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Study on Mechanical Behaviour of Pneumatic Artificial Muscle and Methods to Improve it

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ABSTRACT

Pneumatic Artificial Muscle (PAM) is an actuator which gets charged and discharged when filled with air.As it is made up of thin rubber tube covered by braided mesh shell,it is very light weighted.It is so soft that it can replace a defective muscle.It has high force to weight ratio, flexible structure, minimum compressed air consumption and low cost.Along with the bio- medical field,these all advantages extend the application of PAM to robotics.Apart from these properties, PAM has a highly non-linear behaviour.This limits the application of PAM.In this paper, we are going to study the mechanical behaviour of PAM and even its mathematical modelling to study the behavourial analysis of PAM.This paper also deals with a method for suppression of erroneous temperature increase in the PAM.

***Keywords:** E-GaIn, Kevlar, Pneumatic Articial Muscle, pressure, stiffness, temperature*

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1. INTRODUCTION

PAMs are devices which contract or extend when operated by pressurized air filling a pneumatic bladder.PAMs were first develped by McKibben in 1950s in order to utilize in artificial limbs.PAMs are very lightweight because they are made up of thin membrane.This permits them to be directly connected to the structure they power which is benificial when used for the replacement of a defective muscle.

Another advantage of PAM is their inherent compliant behaviour when a force is exerted on it, it 'gives in',without increasing the force in actuation.This characteristic plays a vital role when PAM is used in a robot which is connected to a human or when delicate operations have to be performed.The loose weave nature of the outer fiber shell also permits PAM to be flexible and to replicate biological systems.

The PAM has various advantages over conventional pneumatic actuator such as high force to weight ratio,variable installation possibilities,no mechanical wear, minimal compressed air consumption, size availability and strong reliability for human use. As the size of PAM is relatively small it consumes minimum compressed air.Hence PAM produces large pulling forces with the least amount of compressed air consumption.They respond quickly.When they are completely stretched they generate an incredible force.Due to their flexible material they are permantely cushioned while extending and are self damping while contracting.

Along with these advantages they posses certain disadvantages.PAM exhibits highly non-linear characteristics due to compressibility of air,inherent properties of elastic-viscous material and geometric behaviors of the PAM shell.As the fluidity of air at the end is less while charging and discharging of compressed air,the temperature at the end increases.They pose a particularly difficult control problem.When measurements devices are used (for eg:measurement of diameter or the length) ,the whole system becomes complicated and heavy.Hence we are going to study measures taken to eliminate the disadvantages.

Fig-1:Extended and contracted air muscle [5]

2. MECHANICAL BEHAVIOUR OF PAM

When the PAM is supplied with compressed air at the inlet port, the internal bladder increases its volume in contrast to the braided mesh shell.The threads of the braided mesh which are non-extensible cause the actuator to shorten and produce pulling forces if it is connected with the load.This means that as the inlet pressure increases the length decreases but the diameter increases.When the air pressure withinn the PAM changes from low pressure to higher pressure,it contracts until it reaches its new equilibrium length.The maximum contraction length is called as the unstretched length.This unstretched length changes according to the air pressure.When a pulling force is applied (keeping the pressure constant), the contracted PAM tends to increase its length according to the pulling force F, with which it is exerted.This is the instantaneous length. So the stretched length is defined as the length difference between the instantaneous length and the unstretched length.The pulling force balances the elastic force.It is obsereved that non linearity takes place due to hysteresis at various air pressure.As the unstretched length at low pressures is longer,the stretched length at lower pressure is shorter than the stretched length at higher pressure. [1]

From this behaviour we can make out that PAM behaves in a similar way to a mechanical spring whether it is driven by pulling forces or without it.But the stiffness of the spring system is constant and it is dependent upon the material properties and the geometry of the spring.Whereas the stiffness of the PAM is a variable parameter and it depends upon material properties,geometry as well as the operating air pressure within the PAM. [1]

