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Fluid Filled Hyper Elastic Robot Finger Model With and Without Initial Pressure for Object Manipulation

[1,] P.Subramaniam , [2,] R.Marappan
[1,] *Department of Mechanical Engineering, Sengunthar Engineering College*
[2,] *Department of Mechanical Engineering, K.S.R College of Engineering*

ABSTRACT
A semi cylindrical shaped , hyper elastic, thin wall, fluid filled, soft robot finger model with adequate length and radius has been designed. While applying normal load, the deformation parameters such as contact width, vertical deflection and stress in the wall are analytically calculated. The procedure is repeated with addition of initial pressure inside the finger. It is found that the contact width and vertical deflection of the finger with initial fluid pressure are lesser and stress in the finger wall is more than those without initial fluid pressure. While object manipulation, these deformation parameters determine the load lifting capacity of the finger. To validate this analytical findings, experiments were conducted on fluid filled silicone rubber fingers with and with-out initial fluid pressure. The analytical results are found to be very close to the experimental results.

KEYWORDS: *Anthropomorphic, Finger deformation, Fluid filled robot finger, Hyper elastic material, Object manipulation, Silicone rubber, Semi contact width.*

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I. INTRODUCTION

An industrial robot is a general purpose programmable machine possessing certain anthropomorphic characteristics. The most typical anthropomorphic characteristics are found in the ‘robot arm’. The arm makes the robot ideally suitable to do a variety of production works like material handling, machine loading, spot welding, spray painting and assembly. The end of arm or end effectors is the bridge between the robot and the environment. The end effectors action will vary according to the task to be performed. The most important task is to grasp and hold objects, which are to be transported from one point to another. The end-effectors of a robot are designed to have several fingers, joints and degrees of freedom. Combinations of these factors give different grasping phenomena like human finger grasping [1].Two or three finger gripper is more popular in object grasping.

Soft contact interaction is important in robot object gripping. For that the robot fingertips are basically made to imitate the structure of human finger, which consists of soft epidermis and a cutis layer. The design of gripper and gripping force calculation is an important task in end-effectors design. The first elastic fingered robot hand was proposed by Asada and Hanafussa [2],[3]. Then Salisbury [4] attempted to develop a three fingered robotic hand. Since then many hand designs have been proposed ranging from rather simple devises to very sophisticated multi fingered hands such as the Utah-MIT hand [5]. In most of the previous models the experimental researchers have considered a hemispherical fingertip completely made up of homogeneous material. Later the fingers are synthesized by an internal rigid structure covered by a soft external epidermal layer. Selina, Mote and Rompel [6] modeled a liquid filled membrane model for the finger tip bulb based on the theory of elastic membrane. Berselli and Vassura [7] modeled fluid filled hyper-elastic models of outer continuous skin layer and an internal layer having communicating voids, which are hermetically sealed and filled with a viscous fluid. Xydas and Koa [8] developed a contact model and studied soft fingertip contact mechanics using FEM and validated the results by experiments. An analytical model for force distribution has been developed by Mirza, Hanes and Orin [9]. A method for calculation of additional grasping force required for stable power grasping of objects is developed by Ismail and Ellis [10]. To achieve human like grasping, still more work is to be done in robot soft finger area.

Hence an attempt to achieve humanoid grasping in robot fingers, a semi cylindrical, hyper elastic fluid filled robot finger has been modeled [11]. The deformation parameters such as semi contact width, vertical deflection and stress in the finger are analytically calculated without and with different inside fluid pressures and applied normal loads. The analytical results are validated with the experimental results.

II. FLUID FILLED FINGER MODEL

To simulate the structure of the human finger the geometry of 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. Fig.1 shows the cross section of a semi cylindrical finger model which has been modeled for the deformation analysis. The radius of the semi cylindrical cross section is 'R' and the outer wall thickness 't'. The length of the finger is taken as 'L'. For simplicity of calculation it is considered as unity. The varying Young's Modulus of the finger material is taken as 'E'. The inside cavity of the finger is filled with incompressible fluid at atmospheric pressure.

