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CONTENTS OF NO 22/2009

1. APPLICATION OF A REMOTE SENSING METHOD BY ENVIRONMENTAL PROTECTED MANURE UTILIZATION L. FENYVESI – Sz. KÉSMÁRKI Hungarian Institute of Agricultural Engineering, Gödöllő <i>Lector: László MAGÓ</i>	5
2. DETERMINATION OF DROPLET SIZE DISTRIBUTIONS OF STANDARD AND DRIFT GUARD NOZZLES István SZTACHÓ-PEKÁRY Kecskemét College, Faculty of Horticulture <i>Lector: Péter SZENDRŐ</i>	10
3. SOME OF THE POSSIBILITIES OF REDUCING PESTICIDES BY APPLYING SPRAY TECHNICS Dr.habil KALMÁR Imre PhD – Dr. KALMÁRNÉ Dr. VASS Eszter – NAGY Valéria University College of Szolnok Technical and Agricultural Faculty.....	13
4. CORN PHYSICAL PROPERTIES DURING POSTHARVEST HANDLING Jenő CSERMELY – Mihály HERDOVICS – Attila CSATÁR – József DEÁKVARI Hungarian Institute of Agricultural Engineering (MGI) <i>Lector: László FENYVESI</i>	16
5. ENERGETIC ANALYSIS OF TUBERS DRYING János BEKE Faculty of Mechanical Engineering, Szent István University Gödöllő <i>Lector: Aníal LENGYEL</i>	19
6. COMMINUTION OF CEREAL FEED COMPONENTS – NEW TECHNOLOGICAL FACILITIES P. KORZENSZKY ¹ , L. FOGARASI ² ¹ Department of Measurement Technology, Institute of Process Engineering, Faculty of Mechanical Engineering, Szent István University, Gödöllő ² Dept. of Machines for Agriculture and Food Industry, Institute of Mechanics and Machinery, Faculty of Mechanical Engineering, Szent István University, Gödöllő <i>Lector: Károly PETRÓCZKI</i>	22
7. EVALUATION OF CHANGES IN CONSTRUCTION MATERIALS USED IN COLD STORAGE SYSTEMS FOR APPLES IN TURKEY, WITH REGARD TO ENERGY SAVING H. I. Yilmaz ¹ , H. B. Unal ¹ and R. C. Akdeniz ² ¹ Department of Agricultural Structures and Irrigation, Ege University Bornova., Turkey ² Department of Agricultural Machinery, Ege University Bornova., Turkey.....	26
8. MECHANISATION OF FRESH MARKET APPLE PRODUCTION BASED ON A SPECIAL TRELLIS Zoltán LÁNG, Sándor KURTÁN, Sándor NAGY, Kálmán SERLEGI, Botond SINÓROS-SZABÓ Technical Department, Faculty of Horticultural Sciences, Corvinus University of Budapest <i>Lector: István SZTACHÓ-PEKÁRY</i>	31
9. RESEARCH OF TRACTION FORCE DURING THE TRACTORS POWER SHIFTING A. LENGYEL – A. SZEGEDI College of Nyíregyháza Faculty of Engineering and Agriculture Department of Vehicle and Agricultural Engineering <i>Lector: Péter KISS</i>	34
10. COMBINATION OF SENSOR NETWORKS AND MOBILE ROBOTS TECHNOLOGIES FOR EFFECTIVE MONITORING (SYNERGY2009) CONFERENCE, GÖDÖLLŐ, HUNGARY Z. BLAHUNKA ¹ , P. ILOSVAI ¹ ¹ Systems Engineering and Management Institute, Szent István University, Gödöllő <i>Lector: Dezső FAUST</i>	37
11. STATIC AND DYNAMIC COMPRESSIVE TESTING INSTRUMENT FOR BIOLOGICAL MATERIALS K. PETRÓCZKI Department of Metrology Institute of Process Engineering, Szent István University, Gödöllő <i>Lector: Péter SEMBERY</i>	41
12. A COMPARATIVE STUDY OF METHODS USED FOR TESTING TOWED VEHICLES László GURMAI Szent István University – Faculty of Mechanical Engineering – Institute of Process Engineering – Department of Automotive Technology, Gödöllő.....	46
13. NEW MATHEMATICAL MODEL FOR PNEUMATIC ARTIFICIAL MUSCLES József SÁROSI ¹ , Tamás SZÉPE ² , János GYEVIKI ³ ¹ Department of Technical and Process Engineering, Faculty of Engineering, University of Szeged ² Department of Computer Algorithms and Artificial Intelligence, Faculty of Science and Informatics, University of Szeged ³ Department of Technical and Process Engineering, Faculty of Engineering, University of Szeged <i>Lector: István BÍRÓ</i>	49
14. DESIGNING AND MANUFACTURING A MECHATRONIC POWER TRANSMISSION FOR AN AUTOMATIC GUIDING FIELD VEHICLE M. R. Khadem ¹ , M. Khadem ² R. Mohamadi Kaleibar ³ ^{1,3} Mechanical Engineering Dept., Shiraz Islamic Azad University, Gha'ani St., Shiraz, ² Mechanical Engineering Dept., Shiraz University, Molla Sadra, Shiraz.....	53
15. DETERMINATION OF THE COST OF MECHANISATION OF FIELD VEGETABLE PRODUCTION TECHNOLOGIES László MAGÓ Hungarian Institute of Agricultural Engineering Gödöllő <i>Lector: István HUSTI</i>	56
16. PYROLYTIC CHAR IN CLIMATE MITIGATION AND SOIL IMPROVEMENT: POSSIBLE TECHNICAL AND ECONOMICAL SCENARIOS TO UTILIZE BIOMASS IN HUNGARY ¹ Zsolt GEMESI, ² Csaba FOGARASSY, ³ Akos LUKACS, ⁴ Gabor HOLLO, ⁵ Richard MCRUSE,	