Larger diameter PAM is usefull for the higher force application rather than small diameter with the same length. In case of compact applications small diameter PAMs can be utilized.By controlling the compressed air the stiffness parameter of the PAM can be adjusted in order to handle the pulling force for a given length of the PAM. We can regulate the dynamic behavior of PAM by knowing this information. [1]

3.MATHEMATICAL MODELLING OF PAM

As mentioned above the behavior of PAM is depent on the material properties.Experiment was performed and static and dynamical characteristics were measured

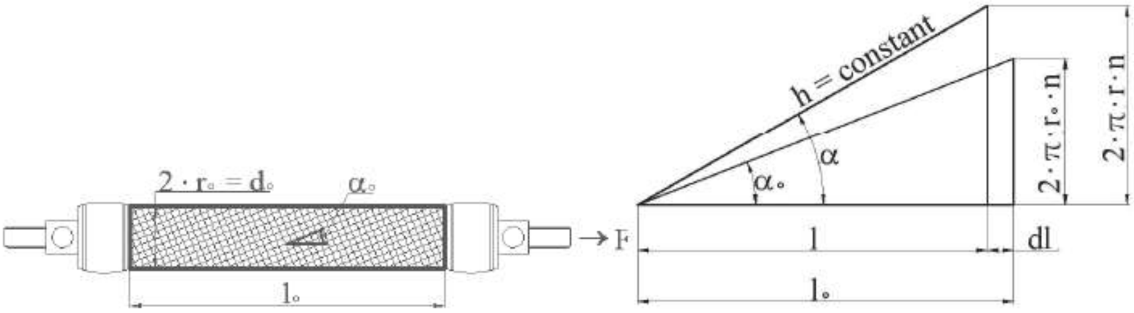

Fig 2:Geometric parameters of PAM [7]

The Fig 2 shows the geometric parameters of PAM.
F-pulling force
p-applied pressure
r_0,l_0,α_0-initial inner radius, length of the PAM, the initial angle between the thread and the muscle long axis
r,l,α-inner radius,length of the PAM, angle between the thread and the muscle long axis when the muscle is contracted
h - constant thread length
n - number of turns of thread
k- contraction

With the help of the figure force can be calculated as
$\cos\alpha_0=l_0/h$, $\cos\alpha=l/h$, $l/l_0=\cos\alpha/\cos\alpha_0$
$\sin\alpha_0=2*\pi*r_0*n/h$, $\sin\alpha=2*\pi*r*n/h$, $r/r_0=\sin\alpha/\sin\alpha_0$
$dr/dl=(-r_0/\sin\alpha_0)*(l*\cos^2\alpha_0/l_0{}^2)*(1/(1-\cos\alpha_0*l^2/l_0)\wedge^{1/2})$
$F=2*\pi*p*r*l*dr/dl-p*\pi*r^2$
$F=\pi*p*r_0{}^2*(3/t*g^2*\alpha_0)*(l^2/l_0{}^2)-(1/\sin^2\alpha_0)$
$F= \pi*p*r_0{}^2*(a(1-k)^2-b)$ (1)
where, $a=3/t*g^2*\alpha_0$,$b=1/\sin^2\alpha_0$, $k=(l_0-l)/l_0$

On the basis of the above equation graph of contraction against force was plotted in Matlab and the measured data and force model was compared.Differences were obsereved between the experimental force and the model.

Equation (1) does not consider the material of the muscle and it gives the same maximal contraction for various pressures.Later the factor μ was considered to complete this initial approximation.The new equation developed was good for higher pressures especially pressures greater than 2 bar .Thus the factor ε was introduced to consider the aproximation for smaller pressures [7]

The modified equation is

$$F(p,k)=\mu*\pi*p*r_0^2*(a(1-\varepsilon*k)^2-b) \qquad (2)$$

where $\varepsilon=a_\varepsilon*e^{-p}-b_\varepsilon$ and $\mu=a_k*e^{-40*k}-b_k$

