CHAPTER 1

BACKGROUND OF STUDY

1.1 Background of Pneumatic Artificial Muscle:

According to Catalin CHIVU (2007) Pneumatic Artificial Muscle (PAM) was an actuator that used air pressure to operate. The use of this actuator is not really wide compare to pneumatic cylinder actuator. Pneumatically actuator artificial muscle represent a relatively recently developed and utilized element in the pneumatic drives of a mechanical system. A PAM is a system employing a contracting membrane that under the action of air pressure increases its diameter while decreasing its length. Researchers from the Orthopaedic Centre of Heidelberg in 1948, the pneumatically actuated arm developed by the American J.L. McKibben, the stepping robot WAP 1 developed by the Waseda University of Tokyo (1969) or pneumatic membranes built by the AI Research Centre of Karlsruhe, Germany (2002) [1]. Pneumatic muscles have been commercialized by the Bridgestone Rubber Company of Japan since 1980, and more recently, by the U.S. Shadow Robot Company and the FESTO Corporation of Germany.

1.2 Background of Thesis:

The thesis started on the first month of the year during the first semester. The thesis basically continues to the 2nd semester from the 1st semester. During the period the following are the objectives achieve: Able to Identify the literature review for the PAM and the theoretical Equation of the Pneumatic Artificial Muscle. Then, the PAM underwent construction of a model in ANSYS software as well as analysis using Finite Element Analysis.

The analysis of the PAM was move on to the ANSYS Software using Finite Element Structural analysis. A model in Ansys was constructed by using $L = 180\ mm$ and $D = 60mm$

1.3 Problem Statement:

1. The PAM is a nonlinear behavior of a spring itself. Thus, Finite Element Analysis (FEA) needs to be applied to meet the following assumption.
2. The material type property of neoprene rubber must be accurate in order to have the desired result of deformation.
3. The PAM supposed to have air pressure inserted into the neoprene rubber. So, a pressure was applied inner to the surface of the PAM.

1.4 Objective:

1. Analyze the behavior of Pneumatic Artificial Muscle.
2. Identify the criteria of material selection for Pneumatic Muscle Membrane.
3. Construct a model of Pneumatic Artificial muscle and then go through the analysis process using ANSYS software using Finite Element Analysis.

1.5 Scope of Study:

The thesis involves modeling in ANSYS software after choosing the material type for the membrane and undergoes Finite Element analysis. The analysis in ANSYS software is specific towards the deformation of the muscle and study the structure deformation itself.

CHAPTER 2

LITERATURE REVIEW

2.1 Concept and Operation

Pneumatic muscle is actuating elements that transform pneumatic energy into mechanical energy. A characterization of the behavior and the performances of these actuating elements entail both analytical calculations and thorough experimental research. In order to determine the functional characteristics of a pneumatic muscle, first it structure needs to be explored.

A pneumatic muscle includes an interior tube of various lengths made from elastic material, typically Silicone rubber or Neoprene rubber. This tube is wrapped in a multi-layer nylon fiber ensuring its strength and protection from the influence of working environment. The behavior of the pneumatic muscle is similar to that of a spring, meaning that for a completed maximum stroke the generated force is equal to zero. Pneumatic muscle usually operates at an overpressure: generating and supplying compressed gas is easier to accomplish and, with ambient pressure mostly at about 100kPa, a lot more energy can be conveyed by overpressure than by under pressure. Charging an overpressure, pneumatic muscle with pressurized gas enables it to move a load, discharging it, conversely, make yield to a load. [5]

From the latter property one can deduce the length to load relation. During a time interval dt energy is fed to the muscle, which is at a gauge pressure of $p = P - P_0$ relative to the ambient pressure, by forcing an infinitesimal mass dm of gas into it. Thereby, the membrane's volume increases by dV and a net amount of work

$$dW_m = p\, dV \qquad (1)$$

crosses its boundary (which is taken bordering the inside surface of the diaphragm, so it encompasses the gas inside the muscle but not the diaphragm itself). During the same period dt, the actuator's length changes by dl (< 0 for shortening) and a load F is displaced over the same distance, requiring an amount of work

$$dW_l = -F\,dl \qquad (2)$$

Also, the membrane's material is deformed, requiring dW_d. Estimating this depends on material behavior laws—e.g. elastic, plastic, visco-elastic. Disregarding work to deform the membrane and assuming quasi-static conditions, dW_l and dW_m equal out, leading to the fundamental expression of the ideal load to length relation: [5]

$$F = -p\frac{dV}{dl} \qquad (3)$$

In reality, however, dW_d cannot usually be disregarded and the developed force will have a lower value. Part of F is needed to compensate the inertia of the diaphragm's moving parts, but, as these have a very low mass, this is negligible. Eq. 3 shows how the generated force depends on gauge pressure and on change of volume with regard to length. As the evolution of volume to length is dependent on the type of membrane that is used, especially its geometry and the way it inflates, the contractile state of a pam is determined by its length and gauge pressure. Whatever the type, since contraction happens as a natural consequence of inflation, volume will be increasing with decreasing length and therefore force will increase with length.

To see how the pneumatic muscle works, two experiments being conducted. PAM is operated by gas pressure and is contractile naturally upon inflation. Their construction material simply consist of a flexible inflatable membrane, reinforced with fibrous filament and fitted with gas closure fitting for mechanical load-carrying at its ends. As the membrane is pressurized, it bulges outward in the radial direction, whilst contracting in length along is axial direction. It is during this axial contraction where PAM exerts a pulling force on its end-effectors. [5] This force generated from contraction and the subsequent motion on the loads moved is unidirectional. This differentiates PAM from other pneumatic devices like the bellows, which extends in length when pressurized. PAM sourced of energy comes from the pressurized gas, usually air, which is forced into the membranes. This pressurization creates a gauge pressure or differential pressure, which simply means the difference between the air pressure inside the membrane and that of the ambient atmospheric pressure outside the membrane. Therefore, a PAM is in fact powered by gauge pressure or differential pressure to carry load. To understand the characteristic of PAM, two simple experiments can be reviewed.

Experiment 1, consider a mass M hanging at one end on PAM which is fixed on the other end. The gauge pressure is increased from initial value of zero. At zero gauge pressure, the enclosed volume is V_{min} and the length is maximum which L_{max}. As the gauge pressure in the muscle is increased to a value P1. The enclosed volume is now V1, bulging radially, as the overall lengths begins contracting, generating a pulling force on the mass M lifting it upwards until force equilibrium achieved, i.e., when the generated pulling force reaches the value of Mg, g = gravitational constant, 9.81 m/s^2. A further increase in pressure to P2, increases the enclosed volume to V2, lifting the mass M further upwards by newly generated pulling force. This experiment revealed two obvious characteristics of PAM. Firstly, PAM shortens in length by increasing its enclosed volume and secondly, it will contract against a constant load as pneumatic pressure is gradually increased refer from Frank Daeden and Dirk Lefeber. (2006)

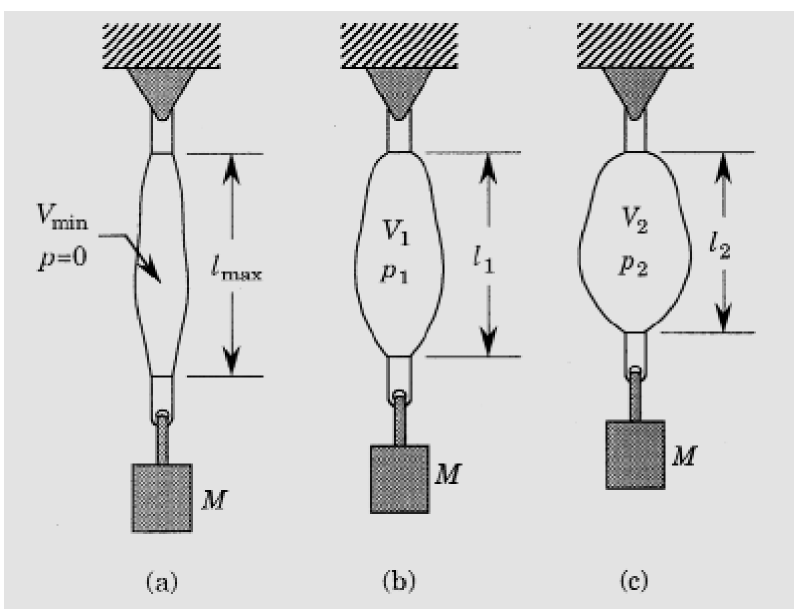


Figure 2.1**:** PAM operation at constant load [5]

Experiment 2 setup will be reviewed for another characteristic of PAM. This time the gauge pressure is kept at a constant value, while the mass will be reduced from the initial value of that consists of 2 masses. As the mass is reduced to 1 mass, the PAM shortens, while increasing its enclosed volume. As all mass completely removed, the bulging goes to its full extent, PAM shortens to a minimal length L_{min} and the pulling force will drop to zero. At this point, there is no more contraction is possible on the PAM. Further, deduction can be added to the existing PAM characteristic. Firstly, PAM contracts in length under constant pressure as loading is reduced and secondly, it reaches an optimal point at which no more contraction is possible and the pulling force subsequently falls to zero, under maximum enclosed volume. Based on both the experiments carried out and the four characteristics observed, a fifth characteristic can be derived which is for each configuration of applied pressure and attached pulled load, there exists an equilibrium length on the PAM, exhibiting s spring-like behavior according to Frank Daeden and Dirk Lefeber. (2006)

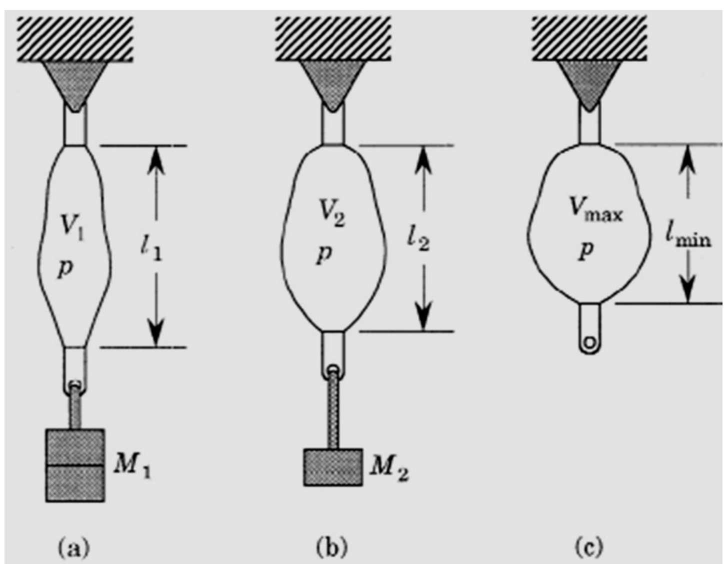


Figure 2.2: PAM operation at constant pressure [5]