¹PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, Godollo, associate of the RFH, Regional Development Holding, Budapest

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⁵Professor, Iowa State University, Department of Agronomy, Ames, IA, USA

Lector: *Ferenc LIGETVÁRI*60

17. THE ECONOMICS OF WOODTRANSPORT DISTANCE TEST

Katalin SZAKÁLOS – MÁTYÁS

Institute of Forest- and Environmental Techniques
University of West Hungary, Faculty of Forestry

Lector: *Béla HORVÁTH*64

18. PARTICLE SIZE DISTRIBUTION OF SOME BIOMASS GRINDS CHOPPED WITH A MANUAL STRAW CHOPPER

A. HUSSEIN and L. NOZDROVICKÝ

Department of machines and production systems,
Faculty of engineering,

Slovak agriculture university in Nitra. Slovak Republic. 67

19. ENVIRONMENTAL IMPACTS OF WIND POWER PLANTS IN TECHNOLOGICAL ASPECTS, NOISE AND SHADOW IMPACTS, AND PHOTOMONTAGE

L. TÓTH, N. SCHREMPF, A. KONCZ

Department of Energetics, Szent István University,
Faculty of Mechanical Engineering, Gödöllő.....70

20. THE MAXIMUM TECHNOLOGICAL ENERGY INPUT PRINCIPLE IN THE PLANT PRODUCTION

M. NEMÉNYI

Institute of Biosystems Engineering,

University of West Hungary.....74

21. EXTENDED POSSIBILITIES OF USING WASTE HEAT FROM BIOGAS PLANTS THROUGH COOLING WITH ABSORPTION TECHNIQUE-RESULTS OF PILOT PLANTS AND ANALYSIS OF GREENHOUSE (CLIMATE HARMFUL) GAS EMISSIONS

Erweiterte Möglichkeiten der Abwärmenutzung aus Biogasanlagen durch Kühlung mit Absorptionskälte – Ergebnisse aus Pilotbetrieben und Analyse von klimarelevanten Gasemissionen

Dr. Günter BEYERSDORFER,

Thüringer Landesanstalt für Landwirtschaft Jena
Mattias PILZ,

Landesanstalt für Umwelt und Geologie

07745 Jena77

22. BIOGAS PRODUCTION POSSIBILITIES AND TECHNOLOGICAL BACKGROUND (MANURE AND CARBON MANAGEMENT) IN THE HUNGARIAN ANIMAL HUSBANDRY

¹Attila KOVACS, ²Maria BOROCZ,

³Csaba FOGARASSY, ⁴R. HALASZ

¹Assistant Professor of School of Economics and Social Sciences, SZIE, Godollo

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⁴PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, Godollo

