Materials Science Research India Volume **3(2),** 149-156 (2005)

DESIGN AND MODELLING OF A MODULAR BORE GAUGE AND FEM ANALYSIS FOR EVALUATION OF ITS LIFE CYCLE

F. Farhani*, B. Hemati and P. Boland

Mechanical Engineering Department,
Iranian Research Organization for Science and Technology (IROST), Tehran (Iran)

(Received, 29 October, 2005)

ABSTRACT

Accurate measurements and the associated instrumentation play vital role in the development of different industries. It is generally accepted that without special purpose measuring instruments, it would be impossible to repeat the work done by another individual in any field of research. Application of gauges as a substitute for the direct measurement methods can significantly enhance the manufactured parts verification process, both in terms of speed with which the process is performed, and also the desired accuracy with which the process must be done. On the other hand, the direct transfer of measurement data from the gauge to computer can further improve and reduce the tedious process of Statistical Process Control (SPC). To fulfil the above goals, we have used CAD software to perform a feasibility study for the design and modelling of various modular bore gauge mechanisms, considering the requirements of a precise measurement instrument. We studied several mechanisms, and selected the best mechanism for this purpose. Using FEM tools, a fatigue analysis was then performed to analyze a critical part in the instrument, which experiences the maximum fatigue due to continuous operation. The life cycle calculations for this critical part show that our design and analysis process has been satisfactory, and that the method can be used for the design of precise modular bore gauges.

Keywords*:* Measurement instruments, CAD software, modular bore gauge, FEM, Fatigue strength.

INTRODUCTION

Metrology is the science of measurement, and measurement is the language of science. Measurement is the comparison of given dimension obtained through a physical test with an assumed (assigned) reference unit. The result of measurement expressed as a number, shows the ratio of the unknown quantity to the selected measurement unit. This comparison is performed with the help of a measuring instrument[1].

In the present day industrial world it is necessary to produce standard equipment, which can be repaired by replacement of the faulty parts. In addition, to keep cost low it is desired to have uniform products[1, 2].

Every industry has a department which is responsible for the quality and product control. Concepts of Total Quality Management (TQM) in the present day industries, demonstrates the important fact that the inspection process begins with the worker producing the items under consideration[3]. On the other hand, in many industries the system of “piece-part paying” is followed, in which a worker’s pay is estimated on the basis of the number of parts completed by him. Therefore, it is important to have gauges to identify the products that pass the standard qualification requirements, and also decrease the production time while increasing the reliability of the measurements[2, 3]. On the other hand, when a large number of parts with closed tolerances are to be produced, and the products have to be inspected by semi-skilled persons, it is desirable to use gauges instead of direct measurement. The gauges can be easily interfaced with computers, resulting in more efficient Statistical Process Control (SPC)[3].

General requirements of a measuring instrument

In the process of designing a measuring instrument, the knowledge of features and characteristics of the particular measuring instrument can result in fabrication of an instrument that can produce measurements with minimum errors.

A measuring instrument, depending on its application, has unique characteristics. However, the following parameters are the general requirements for any measuring instrument:

i) Accuracy and Precision

Accuracy of a measuring instrument is the difference between the mean of certain number of measurements of a quantity and the actual value of the measured quantity. The precision is the distribution population around the mean value. In other words, the measuring instrument should be able to repeat the same measurement with a high distribution population around the mean value of the measured value, and the mean value of measurements should be equal to the actual value of the measured quantity[2].

ii) Sensitivity

Sensitivity is the slope of variation of the output to the variation of the input, and higher sensitivity results in higher precision[1].

iii) Resolution

Resolution is the smallest measurable quantity, which a measuring instrument can detect and measure with a high degree of reliability.

iv) Repeatability

Another important parameter for a measuring instrument is its ability to return the same measurement results at different times or with similar inputs. This capability diminishes with time. In mechanical instruments this diminishing in repeatability is due to increased play between the sliding parts or bolt and nut, and in electrical instruments it is due to increased levels of temperature and noise[1].

v) Measurement Range

It is the difference between the maximum and the minimum value detectable by the measuring instrument[2].

