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Assessment of Minimum Normal Force to be Applied on a Fluid Filled Robot Finger to Lift an Object at Slip-less Condition

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Abstract: *In this paper the minimum amount of gripping force that should be applied to lift an object by a flexible, hyper elastic, fluid filled robot finger is analytically estimated. The finger is pre-stressed with a normal force to deform and get surface contact with the object to be manipulated .The deformation parameters such as contact width and normal deflection are obtained from the basic principles of mechanics. Considering slip, limiting shift and limiting stress of the finger material, the safe and workable region for object manipulation is determined. To validate this analytical finding, experimental load tests were conducted on the fluid filled silicone rubber finger and it has been found that the analytical findings are very close to the experimental results.*

Keywords: *Object manipulation, Coefficient of friction, Hyper Elastic material, Deformation, slip, Permissible stress.*

1 INTRODUCTION

Human hand is unrivaled in its ability to grasp and manipulate objects. The benefit of human hand gripping is that the fingers conform to the shape of the object and its surface geometry. While handling the object, the finger surface can feel the contact nature and the slipping tendency of the object. From this, it can increase the contact area so as to apply larger frictional force to avoid slipping. To emulate the human grasping by robot fingers a lot of study and analysis is being done.

Object grasping analysis uses different contact models [1] to describe the force transmission from the finger to object surface. The first contact theory was developed by H.Hertz [2] for linear elastic models, then it was modified by Pawluk and Hore [3].Then Sinha and Abel [4] proposed an elastic contact model for finger-object contacts in multi-finger grasping. Human finger is made of blood, bone and flesh tissues. The finger skin property is not of linear elastic nature, but it behaves like hyper elastic materials [5].

Jiyong Hu, Ding Xin and Rubin Wang [6] developed a finite element model based on the physiological structure of the fingertip to simulate the contact interactions between a fingertip and a flat plate. They analyzed the characteristics of the contact pressure distribution, strain energy density distribution, stress and strain distribution within the soft tissues. They showed that the soft tissues of fingertips are very sensitive to stimuli. To simulate the structure of human finger, robotists tried to model the robot finger in multi layer structure [7]. Considering this, a simple model was proposed by Winkler [8]. Selina, Mote and Rompel [9] modeled a liquid filled membrane model for the fingertip, based on the theory of elastic membrane. Berselli and Vassura [10] modeled a finger having rigid inside core, surrounded by an internal layer having communicating voids filled with fluid and an outer thin layer. This model showed less compressive stiffness in the finger.

From the above studies it is presumed that thin layered fluid filled robotic fingers could be more suitable to substitute human fingers. On that basis, a semi cylindrical fluid filled hyper elastic finger model has been designed and its deformation parameters have been evaluated with experimental results. The gripping ability of the finger is being determined using the finger deformation parameters and its material properties. In this paper the minimum amount of gripping force that should be applied to lift a load by the flexible robot finger is analytically found out.

2 FINGER MODEL

A semi cylindrical shaped soft finger model with adequate length and radius has been designed [11]. The finger model is made as a thin skin like hyper elastic outer wall filled with incompressible fluid, which uniformly distributes the applied force to the outer wall. The force-deformation relationship has been formulated from the basic principles of mechanics. The radius of the semi cylindrical finger is taken as 'R' and its outer wall thickness't'. The length of the finger is 'L' and for simplicity of calculation it is considered as unity. The Young's modulus of finger material is 'E', which varies with applied load .The finger model is placed against a rigid flat surface as shown in figure-1.