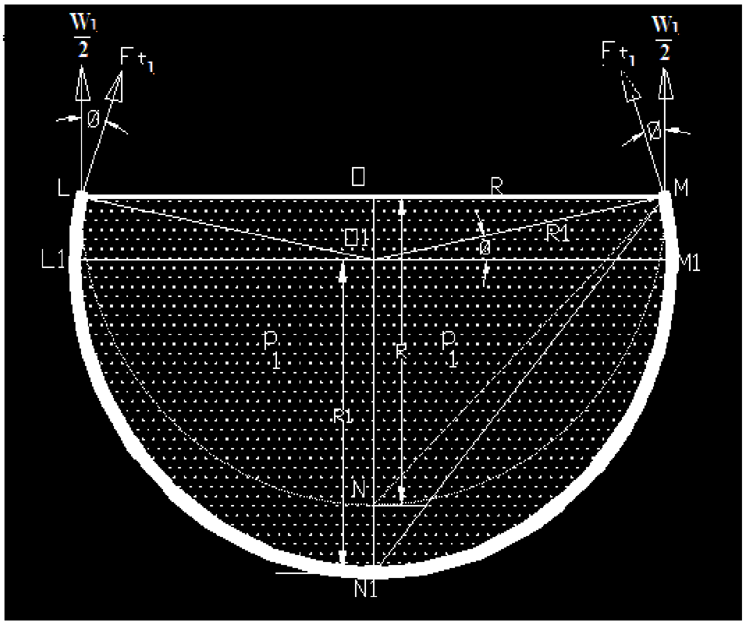

Figure.1 Hyper elastic finger deformation due to initial pressure

To increase the internal pressure, some more amount of fluid is pumped inside and sealed. It increases the volume and the force exerted on the finger wall. The outer layer is stretched to accommodate the additional volume of fluid and at equilibrium condition, the new radius is 'R_1 and the centre shifts downwards. The outer wall thickness reduces to ' t_1'. From the fig.1 the angle MO_1M_1 is 'Ø'. The tangential force 'F_{t1}' which is acting at point 'M' is at an angle of Ø° with vertical.

The pressure intensity of inside fluid is taken as 'p_1'

So, the total force acting on the finger, $W_1 = p_1 \times 2 \times R$.

Due to this load, the tensile reaction at fixed end points L and M is $\frac{W_1}{2} = p_1 \times R$

As the geometry is symmetrical about vertical axis, only one quarter of the model is considered for analysis.

The elongation of outer wall due to this tensile force , $\Delta l = \frac{W_1 l}{2 \times t \times 1 \times E}$

Before the deformation it's curve length $l = \frac{\pi \times R}{2}$

Now the new curve length $l_1 = l + \delta l$ -------------------(1)

From the geometry of the deformed finger new curve length $= \frac{\pi R_1}{2} + (R_1 \times \emptyset)$-----------(2)

Equating (1) and (2), $l + \delta l = \pi \frac{R_1}{2} + (R_1 \times \emptyset)$

Also $R_1 = \frac{R}{\cos \emptyset}$

So $l + \frac{W_1 l}{2 \times t \times 1 \times E} = \frac{\pi R}{2 \times \cos \emptyset} + \frac{R}{\cos \emptyset}(\emptyset)$

Then , $(\frac{l}{R} + \frac{p^1 l}{t E}) = \frac{\pi}{2 \cos \emptyset} + \frac{\emptyset}{\cos \emptyset}$

Using a computer program, by iteration the exact value of 'Ø' is estimated for a particular initial pressure.

The vertical centre shift $'OO_1' = R \times tan\emptyset$

Area of the deformed quarter section $A_1 = \frac{\pi R_1{}^2}{360} \times (90+\emptyset) + (\frac{OO_1}{2} \times R)$

Also $t_1 = \frac{l \times t}{l_1}$

Then, the initially pressurized model is placed on a thick, flat plate and a vertical load 'W_2 / unit length' of finger is applied over it. Now the fluid pressure is further increased and the model deforms until a force balance exists as shown in fig. 2. The hyper elastic outer wall undergoes a radial deformation and an elastic linear expansion creating more space to accommodate the displaced volume of fluid due to radial compression. The vertical deflection of the model is 'b' and the radius of the curved sector from the centre 'C' is 'R_2'. It has the contact width 'w' with the target surface.

