Modal analysis of Pneumatic two Finger Robotic hand by Finite Element Analysis and Experimental Testing

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Abstract**-- The objective of the present work was studying the technique of modal analysis using theoretical, numerical and experimental methods .Two axis modal finger of pneumatic robotic hand was designed and built. The theoretical modeling was done by deriving equations of stress and deflection depending on the free body diagram of robotic clamp, finite element analysis was performed using Comsol Multi physics 3.5a software program. The modal testing was done by dial and pressure gauges. For each method dynamic stress and deflection were found, and the results from all three analyses were compared and proved that the rated deflection and stresses that calculated from the theoretical calculation make a good agreement with the results obtained from the finite element analysis and experimental testing. The acceptable maximum holding weight of designed hand was found to be 400g.**

Index Term**-- pneumatic hand, two axis finger, Comsol software, Finite Element Analysis.**

I. INTRODUCTION

Robotic grippers are the part of robots end effectors that have the capability to grasp definite objects and reposition it according to requirement. They are widely used for automated manufacturing, assembly, and packing. Grippers are actuated by various mechanisms which include mechanical, electrical, hydraulic and pneumatic drives. Among this the widely used one is the hydraulic grippers but most favorable one is pneumatic gripper [1].

Gob-Soon Kim, 2001 [2] designed a two-axis force sensor of robots finger using several parallel plate beams the derived equations for calculating strain in the beams in order to design the two–axis force sensor sensing element, the reliability of derived equations are verified by using FEA of the sensing element. Wang, 2002 [3] designed and developed the three-fingered gripper actuated by a linear servo actuator for precise speed and position control was capable of handling a large variety of objects. The above grippers can stably grasp objects, many of them can carry out by the force control of grasping direction but not known for grasping force. Higashimori, 2005 [4] discussed the design of the 100g capturing robot from the point of view of dynamic pre –shaping where all finger links make contact with the target object simultaneously, mechanical parameters were determined by mathematically formulating dynamic pre-shaping problem and experimentally. Ho Choi & Koc, 2006 [5] present feasibility test results of a flexible gripper design, a flexible gripper based on the use of compliant materials (i.e., rubber) with pneumatic inflation was designed, analyzed, built and tested. Parametric FE analyses were conducted to investigate the effects of process and design parameters, such as rubber material, pressure, initial jaw displacement and friction. Based on the FEA results, a simple, single rubber pocketed flexible gripper was designed and built. Feasibility experiments were performed to demonstrate and obtain an overall understanding about the capability and limitations of the gripper. He proved that objects with different shapes (cylindrical, prismatic and complex), weight (50 g–20 kg.), and types (egg, steel hemi-spheres, wax cylinders, etc.) could be picked and placed without any loss of control of the object. Biswal, 2010 [6] designed a two jaw actuated gripper which was different from the conventional cam and follower gripper in the way that controlled movement of the jaws was done with the help of pneumatic cylinders using air pressure, and the force and torque for the gripper have been calculated for different set of conditions. Aaron and Robert 2010[7] demonstrate a novel adaptive and compliant grasper that can grasp objects spanning a wide range of size, shape, mass, and position/orientation using only a single actuator. The hand is constructed using polymer-based Shape Deposition Manufacturing (SDM) and has superior robustness properties, making it able to withstand large impacts without damage. And also they present the results of two experiments to demonstrate that the SDM Hand can reliably grasp objects in the presence of large positioning errors, while keeping acquisition contact forces low. In the first, they evaluate the amount of allowable manipulator positioning error that results in a successful grasp. In the second experiment, the hand autonomously grasps a wide range of spherical objects positioned randomly across the workspace, using feed-forward control of the hand. Tian & Jia, 2011 [8] numerically studied two-finger grasping of deformable curve-like objects under frictional contacts. Deformation is modeled by a degenerated version of the thin shell theory. Several differences from rigid body grasping were shown. Under a squeeze, the friction cone at each finger contact rotates in a direction that depends on the deformable object’s global geometry. The magnitude of the grasping force has to be above certain threshold to achieve equilibrium, and the set of feasible finger placements may increase significantly compared to that for a rigid object of the same shape. Finally, the ability to resist disturbance was bounded in the sense that increasing the magnitude of an external force could result in the breaking of the grasp. Aaron & Robert 2011[9] examined joint coupling in under actuated robotic grippers for unstructured environments where object properties and location may not be well known. A simplified grasper consisting of a pair of two-link planar fingers with compliant revolute joints was simulated as it grasped a target object. The joint coupling configuration of the gripper was varied in order to maximize successful grasp range and minimize contact forces for a wide range of target object sizes and positions. They used various numbers of actuators in order to test performance for varying degrees of under actuation; they proved that an actuator for each gripper finger performs no better than a single actuator for both fingers. Fei Chen 2012 [10] was designed and built an intelligent robotic hand – i-Hand, which was equipped with multiple small sensors, designed and built for successful accomplishment of the assembly task, and also for human and robot coworker coordinated assembly. Mating connectors by robot, as an experimental case was studied to evaluate i-Hand performance. Naoki Saito 2012 [11] was examined a placing motion of a grasped object by a robot hand equipped with a flexible sensor on the finger, They derived dynamic model of the motion, The validity of the model and the effect of the sensor's flexibility were examined through simulation, then confirmed experimentally that the robot hand puts down the object without an excessive impact force using the obtained trajectory. Alberto Matthew 2012[12] introduced a principle to guide the design of finger form: invariance of contact geometry over some continuum of varying shape and/or pose of the grasped object in the plane. They presented a general technique to solve for finger form, given a continuum of shape or pose variation and a property to be held invariant. They applied the technique to derive scale-invariant and pose-invariant grasps for disks, and also explore the principle's application to many common devices from jar wrenches to rock-climbing cams.