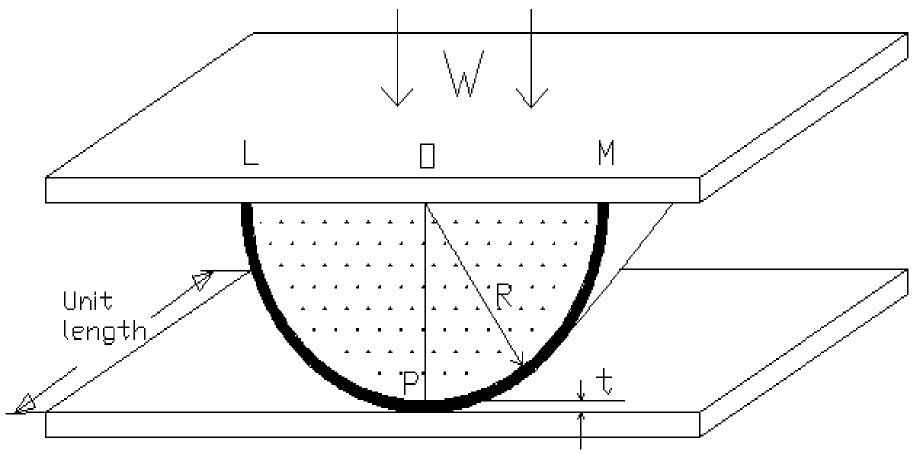

Figure 1. *Normal load action on the semi cylindrical cross section of the finger*

Over the cross section of finger, the normal load 'W' per unit length is acting. This causes compression of finger against the target surface and its vertical deformation is 'b'. Due to this compression, the pressure intensity of inside fluid increases to 'p'. This inside pressure acting on the free curved surface, creates a tensile stress in the finger wall and it elongates by 'δl'. The reduction in volume of the finger due to the compression is compensated by this elongation, with lateral bulging of the finger. At the balanced condition, a tangential force 'Ft' is acting along the finger wall at the fixed ends. Due to this tensile force, the wall thickness is reduced to 't_1'. The half contact width of finger with the object surface is 'w' and new radius of the free curved surface is 'R1', which is less than the original radius 'R'. The deformed finger model is shown in figure 2. Due to symmetry of the finger with respect to vertical axis, one quarter section is considered for analysis.

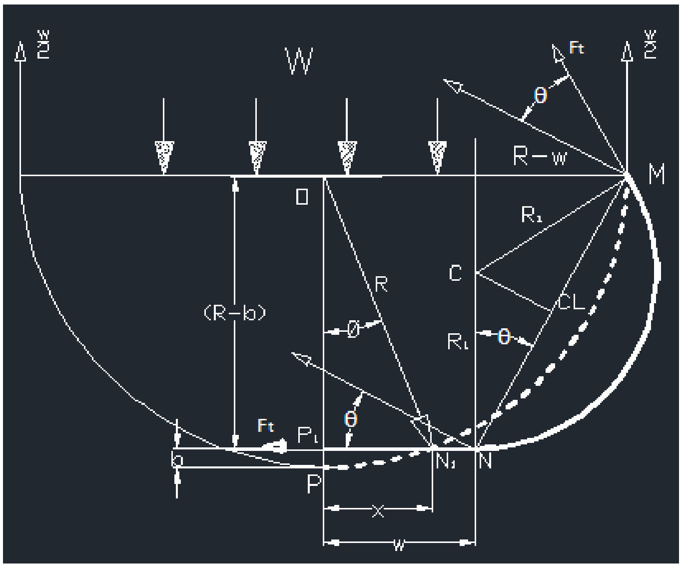

Figure 2. *Finger deformation due to Normal applied load*

3 GRASPING AND LIFTING

On the above deformed finger model, a tangential pulling force 'F' is applied along the contact surface as shown in figure 3. This applied force causes force imbalance on both sides of the finger with respect to the vertical axis 'OP'.