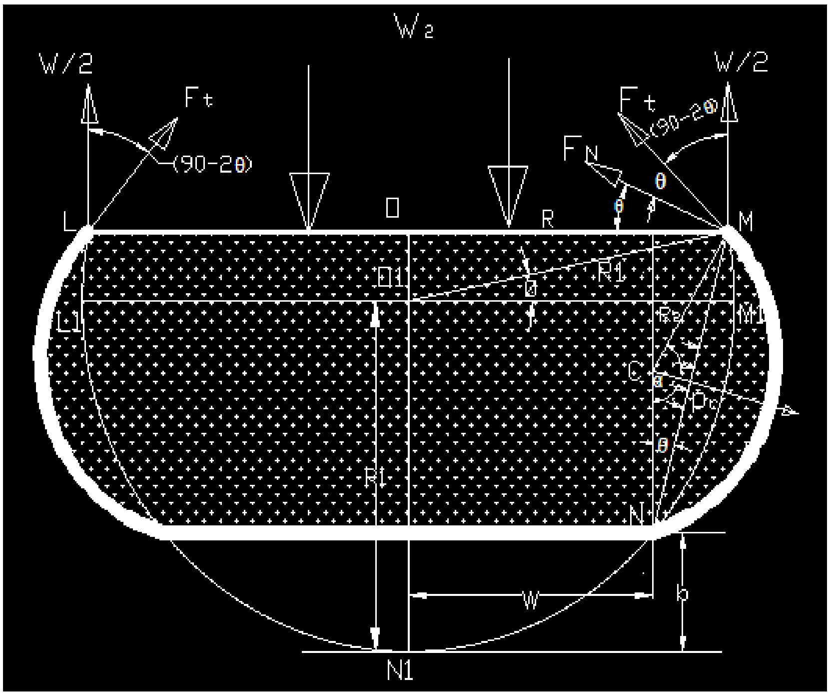

Figure 2 . Finger deformation at equilibrium condition due to initial pressure and additional normal load

The area of quarter section after deformation is

$$A\,(deform) = w\,(\;R_1 - b + OO_1) + \frac{(R-w)\,(\,R_1 - b + OO_1)}{2} + \frac{R_2{}^2}{2} \times (\alpha - \sin \alpha)$$

where '2α' is the subtended angle of the circular sector MN at the centre 'C

But, before the load application the un-deformed area is

$$A\,(un\;deform) = A_1 = \frac{\pi R_1{}^2}{360} \times (90+\emptyset) + (\frac{OO_1}{2} \times R)$$

Since the fluid is incompressible, the volume before and after deformation remains same. It is assumed that the friction at the contacting surface is negligible and hence not taken in to account for the deformation calculation.

At equilibrium condition, the total downward load $'W'$ is balanced by the reaction forces $\frac{W}{2}$ at both ends. The deformed free-body is tangential to the bottom plate at the contact point and is inclined to the top horizontal plate. Due to linear elongation of the outer wall, its thickness 't_1' is reduced 't_2'. If 'p_r' is the total fluid pressure, then the thrust force acting on the free wall will be equal to the pressure multiplied by projected area 'MN'.

That is $F_N = p_r \times MN \times 1.$

At each end the reaction force is $\frac{F_N}{2} = \frac{p_r \times MN \times 1}{2}$ in the direction normal to $'MN'$.

The component of this force along a line, tangent to the free wall at the tip has to balance the force due to elongation of the outer layer.

Force due to elongation of the hyper elastic wall is $Ft = \frac{A \times E \times \Delta l}{l}$

where 'A' is the area of cross section, 'E' the Young's modulus of the material and 'l' its length and $'\Delta l'$ its elongation.

$\frac{W}{2}$ and $Ft\,cos\,(90 - 2\theta) + (p_r \times w)$ will be equal under equilibrium condition, where 'θ' being the angle between the direction of pressure force and outer wall tensile force .

For a random value of 'b' the difference between $\frac{W}{2}$ and $Ft\,cos\,(90 - 2\theta) + (p_r \times w)$ is obtained. This difference is minimized to fourth digit through iteration using different values of 'b' through computer program and the load carrying capacity $\frac{W}{2}$ is estimated . For this value of 'b' the contact width. and stress in the finger layer are estimated and recorded.

III. FINGER LOAD TEST

Silicone rubber fingers similar to the analytical model were fabricated by liquid injection molding as per ASTM D 695 standard. The mean radius of finger is 10 mm, thickness of outer wall as 2 mm and finger length is 30 mm. The top opening is sealed by screwing a flat steel plate over it. At this cover plate one way valve is provided through which the inner cavity is filled with SAE-30 oil. The test is conducted in a compression testing machine. The machine set-up is shown in Fig.3. Quality finger-print ink is applied over the finger surface. The finger specimen is placed between the movable and fixed steel platforms. A recording paper is placed between the finger surface and the top target platform. As the recording paper is very thin, the influence of its thickness is negligible. Initial contact between the specimen and top platform is determined, when force reading in load cell indicator shows as 0.01 N.