II. Aim of the Research

The purpose of this work was design and analyzing the robot's hand for increasing the surface contact of grasping mechanism, easily detects the effect of grasp and gravity forces, light in weight, and more economy. It composed of two curved fingers using several plate beams made from low carbon steel, actuated pneumatically. In order to stably grasp an unknown object, the finger should detect the force of grasping direction and the force of gravity direction, and perform the force control using pneumatic actuator [2,4 ,5]. The precision accuracy of two finger robot hand can be estimated by non-linearity, repeatability, and relative error. The relative errors can be reduced by accurately locating the dial gauge of deflection [13].

The equations which were used for calculating the deformation and stress of the beams were derived, and these equations were used in determining the value of stress and deformation of designed robotic hand. The reliability of the derived equations was verified by performing a Finite Element Analysis in COMSOL Multi physics 3.5a software program for each part of the hand. The validity of the calculation condition of the approaching allowable holding mass was confirmed through computer simulation. The deflection obtained through this process was compared with theoretical analysis, and the deflections obtained from theoretical analysis were used to determine the attachment location of the dial gauge.

III. Materials and Methods

Modeling of the robotic hand

The Designed robot's hand consists of two fingers; they composed from four parallel plate beam, two links, two triangle support links, and a pneumatic actuator to transfer forces and moments from the actuator to the fingers. The amount of the moment is directly related to the supply air pressure which can be regulated by using pressure gauges. This hand can stably grip any object without the breakage or drop.

When a compressed air applied to actuator, in this case double acting pneumatic cylinder, advancing the piston leads to open the hand fingers by help of support and side links (Figure1). Generally when the pressure increases inside one chamber, the hand stretches in the axial direction but the actuator bends in opposite direction to the pressure increased chamber. Thus, the grip has two degrees of freedom; rotation and transportation of motions.

The deformation characteristic of robot hand depends on the type and position of the applied force, cross sectional area of beams, grip length, and type of the material. Non-linear finite element analysis is very effective to design suitable hand [14].

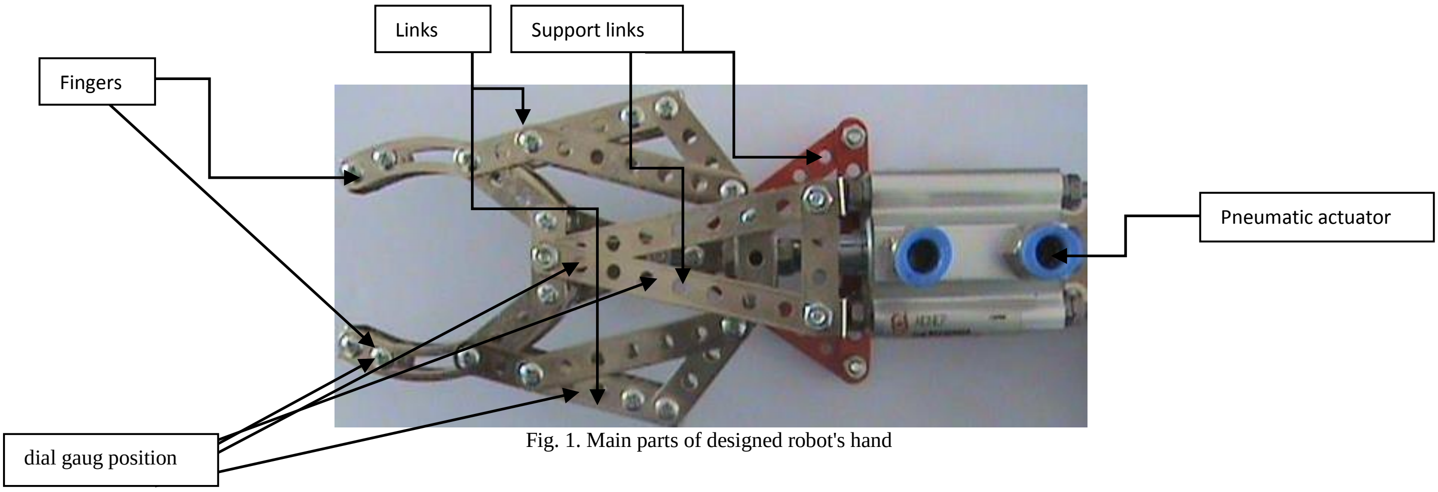


Fig. 1. Main parts of designed robot's hand

IV. THEORETICAL ANALYSIS [14]

During grasping an object, the force Fy (object weight) will act in the direction of gravity on both fingers, and the force F_p (due to air pressure) will act in the longitudinal direction of both fingers. The two fingers are symmetrical based on the horizontal center axis of the direction of applied force F_y, and vertical center axis of the direction of applied force Fp.