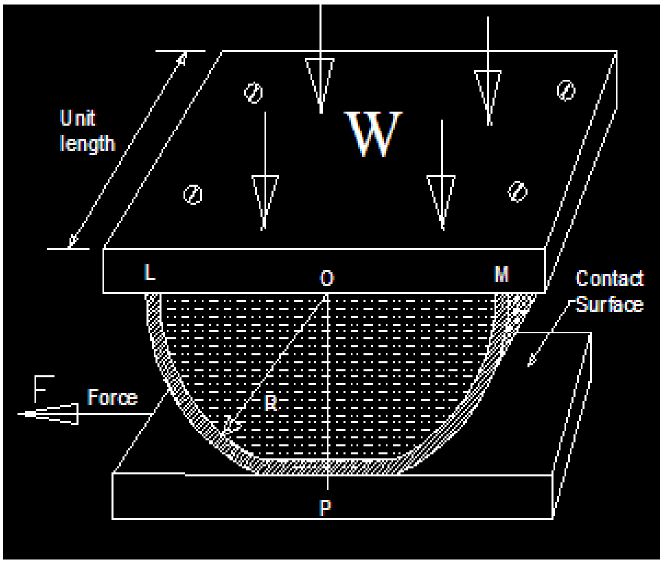

Figure 3. *Application of tangential force along the finger contact area.*

The moment caused by this force is balanced by a couple acting through the fixed ends creating a static balance. Since the fluid volume is constant, during deformation, some amount of fluid from the right side quadrant is shifted to left side. By equating the volume reduction in right side, to the gaining of left side, the volume balancing is achieved. Using deformation parameters of the model such as inside pressure, tangential force and contact width, the force balancing has been achieved through iteration using a computer program by varying the value of $'\theta'$. After reaching the force and volume balance, orientation of the deformed shape, its shift along the direction of force and stress in the finger are calculated. The finger model under balanced condition is shown in figure 4.

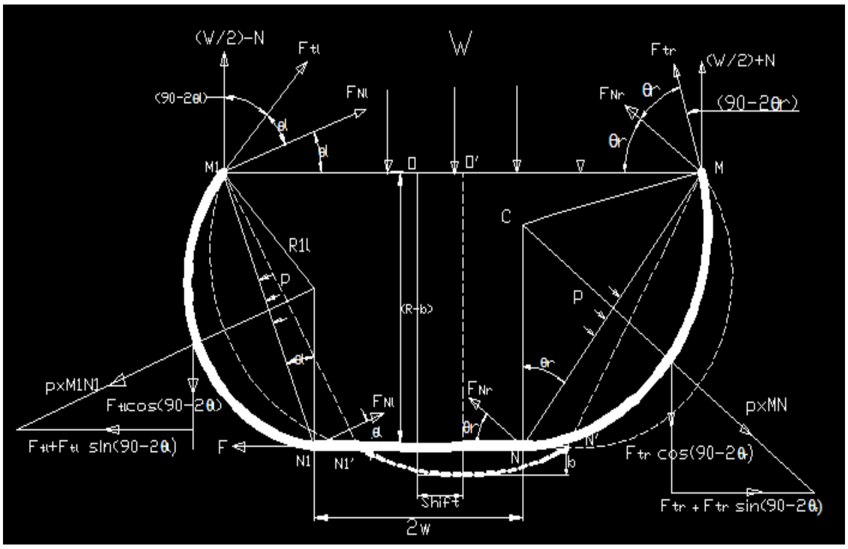

Figure 4. *Finger model under force balanced condition*

3.1. Finger Centre 'Shifting'

Because of application of the tangential force 'F' on the contacting surface, the centre point of the contact area shifts in the direction of force. It is measured from the shifting of the chord 'MN' to the new orientation. Due to this shifting, the tensile stress in the right side wall increases than the left side wall. The maximum tensile stress in the right side layer is calculated. Using the computer program, applying different normal load and tangential applied force, the corresponding centre shift and maximum stress in the finger was found out.

4 LOAD CARRYING CAPACITY TEST

Silicone rubber fingers similar to the analytical model were manufactured by liquid injection molding as per ASTM D 695 standard. The mean radius of finger was 10 mm, the outer wall thickness as 2 mm and the finger length was 30 mm. The inner cavity was filled with SAE- 30 oil, and the top opening was sealed by screwing a flat steel plate over it.

A special sliding table mechanism was designed and fabricated for testing purpose. It consisted of a top sliding table over a bottom rigid plate and in between them frictionless spherical steel balls are provided in horizontal semi cylindrical guide ways. They freely roll in the guide ways to provide sliding motion to the top sliding table over the bottom one. The sliding action of the top table is nearly frictionless. Over this table, the fluid filled hyper elastic robot finger was rigidly fixed using a face plate.