2.2 McKibben Muscle

Figure 2.3: Mckibben Pneumatic Artificial Muscle Fabricated in House

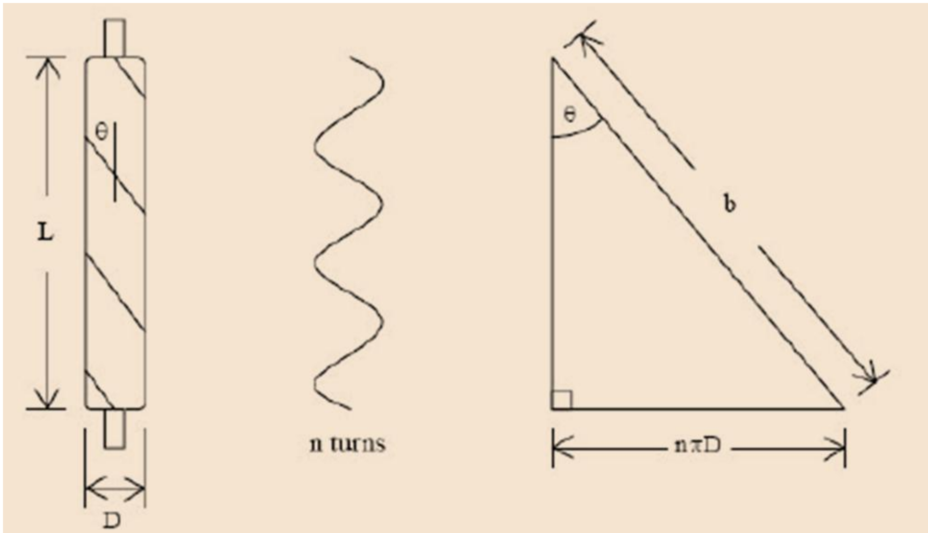


Figure 2.4: Dimension Involves at the PAM according to Catalin CHIVU (2007)

This type of pneumatic artificial muscle is the most frequently used and published about at present. It is a cylindrical braided muscle that has both its tube and its sleeving connected at both ends to fittings that not only transfer fiber tension but also serve as gas closure. Typical materials used are latex and silicone rubber and Nylon fibers. By changing its pitch angle the braid changes its length and diameter. Notating *ls* as the length of each strand of the braid and *N* the amount of encirclements it makes about the tube, one can easily deduce the volume enclosed by the diaphragm:

$$V=\frac{l_s}{4\pi N^2}\cos\theta sin^2\ \theta \qquad (4)$$

$$F=-p\frac{dv}{dl} \qquad (5)$$

Maximum volume is thus attained at a weave angle of about 54.7°. Increasing the angle beyond this value is only possible by axially compressing the muscle. This will not be considered as it is not stable: the flexible muscle shell has no flexural stiffness and thus it would immediately buckle. When stretching, the pitch angle decreases to a lower limit, which is determined by fiber thickness, the amount or density of fibers, the number of encirclements and the diameter of the end fittings. Typical values of pitch angles, given by Caldwell et al. [1995], are 59.3° for the maximum inflation state and 20.0° for the fully stretched state. Tension can be related to weave angle (Schulte, 1961; Chou and Hannaford, 1996) using (5):

$$F = \frac{\pi D_{max}^2}{4}(3cos^2\theta - 1) \qquad (6)$$

with D_{max} the muscle's diameter at a braid angle of 90°, which is the limiting case. Defining contraction as

$$\varepsilon = 1 - \frac{l}{l_o} \qquad (7)$$

where l stands for muscle actual length and l_0 muscle length at rest, tension can also be related to contraction [Tondu et al., 1995; Inoue, 1987]:

$$F = \frac{\pi D_o^2 p}{4}\left(\frac{3}{tan^2\theta_o}(1 - \varepsilon)^2 - \frac{1}{sin^2\theta_o}\right) \qquad (8)$$

with D_0 and θ_0 the diameter and the weave angle at rest, respectively. The rest state is determined by the original tube size and braid characteristics. Elongation beyond the rest size is possible, as stated before, until the minimum pitch angle is reached. The range of contraction-extension depends on the lower pitch angle limit and, consequently, on the density of strands in the weave and on their thickness. Chou and Hannaford (1996) report ranges of 0.75- 1.1 of initial length for Nylon fiber McKibben Muscles, 0.86-1.14 for fiberglass McKibben Muscles and 0.79-1.02 for the Rubbertuator—which is in accordance with Inoue (1987).

Friction and non-elastic deformation of the diaphragm will show up as hysteresis and threshold pressure (i.e. the pressure difference to be exceeded in order to start radial diaphragm deformation), while elastic lateral deformation will lower tension. The force needed to elongate or compress the tube with regard to its rest length can be modeled as a passive spring force acting in parallel with the active force calculated by equation (3). This passive force will increase tension at $l > l_0$ and lower it at $l < l_0$.

According to Chou and Hannaford (1996) A threshold pressure of 90kPa, hysteresis width of 0.2–0.5cm and height of 5–10N for a Nylon braid muscle of 14 cm rest length and 1.1 cm rest diameter and more or less double these figures for an approximately equal sized fiberglass braid muscle (cf. Fig. 2.5). They also show hysteresis to be substantially due to dry friction. Caldwell et al. (1993b) report forces attaining only 53% of their values predicted by Eq. 3. The typical operating gauge pressure range of McKibben Muscles is 100–500kPa.

The maximum allowable gauge pressure is determined by the strength of the tube: too high a pressure would make the tube bulge through the meshes of the net and it would subsequently burst. The higher this pressure the more energy can be transferred, but equally the higher the pressure threshold value because of the increasing toughness of the diaphragm. As a result of this, low forces cannot be generated.

As for power to weight ratios of McKibben Muscles, values cited by Cald-well et al. (1993b) range from 1.5 kW/kg at 200kPa and 3 kW/kg at 400 kPa. Hannaford et al. (1995) cite a value of 5 kW/kg and Hannaford and Winters (1990) even 10 kW/kg. To determine these values, no auxiliary elements such as valves, were taken into consideration. The weight of McKibben Muscles is typically about 50 g (Tondu et al. (1995), $l0$ = 34cm, $D0$ = 1.4 cm), but can be as low as 5.5 g (Caldwell et al. (1993a), $l0$ = 9cm, $D0$ = 1cm).

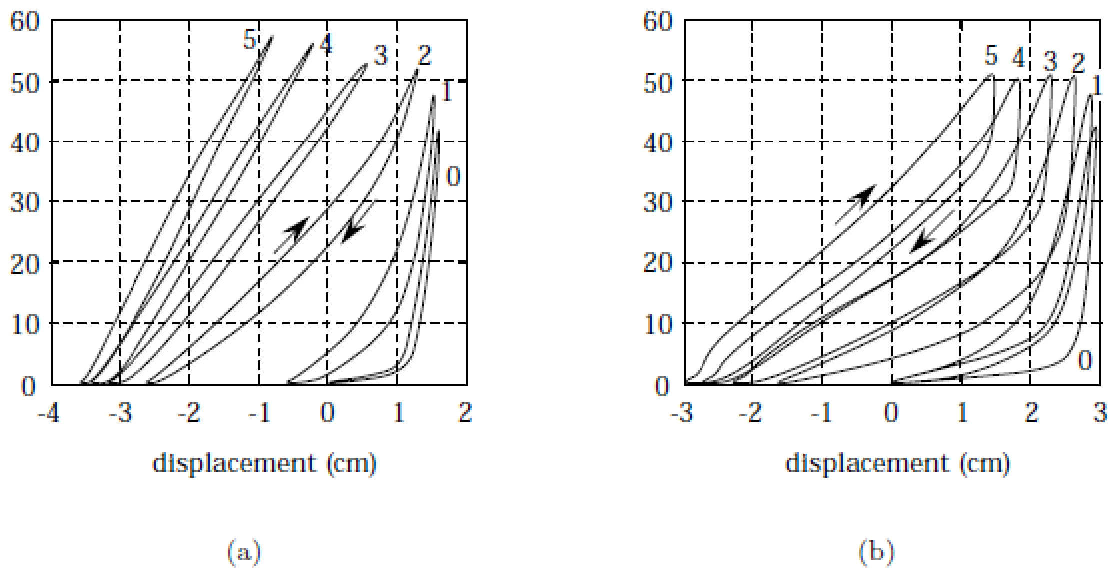


Figure 2.5**:** McKibben Muscle tension (N) and hysteresis at isobaric conditions (0, 100, 200, 300, 400 and 500kPa), (a) Nylon braid, (b) fiberglass braid. (Chou and Hannaford, 1996)

CHAPTER 3

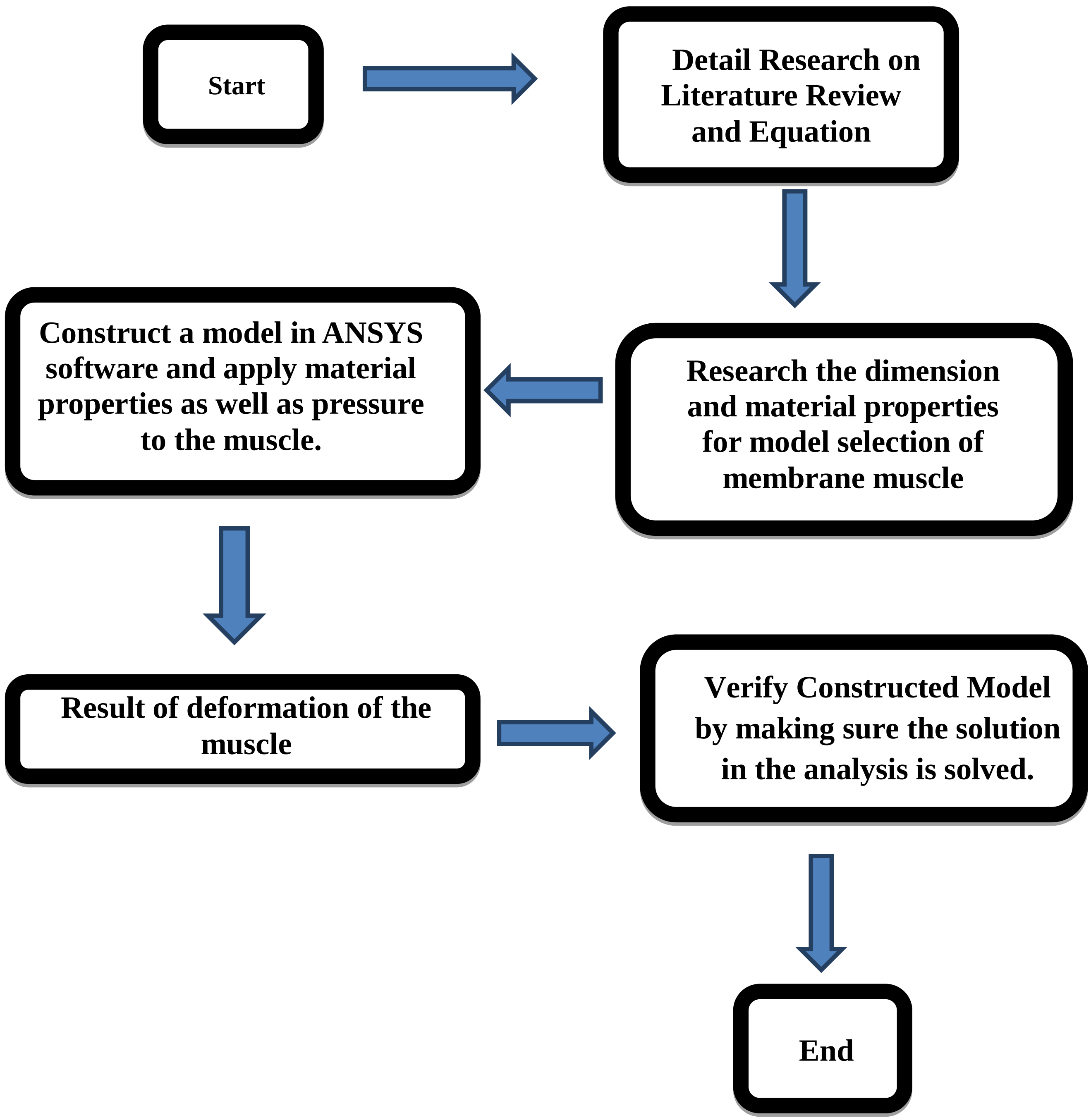
METHODOLOGY

3.1 GANTT CHART/ PROJECT MILESTONE

Analysis of Pneumatic Artificial Muscle and Construction of a Model

Acitivity / Duration	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
First Semester												
1. Study the basic concept of PAM												
2. Study the PAM working principle												
3. Study the theoretical equation												
Second Semester												
1. Identify the exact material type of membrane use for PAM												
2. Training the Finite Element Analysis												
3. Construct a PAM model in ANSYS Software												
4. Undergo Finite Element Analysis to show the structure deformation when load apply												
5. Final Report Writing												

