's viscosity, the so-called magneto-viscous effect, whereas the increase in shear velocity is conducive to a decrease in viscosity (shear-thinning effect).
Considering that the magnetic induction $B = \mu \cdot H$, where $\mu = \mu_0 (1 + \chi)$ is the environment permeability, there results that the magneto rheological fluid viscosity $\eta(B) = \eta_0 + \eta_c(B)$ depends on the value of the magnetic induction *B*. In case the magnetic field is generated by a coil, the value of magnetic induction depends on the electric current *I* that pass the coil spirals, $B = B(I)$ respectively.
There derives that one may control a magneto rheological fluid flow through a circular pipe fitted with a coil traversed by an electric current I. By adjusting the intensity of the electric current I the η_c value of the dynamic viscosity is being altered in the presence of the magnetic field.
The applications of magneto rheological fluids related to every field (areas) where high shear stresses are being required: vehicle suspension systems, suspension chairs and rehabilitation exercise equipment's.
The present paperwork provides a new technical application for magnetic fluids, therefore a new type of actuator that makes use the rheological properties of magneto rheological fluids. The actuator that was built is allowing the velocity control of a mechanical component, as well as for positioning the latter by controlling the liquid flow velocity subjected to an external applied magnetic field. Thus, one may obtain a driving element that utilizes the fluid's rheological properties.
Our paperwork is presenting the conceptual model of the new type of actuator, construction data, calculation elements, the schedule of carrying-out experiments, the results attained, and the conclusions.

2. The actuator conceptual model

The schematic diagram of the new type of actuator is being illustrated in Figure 1.

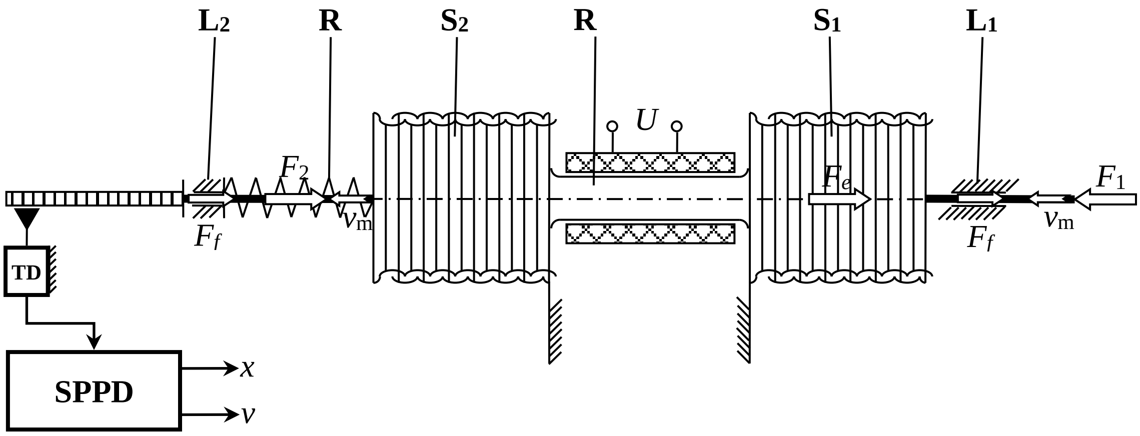

Fig. 1. The actuator schematic diagram

The watertight hydraulic system made of the identical bellows S_1 and S_2 and the tubular hydraulic resistance RH, of diameter *d*, contains a MRHCCS4-B type magneto rheological fluid made by the company Liquids Research Limited. The advantage of using the bellows consists in the complete lack of relative movement parts, and the lack of sealing components. The bellows present a linear characteristic of axial deformation when subjected to a variation in a certain domain of the applied external force.

The value of hydraulic resistance RH is being controlled by the value of the external magnetic field, of intensity H, generated by the coil under the electric tension U. Thus, the magnetic induction B is being modified, and, subsequently, the magnetic fluid viscosity, η.

The flow velocity of the magneto rheological fluid V_{RH}through the hydraulic resistance RH and implicitly the axial deformation velocities of the bellows V_{s1} =V_{s2} = V_m depend on the viscosity of the fluid.

Since the fluid dynamic viscosity η is being influenced by the intensity of the external applied magnetic field H, there results the loss of pressure function Δp[η(H)].