The test was conducted in a compression testing machine, supplied by AVJ Engineering Industries, India. It has the maximum loading capacity of 25 kN, with a least count of 0.01 N. A electronic strain gauge load-cell was mounted with its fixed top platform to measure the applied vertical load. One mechanical dial gauge was fitted between the top and bottom platforms to measure the vertical compression and the other one between the fixed and moving table to measure the shift of contact area of the finger. The accuracy of the dial indicators was ± 0.001 mm.

The finger specimen was placed over the moveable bottom platform and rigidly fixed. The finger mounted slide was tied to a string, to the other end of which a dead-weight hanger was attached and suspended through a pulley mechanism for loading purpose. By applying vertical load on the finger, grasping contact was created between the finger and the target surface. Figure 5 shows the test set-up.

Figure 5. *Slip and shift testing set up for robot fingers*

Then a tangential pulling force was slowly applied to the slide through the string by the pulley and dead weight arrangement. By increasing the dead weight the horizontal shift was noted down until the plate slipped. At slipping condition the tangential applied load and the applied normal load were noted down. The test was repeated for three times and the mean value was noted down. The experiment was repeated for different normal loads and the shift, slip details were noted down.

The tangential load at which slipping takes place is found from experiments and plotted against the applied normal load in a graph as shown in figure 6. The coefficient of friction between silicone rubber and steel surface is taken as 0.6 [9] and the tangential load at which slipping takes place is analytically calculated for the same applied normal load and is also platted against the normal load in the same graph. The coefficient of friction assumed, gives the slipping load, which is closer to that of experimental results.

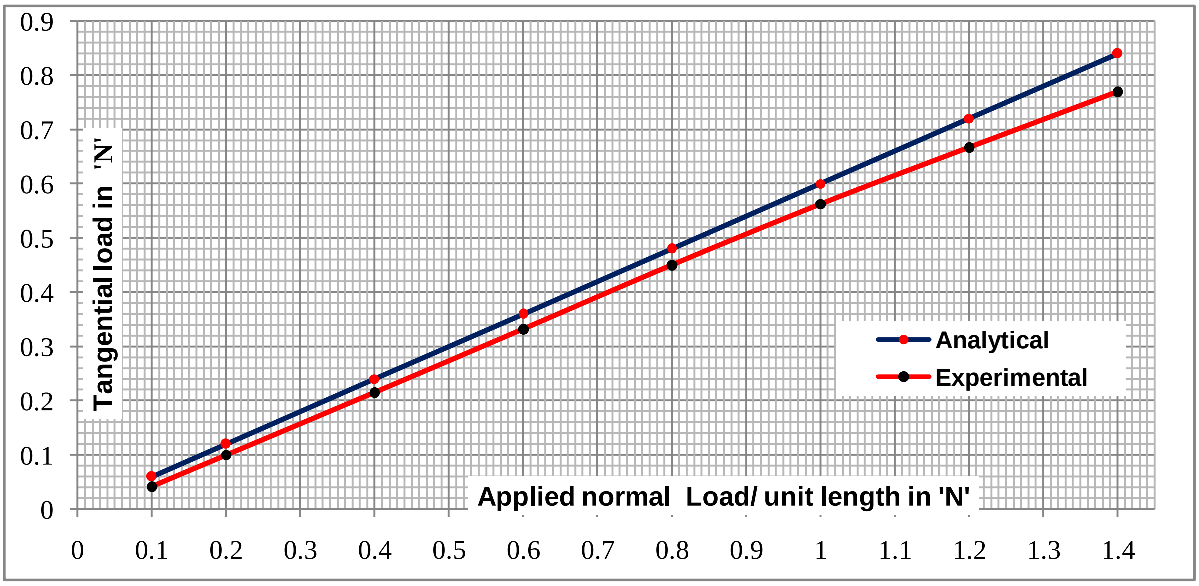

Figure 6. *Analytical and experimental slip plots*

5 RESULTS AND DISCUSSION

From the tabulated data the shift of contact area and the tensile stress in the finger outer wall are plotted against normal load as shown in Figure 7. The horizontal axis shows normal load in N/ unit length of finger and the primary vertical axis shows the shift of the contact area in ‘mm’. The secondary vertical axis gives the tensile stress in the finger outer wall in ‘N/square mm’.