Figure. 3 Finger compression test rig

While loading, the finger is compressed against target surface, deforms and leaves a vivid print of its contact area over the recording paper. Fig.4 shows the sample prints of finger contact area at different initial pressures and applied normal loads.

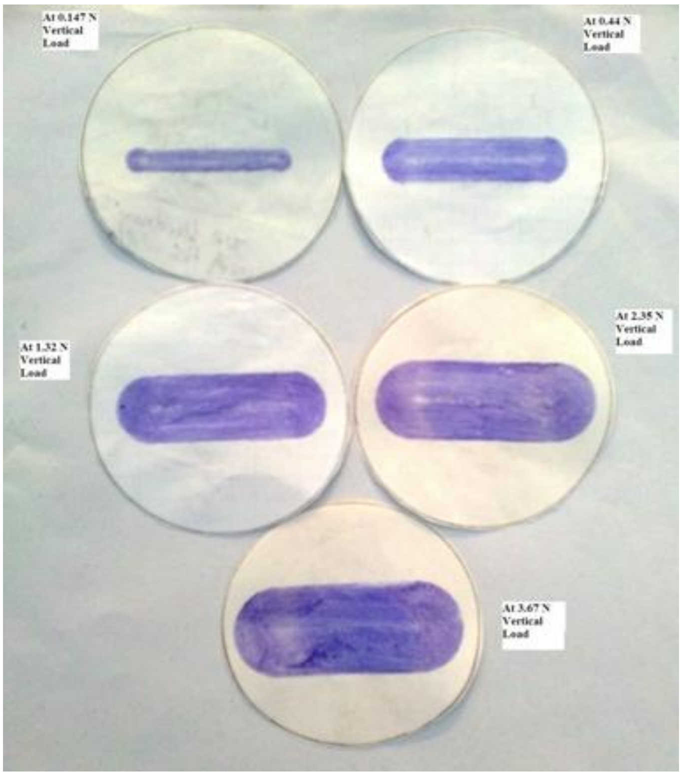

Figure 4 Sample prints of finger contact area

The contact width is measured by scanning the recorded image. The applied normal load is measured by Load-cell, which is mounted above the top platform and the vertical deflection is measured by a mechanical dial indicator fitted between the platforms. The accuracy of the dial indicator is ± 0.001 mm. The test is repeated three times and the average values are noted. The tests are conducted at atmospheric pressure, 0.005 N/sq mm, 0.01 N/sq mm and 0.02 N/sq mm gauge pressures of the inside fluid. The results are noted down.

IV. ANALYSIS AND DISCUSSION

The results of analytical and experimental findings are plotted in figs 5, 6 and 7 and they are discussed below.

Fig. 5 shows the semi contact width of the finger against the applied normal load at no initial pressure condition, 0.005 N/sq mm, 0.01 N/sq mm and 0.02 N/sq mm initial pressure conditions of the inside fluid. From this, it is inferred that the semi contact width increases with increasing normal load. The rate of increase is initially high and almost linear at higher applied normal loads.