In the hand, as in fingers it composed of two symmetric structures of beams of the same size the amount of force F_{yy} on each side can be expressed as:

$$F_{yy} = \frac{F_y}{2} \qquad (1)$$

Where F_{yy} is y-direction force applied to the plate beam due to force F_y which representing the object weight. By the same way, the force F_{pp} can be calculated by:

$$F_{pp} = \frac{F_p}{2} \qquad (2)$$

Where F_{pp} is x-direction force applied to the plate beam due to force F_p which representing axial force of air pressure.

The free body diagrams for analyzing the deflection of each plate beam when the force F_y and F_p are applied on the hand and their effect are shown in fig. 2.

1. Deflection calculations

The Total extension (contraction) of each uniform beam in pure tension (compression) was found by:

$$y_1 = \pm \frac{F_P.l}{AE} \qquad (3)$$

The amount of bending of the beam when it is subjected to the vertical force (object weight) was found by:

$$y_2 = \pm \frac{(F_y.distance).C}{I} \qquad (4)$$

Then the total deflection (y) of each beam can be found by summing the equations (3) and (4).

So the total deflection for cantilever beams (Fig. 3. a, b, d) was found by

$$y = \frac{-F_P.L}{AE} + \frac{F_y.L.C}{I} \qquad (5)$$

Where: *y*- is the total deflection of the flat beams, F_p- axial force of air pressure in the x-direction, where F_p = Pressure × cross sectional area of the piston, *l*- total length of each part, *E*- modulus of elasticity, *I*- moment of inertia, A- cross sectional area of the flat beam., F_y- weight of the object (F_y = m × g) where m-mass of object, g- gravitational acceleration.

While for simply supported beam as shown in (Fig. 2. c), by assuming the load as intermediate the total deflection can be found by the equation

$$y = \frac{-F_P.l}{AE} + \frac{F_y.b.x}{6EIl}(x^2 + b^2 - l^2) \qquad (6)$$

Where: $b=l_4/2$, $x= l_3/2$, $l=l_3+b$.

According to the results of deflections, it found the maximum deflection due to pressure force is very small if compared with the effect of object weight, therefore it was neglected in stress calculations.

2. Stress calculations

Force F_y due to deflection *y* in a cantilever beams a, b, and d was related by

$$F_y = \frac{6yEI}{x^2(x-3l)}$$

stress σ and deflection *y* are related by

$$\sigma = \frac{Mc}{I} = \frac{F_y x}{2}.\frac{c}{I} = \frac{6yEIx}{2x^2(x-3l)}.\frac{c}{I} = \frac{3yEc}{x(x-3l)} = Ky \qquad (5)$$

Where $$K = \frac{3Ec}{x(x-3l)}$$

Also the force F_y due to deflection *y* in a simply supported beam c was related by

$$F_y = \frac{6yEIl}{bx(x^2+b^2-l^2)}$$

Then stress σ due to deflection *y* was related by

$$\sigma = \frac{Mc}{I} = \frac{F_y x}{2}.\frac{c}{I} = \frac{6yEIlx}{2bx(x^2+b^2-l^2)}.\frac{c}{I} = \frac{3yElc}{b(x^2+b^2-l^2)} = Ky \qquad (6)$$

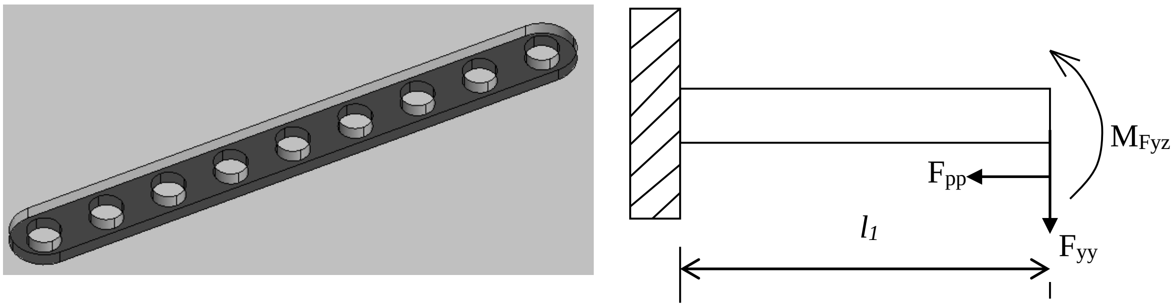
Where $$K = \frac{3Elc}{b(x^2+b^2-l^2)}$$

According to the equations (7) and (8), the experimental stresses of the flat beams were calculated.