Specific design parameters for a bore gauge

The following specific design parameters are important as far as a bore gauge design is concerned:

- Good resistance under severe operating conditions,
- Watertight- resistant against coolant, soap water solution and chips produced as the result of machining,
- Resistance against shock and impacts,
- Data Storage Capability and data transfer for Statistical Process Control (SPC),
- Simple to use- the operator can use the instrument without prior experience and with ease and without error.

Transducer

Today, electrical devices are used extensively in the measuring instruments. Almost every electrical property (resistance, capacity, induction coefficient, simple on-off switching) can be used in various amplifier circuits, and for performing linear measurements[4]. Transducers are classified as Contact and Non-contact types. Optical and Eddy Transducers are of Non-contact type, and Half-bridge Transformers (HBT) and Linear Variable-differential Transformer (LVDT) are of Contact type. The important parameters for selection of a transducer are size and cost[5]. On this basis we have selected LVDT for our work. The specifications of LVDT are given in Table - 1.

Table - 1: Specifications of LVDT

Repeatability	$\leq$ 1 µm
Thermal Drift	$\leq$ 0.3 µm/ÚC
Measuring Force	0.45 N to 0.9 N
Sensitivity	**2.7 (mV_{out}/mV_{in})**

Table - 2: Mechanical properties of the work piece

Mechanical Property	Value (MPa)
Ultimate Stress (S_{ut})	1275
Yielding Stress (S_y)	1030
Modulus of Elasticity	207
Poisson Ratio	0.3

In general, the circuits used are simple Wheatstone bridges (Fig. -1). In this resistive bridge, if the four resistances are equal, there will be no decrease in the meter voltage. But, if the resistances change, the meter pointer will move proportional to the change. Therefore, it is possible to use this property and make a mechanical device, which on changing the resistance produces a change in the length, and vice versa. In the said