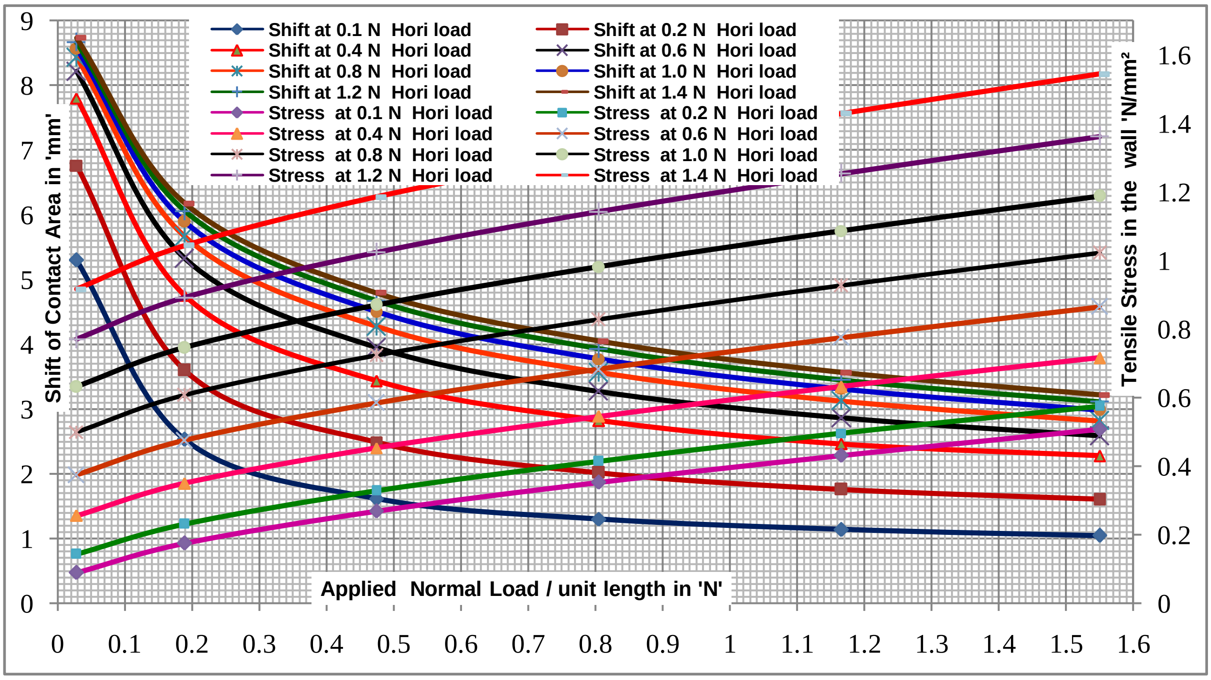

Figure 7. *Shift of contact area and tensile stress in the wall against Applied normal load*

From the above plot it is observed that:

i) Increasing normal load on the finger decreases the shift of contact width. But the rate of decrease is pronounced at lower normal loads and is almost steady at higher loads.

ii) The tensile stress in the finger wall depends on applied normal load and tangential lifting load and is almost linearly increasing.

In a robot object manipulation, the performance of the task depends on the correct orientation of objects by the robot fingers. Considering this, to limit the shift and the stress in the finger layer, suitable shift limit and stress limit are taken as 3.00 mm and 0.9 N/square mm respectively and these limits are super-imposed on this plot.

Based on the shift limit, the stress in the finger wall is calculated nalytically and plotted over the stress curve. The line joining these points is the stress boundary based on limiting shift. Based on the selected stress limits, the shift of the contact width is analytically calculated and plotted over the shift curve. The line joining these points is the shift boundary based on stress limit. Safe operating region is bound by these two boundary lines. This is shown in Figure 8. Any operating point lying outside these boundaries will result in either the stress being more than the limiting stress selected or the shift being more than the limiting shift selected.