Lector: *Ferenc LIGETVÁRI*80

23. POSSIBILITIES TO ESTABLISH BIOGAS PLANTS IN THE NORTHERN GREAT PLAIN REGION, BASED ON CATTLE AND PIG MANURE*

Gábor GRASSELLI, Tímea GÁL, János SZENDREI

University of Debrecen, Centre for Agricultural Sciences and Engineering

Lector: *Attila BAL*85

24. PROFESSIONAL AND TRAINING NEEDS IN THE AREA OF HYBRID POWER SYSTEM – ALTERNATIVE ENERGY CONDITIONS OVERVIEW IN HUNGARY TO IDENTIFY THE VOCATIONAL TRAINING PRIORITIES AND INFORMATION CONTENT LEVELS

¹Csaba FOGARASSY, ²Akos LUKACS,

³Zsolt GEMESI

¹Associate Professor of School of Economics and Social Sciences, SZIE, head of research group, Godollo

²PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, Godollo, Climate Advocate of the British Council, Budapest

³PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, Godollo, associate of the RFH, Regional Development Holding, Budapest

Lector: *Ferenc LIGETVÁRI*88

25. THE IMPACT OF WEATHER CONDITIONS ON THE PARAMETERS OF LANDFILL GAS PRODUCTION

Tamás MOLNÁR

University of Szeged, Faculty of Agriculture, Animal Nutrition and Engineering Institute, Hódmezővásárhely

Lector: *István BARÓTFI*91

26. TECHNICAL DESCRIPTION OF THE CO² REDUCTION PROGRAMMES – PROJECT DESIGN DOCUMENT (PDD) PREPARATION IN THE CASE OF VOLUNTARY CARBON EMISSIONS REDUCTIONS

¹Akos LUKÁCS, ²Zsolt GÉMESI, ³Gábor HOLLÓ,

¹PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, Climate Advocate of the British Council.

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³PhD. Student of the Doctoral School of Economics and Business Administration of SZIE, associate of the FVM, Ministry of Agriculture and Rural Development.

Lector: *Ferenc LIGETVÁRI*95

27. COFERMENTATION OF ORGANIC WASTE OF THE PILOT FARM OF SZTE MGK

László SALLAI

SZTE MGK, Science of animal nutrition and agricultural engineering Institute, Hódmezővásárhely

Lector: Dezső FODOR98

28. HEATING OF MULTI SPAN GREENHOUSES, UTILIZING POWER PLANTS' LOW TEMPERATURE COOLING WATER

Viktor MADÁR¹, Endre JUDÁK²

¹Termo Energo System Ltd, ²Szent István University, Faculty of Mechanical Engineering, Gödöllő.....102



NEW MATHEMATICAL MODEL FOR PNEUMATIC ARTIFICIAL MUSCLES

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Abstract

There are several types of pneumatic actuators in industrial environment. The newest and most promising is the pneumatic artificial muscle (PAM).

Many researchers have investigated the behaviour of PAM and some of them have introduced different mathematical models for this actuator. However, we have noticed significant differences between the theoretical and experimental results.

This paper presents our new mathematical model of PAM, comparing with measured and literary data.

Objective

Pneumatic artificial muscle is an actuator, which converts pneumatic energy into mechanical form by transferring the

pressure applied on the inner surface of its bladder into the shortening tension. PAMs' source of energy comes from pressurized gas, usually air. The principle of pneumatic artificial muscle is well described in [1] and [2].

There are a lot of advantages of artificial muscles like the high strength, good power-weight ratio, low price, little maintenance needed, great compliance, compactness, inherent safety and usage in rough environments. The main disadvantage of these muscles is that their dynamic behaviour is highly nonlinear ([3], [4] and [5]).

There exists several types of artificial muscles that are based on the use of rubber or some similar elastic materials, such as the McKibben muscle, the Rubbertuator made by Bridgestone company, Air Muscle made by Shadow Robot company, Fluid Muscle made by Festo company, Pleated PAM developed by Vrije University of Brussel, ROMAC (RObotic Muscle ACtuator), Yarlott and Kukulj PAM and some others ([5] and [6]).

The PAM that was selected as the actuator for our study is the Fluidic Muscle (DMSP-10-250N-RM-RM ($d_0 = 10$ mm, $l_0 = 250$ mm, see Fig. 2)) manufactured by Festo. (We have investigated type DMSP-20-200N-RM-RM ($d_0 = 20$ mm, $l_0 = 200$ mm) in [7]).