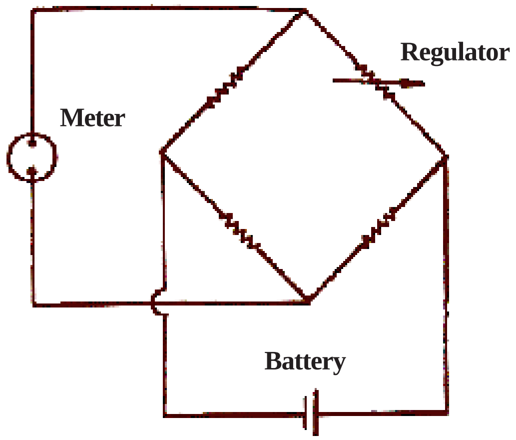

Fig. - 1: Wheatstone bridge

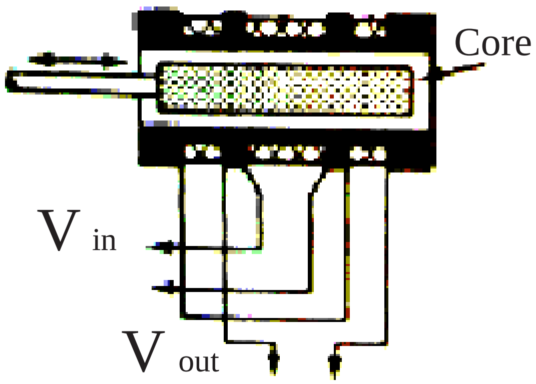

Fig. - 2: LVDT schematic

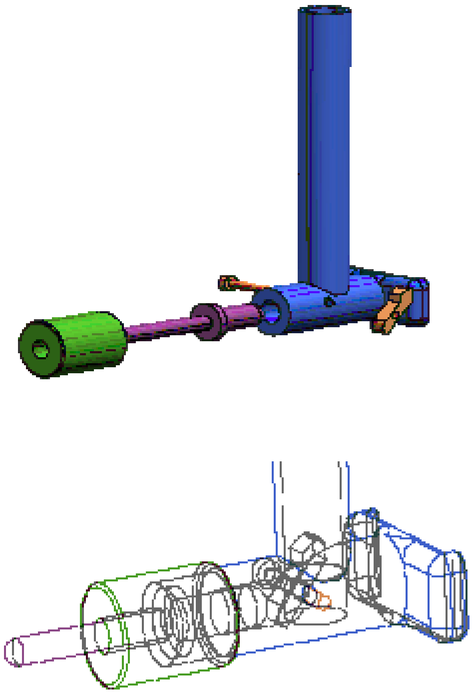

Fig. - 3: First design

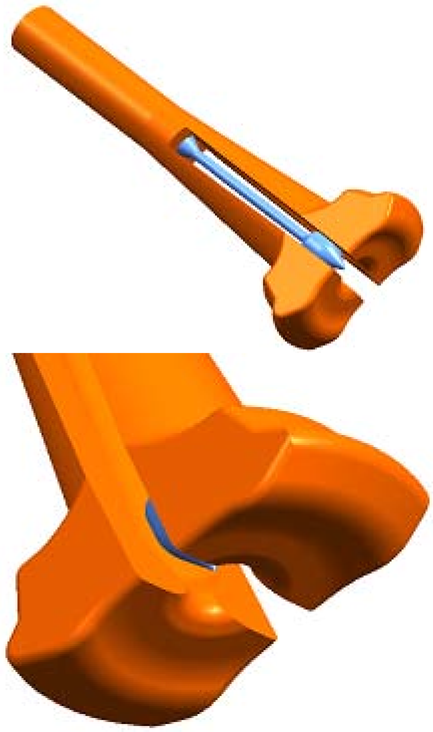

Fig. - 4: Second design

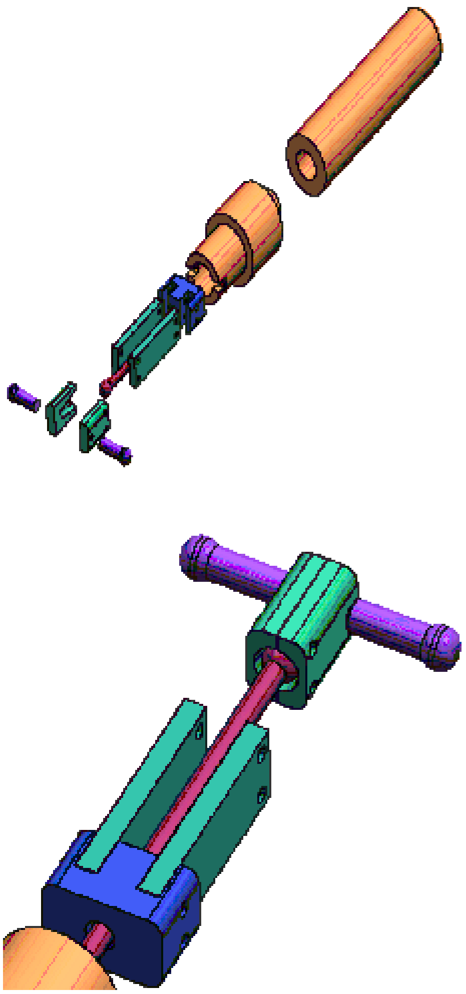

Fig. - 5:Third design

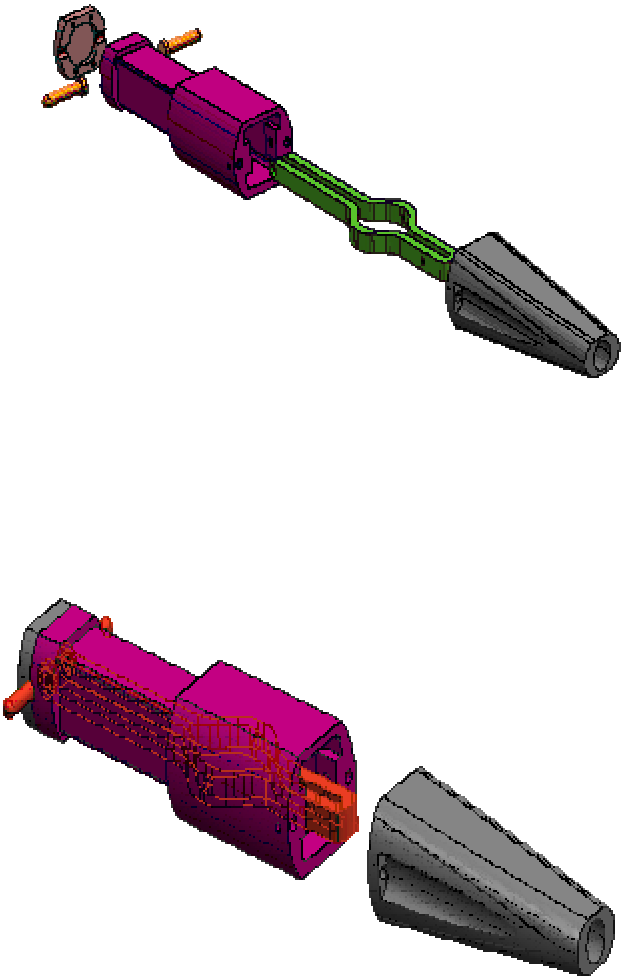

Fig. - 6: Fourth design

circuit, the reading value is proportional to the battery voltage, which destabilizes the measuring instrument. For the correction of this instability, an inductive bridge is used. A special transformer called LVDT is used, in which impedance change is proportional to change in the core position. In other words, as shown in Fig. -2, the output voltage from LVDT is linearly proportional to the linear change in core position[2, 6].

Design and Modelling of the Bore Gauge

In order to select the best design, the following parameters were considered:

1. The ability to meet requirements outlined in section 1.1[1].
2. The transducer used must have small size and low cost[5].
3. Low inertia and friction in the instrument's mechanisms[1].
4. Wide measurement range, i.e., it should be able to measure small diameter bores (of the order of few millimetres) as well as large diameter bores (of the order of 100 mm), and it should be easily replaceable[1, 2].
5. Manufacturability of parts to a high degree of accuracy at low cost and using conventional machines.

As the first step in the design process, we have modelled four different designs of bore gauge, using the *Unigraphics NX* software[7] (Figs.- 3, 4, 5, 6).