The results of equation (2) and the measured data was compared.Using the least square method in Matlab the unknown parameters $a_\varepsilon,b_\varepsilon$,a_k,b_k were found.There was still difference in both the datas and the theoretical and experimental data could not match. A better approximation was 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 all pressures (p > 0 bar).Although the changes were made there was a little difference.[7]

To obtain the best results a new mahematical model was worked out.The contraction to force fuction was approximated with general exponential function with first order correction polynomials of contraction under fixed pressure.[7]

$$F(k)=a*e^{(b*k+c)}+d*k+e \qquad (3)$$

The equation (3) was further generalized to obtain the pressure dependency and variables were replaced with first order polynomes of pressure.

$$F(p,k)=(a*p+b)*e^{(c*k+d)}+(e*p+f)*k+g*p+h \qquad (4)$$

The unknown parameters a,b,c,d,e,f,g and h were found using least square method in Matlab.The theoretical data using the equation (4) and the experimental data was matched.Thus this new equation can predict the correct force for different pressures and contraction and hence a correct mathematical model is developed.[7]

4. A METHOD TO SUPPRESS THE TEMPERATURE INCREASE AT THE END OF PAM

As PAM is used in applications related to humans,the temperature rise at the end of the PAM can be proved to be dangerous.When PAM is inflated or deflated, compressed air is charged or discharged through the inlet of the PAM.When the PAM is supplied with air,it expands radially and contracts axially.The closed end is considered as the end part. The fluidity of air at the closed end is less.So when a PAM is pressurized repeatedly ,the temperature at the closed end increases rapidly.This temperature increase has a bad influence on properties such as continuous drive and on operating life of PAM.High temperatures can be dangerous as PAM systems are used in human contact applications.This occurs due to lack of convection at the end

This problem can be solved by installing a pipeline in the PAM.This pipeline made up of nylon which has thermal conductivity of 0.25.In order to support convection at the end,compressed air is charged or discharged through installed pipeline. Thus the temperature at the end part remains low. As a result, the temperature increase in the PAM is suppressed. [2]

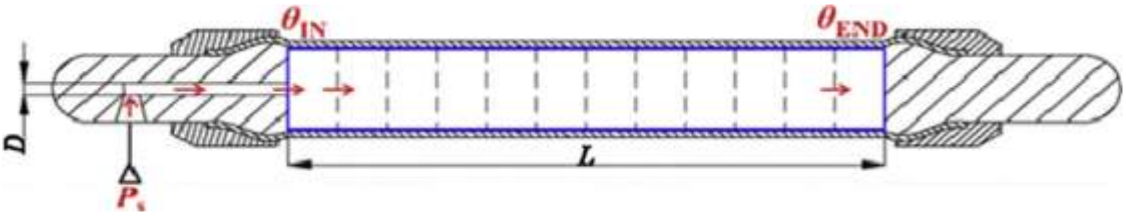

Fig-3: PAM Without pipeline [2]

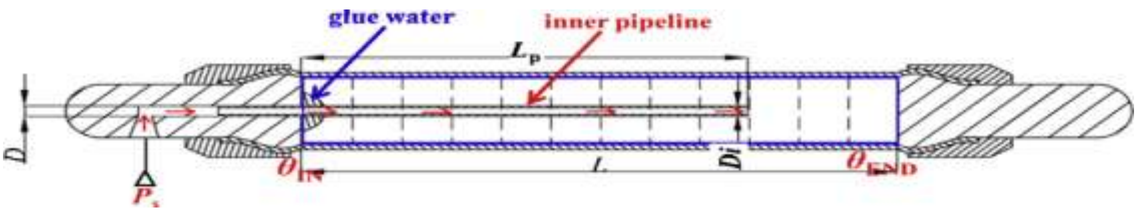

Fig-4: PAM with installed pipeline [2]

As compared with the temperature results without a pipeline, the temperature increase is reduced with a considerable amount.However,the temperature at the inlet part of the PAM with a pipeline increases than that without a pipeline.Although the temperature increases,it is still lower than the temperature at the end of the PAM without a pipeline.This happens due to diffusion of air at the inlet. [2]