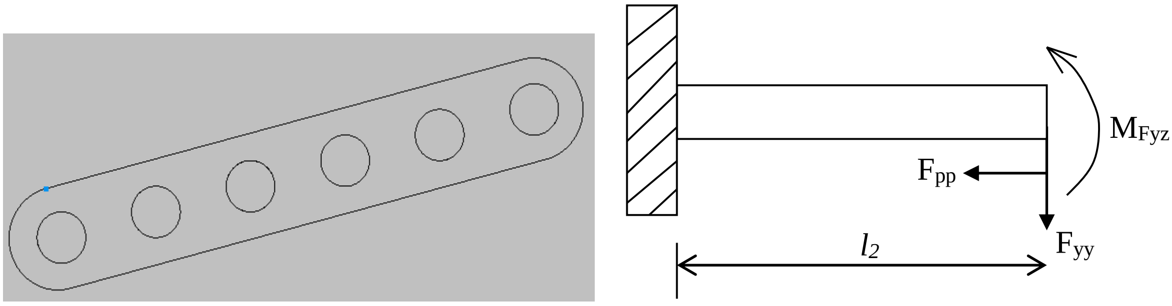
V. FEM SIMULATION

In order to confirm the stress and deflection which calculated through the theoretical analysis, the finite element analyses were performed on the flat beams of the robot hand. In this study three different values of pressure with respect to twenty different values of object weight were studied. In COMSOL Multi physic's software, which is one of the most popular commercial FEM software; for each part, von misses stress and total deflection were found by assuming the remained parts rigid. The flat beams properties; material: low carbon steel (AISI 1015 HR) with modulus of elasticity 200 GPa, yield and tensile strengths 190 and 340 MPa respectively, Poisson's ratio *v* = 0.3, density of 7850 kg/m³, cross sectional area 10 mm², inertias $I_{x1}=I_{x2}=6251mm^4$, $I_{x3}=I_{x4}=563mm^4$, length of l_1= 90 mm,

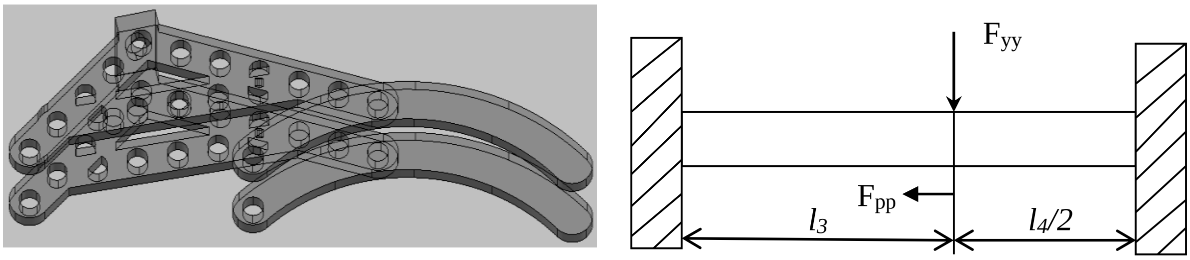
l_2= 60 mm, l_3= 90 mm, l_4=70 mm, the total mass of grip is 150 g, and a pneumatic double acting cylinder with 32 mm piston diameter, length of stroke 20 mm was used Figure 3 shows the FEM model of the robot grip.



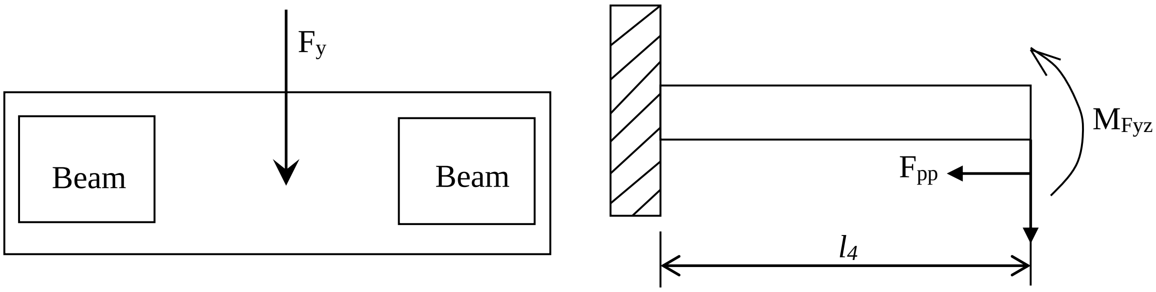
(a) Upper beam support link, part one



(b) Lower beam support link, part two



(c) Pressure transmitting link, part three



(d) Robot finger, part four

Fig. 2. Free body diagram of plate beams under the force F_y, and air pressure F_p.