In the first, second and third designs

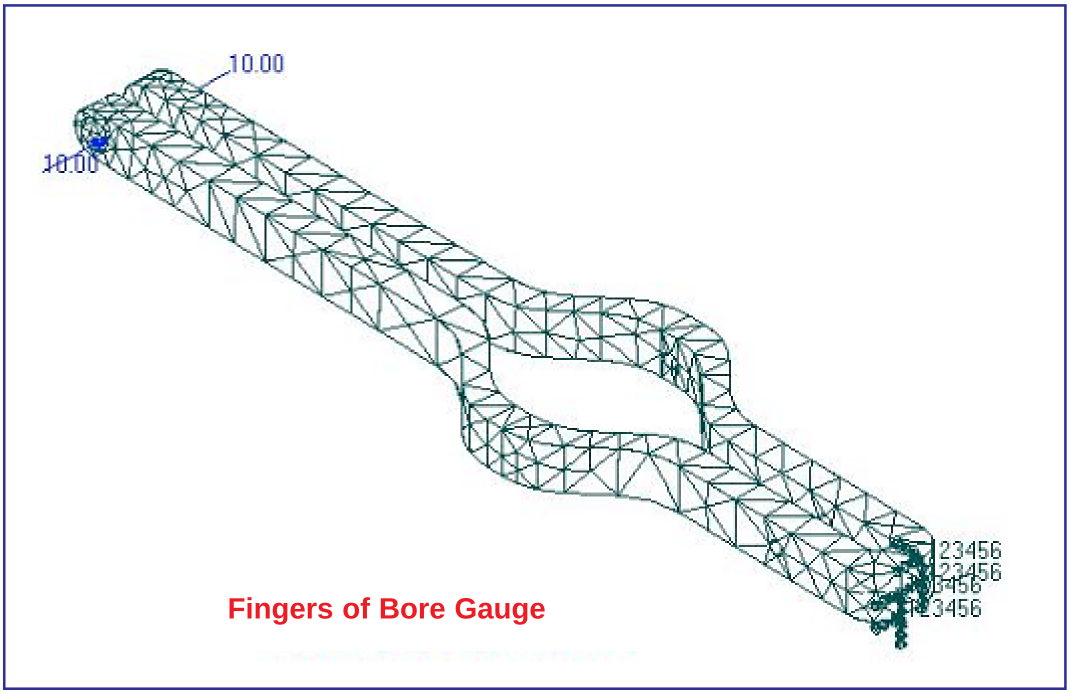

Fig. - 7:The FEM model with loading and supports

(Figs. - 3, 4, 5), the horizontal displacements of the probes has to be converted into vertical displacements, and the transducer is positioned at the end of the rod which converts the displacements mentioned above. This requirement for conversion of displacements does not fulfil the third item in the above list. In addition to that, these designs are difficult to manufacture. The second design has a small measuring range.

In the fourth design, the probe can move the finger directly (without any intermediate), and the transducer which is situated in the O-shape section (Fig. -4) is displaced, and the measurement is made. It is possible to change the measuring range by changing the probes, and for the large bores the lower part of the plug can be changed, too. Therefore, out of the four designs considered, the fourth design fulfils all of the above requirements, and hence it has been selected for further study and analysis.

The measuring device considered here is used for precision measurement and control of holes, with an accuracy of 1 µm, in mass produced high accuracy parts. The main parts of the bore gauge are:

- The main body made up of steel 1.0727,
- The handle made up of plastic,
- Fingers made up of steel 1.0970,
- The plug made up of steel 1.0727,
- The probe made up of Tungsten Carbide.

The repeated opening and closing of the finger will result in failure of the finger due to fatigue. The fatigue strength of the finger has been calculated using FEM and the classical method, and its life cycle has been estimated on the basis of its calculated fatigue strength.

Calculation of Fatigue Strength Using FEM Analysis

For the fatigue analysis of fingers, they should be subjected to alternative loads, and the produced stresses should be determined. Therefore, prior to any fatigue analysis a static analysis, consisting of at least two load steps, should be done. Then, on the basis of stress contours, the critical nodes are identified and the evaluation of fatigue is performed for these nodes.

In order to determine the fingers' life, a fatigue analysis has been performed. For this purpose the finger model was constructed using