By controlling the fluid's flow velocity subjected to the external applied magnetic field one may obtain an actuator that allows for controlling the speed, as well as he positioning of a working part that supports the S_2 bellow axial deformation. The actuator is therefore a command element that makes use of the magnetic fluid rheological properties.

The value of the pressure p_1 from the chamber of the S_1 bellow is given by Equation 1:

$$p_1 = \frac{F_1 - F_{f1} - F_{es}}{S_s} = \frac{F_1 - F_{f_1} - k_s \cdot \frac{x}{2}}{S_s} \tag{1}$$

where F1 is the external applied force, F_{f1}represents the friction force present in the bearing L_1, whereas F_{es} is the elastic force corresponding to an x axial deformation of the S_1 bellow of S_s transversal section.

The value of the pressure p_2 from the S_2 bellow chamber is given by Equation 2:

$$p_2 = \frac{F_2 + F_{f2}}{S_s} = \frac{F_{es} + F_{ea} + F_{f2}}{S_s} = \frac{k_{sa} \cdot \frac{x}{2} + F_{f2}}{S_s} \tag{2}$$

Where F_2 is the operational charge of the system, from which there derives the p_2 counter-pressure in the S_2 bellow chamber. That force is caused by the cumulated elastic forces of the spring load Rand of the S_2 bellow.

For the elastic constants corresponding to the components utilized, we've used the notations k_s=k_{s1}=k_{s2}, for elastic constants corresponding to the $S_1$and S_2 bellows, k_a the elastic constant of

the spring load R. The elastic constant equivalent to the 2 springs connected in series (S_2 and R), was marked k_{sa}. We are also naming the overall sum of friction forces $F_f=F_{f1}+F_{f2}$ ($F_{f2}$is the friction force present in bearingL_2*).*
Given the hydraulic resistance RH, the flow of the magnetic fluid occurs when the difference in pressure is the one expressed by Equation 3.

$$\Delta p = \frac{F_1 - F_f - \frac{x}{2}(k_s + k_{sa})}{S_s} \quad (3)$$

For the purpose of measuring the parameters of the motion, it is required that the magneto-rheological fluid characteristics be known and that the fluid may be characterized as Bingham fluid. The manufacturing company is offering the physical properties, for the MRHCCS4-B magneto rheological fluid, as well as the characteristics of the variation of induction B (H) and of tension τ [Pa] according to the shear velocity $\dot{\gamma}$ [s^{-1}] at various temperatures.
From the linear zone of the characteristics induction- magnetic field intensity B(H), one may calculate the magnetic permeability coefficient of the magneto rheological fluid $\mu = \frac{B}{H}$.
By knowing the magnetic permeability in conditions of vacuum, there derives the magneto rheological fluid relative permeability $\mu_r = \frac{\mu}{\mu_0}$.
In the case of the coil that induces the magnetic field H applied to the magneto rheological fluid from the hydraulic resistance RH, the magnetic induction B is being calculated with the formula given by Equation 4.

$$B = \mu \frac{NI}{L} \quad (4)$$

WhereN is the number of spirals of the coil, I [A] is the electric current intensity, whereas *L* [m] is the length of the coil.
The displacementand the average velocity at the exit from bellow S_2 are obtained from the SPPD system that takes over and processes the data as shown in fig. 1. Once we've calculated the average velocity and the bellow transversal section S_s, the flow rate transiting the actuator is $Q= V_m S_s$
In processing the experimental data we've utilized the following values: D= *26 mm* - the average value of the diameters of bellows S_1 and S_2, the section of bellow S_s = *5.3 cm*^{2}, d = *2.5mm* - the diameter of hydraulic resistance*,* l= *0.14 m* - the length of hydraulic resistance, k_s = *1522* N/m - the elastic constants corresponding to bellows S_1 and S_2, k_a = *110 N/m* - the elastic constant of the spring load, k_{sa} = *103 N/m* - the equivalent elastic constant, L = *0.056 m* - the length of the coil, N = *1480* - the number of spirals of the coil, μ = *5 10^{-6} Tm/A* - the magnetic permeability, μ_0 = *4π 10^{-7} Tm/A* - the magnetic permeability of vacuum, μ_r= *3.9*- the relative magnetic permeability, F_f *= 0.6 N* - the sum of friction forces.
The experimental measurements were made for six values of the applied external force, F_1= *5 N; 10 N; 15 N; 20 N; 25 N; 30 N*. For each value of force, by adjusting the tension Usupplied to the coil, distinct magnetic fields were obtained, for which there correspond values of the magnetic induction B, as seen in table 1.