VI. RESULTS

A. Theoretical results

Depending on equations derived from hand modeling the stresses and deflections for each part of the built hand the results were as follows:

Condition/Part No.		**Part I**		**Part II**		**Part III**		**Part IIII**	
P(bar)	**Max. holding mass (Kg)**	**σ(MPa)**	**y(mm)**	**σ (MPa)**	**y (mm)**	**σ (MPa)**	**y (mm)**	**σ (MPa)**	**y(mm)**
2	0.750	42.4	1.431	28.3	0.424	74.88	0.86	183	3.73
3	1.500	84.77624	2.861198	56.5	0.85	150	1.73	366	7.5
4	2.000	113.03	3.81	75.3	1.130	199.6	2.305	487.1	9.961
5	2.000 (failure)	113.04	3.813	75.35	1.131	199.65	2.306	487.16	9.962

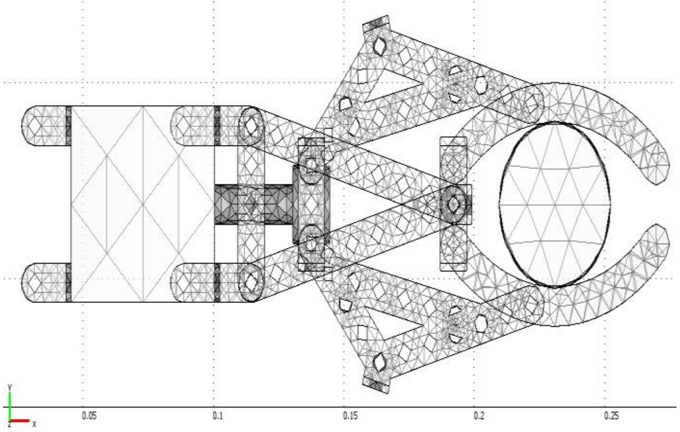
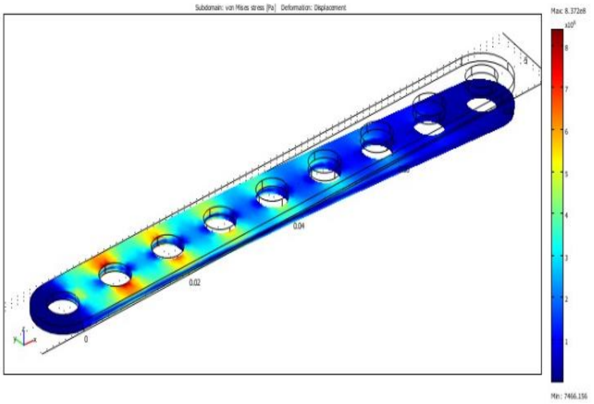


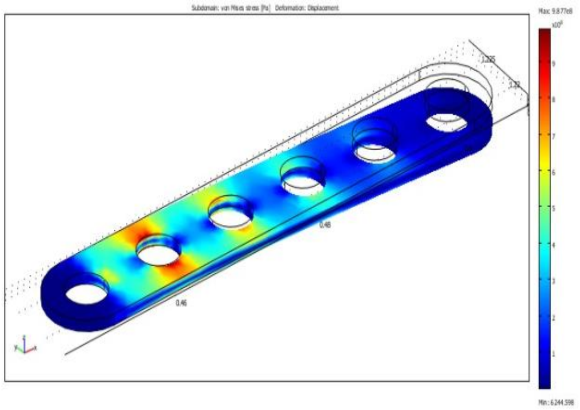
Fig. 3. Typical FEM analytical model of robot hand.

B. FEA Results

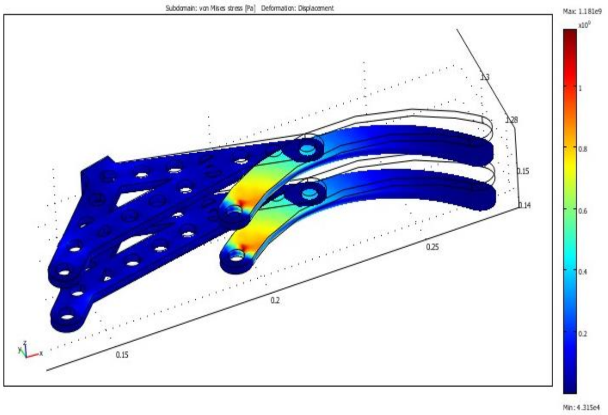
Figure 4, shows the results of maximum stress for each part at maximum weight and pressure (Failure point). Pneumatic pressure load varied from (2-5) Bar. Weight is directly related with the applied pressure load. It is clear that the maximum stress in part one, two, and four occurs near the fixed point of the link because they are cantilever. But in part three the load is intermediate which was 90 mm far from the fixed end, this makes the maximum stress occur at hinged point.