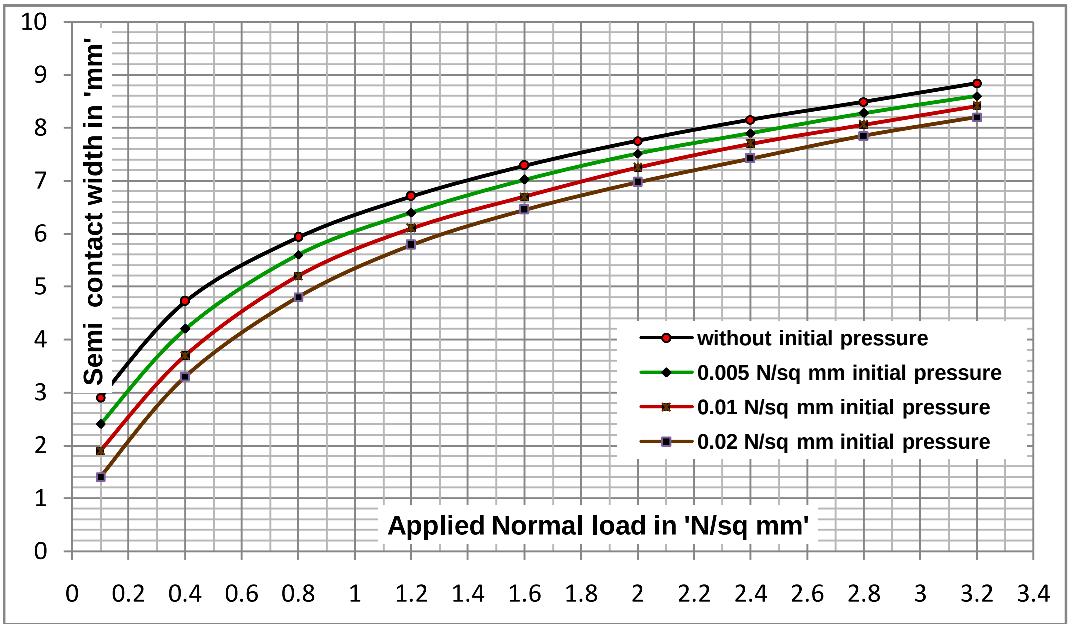

Figure 5 Variation of Semi contact width against applied normal load of fingers with and without initial fluid pressure

But it reduces with increasing initial fluid pressure. When additional fluid is introduced inside the finger the outer wall expands linearly to accommodate the excesses volume and the centre shifts downwards. This increases the radius of curvature of the outer wall. Now the tangential reaction at the fixed end increases and makes an angle with vertical. When a normal load is applied on the finger , the vertical component of the tangential reaction due to initial pressure resists the applied normal load. Thus the total normal load acting on the finger is reduced, which causes lesser contact width against the target surface than that of the finger with no initial pressure for the same applied normal load. The analytical results closely follow that of the experimental results. The deviation marginally reduces with increasing normal load. Similar trends are observed in vertical deflection against normal loads as seen from fig. 6. Vertical deflection and corresponding contact width are inter-related.

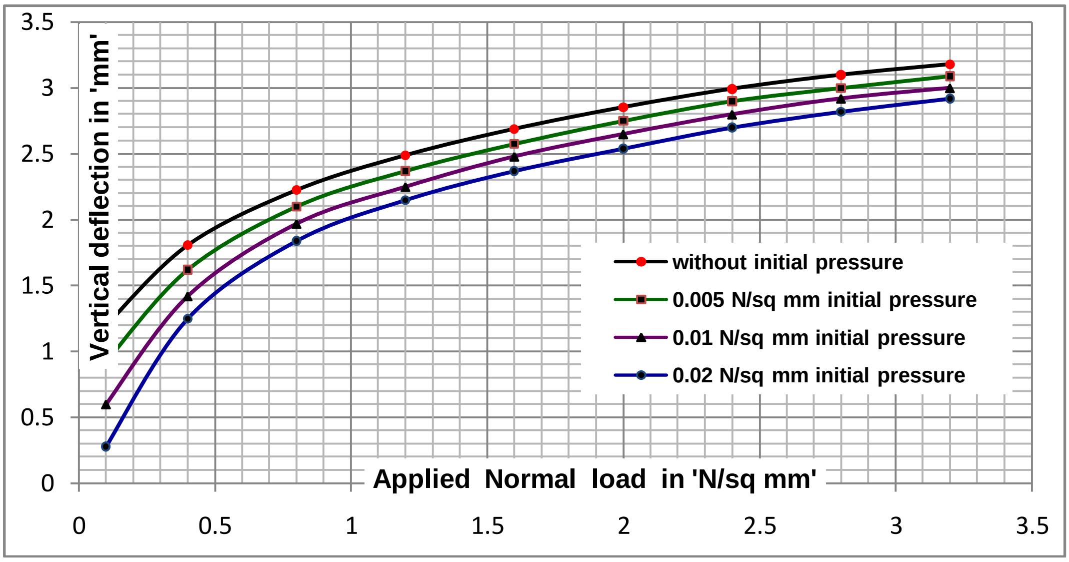

Figure 6 Variation of vertical deflection against applied normal load of fingers with and without initial fluid pressure

Fig. 7 shows the dependence of the tensile stress in the outer wall on the applied normal load. Stress increases linearly with applied normal load , when there is no initial fluid pressure. But when initial fluid pressure is introduced, the stress in the finger wall increases exponentially with increasing normal load. This exponential increase in the tensile stress with increasing normal load is due to the fact that the horizontal thrust increases resulting in larger elongations, but without much support to balance the vertical load.