Similar boundary lines are super-imposed on this plot based on analytical and actual slipping conditions taken from experimental results. The analytically obtained boundaries and the experiment based boundaries are found to be very close. Analytical boundaries are found to be giving slightly broader region, compared to that of the experimental one. The reason is that the coefficient of friction assumed may be slightly on the higher side. For hyper elastic materials the coefficient of friction varies over a range and hence the exact value to be used in the analytical treatment can be obtained from actual experiments.

The above plot shows that the load carried by the finger increases as the normal load increases up to a particular value (0.75 N in the case of a finger wih 2 mm wall thickness), beyond which the increasing normal load is found to have limited influence on the load carrying capacity. Actually there is a slight dip in load carrying capacity, because the stress in the finger wall increases due to increasing component of normal load, which is to be balanced by a decrease in the load lifted.

From this analysis , the minimum amount of normal force which is to be applied on the fingers to lift a particular tangential load (object) within the permissible shift and stress limit of the finger can be determined at slipp-less condition.

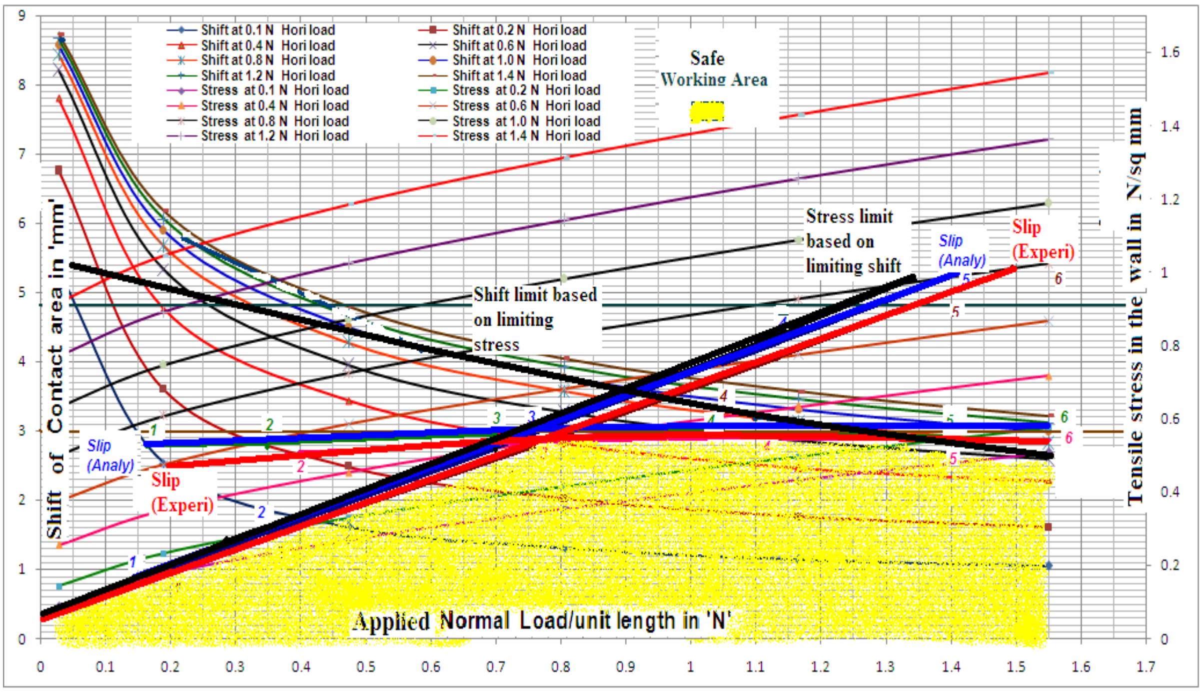

Figure 8. *Safe working area of the finger with 2 mm wall thickness*

6 Concluding Remarks

- The stress in the finger outer wall increases almost linearly with increasing normal load.
- The shift of the contact area decreases sharply first and remains almost steady, with increasing normal load.
- By super-imposing stress and shift limits on this plot, the boundary lines for operating limit is obtained.
- Load carrying capacity of the finger increases linearly with increasing normal load up to a critical value. Beyond this value, increasing normal load does not have much influence on the load carrying capacity
- It is judicial to operate the finger below the critical normal load.

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