Methods and materials

A good description of our test-bed (Fig. 1) and experimental results can be found in [8].

With the specially constructed testing machine, we are able to measure the static and dynamic characteristics of several versions of these pneumatic actuators.

The general behaviour of PAM with regard to shape, contraction and tensile force when inflated depends on the geometry of the inner elastic part and of the braid at rest (Fig. 2), and on the materials used ([6]). Typical materials used for the membrane construction are latex and silicone rubber, while nylon is normally used in the fibres.

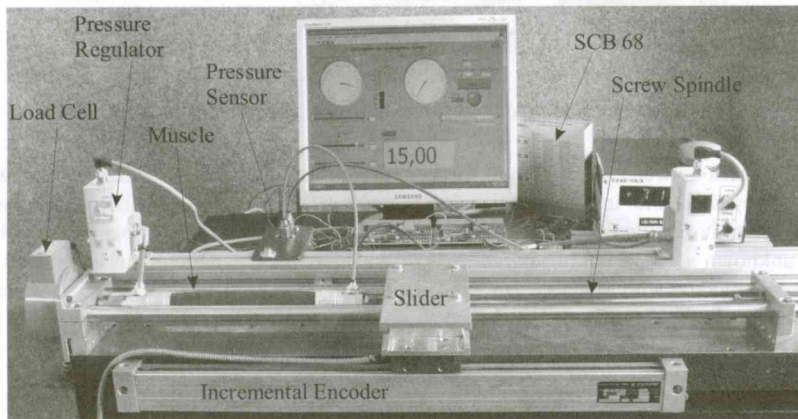


Figure 1. Experimental set-up for analysis of the pneumatic artificial muscle (fixed slider position)

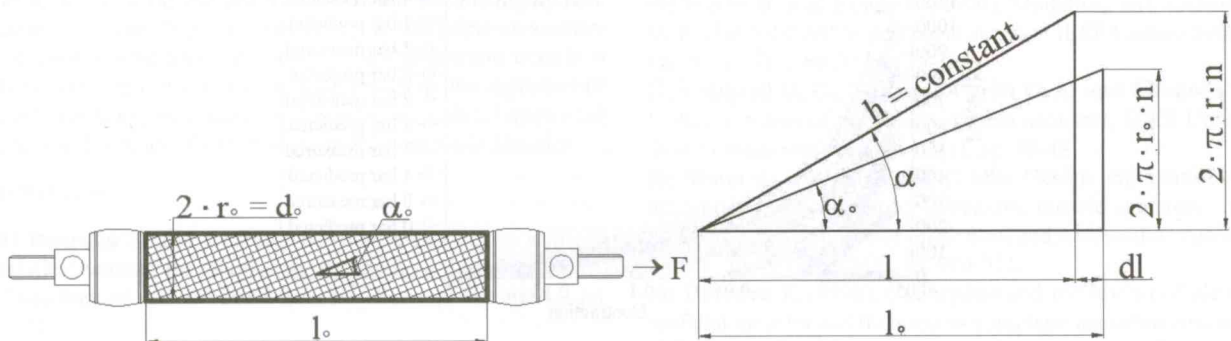


Figure 2. Geometry parameters of PAM

With the help of [3], [9] and Fig. 2, the force can be calculated:

$$\cos\alpha_0 = \frac{l_0}{h} \text{ and } \cos\alpha = \frac{l}{h} \cdot \frac{1}{l_0} = \frac{\cos\alpha_0}{\cos\alpha_0} \quad (1)$$

$$\sin\alpha_0 = \frac{2 \cdot \pi \cdot r_0 \cdot n}{h} \text{ and } \sin\alpha = \frac{2 \cdot \pi \cdot r \cdot n}{h} \cdot \frac{r}{r_0} = \frac{\sin\alpha_0}{\sin\alpha_0} \quad (2)$$

$$\frac{dr}{dl} = \frac{r_0}{\sin\alpha_0} \cdot \frac{1 \cdot \cos^2\alpha_0}{l_0^2} \cdot \frac{1}{\sqrt{1 - \cos\alpha_0 \cdot \frac{1}{l_0}}} \quad (3)$$