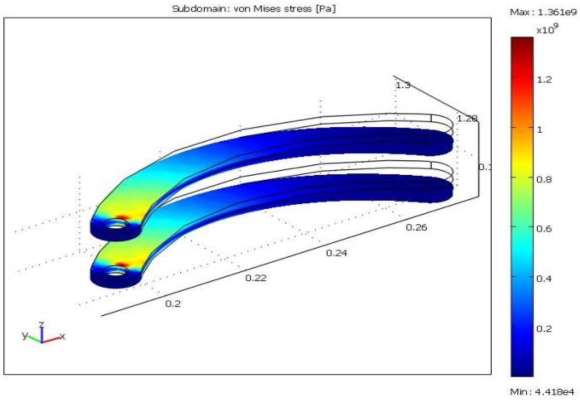
Part one



Part two



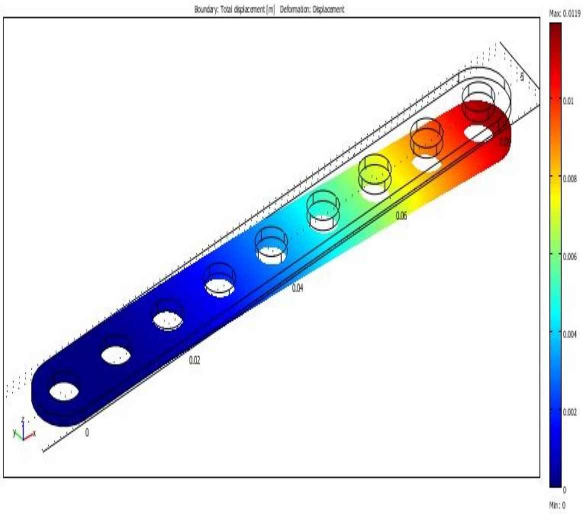
Part three



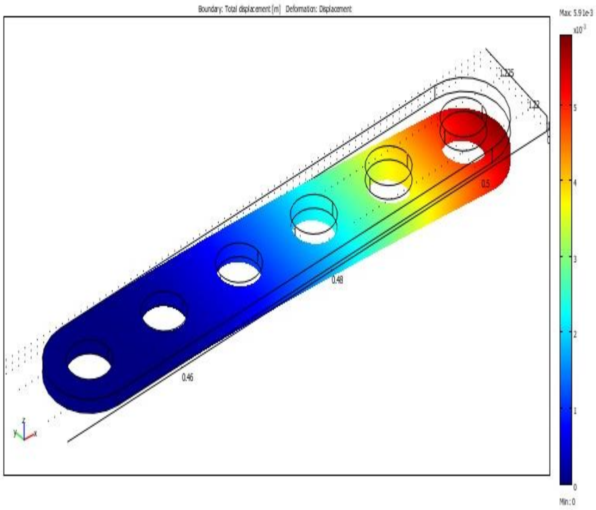
Part four

Fig. 4. Stress distribution at different parts (Failure point)

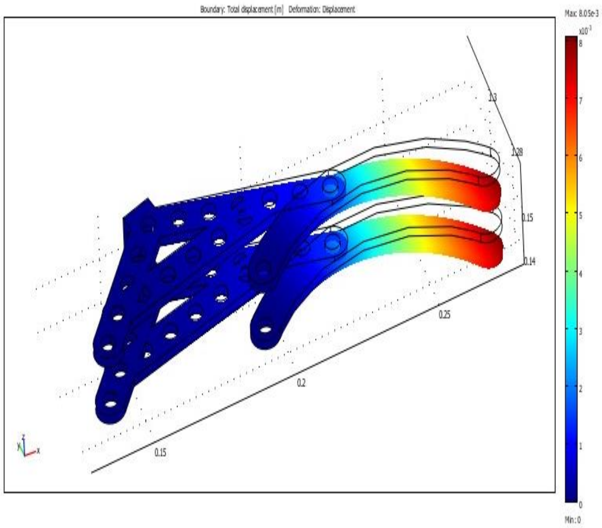
Figure 5, shows the maximum deflection results of each part in the same conditions. It found that the maximum deflection occurs in the position of applied load, which was the object weight



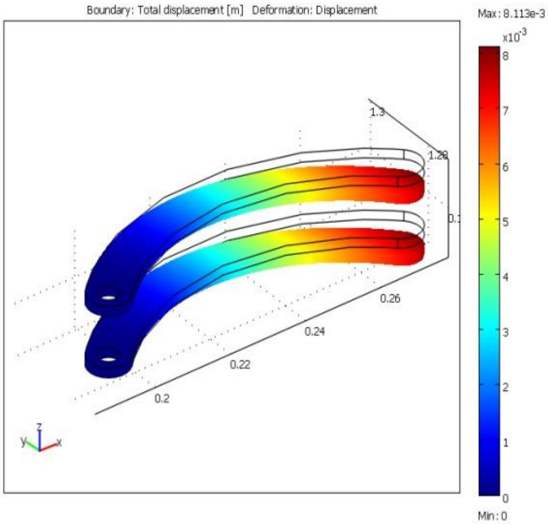
Part One



Part Two



Part Three



Part Four

Fig. 5. Deflection at different parts (Failure point)