Table 1: Magnetic induction related to tension supplied to the coil

U [V]	0	1	2	3	4	5	6	7	8	9	10	15	20
B [T]	0	0.017	0.033	0.055	0.075	0.094	0.114	0.132	0.151	0.170	0.193	0.288	0.383

3. Experimental results

Figures 2, 3 and 4 are presenting the characteristics of the variation of mean velocity $V_s(B)$,of the variation of the difference in pressure *Δp(Q)* and of the variation of the distance of travel x(B)for different values of applied external force F_1 = constant, at the output of the actuator.

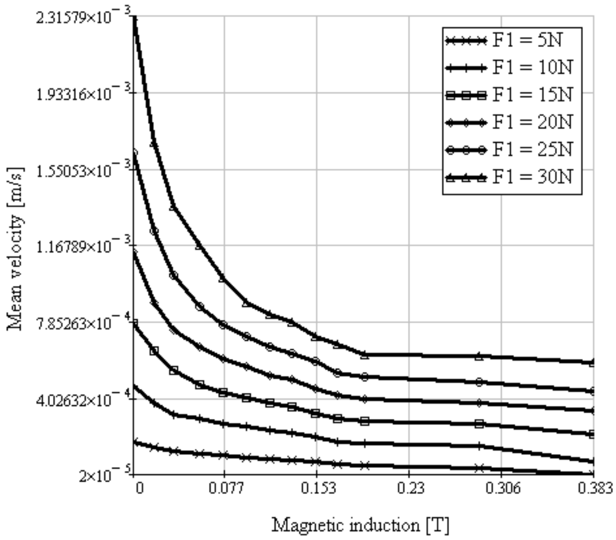

Fig. 2. The variation of the axial deformation speed for bellow S_2 according to the magnetic induction B

By analyzing the mean velocity $V_s(B)$characteristics of variation (Figure 2), at the actuator output, and according to the applied force F_1, we've observed:

- at the actuator output, the velocity decreases according to the value of the magnetic field applied, for F_1 = constant.
- The$V_s(B)$ characteristic, for F_1 = constant, is nonlinear.
- the velocity gradient according to the magnetic induction, for F_1 = constant, increases according to the value of the induction.

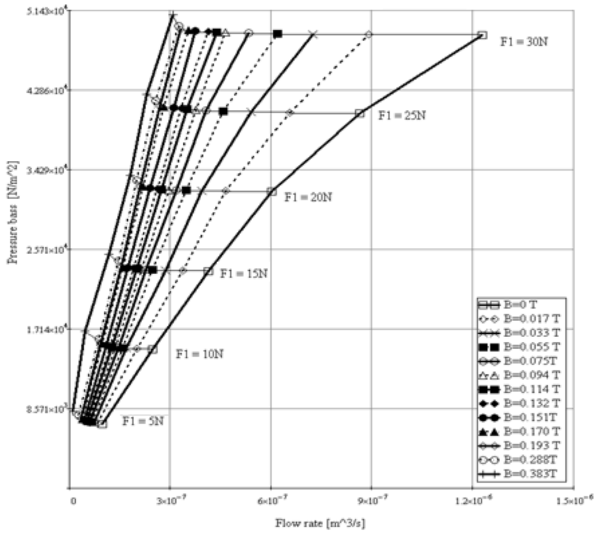

Fig. 3. The variation of pressure drop Δp according to flow rate Q

By analyzing the characteristics of the variation in pressure drop according to the flow rate Δp(Q) (Figure 3), for different values of the magnetic field Bit is established that:

- the loss of pressure increases according to the increase in flow rate.
- the loss of pressure, at the same flow rate, is greatest in elevated magnetic fields.

- the gradient of the increase in pressure loss according to the velocity is increasing according to the values of the applied magnetic field.