3.2 PROJECT PLANNING



During operation L, D and θ are variable (θ changes as length L changes),

$$L = b\ cos\theta \qquad (9)$$

$$D = \frac{b \sin\ \theta}{n\pi} \qquad (10)$$

The volume of any cylinder is equal to its length times the cross sectional area.

$$V = \frac{\pi D^2}{4} L \qquad (11)$$

Substituting equations (9), (10) into (11) results

$$V = \frac{b^3}{4\pi n^2} sin^2\theta \cos\theta \qquad (12)$$

The maximum contracted length (minimum length) occurs when the actuator volume is at its greatest. This results in equilibrium of the system. To be able to simulate the static model it is chosen a PAM that has the maximum interweave angle θ = 54.7° and the corresponding length and diameter L = 140 mm, D = 15 mm. These value together the hypothesis that b and n parameters are constant during operation, are used to determine this functional parameters. Thus, from equation (9, 10) results:

$$b = \frac{L}{cos\ \theta} = \frac{140}{cos\ 54.7^o} = 242.27\ mm$$

$$n = \frac{b\ sin\theta}{\pi D} = \frac{242.27 \cdot sin\ 54.7^o}{\pi \cdot 15} = 4.196$$

$$0.196\ x\ 100 = 19.6\% \approx 20\%$$

Thus it is obtained that a single thread has 4 complete turns and 20% from the fifth.

$$F = -P_g \frac{dV}{dL} \qquad (13)$$

Using the geometry that was established can be developed an equation for force as a function of pressure and interweave angle.

$$F = -P_g \frac{\frac{dV}{d\theta}}{\frac{dL}{d\theta}} = \frac{P_g b^2 (2cos^2\theta - sin^2\theta)}{4\pi n^2} \qquad (14)$$

Thus, results an equation of force as function of P_g and θ.

$$F = \frac{P_g b^2 (3cos^2\theta - 1)}{4\pi n^2} \qquad (15)$$

P_g = gauge pressure, kPa

n = number of turn in single thread

θ = interweave angle

F = Force output produce, N

The table below show the relation between length and force theoretically when apply two pressure values to the PAM into the equation (15):

Table 3.1: Length and Pressure Neoprene Membrane

Length / Pressure	100kpa	200kpa
80 mm	5784.32 N	11568.64 N
90 mm	7320.78 N	14641.56 N
100 mm	9038.00 N	18076.00 N
110 mm	10935.98 N	21871.96 N
120 mm	13014.72 N	26029.44 N
130 mm	15274.22 N	30548.44 N
140 mm	17714.48 N	35428.96 N

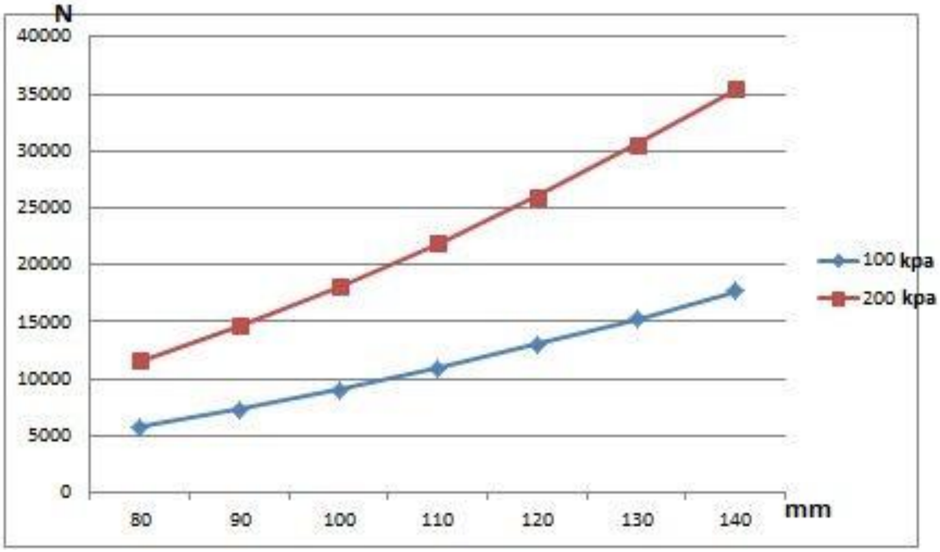


Figure 3.3: Force vs. Length at 100 and 200kpa pressures

The graph above shows the Force with respect to the length displacement. The red line indicating the pressure set at 200kpa. Meanwhile the blue line indicating 100kpa pressure applied.

From the two plots, we can observe that the force is a nonlinear function of length. This is because the material is a neoprene rubber which exhibit the spring like characteristics. The force that produced shows high value, meaning that pneumatic muscle can produce high force to weight ratio. So the pneumatic muscle can produce high force with low weight.

3.3 Model Selection

3.3.1 Criteria of Membrane

The technical requirements that are to be met for the membrane material are set by the geometric design, the operational conditions and the assembling of the pam. The main design feature is the braided, which demands a good flexibility and low brittleness, in order to fold easily and prevent cracks due to flexing.

The technical requirements set by the operational conditions are:

1. High tensile stiffness and high strength, in order to minimize strain energy and membrane thickness;
2. Good wear and tear resistance, to ensure a long life under cyclic operation;
3. Low creep/relaxation, to retain initial sizes;
4. Good fatigue resistance, because of the cyclic operation;
5. gas-tightness;
6. low influence of environmental factors, such as moisture, heat, light, oxygen, to ensure reliability;

3.3.2 Selection

Neoprene Rubber, This rubber has a generally good balance of mechanical properties and fatigue resistance second only to natural rubber, but with superior chemical, oil, and heat resistance. It is widely used in general engineering applications. It is less resistant than natural rubber to low temperature stiffening but can be compounded to give improved low temperature resistance. It has good ozone resistance. It is suitable for use with mineral oils and greases and dilute acids and alkalis, but is unsuitable in contact with fuels. It has generally poorer set and creep than natural rubber.

Thus for this thesis we select Neoprene rubber as the material type for the membrane as it suits the criteria earlier. Detail Comparison on the Neoprene rubber show at Table 3.2

Table 3.2: Type of Rubber Material Comparison According to Novus Sealing Pty Ltd.

RTIES	NR	NEOPRENE	NITRILE	EPDM	BUTYL	VITON	SILI
ore A)	65	60	60	70	60	72	6
	4	4	10	7	8	9	[illegible]
Break (%)	200	200	350	300	400	160	3
	E	G	G	E - G	G - F	E - G	[illegible]
	E	E	G	G	F	F	[illegible]
	G	G	G	G	E	E	[illegible]
olymer)	E	F	F - P	E	E	G	[illegible]
	70°C	90°C	110°C	120°C	100°C	204°C	20
OPERTIES							
	E	G	F	G	G	G	[illegible]
	E	E	E	G	F	G	[illegible]
	E	G	G	F	G	G	[illegible]
	E	G	G	G	E	G	[illegible]
ial	E	E - G	E - G	F	G	G	[illegible]
INGS							
ng	F - P	G	P	E	E	E	[illegible]
	G	E	G	E	E	E	[illegible]
	N	E	F	E	E	E	[illegible]
	G	G	G	G	G	G	[illegible]
	E	G	E	E	E	E	[illegible]
ted	E/G	E/E	G/G	E/E	E/E	E/E	E
ed	E/G	E/E	G/G	E/E	E/E	G/F	G
(Petrol, Kerosene)	N	F	E	N	N	E	[illegible]
(Benzene, Toluene)	N	G	E - G	N	N	E	[illegible]
ons (Degreaser, Solvents)	N	P	G - F	N	N	E	[illegible]
	E - G	E	G - F	G	G	G	[illegible]
Oils	G - F	G	G	G	E - G	E	[illegible]

CELLENT G = GOOD F = FAIR P = POOR N = NOT RECOMMENDED

3.4 Model Construction and Analysis Process

3.4.1 Outline of Methodology in ANSYS Software

1. DEFINE UNITS
2. MODEL GEOMETRY
3. MESHING
4. PRESSURES APPLY

3.4.2 Define Units to Be Use

The analysis started by defining the units to be used for the analysis. All the define unit shown in Table 3.1:

Table 3.3: Define Unit

Unit System	Metric (mm, kg, N, °C, s, mV, mA)
Angle	Degrees
Rotational Velocity	rad/s
Pressure	Mpa

3.4.3 Model Geometry

A Model geometry being setup that meet specific dimension which is Length = 180mm and Diameter, D = 60mm. A detail specification shows below in Table 3.4 and 3.5. Table 3.4 shows the material data properties to be inserted in material specification in Neo-Hookean analysis

Table 3.4: Neoprene Rubber Material Property

Initial Shear Modulus Mu MPa	2.72×10^{-2}
Incompressibility Parameter D1 1/MPa	1.4716×10^{5}

Table 3.5: Model Geometry Specification

Object Name	*Geometry*
State	Fully Defined
Definition	
Type	Design Modeler
Length Unit	Millimeters
Bounding Box	
Length X	60. mm
Length Y	60. mm
Length Z	180. mm
Statistics	
Bodies	1

Active Bodies	1
Nodes	14448
Elements	9491

Table 3.6: Geometry Parts

Object Name	*Solid*
State	Meshed
Graphics Properties	
Visible	Yes
Transparency	1
Definition	
Suppressed	No
Material	Neoprene Rubber
Stiffness Behavior	Flexible
Nonlinear Material Effects	Yes
Bounding Box	
Length X	60. mm
Length Y	60. mm
Length Z	180. mm

Properties	
Volume	5.0894e+005 mm³
Mass	0. kg
Centroid X	3.085e-016 mm
Centroid Y	1.2726e-015 mm
Centroid Z	90. mm
Moment of Inertia Ip1	0. kg·mm²
Moment of Inertia Ip2	0. kg·mm²
Moment of Inertia Ip3	0. kg·mm²
Statistics	
Nodes	14448
Elements	9491

3.4.4 Meshing

After the model geometry completed, a mesh must be apply to the model in order to show the structure of muscle before and after the deformation. The Table 3.7 below shows the characteristic of the mesh applied.