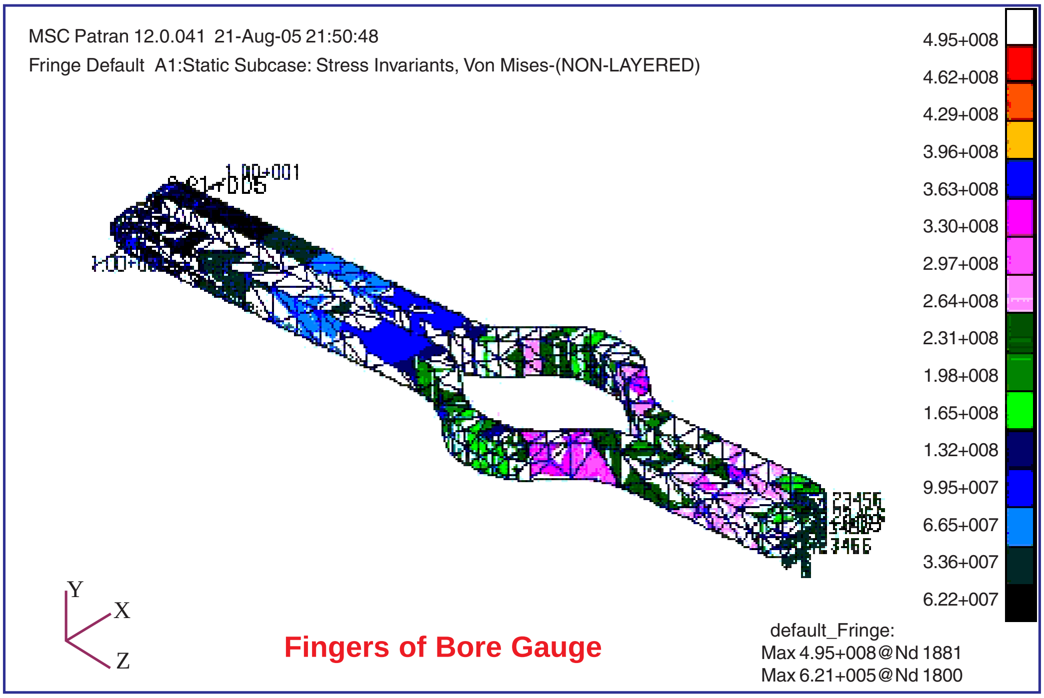

Fig. - 8: Von Mises stress analysis and maximum stress calculation

Nastran/Patran software. The mechanical properties of the work piece are presented in Table -2.

The governing equation for structural problems is of the following form:

 (1)

The above equation is a general equation of motion, which consists of damping and inertial forces. For the linear static condition, since the load is constant and does not change with time, Equation (1) can be written as:

$$[K]\{u\}=\{P\} \qquad (2)$$

Where,

$[K]$ = Stiffness matrix

$[u]$ = Nodal displacement vector

$[P]$ = Loading vector

The finger has been meshed using the Tetra10 mesh. There are 3198 nodes and 1497 elements. A force of 10 N magnitude is applied on tip of the finger on both sides, and the supports are located at the end of the finger (Fig. - 7)[8, 9].

We have considered the following assumptions in our static analysis of the finger:

1. Linear properties of the material: The material is considered as isotropic and homogeneous, and that the environment is continuous with no cracks.
2. Small displacements: on the basis of this assumption, if displacements exceed 20% of the plane thickness and 2% of the length, nonlinear analysis must be used.
3. Application of load is gradual: the finger is under static equilibrium, and if the application of load does not take place gradually, dynamic effects will appear. In other words, in this analysis impact loading has not been considered[9].

In this analysis magnitude of displacements is directly proportional to magnitude of loading, and the superposition principle can be used for integration of the analysis results[8].

The results of analysis of Von Mises stress has been shown in Figure (8). The maximum value of Von Mises stress is 495 MPa and occurs at the supports.

We have done analyses for steel types 1.0903, 1.0961, 1.7176, 1.7701 and 1.8159 [10]. However, the results obtained for steel type 1.0970 are more satisfactory, and therefore, we have presented the results for this type of steel.

Calculation of Fatigue Strength Using the Classical Method

The finger has a uniform cross section, and the maximum bending torque is applied on the end bend which has higher stress concentration. Therefore, there is a possibility of fracture in the finger bends. The following relations are used for calculation of fatigue strength [11]:

(i) Bending torque in the end bend:

$$M = F.d \tag{3}$$

(ii) Maximum fatigue strength

(4)

Where,

$$Z = \frac{bh^2}{6}, \tag{5}$$

Here, *h* is the height and *b* is the width of the finger

The fatigue strength is equal to 464.7 MPa, which is very close to the value calculated using the FEM analysis. Additionally, the initial guess about the location of fracture or the maximum stress has been validated.