If the diameter of the pipeline is kept same and increase the length,the temperature at the end decreases and at the inlet it increases.The temprature at the inlet increases because of lower air convection around the inlet. [2]

If the length is kept same and the diameter increases,the temperature at the end increases whereas the temperature at the inlet decreases.The temperature at the end increases because the flow velocity decreases which in turn reduces the convection of air. [2]

Thus by this method we can suppress the temperature increase effectively

5. PAM WITH EMBEDDED MICROFLUIDIC SENSING

Due to the non-linearity and usage of external measuremen device the PAM system becomes very complicated and heavy.Many times there is a need to measure the contraction length.Thus an alternative was found out to measure it i.e. by using hyperelastic train sensing with embedded microchannels filled with liquid conductor such as eutectic Gallium Indium(eGaIn).The structure is double layered elastomer tube.The inner layer consists of parallel Kevlar threads and the outer layer has helical microchannel filled with eGaIn as shown in the Fig 5. [4]

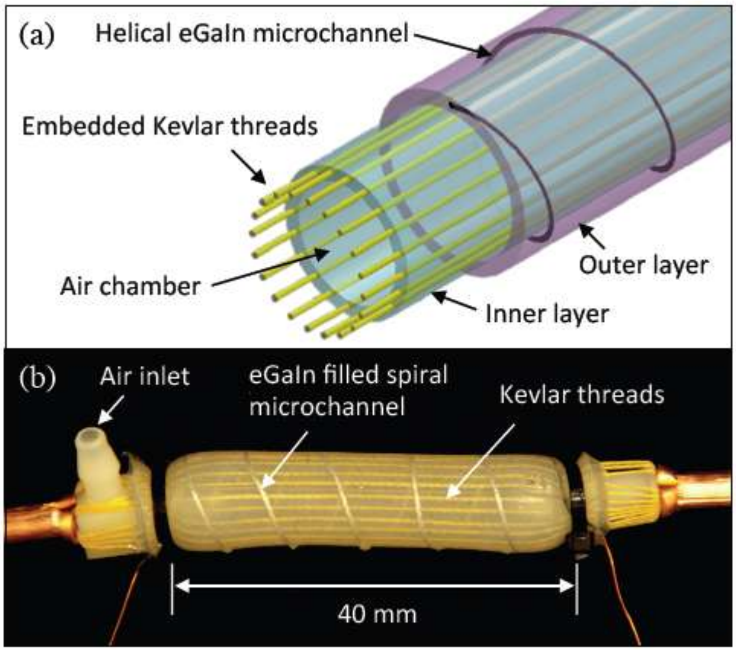

Fig-5: (a) Multi-layered elastomer tube design with embedded Kevlar threads and a helical microchannel (b) Complete prototype [4]

When the air is compressed into the air chamber the muscle expands in the radial direction and axial contraction is created by the Kevlar threads.The elongation of the microchannels is caused by the radial expansion of the muscle during axial contraction.This leads to increase in the electrical resistance of the microchannel.The contraction length can be determined due to change in the resistance of the microchannel.The shape change of the microchannel is dependent on the change in geometry of the whole tube because the microchannel is embedded outside of the Kevlar threads.Though the actuation behaviour was still non linear,the sensor characteristics revealed to be excellent.When the graph of contraction of the muscle against resistance change was plotted,it was highly linear and showed low hysteresis. [4]

Hence this method can be applied instead of external measuring devices

6. CONCLUSION

The uses of PAM has wide application due to its high force to weight ratio.If the changes mentioned above are made the PAM can be used in various fields.So far it is used mostly in the bio-medical application but its usage can be extended to robots in space program.It is used to develop exo-skeleton which can be helpful for the older population as it can carry a greater weight and reduce the burden.It can completely replace the limbs.It can also be used in the Army field as it has low weight.Thus the PAM has a promising future

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