Table 3.7: Meshing Properties

Object Name	*Mesh*
State	Solved
Defaults	
Physics Preference	Mechanical
Advanced	
Relevance Center	Coarse
Element Size	Default
Shape Checking	Standard Mechanical
Solid Element Midside Nodes	Program Controlled
Initial Size Seed	Active Assembly
Smoothing	Low
Transition	Fast
Statistics	
Nodes	14448
Elements	9491

Table 3.8 Mesh Controls

Object Name	*Refinement*
State	Fully Defined
Scope	
Scoping Method	Geometry Selection
Geometry	3 Faces
Definition	
Suppressed	No
Refinement	1

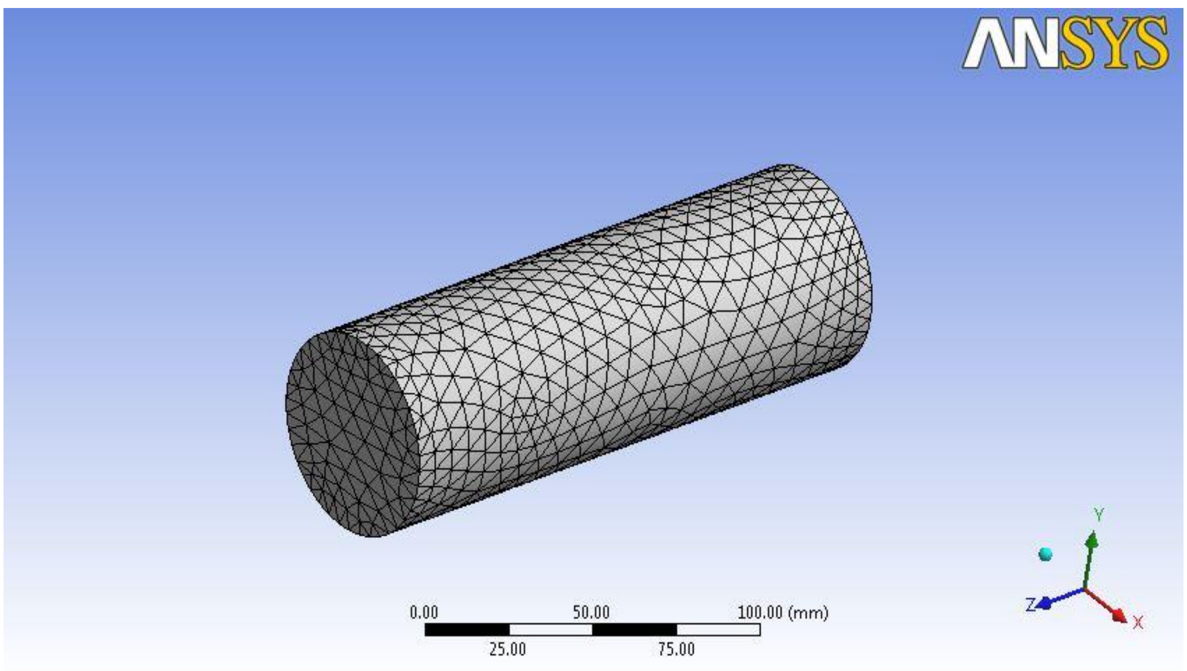


Figure 3.4: Meshed Pneumatic Muscle Model

3.4.5 Structural Analysis

There are a few analyses that can be used in ANSYS such as

1. Static Structural
2. Flexible Dynamic
3. Rigid Dynamic
4. Harmonic response
5. Linear Buckling

For this project, Static Structural analysis applied to the muscle. The analysis can show the deformation of the muscle before and after pressures apply into the muscle. More it enables the properties of material for nonlinear material to be inserted and use for this analysis. From Table 3.8 shows the characteristic of the analysis which the type of analysis used and also the constant temperature applied to the muscle. Then Table 3.9 shows the setting set in the analysis of static structural.

Table 3.9: Analysis

Object Name	*Static Structural*
State	Fully Defined
Definition	
Physics Type	Structural
Analysis Type	Static Structural
Options	
Reference Temp	29. °C

Table 3.10: Analysis Settings

Object Name	*Analysis Settings*
State	Fully Defined
Step Controls	
Number Of Steps	1.
Current Step Number	1.
Step End Time	5. s
Auto Time Stepping	Program Controlled
Solver Controls	
Solver Type	Program Controlled
Weak Springs	On
Spring Stiffness	Program Controlled
Large Deflection	On
Inertia Relief	Off
Nonlinear Controls	
Force Convergence	On
--Value	ANSYS Calculated
--Tolerance	0.5%
--Minimum Reference	1.e-002 N

Displacement Convergence	On
--Value	ANSYS Calculated
--Tolerance	0.5%
--Minimum Reference	0. mm
Output Controls	
Calculate Stress	Yes
Calculate Strain	Yes
Calculate Results At	All Time Points
Analysis Data Management	
Future Analysis	None
Nonlinear Solution	Yes

3.4.6 Apply Pressure

Pressure 1 is applied to the muscle at the surface end of the muscle for 2kpa increment until it reaches 10kpa. Then, pressure 2 of 1kpa is being applied to the muscle. The following Table 3.10 and Table 3.11 show the characteristic of it.

Table 3.11: Load Value

Object Name	*Pressure*	*Fixed Support*	*Pressure 2*
Scope			
Geometry	2 Faces	1 Face	
Definition			
Define By	Normal To		Vector
Type	Pressure	Fixed Support	Pressure
Magnitude	Tabular Data		1.e-003 MPa (ramped)
Suppressed	No		
Direction			Defined

Table 3.12: Pressure 1 Data

Steps	Time [s]	Pressure [MPa]
1	1.	2.0×10^{-3}
1	2.	4.0×10^{-3}
1	3.	6.0×10^{-3}
1	4.	8.0×10^{-3}
1	5.	1.0×10^{-2}

CHAPTER 4

RESULT AND DISCUSSION

4.1 Construction of Basic Conceptual Model (Finite Element Analysis)

The result shows the steps in producing a PAM model using Ansys Workbench Software. Figure 4.1 shows the pressure section acting on the PAM which are A and B with 100kpa and 10kpa respectively. Section C shows the fixed support of the Pneumatic Muscle.

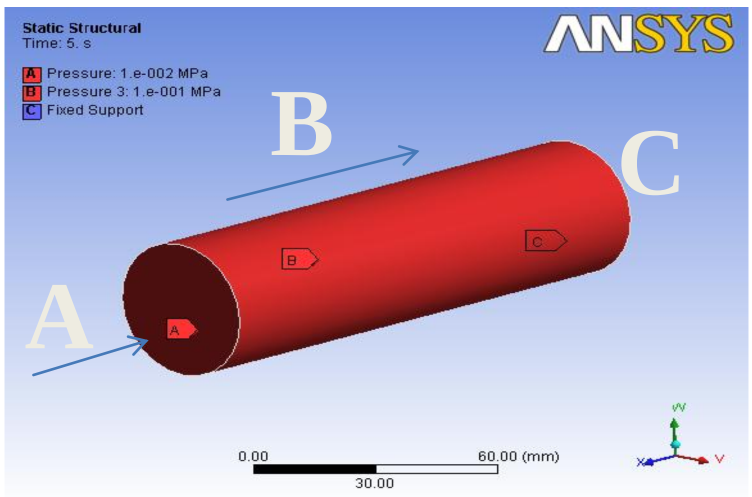


Figure 4.1: Model Geometry of PAM before implementing pressure

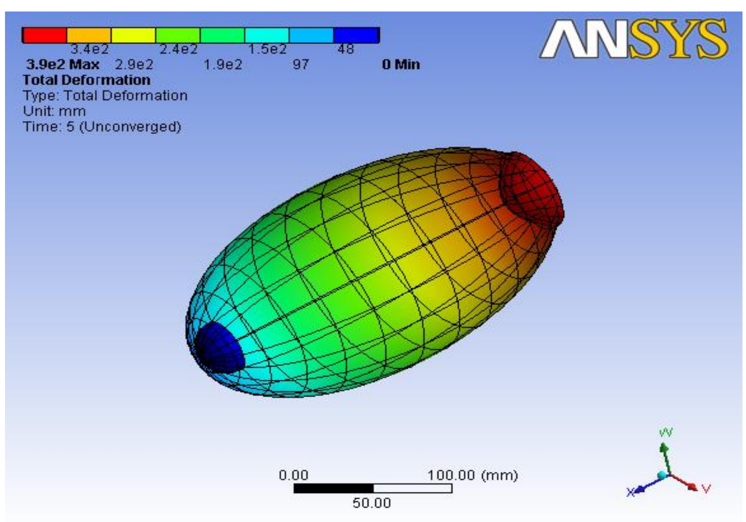


Figure 4.2: Model Geometry of PAM after implementing pressures

4.2 Model Verification Specification

Table 4.1: Solution

Object Name	*Solution*
State	Solved
Adaptive Mesh Refinement	
Max Refinement Loops	1.
Refinement Depth	2.

Table 4.2: Solution Information

Object Name	*Solution Information*
State	Solved
Solution Information	
Solution Output	Max DOF Increment, Displacement Convergence, Force Convergence
Newton-Raphson Residuals	2
Update Interval	2.5 s
Display Points	All