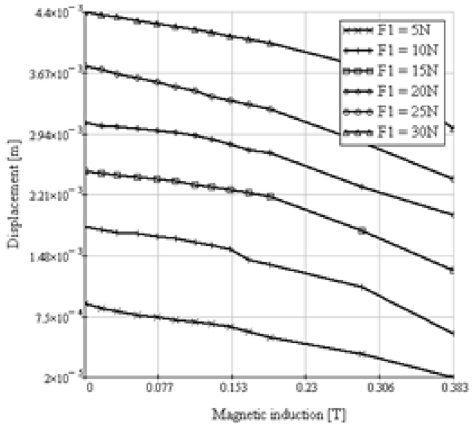

Fig. 4. The variation of axial deformation x according to magnetic induction B

By analyzing the characteristics of the variation of the displacement at the actuator output x(B) (Figure 4), it is established that:
- the displacement xincreases according to the value of the applied force for B = constant.
- the increase in the magnetic field applied is conducive to a reduction in the displacement xfor applied force F_1 = constant.
- for an applied force F_1 = constant, and through the variation in the intensity of the magnetic field one may gain control over the displacement, and a control of the positioning at the actuator output.

4. Technical application

A possible application for making use of the studied actuator is controlling the displacement of the drawer of a hydraulic distributor by varying the tension Usupplied to the coil, and of the induction B, respectively. One may obtain controlled openings of the slot the distributor. One may therefore adjust the flow and the velocity of the hydraulic working part.
The testing of the actuator was carried out on an experimental stand whose schematic principle diagram is presented in figure 5. The actuator 3 was commanding the opening of the hydraulic distributor 2 and the supply flow rate of the hydraulic rotating motor 4, at whose exiting the rpm should be *n*, interpreted by the transducer 5. The value of force F_1 applied at the actuator input was decided based on analysing the experimental characteristics x(B) - Figure 4. For the value F_1= *20 [N],* one is able to control the value of the displacement up to $3\ 10^{-3}$ *[m],* value that covers the maximum displacement of the distributor's piston.

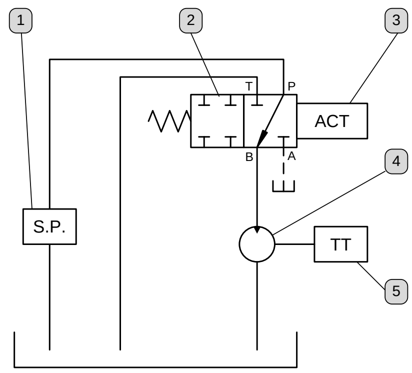

Fig. 5. The hydraulic scheme of the experimental stand

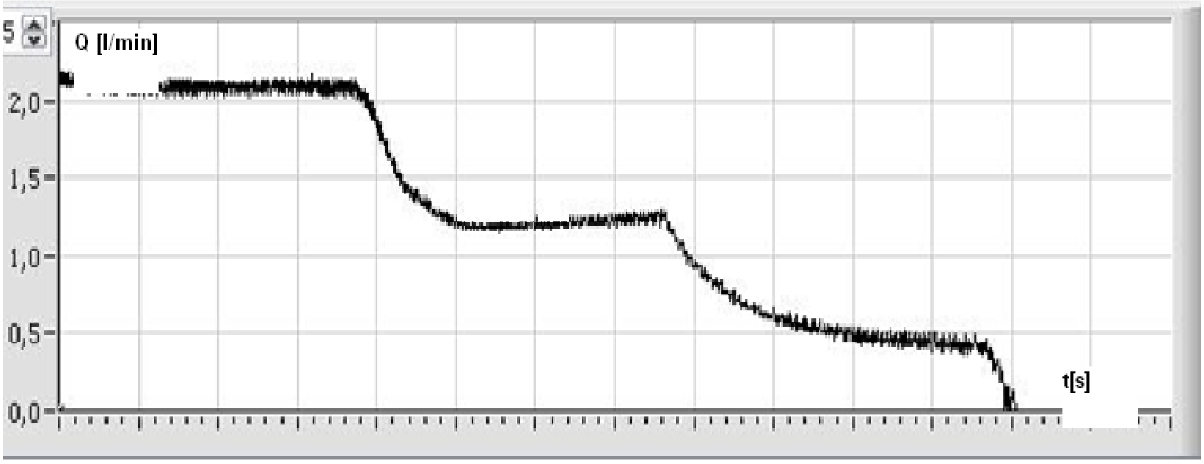

Fig. 6. The step response Q(t).