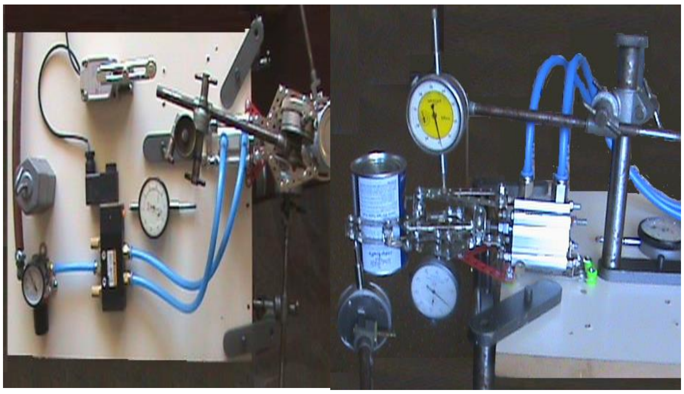
Supports links were designed to prevent deformation of the grip and to reduce stretching effect of pneumatic actuator. Pneumatic pressure was applied to the chamber, while pressure in other chamber was kept at atmospheric pressure.

C. Experimental results

Designed grip was built and tested by using twenty different object weights with different amounts of input pressure (2-5)bar . Four dial gauges were used, to indicate the value of deflection in four critical positions of the hand. The test started from a two bar of pressure input, because the fingers weren’t able to hold objects with less than this amount of pressure due to low grasping force. In this pressure the maximum holing weight was only 750g, with increasing pressure to three Bars, the weight is increased to 1500g, and in 4 Bar object weight reached 2000g without slippage. Failure of the grip was occurred in pressure input of five bar.

It found that grip can hold the maximum preferable object weight of not more than 400 grams, with a safety factor up to 2.

Detail of experimental instrument, and The position of dial gauges for indicating the amount of deflection for variable object weights are shown in Fig. 6-a, while the pneumatic circuit diagram is shown in figure 6-b.



Pneumatic circuit Installed dial gauge

Fig. 6-a. Experimental sketch of the grip.

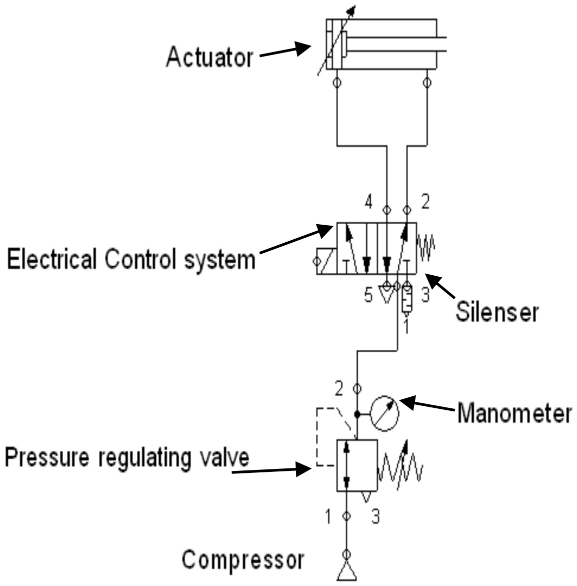


Fig. 6.b. Pneumatic circuit diagram of the grip.

VII. DISCUSSION AND CONCLUSION

By comparing the results of three analyses, a very good agreement was found to us (Figures 7, 8).

The figure 7 shows stress values (MPa) versus object weight (N) for theoretical, experimental and the Finite Element Analysis, is found that the stress is directly proportional to the object weight. But in part four the stress is much more than the other parts because it is near the weight. Also by comparing three methods it seen that the results shows a good agreement between theoretical and FEA, but with the experimental there is some difference; because in the hand there is support links which they prevent deflection and makes the stress to be distributed on them, while these supports are neglected in the theoretical and FEM calculations. In the other hand in experimental calculations the parts were assembled together while in FEM and theoretical calculations they assumed to be alone. while the figure 9 shows the values of deflections(mm) versus object weight(N) for theoretical, experimental and the Finite Element Analysis. It is clear that deflection is also directly proportional to object weight. From comparing results the same difference is found due to the same reason.

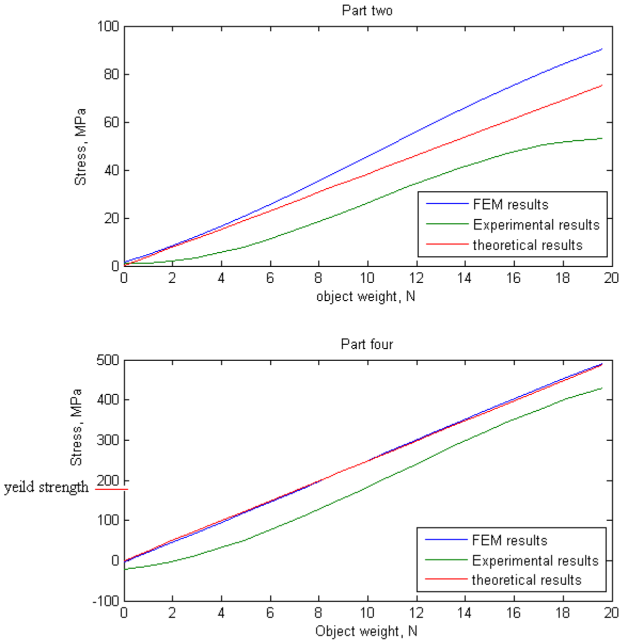


Fig. 7. Relationship between Maximum stress and object weight by three analysis.