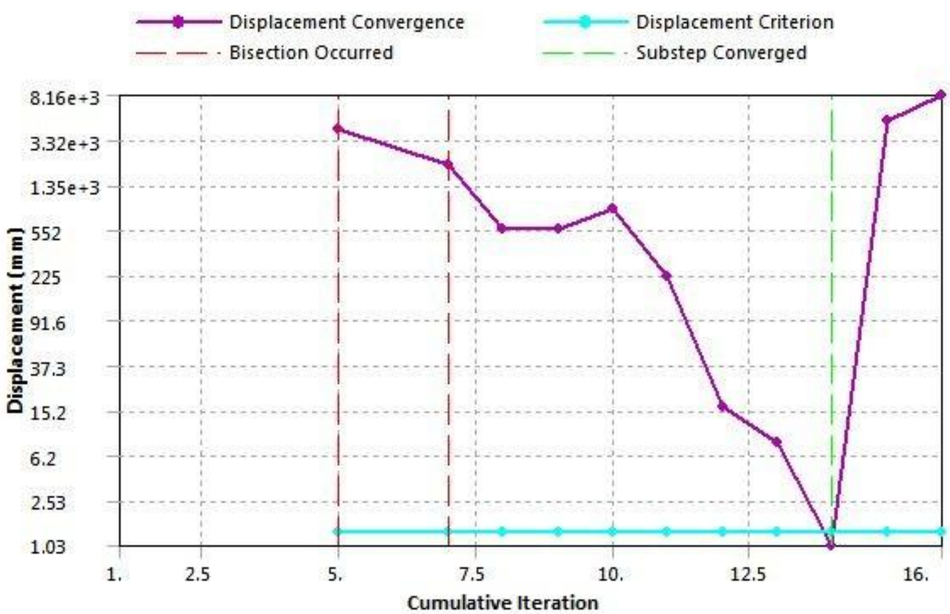


Figure 4.3: Displacement Vs. cumulative Iteration

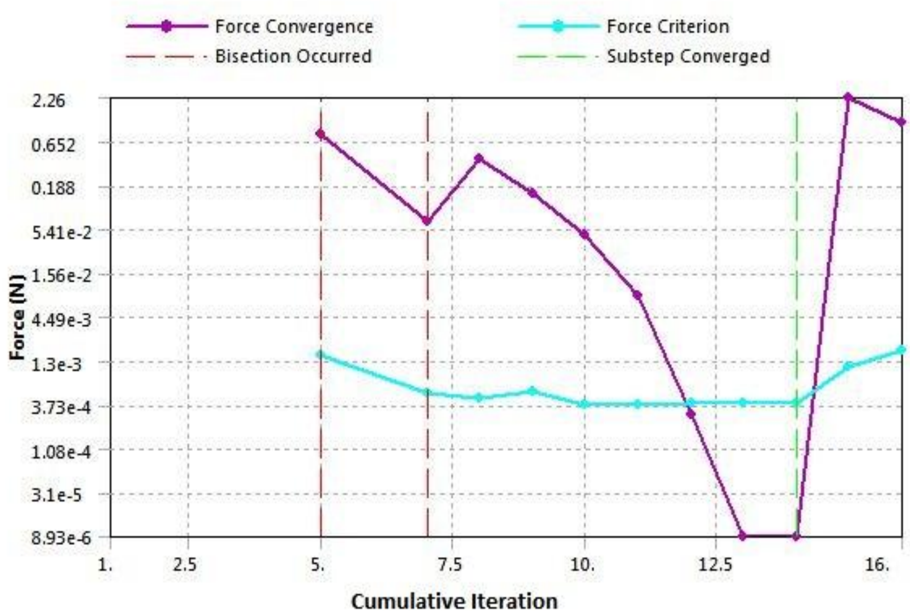


Figure 4.4: Force Vs. cumulative Iteration

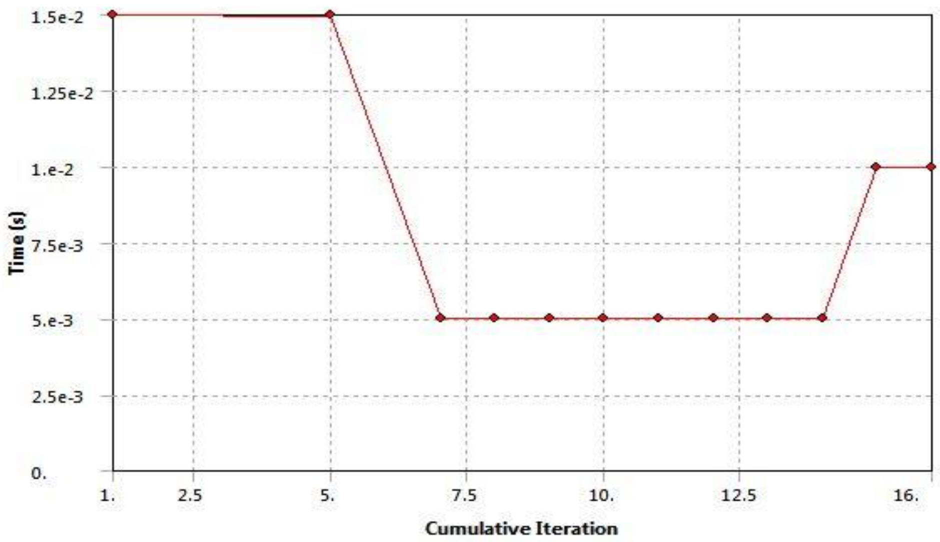


Figure 4.5: Time Vs. cumulative Iteration

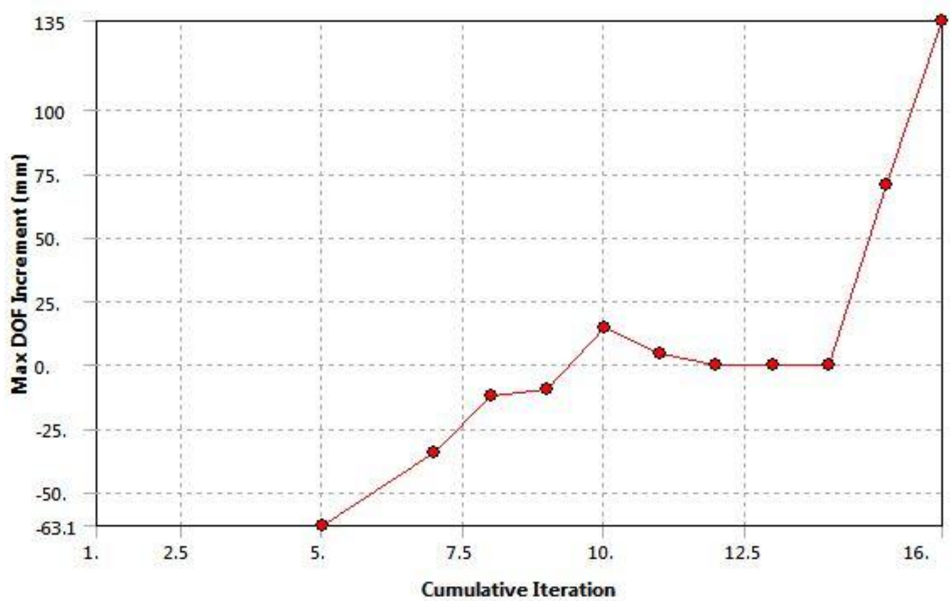


Figure 4.6: Max DOF (Degree of Freedom) Increment Vs. cumulative Iteration

Table 4.3: Newton-Raphson Residual Force

Object Name	*Newton-Raphson Residual Force*	*Newton-Raphson Residual Force 2*
State	Solved	
Definition		
Type	Newton-Raphson Residual Force	
Results		
Minimum	1.3663e-030 N	
Maximum	0.11548 N	5.2778e-002 N
Convergence		
Criterion	1.121e-003 N	1.76e-003 N
Value	2.263 N	1.096 N
Information		
Time	1.e-002 s	
Load Step	1	
Substep	2	
Iteration Number	1	2

Table 4.4: Results of Deformations

Object Name	*Total Deformation*
State	Solved
Scope	
Geometry	All Bodies
Definition	
Type	Total Deformation
Display Time	5. s
Results	
Minimum	0. mm
Maximum	67.443 mm