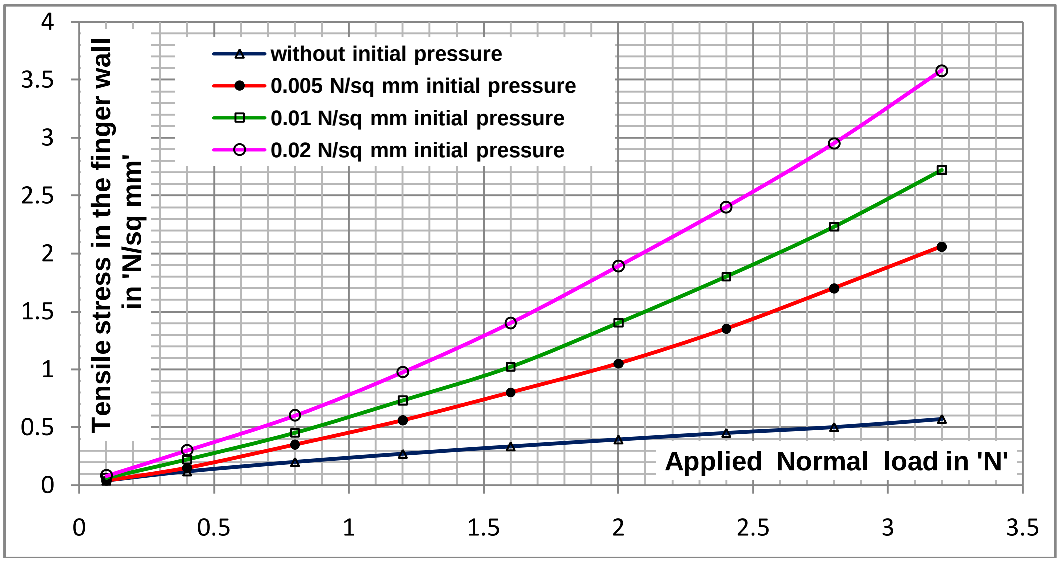

Figure 7 Variation of tensile stress in the finger wall against applied normal load of fingers with and without initial fluid pressure

In object grasping, the gripping force is the product of finger contact area and the pressure intensity of the inside fluid. In the case of initially pressurized fingers the contact area and the vertical deflection are found to be less than that of the fingers having no initial pressure, for the same applied normal load. So the gripping force exerted is less in the case of initially pressurized fingers. Also the tensile stress in the finger wall is more than that of the finger having no initial pressure.

V . CONCLUDING REMARKS

- The deformation parameters such as semi contact width, vertical deflection and tensile stress in the finger wall are calculated for various applied normal loads with-out and with initial pressure values.
- Experiments are conducted to validate the analytical findings
- The introduction of initial pressure in the finger decreases the contact width and the vertical deflection.
- The tensile stress in the finger wall increases exponentially with increasing applied normal load.
- The analytical results closely tally with the experimental results.
- Introduction of initial pressure in the trapped fluid decreases the contact width , which in turn decreases the load carrying capacity of the finger.
- When initial fluid pressure is introduced inside the finger, the stress in the finger wall increases exponentially with increasing normal load. This also brings down the load lifting capacity of the finger.

So, introduction of initial fluid pressure inside the finger causes un-desirable effect on the load lifting capacity of the robot finger.

VI. ACKNOWLEDGEMENTS

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AUTHOR'S BIOGRAPHY

P.Subramaniam has completed his B.E Degree in Mechanical Engineering at Government College of Technology,Coimbatore and his M.E Degree in Computer Aided Design at Government College of Engineering,Salem. He has 18 years of Engineering College Teaching experience. His area of interest are Engineering design , Robotics and Contact mechanics

R.Marappan has studied his B.E in Mechanical Engineering at P.S.G College of Technology, Coimbatore and his M.E Degree in Engineering Design at Indian Institute of Technology, Madras. He has 35 years of Teaching experience and guided more than 10 Ph D scholars. His area of interest are Engineering design , Tribology, Contact mechanics , Robotics.