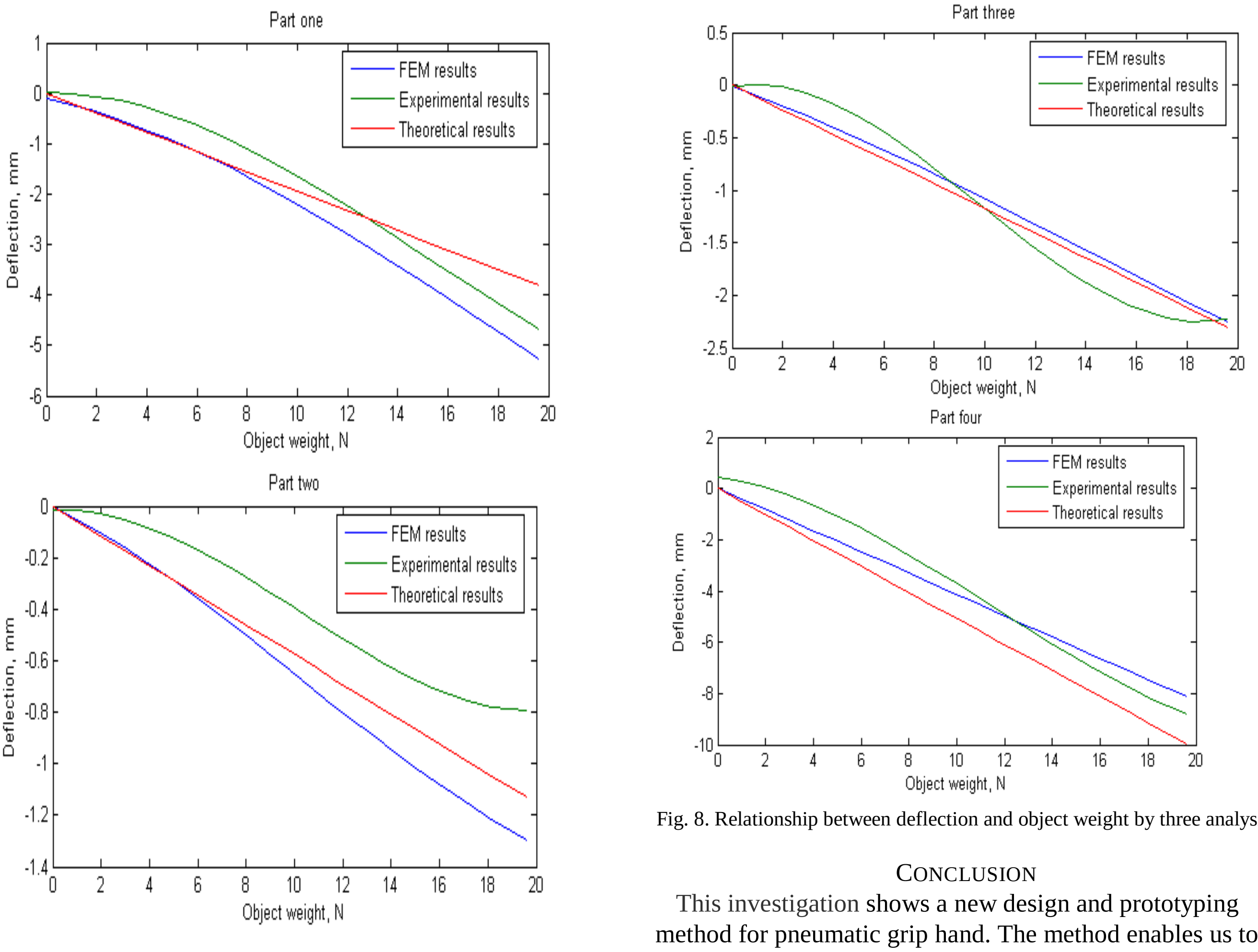


Fig. 8. Relationship between deflection and object weight by three analysis.

CONCLUSION

This investigation shows a new design and prototyping method for pneumatic grip hand. The method enables us to

- Design pneumatic gripper optimally and efficiently based on static analysis using non-linear finite element method.
- A Pneumatic robot hand with two degree of freedom which can be used to hold and transfer

objects in (Kg) not more than quarter of its working pressure in Bars.

- COMSOL Multi physics is dependable soft ware for the purposes of analyzing and design.
- Using finite element analysis is the best method for design purposes because it’s quicker and dependable method.
- In comparison between three deferent analyses the results are near to each other with error about to 5%, therefore the derived equations in this paper are judged to be useful in the stress and the deflection for designing the grip.

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