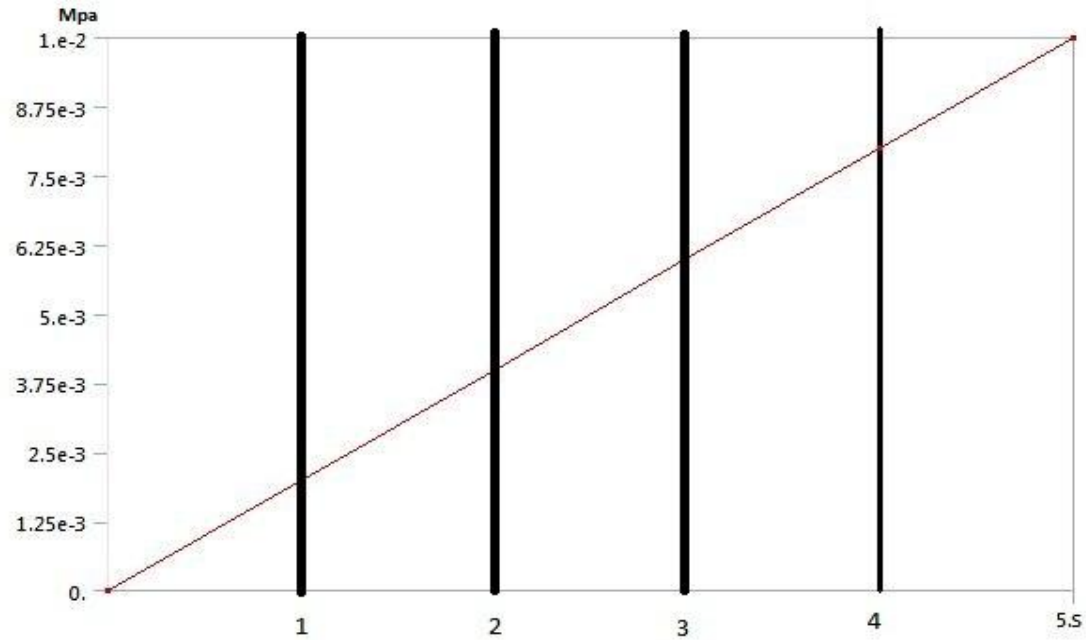


Figure 4.7: Pressure 1 vs. Time

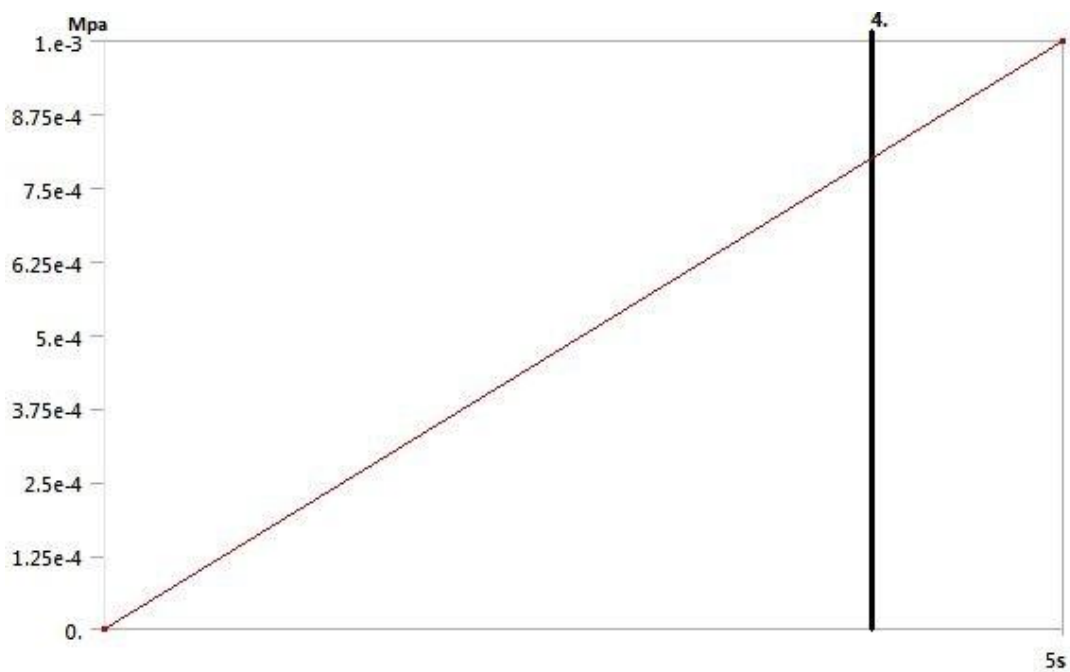


Figure 4.8: Pressure 2 vs. Time

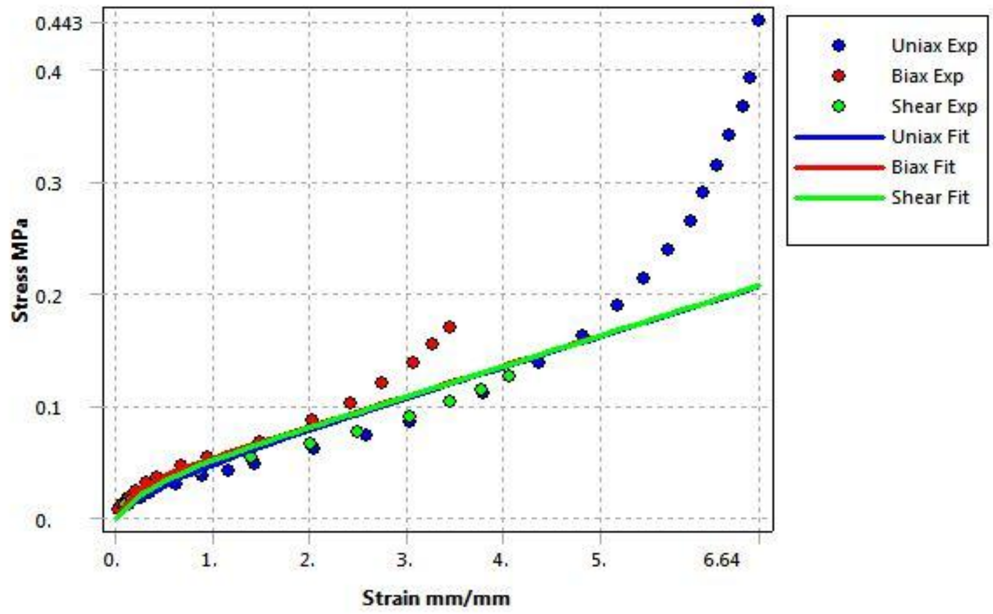


Figure 4.9: Stress vs. Strain

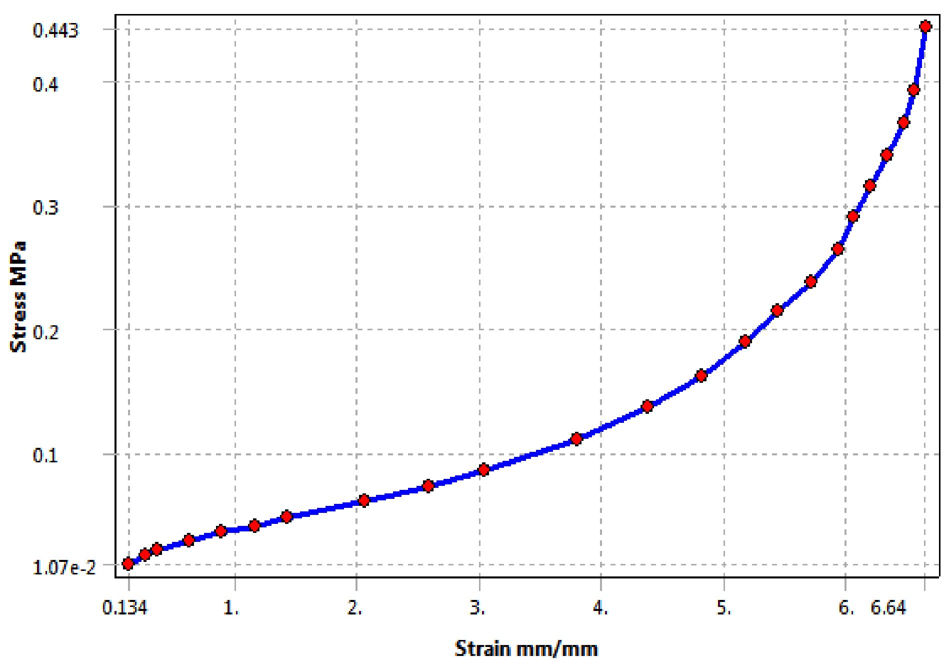


Figure 4.10: Uniaxial Test Data of Neoprene Rubber

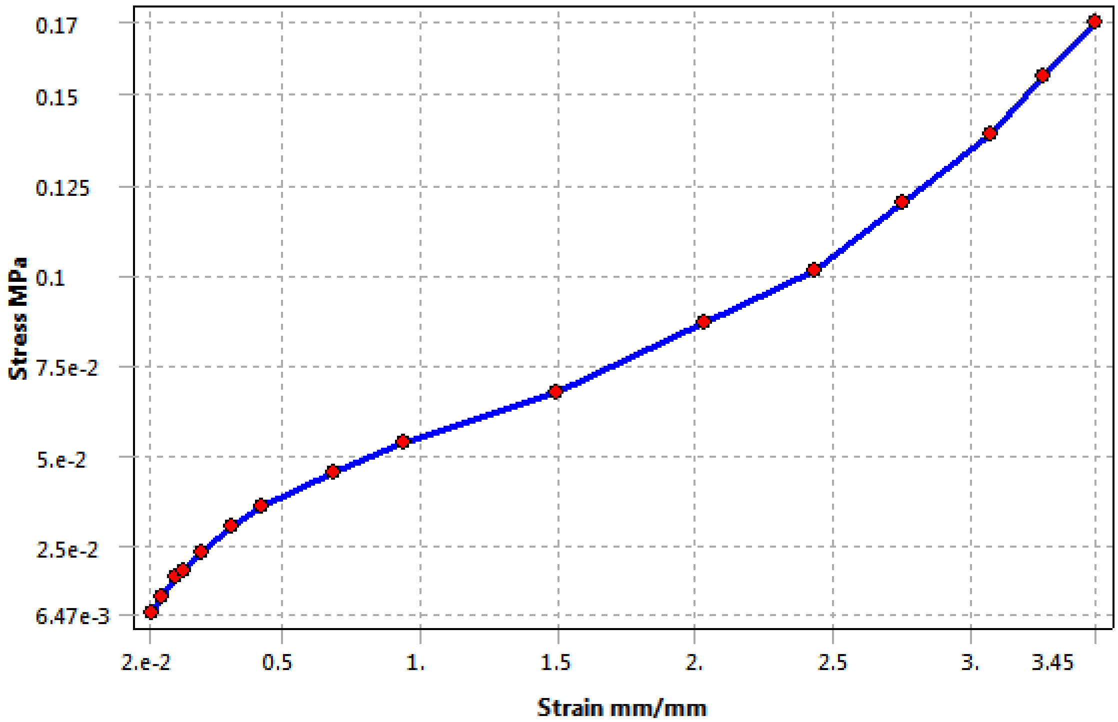


Figure 4.11: Biaxial Test Data of Neoprene Rubber

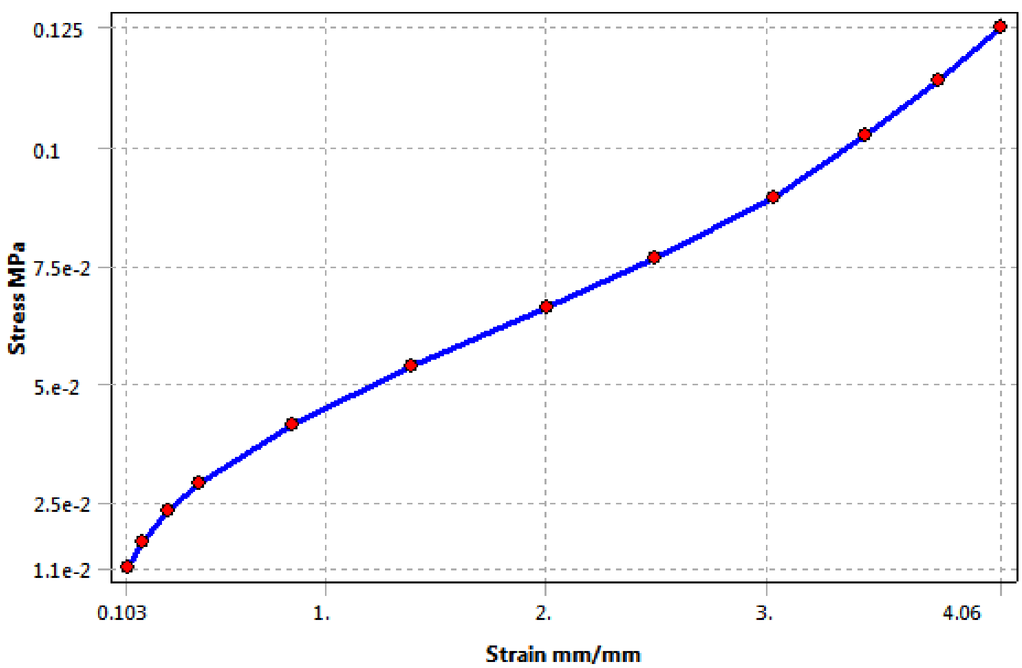


Figure 4.12: Shear Test Data of Neoprene Rubber

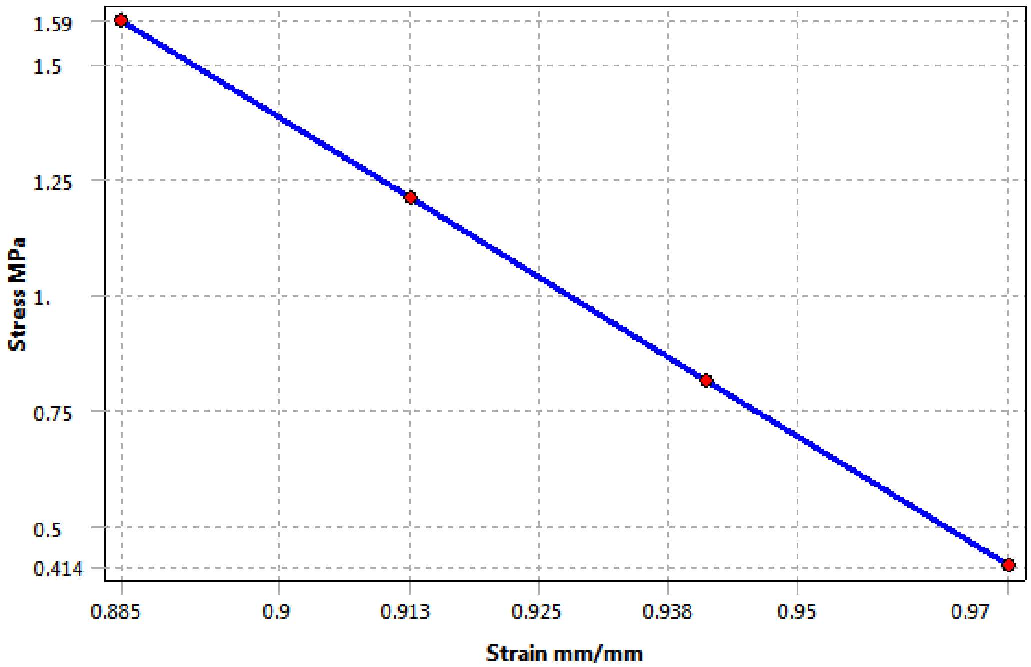


Figure 4.13: Volumetric Test Data of Neoprene Rubber

4.3 Discussion

The artificial muscle reacts towards pressure applied to it and has nonlinear behavior towards length. This shows in Figure 4.3 that indicates the nonlinearity of displacement and cumulative iteration. The muscle react in different shape as it volume was expanding by applying the pressure to the muscle area. Choosing a right element type and material properties is crucial to have the accurate result as neo-Hookean value of initial shear modulus needs to accurately follow the material type of neoprene rubber properties.

More, the incompressibility property needs to be well defined to show the exact behavior of the muscle when pressures were applied to it. For the result, the muscle should be expanding in volume with corresponding shortens of length. The Figure 4.4 shows the force and cumulative iteration that are nonlinear towards each other. This proved the characteristic of the muscle nonlinearity. While in Figure 4.10, 4.11, 4.12 and 4.13 show the test data for stress and strain values.

From the theoretical result shows the graph of Force with respect to length at two applied pressure. There, it proves that PAM producing large amount of force during its operation. From the initial model geometry, the PAM model deformed in expanding its volume and decreasing its length after pressures applied to the PAM.

CHAPTER 5

CONCLUSION

The PAM increases its volume when inflated after pressures being implemented and also the length of the muscle decreases. The PAM also have been shown an impact in force –to-weight ratio as the force produce is high in value compare to its light weight of the muscle. The analysis started after the material type of the membrane which is Neoprene rubber has been identified to the most suitable. The Figure 4.3 shows the nonlinear behavior of the muscle deformation towards its length. The analysis of Finite Element shows the structure deformation as well as the characteristic of the muscle length with respect to the pressure applied.

5.1 Recommendation

1. The PAM in the ANSYS software can be improved by doing the buckling analysis to shows the maximum pressure the muscle can be apply. The muscle will be applying certain pressure until it reaches a point before the muscle broken. Then, the prediction can be justified of the maximum pressure can the muscle attained.

2. The comparison of all types of Pneumatic Muscle can be conducted to identify their performances. The Pneumatic Muscle such as Pleated Muscle, Sleeved Bladder Muscle, Netted Muscle and Yarlott Muscle can be used for the comparison analysis.

REFERENCES

1. Saeed Moaveni, 2008, FINITE ELEMENT ANALYSIS (*Theory and Apllication with Ansys*), Third Edition. Pearson International Edition.