$$F = 2 \cdot \pi \cdot p \cdot r \cdot l \cdot \frac{dr}{dl} - p \cdot \pi \cdot r^2 \quad (4)$$

$$F = \pi \cdot p \cdot r_0^2 \cdot \frac{3}{\text{tg}^2\alpha_0} \cdot \frac{l^2}{l_0^2} \cdot \frac{1}{\sin^2\alpha_0} = \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1 - \kappa)^2 - b) \quad (5)$$

with $a = \frac{3}{\text{tg}^2\alpha_0}$, $\frac{1}{\sin^2\alpha_0}$, $\kappa = \frac{l_0 - l}{l_0}$ and $0 : \kappa : \kappa_{\max}$

F the pulling force, p the applied pressure, r_0 , l_0 , α_0 the initial inner radius and length of the PAM and the initial angle between the thread and the muscle long axis, r, l, α the inner radius and

length of the PAM and angle between the thread and the muscle long axis when the muscle is contracted, h the constant thread length, n the number of turns of thread and κ the contraction.

Tondu and Lopez in [3] recommend that to complete this initial approximation with a correction factor (ϵ), on the one hand, equation 5 does not pay attention to the material that the muscle is made of, on the other hand, it predicts for various pressures the same maximal contraction. This new equation is relatively good for higher pressure ($p \geq 2$ bar). Kerscher et al. in [9] suggest achieving similar approximation for smaller pressure another correction factor (μ) is needed, so the modified equation is:

$$F(p, \kappa) = \mu \cdot \pi \cdot p \cdot r_0^2 \cdot (a \cdot (1 - \epsilon \cdot \kappa)^2 - b) \quad (6)$$

with $\epsilon = a_\epsilon \cdot e^{-p} - b_\epsilon$ and $\mu = a_\kappa \cdot e^{-\kappa 40} - b_\kappa$

Result and discussion

Matlab is common software for modelling, simulating and analyzing. First of all, on the basis of equation 5 we compared the measured data and the force model in Matlab. The results are shown in Fig. 3.

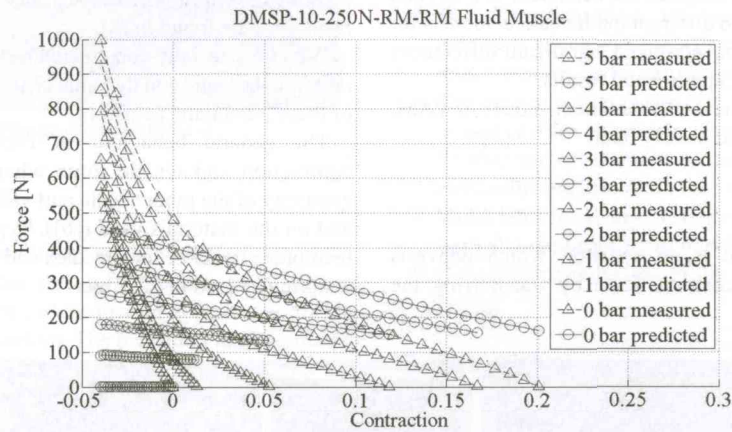


Figure 3. Measured and predicted force (equation 5) under different pressures

We noticed decided differences between experimental force and model. Secondly, we repeated the investigation using equation 6. The results of equation 6 and measured data can be compared in Fig. 4. The unknown a_ϵ , b_ϵ , a_κ and b_κ parameters were found using least squares method with Matlab.

Next, with regard to the significant differences between the

theoretical and experimental results we have improved this method. A better approximation can be generated with normalized parameters using a new expanded search in Matlab. In this case each unknown parameter has an initial scaling factor to ease the search. This model calculates the correct force for almost every pressure ($p > 0$ bar) (Fig. 5).