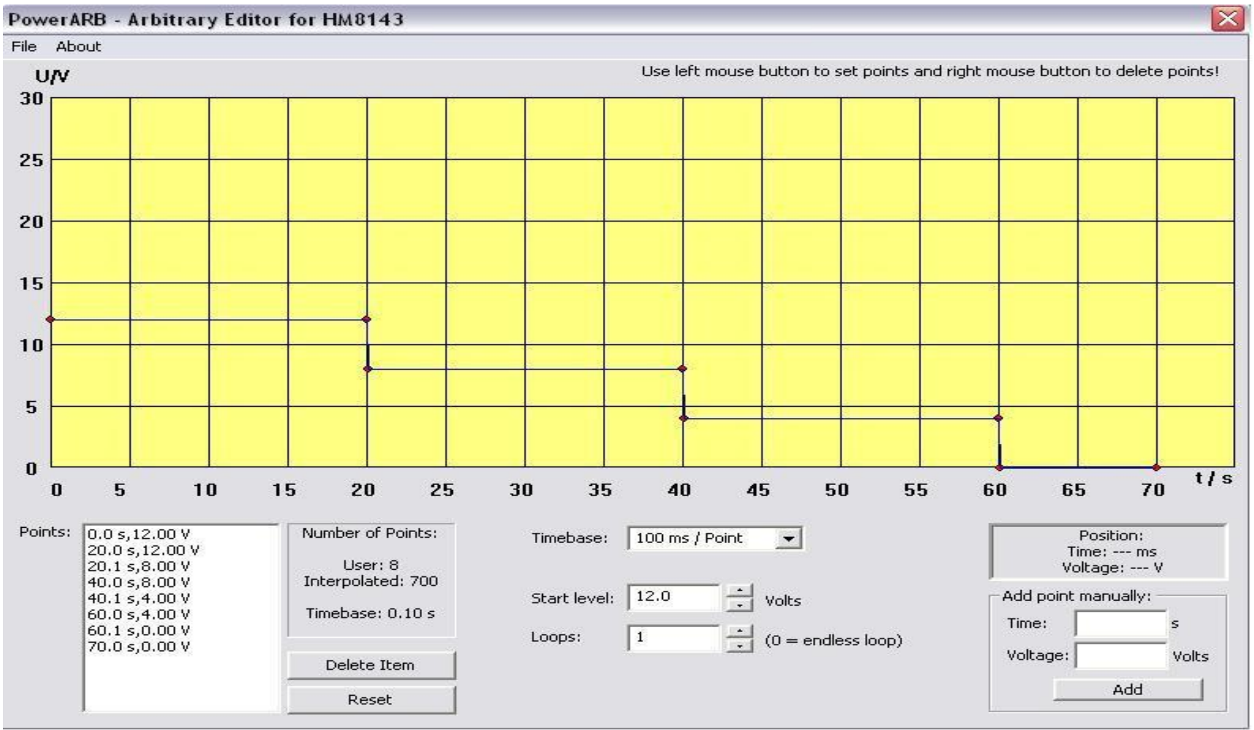

Fig. 7. The system response due to the variation in power supply for an applied force F_1 = 20 [N], at the time the piston of the distributor is executing a closing movement.

The system is dynamically stable. The step responses are non-periodical.

5. Conclusions

The proposed actuator version is a watertight design, simple and reliable, that does not require additional internal sealing components compatible to the magnetic-rheological fluid.

The actuator does not comprise mechanical components in relative motion, thus removing any corresponding friction and therefore reducing wear.

By analysing the experimental results there derives that the drive element of a linear actuator type, using magnetic-rheological fluid, is easily exerting control of kinematic and mechanical parameters (velocity, force), by utilizing the external applied magnetic field.

The actuator is capable of electrically controlling through a non-contact method and allows for precise positioning of the driven element.

The actuator-based technical application using magnetic-rheological fluid is a dynamically stable system.
The use of different diameter bellows may extend the actuator's control capabilities.

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