2. Ahmad Luqman Al-Hakim , 25th June 2010, *Interim Report FYP 1 Pneumatic Artificial Muscle*, University Technology of PETRONAS, Malaysia

3. Deaconescu, A. & Deaconescu, T. 24-26th April 2008, *Contribution To The Behavioural Study of Pneumatically Actuated Artificial Muscle*, 6th International DAAAM Baltic Conference, Industrial Engineering, Tallin, Estonia.

4. Catalin CHIVU, 25-26th October 2007, *Static Model and Simulation of A Pneumatic Artificial Muscle*, “Transilvania” University of Brasov, Romania.

5. Frank Daeden, Dirk Lefeber, 2006 *Penumatic Artificial Muscle: Actuators for Robotics and Automation*, University of Brussel, Department of Mechanical Engineering.

6. D.G.Caldwell, G. A. Medrano-Cerda and M.J Goodwin, 1995 *Control of Pneumatic Muscle Actuators*, IEEE Control System Magazine, Vol. 15, number 1,pp.40-48,.

7. H. F. Schulte, “*The Characteristics of the Mckibben Artificial Muscle”. The Appication of External Power In Prostheticsand Orthotics*, pp-94-115, National of Academy Science-National Research Council, Publication 874, Lake Arrowhead, 1961.

8. S, Rajendran and D.Q.Song, 11-13th Nov 1998, *Finite Element Modelling of Delamination Buckling of Composite Panel Using ANSYS*, Material Technology Application Centre, Singapore.

9. D. B. Reynolds, 24th July 2002, *Modelling the Dynamic Characteristics of Pneumatic Muscle*, Annals of Biomedical Engineering, Vol. 31,pp.310-317.

10. R. Ramasamy, M.R.Juhari, 2005, *An Application of Finite Element Modelling to Pneumatic Artificial Muscle*, DAG Technology Sdn.Bhd, Malaysia.

11. Keith E. Gordon, 20th May 2005, *Mechanical Performance of Artificial Pneumatic Muscle to Power An Ankle-Foot Orthosis*, Journal of Biomechanics.

12. Matthew Wadham-Gagnon, 2007, *Hyperelastic Modelling of Rubber In Commercial Finite Element Software (ANSYS)*, Industriel, Sherbrooke, Québec, J1L 2T9, Canada.

13. Augustin Sanchez, 1-4TH September 1998, *Nonlinear Parametric Identification of a McKibben Artificial Pneumatic Muscle Using Flatness Porperty of The System*., Department of Electrical and Computing Engineering INSA Toulouse, Campus Scientifique de Rangueil 31077 Toulouse, FRANCE

14. Nguyen Huu Chuc, 12-17th May 2009, *Muiti-Jointed Robot Finger Driven by Artificial Muscle Actuator*, Kobe International Conference Center Kobe, Japan

15. Lanka Udawatta and PGS Priyadarshana, 2009, *Control of Pneuamtic Artificial Muscle for Bisep Configuration Using IBC*, Department of Electrical Engineering, University of Moratuwa, Sri Lanka.

APPENDIX 1

McKibben Pneumatic Artificial Muscle with Nylon Braided fabricated at UTP

(a) End Fitting Nylon Braided

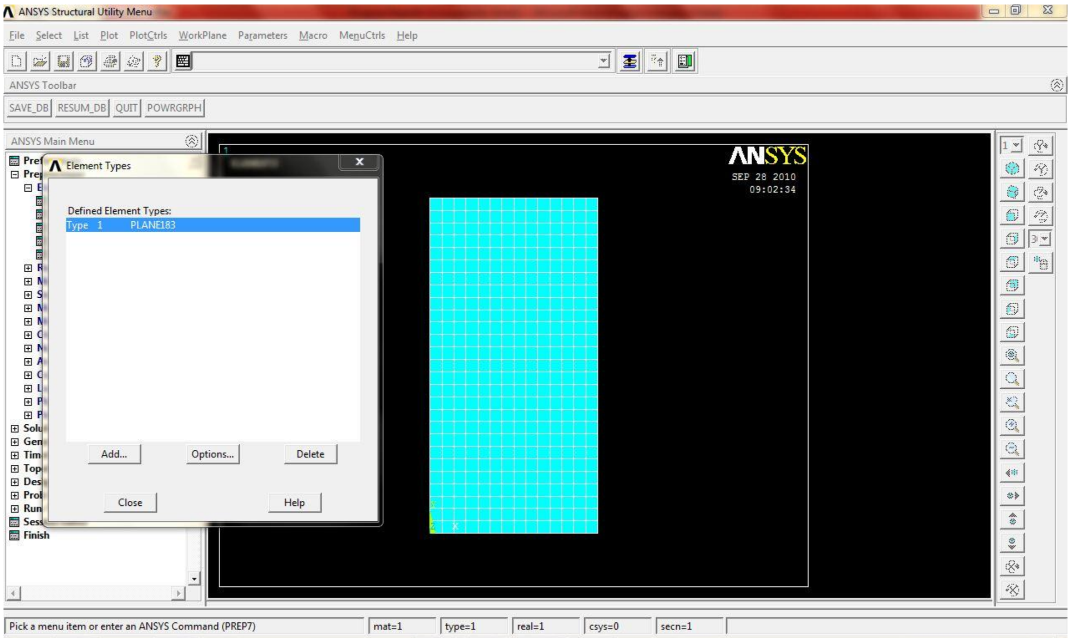
(b) Full View of Nylon Braided

APPENDIX II

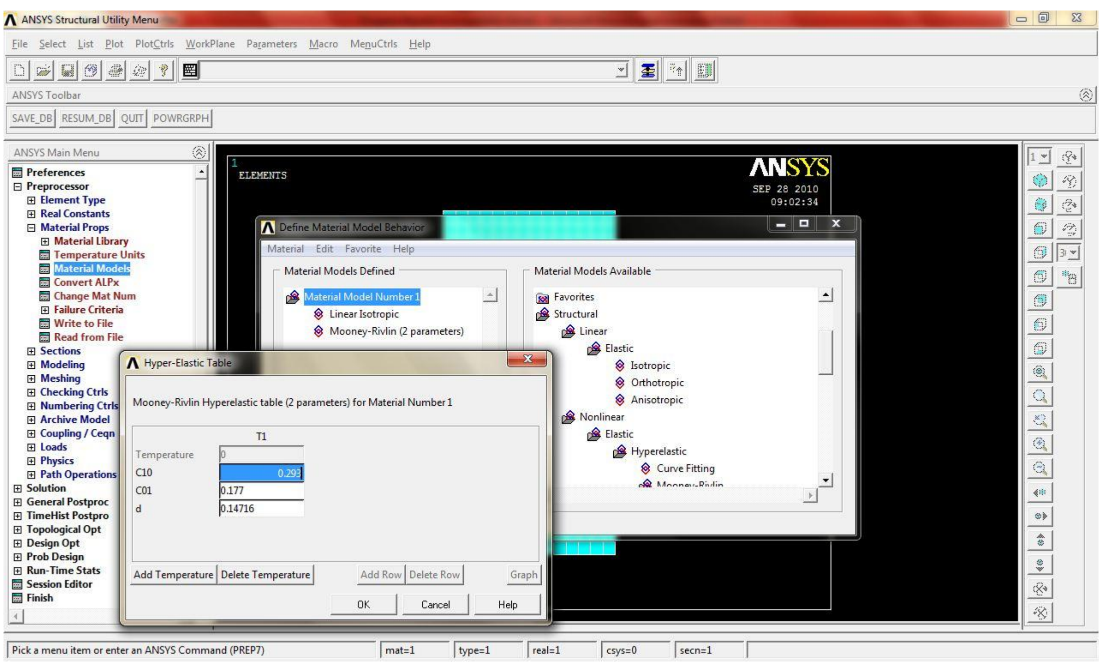
McKibben Pneumatic Artificial Muscle with Carbon-Steel Braided fabricated at UT