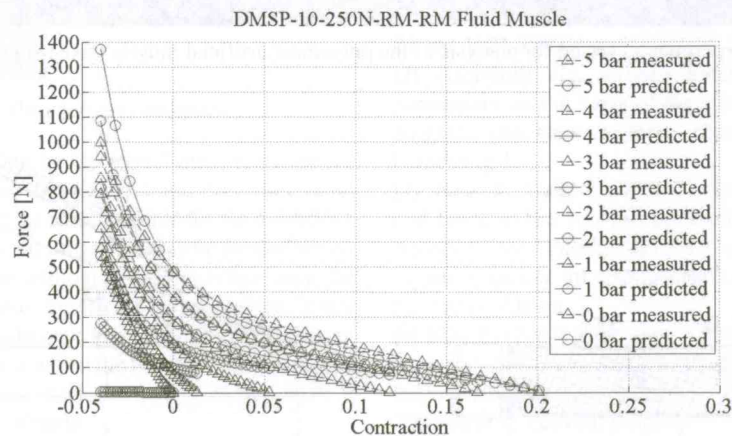


Figure 4. Measured and predicted force (equation 6) under different pressures

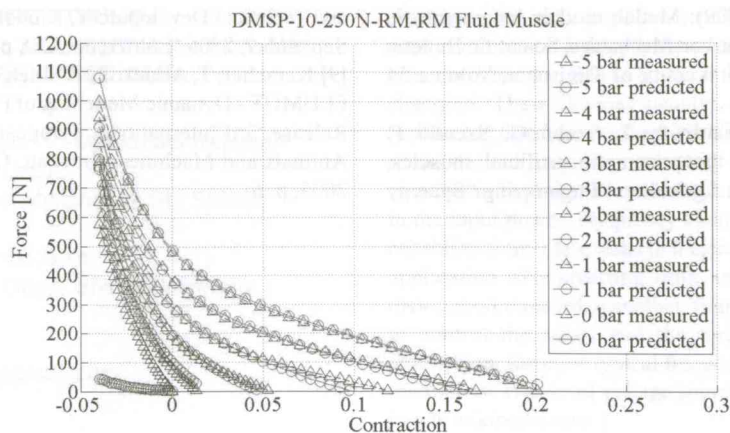


Figure 5. Measured and predicted force (equation 6 by expanded search) under different pressures

Finally, to obtain the best approximation algorithm for the equation of force to reduce the differences between the theoretical and experimental results we have worked out a new mathematical model for Fluid Muscles. Under fixed pressure the contraction to force function can be approximated with a general exponential function with first order correction polynomials of contraction (equation 7):

$$F(\kappa) = a \cdot e^{(b \cdot \kappa + c)} + d \cdot \kappa + e \quad (7)$$

In order to further generalize equation 7 to attain pressure dependency, variables need to be replaced with first-order polynomials of pressure.

$$F(p, \kappa) = (a \cdot p + b) \cdot e^{(c \cdot \kappa + d)} + (e \cdot p + f) \cdot \kappa + g \cdot p + h \quad (8)$$

The unknown a, b, c, d, e, f, g and h parameters were found using least squares method in Matlab. The results of equation 8 and measured data can be compared in Fig. 6. Our new equation predicts the correct force for various pressures and contractions.

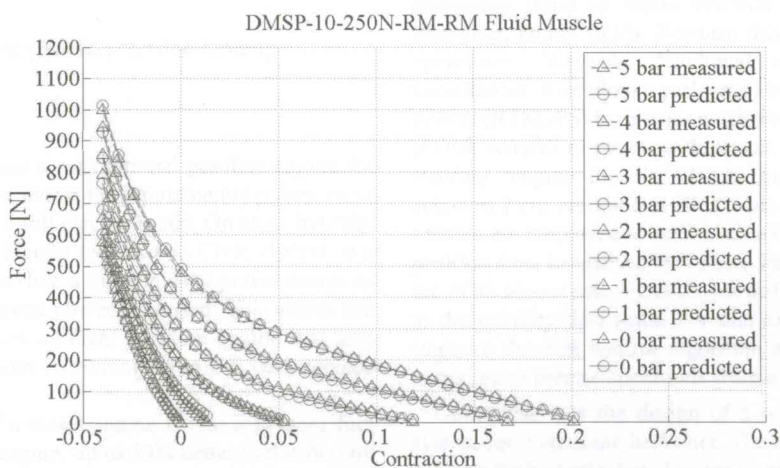


Figure 6. Measured and predicted force (equation 8) under different pressures

Conclusions and future work

Designing an adequate control mechanism for this highly non-linear system needs precise modelling. In this paper an accurate and simple mathematical model of the pneumatic muscle is shown. The agreement of simulation results on the experimental results confirms the viability of the proposed model. Future work is to test this model for hysteresis of different Fluid Muscles.

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