The Finger Life Cycle

To calculate the Endurance-Limit Modifying Factor, the following relation is used [11, 12]:

$$S_e = K_a K_b K_c K_d K_e K_f S_e' \tag{6}$$

Where,

S_e' = endurance limit, calculated using Eqn. (7)

$$S_e = 0.5 S_{ut} \tag{7}$$

(with 15% generous coefficient of variation)

K_a = surface factor.

It is obtained from graph [12]

K_b = size factor (calculated using Equation (8))

$$K_b = \begin{cases} 1 & d \le 8\ mm \\ 1.189 d^{-0.097} & 8\ mm < d \le 250 \end{cases},$$

$$d = 0.808\,(hb)^{1/2} \tag{8}$$

= reliability factor

(with 90% reliability, K_c = 0.0897)

K_d = temperature factor

(calculated using Equation (9))

K (9)

K_f = miscellaneous-effects factor

(calculated with Equation (10))

$$K_f = 1 + q(K_t - 1) \tag{10}$$

K_t and q are obtained from graph [12].

K_e = modifying factor for stress concentration

(calculated using Equation (11))

(11)

The following relation is used for calculation of life cycle:

(12)

Where,

$$b = -1/3 \log \frac{0.8 S_{ut}}{S_e} \quad and \quad c = \log \frac{(0.8 S_{ut})}{S_e} \tag{13}$$

Therefore, on the basis of our calculations, the fatigue strength using the FEM is found to be 165 x 10^3 cycles, and the fatigue strength using the classical method is found to be 178 x 10^3 cycles. In view of the tenfold increase in applied force on the finger, the calculated life cycle is within acceptable range.

RESULTS AND DISCUSSION

The following results can be highlighted:

1. Modelling process has proved to be essential for making better decisions concerning the selection of various mechanisms based on constrains and requirements. It is also possible to optimize any selected mechanism.
2. Using the good interface between the modelling software and the FEM analysis tools, static analysis and life cycle determination have been carried out for the critical part, the finger. The life cycle determination has been done on the basis of the deformation in the finger, the material, and the acting forces and the supports conditions. The process has been repeated in order to arrive at an optimum life cycle.
3. The results of this study can be used for the reduction of cost for performing tests on the instruments.
4. The fatigue strength has been calculated using FEM and classical method, and the results show that FEM calculations are more reliable as verified by the results of classical method.
5. As future work, the finger mechanism may be modified such that two transducers at a time can be used, which makes it possible to identify and measure the eccentricity of any bore in a single step.

REFERENCES

1. R. Thompson: *Fundamentals of dimensional Metrology,* 3rd Ed., 1952, (1990)
2. M.G. Dirpoosh, M.D. Mahmoodzadeh, and S.M. Ziaee: *Precise Measurring Systems,* (In Persian) (2002)
3. S. Kalpakjian: *Manufacturing Processes for Engineering Materials,* 3rd Ed., (1997)
4. D. Prenskey, R.L. Castellacis: *Electronic Instrumentation,* 3rd Ed.
5. 375 Series AC/AC, Sentech WC, Transformers Catalog, Web Site: WWW.sentechlvdt.com
6. W.D. Cooper, A.D. Helfrick: *Electronic Instrumentation and Measurement Techniques, 3*rd Ed., Prentice-Hall, New Delhi, (1991)
7. Unigraphics NX Documentation, (2002)
8. Applied Finite Element Analysis, John Wiley & Sons, (1984)
9. S. Kobayashi: Metal Forming and the Finite Element Method (1989)
10. Steel Website: http://www.matweb.com
11. Strength of Materials, 3rd ed., D. V. Nostrand Co. Inc., New York, (1955)
12. J. E. Shigley: Mechanical Engineering Design, (1986)