(a) End Fitting Carbon Steel Braided

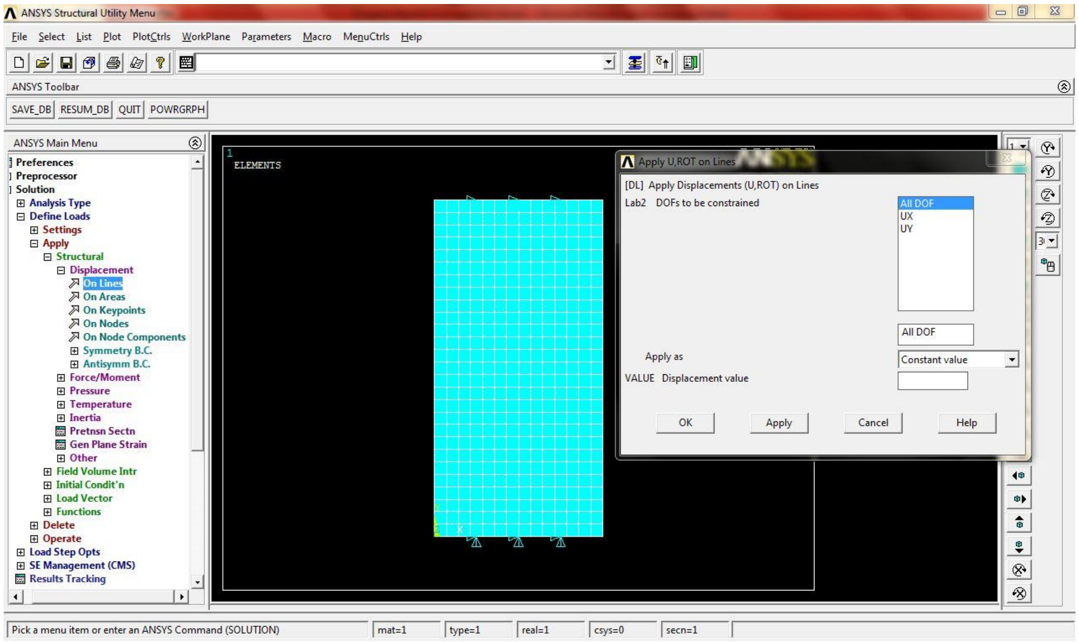
(b) Full View Carbon Steel Braided



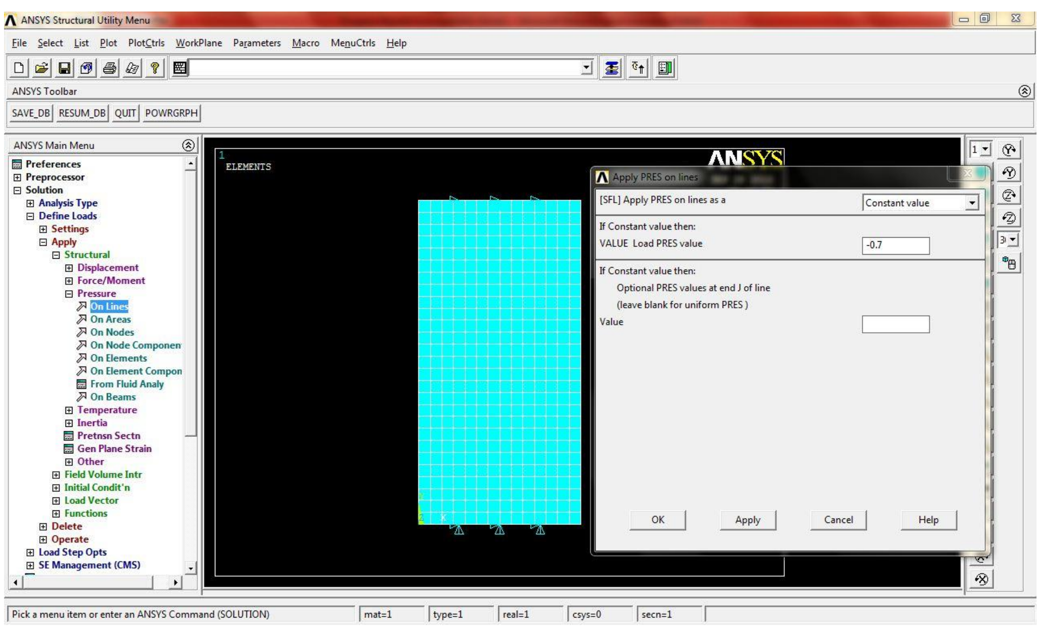
2D Cylinder Muscle Membrane



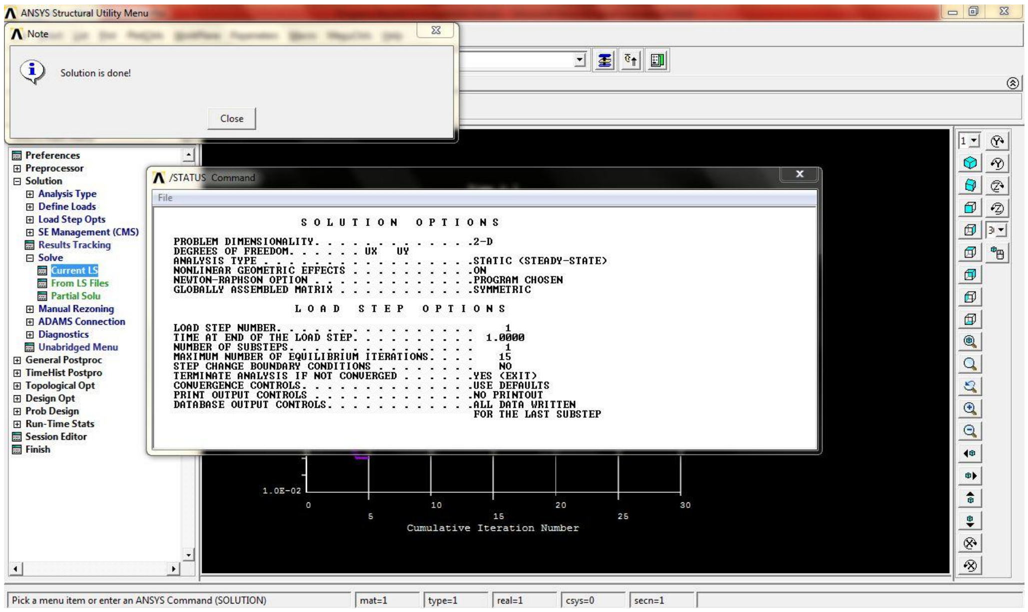
Mooney-Rivlin constant inserted for Neoprene Rubber



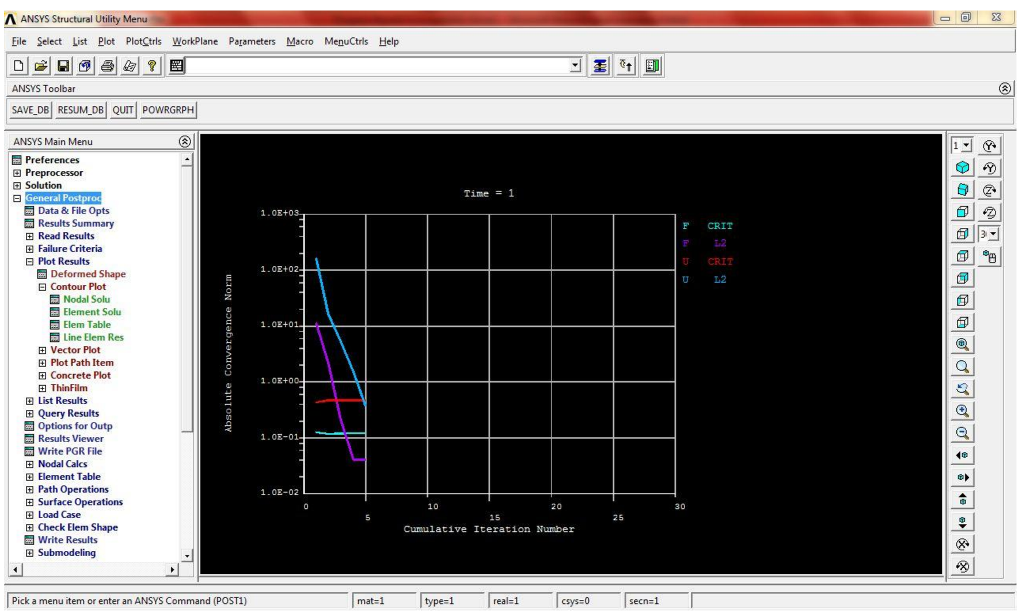
Apply Boundary Condition to All DOF (Degree of Freedom)



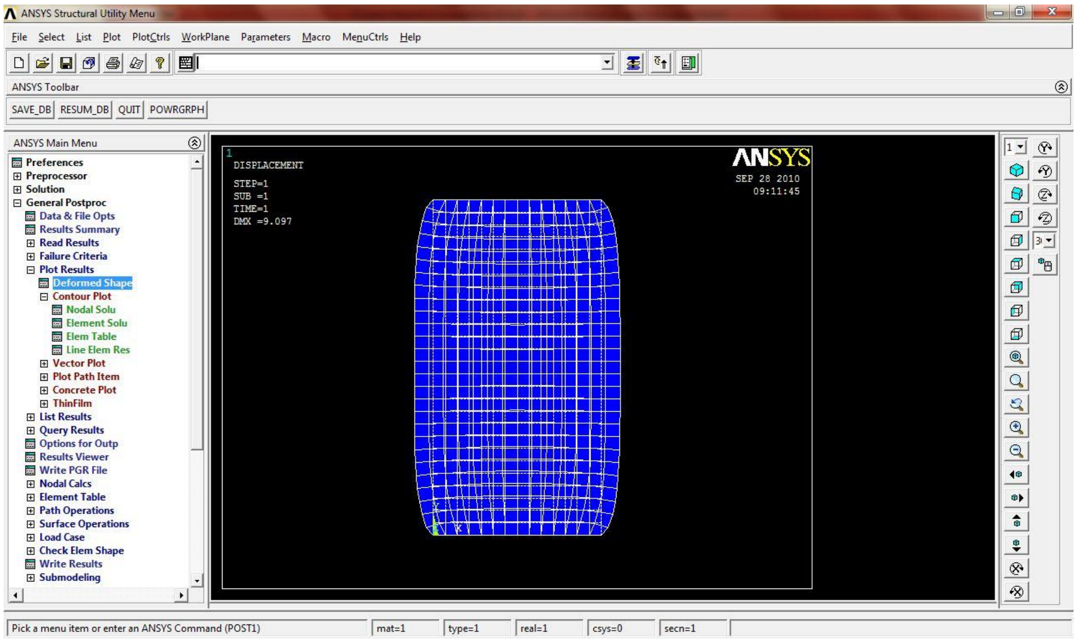
Apply Pressures to Upper and Lower membrane surface



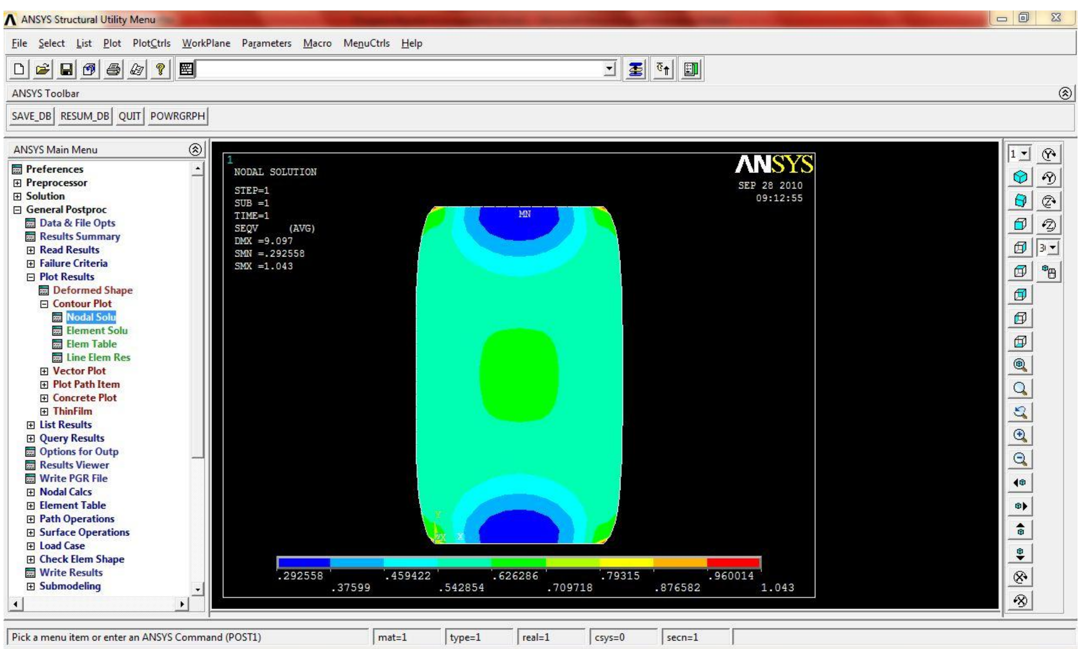
Geometry being solved



Iteration number acquired



Deformed muscle membrane



Nodal plot of von Mises Stress being plot

APPENDIX 4-10

Uniaxial Test Data of Neoprene Rubber

Strain mm/mm	Stress MPa
0.1338	1.0691e-002
0.2675	1.68e-002
0.3567	2.1383e-002
0.6242	2.9019e-002
0.8917	3.6656e-002
1.1592	4.1238e-002
1.4268	4.7347e-002
2.051	6.1093e-002
2.586	7.3311e-002
3.0318	8.553e-002
3.7898	0.11149
4.3694	0.13746
4.8153	0.1619
5.172	0.18939
5.4395	0.21383
5.707	0.23826
5.9299	0.26423
6.0637	0.29019
6.465	0.36656
6.5541	0.39252

6.6433	0.44292

APPENDIX 4-11

Biaxial Test Data of Neoprene Rubber

Strain mm/mm	Stress MPa
2.e-002	6.47e-003
6.e-002	1.0963e-002
0.11	1.6607e-002
0.14	1.8078e-002
0.2	2.2918e-002
0.31	3.0529e-002
0.42	3.5736e-002
0.68	4.5522e-002
0.94	5.3637e-002
1.49	6.747e-002
2.03	8.7116e-002
2.43	0.10122
2.75	0.11997
3.07	0.13862
3.26	0.15479
3.45	0.16998

APPENDIX 4-12

Shear Test Data of Neoprene Rubber

Strain mm/mm	Stress MPa
0.1034	1.1032e-002
0.1724	1.6547e-002
0.2828	2.3166e-002
0.4276	2.8958e-002
0.8483	4.1369e-002
1.3862	5.3779e-002
2.	6.619e-002
2.4897	7.667e-002
3.0345	8.9356e-002
3.4483	0.10259
3.7793	0.11432
4.0621	0.12548

APPENDIX 4-13

Volumetric Test Data of Neoprene Rubber

Strain mm/mm	Stress MPa
0.8847	1.5934
0.9127	1.208
0.9412	0.81496
0.9703	0.41369