



<sup>1</sup>. S. SYATH ABUTHAKEER, <sup>2</sup>. P.V. MOHANRAM, <sup>3</sup>. G. MOHAN KUMAR

## DYNAMIC CHARACTERISTICS ANALYSIS OF MICRO LATHE BED

<sup>1,2</sup> DEPARTMENT OF MECHANICAL ENGINEERING, PSG COLLEGE OF TECHNOLOGY, COIMBATORE – 641 004, INDIA

<sup>3</sup> PARK COLLEGE OF ENGINEERING AND TECHNOLOGY, COIMBATORE, INDIA

**ABSTRACT:** Micro Factory represents an entirely new approach to design and manufacture which minimizes production systems to match the size of the parts they produce. The micro-lathe was one of key components in "Micro-factories" claiming "small machine tools for small mechanical parts". There is an alternative to manufacture micro-components by micro-machine tools and micro-manipulators using conventional mechanical techniques. The machine tools should withstand at higher cutting speeds and operate at high acceleration and deceleration with high quality at lower cost. To achieve high performance, the static stiffness of the machine tool should be increased and moving mass to be reduced. In this study we design and manufacture a prototype of an inexpensive LabVIEW controlled micro-lathe. This will facilitate the micro-machine tool education in India as these activities become active and also replace the conventional Micro-lathe material bed by E-Glass/Epoxy bed to obtain superior static and dynamic properties. The dynamics characteristics of those different Micro-lathe beds were analyzed experimentally. Numerical analysis was done and results were validated with experimental results.

**KEYWORDS:** Micro-Factory, Micro-lathe, LabVIEW, Stiffness, Damping

### ❖ INTRODUCTION AND LITERATURE SURVEY

There is a great effort towards the miniaturization in the last few decades. We can see the effects of that trend in every aspect of our lives. From the laptops to the cellular phones, we always prefer the smallest one since the idea of "the smaller the better" has penetrated into our minds and one can be equipped with more gadgets as miniaturization goes further. Miniaturization process of mechanical components started with micro fabricated sensors and was followed by micro fabricated parts and micro actuators. In recent years integration of micro components such as precision mechanisms, sensors, actuators and embedded electronic circuits into micro systems has become one of the most prominent research areas all over the world. When the micro components were first introduced, they were simple and could be naturally integrated directly into the product. However, developments in micro system technology resulted in a large variety of micro components made from dissimilar materials and technologies. These miniaturized products use even smaller components, and in more and more cases they are micro components with sizes of components less than one millimeter.

A new bid to manufacture pieces with overall sizes smaller than 1mm using conventional mechanical technology was made in [1]. This proposal was based on the development of micro-factories (composed of micro-machine tools, micro-manipulators (MMs), assembly devices, etc.) to manufacture and assemble 3-D micro-devices employing conventional mechanical techniques. The micro-factories can help to reduce the consumption of resources (energy, materials and space); and can help to increase the productivity [2]. The micro-machine tools (MMTs) in such micro-factories must be sufficiently precise to produce components according to industrial and research demands.

The conservation of energy has been the slogan for the past decade in order to reduce energy consumption. The conservation of energy by reducing the machine tool size for machining micro components is attaining popularity as micro-factory. Micro-factory can be said that it is a small manufacturing system for achieving higher throughput with less space and reduced consumption of both resource and energy via downsizing of production processes. The energy-saving effect is large when the size of the processing and assembly Equipment is extremely large compared to the dimensions of the products. As for watch manufacturing, the amount of Energy consumption may be reduced to approximately 30 Percent of the conventional factory by the half-miniaturization of the production systems [3].

The term micro-factory represents an entirely new approach to design and manufacture that minimize production systems to match the size of the parts they produce. In the earliest attempt to turn the concept of micro-factory [4] in to a reality a micro-lathe smaller than a human palm was developed in 1996 [5]. And it was the first big success for the further step into the concentration on process physics of micromachining including materials and micro structural effects, machine tools, tooling and sensing, workpiece and design issues, software and simulation tools, and other issues [6] micro factory. The first micro press was developed in the year 2000[7].

In the micro-world, the error sources of MMTs can be reduced by reducing their sizes [8],[9],[10] and [11]. Some prototypes were made in order to demonstrate the advantages of this proposal. Countries such as Japan, Ukraine and Mexico have developed micro-machine tools with overall sizes from  $130 \times 160 \times 85$  mm to  $32 \times 28 \times 30$  mm [12],[13], and [14]. In Mexico, the research in this area began in 1999 and the main goal was to develop micro-mechanical technology for automated production systems based on low-cost and high efficiency equipment and instrumentation [15]. In the low-cost micro-equipment development, the principal challenge is to obtain high precision employing low-cost components.

Advanced countries like Japan, Taiwan, Korea, Europe, Ukraine, Mexico, Germany and USA not only manufacture production micro-machine tool but also educational micro-machine tool in a balanced manner. As the economic development of India progresses toward becoming an advanced nation there is a need for an effective policy for science, engineering and technology and their education. Particularly, that for the machinery, automobile and electrical industries is more urgent. Because the resources, fund and technology for the domestic industry are not sufficient, and also technology protection policy in the level of advanced nation is nonexistent, there is a great deal of problems associated with the Indian Machine tool Industry.

In particular, Micro-machine tool systems which are based on an industry are less manufactured in India. Therefore, it is an urgent problem that the Indian industry develops capability to manufacture integrated special tool system, such as Micro-factory, Micro-machine tool, micro-manipulators, Robots; Educational high level technicians for the special fields. Sufficient equipment and other necessary materials are needed for experiments essential for effective education. It is more suitable to use specially built micro machine tool for educational uses. In our country, certain educational institutes recognize this problem and utilize educational micro-machine tool, but this machinery depend on total import. Therefore it is expected that this research contributes towards micro-equipment education by domestic production of educational MICRO LATHE so it can reduce the import and foreign exchange and eventually manufacture of Micro-lathe for production.

The necessity of educational Micro-machine tool is considered by this method: and an economical prototype micro-lathe is designed, manufactured and studied. In the low-cost micro-equipment development, the principal challenge is to obtain high precision employing low-cost components. For this reason, we have proposed to use the labVIEW control systems to increase the micro-machine tools accuracy without increasing significantly the total device cost.

---

#### ❖ DEVELOPMENT OF MICRO-LATHE

---

An interest to produce mechanical parts with sizes less than 1 mm arose worldwide in the 80's. Some methods based on micro-electronic technology were proposed; nowadays, these developments are called Micro Electro Mechanical Systems (MEMS) [8]. The micro-electronic technology allows developing micro-mechanical components with simple shapes (two and a half dimensions), and the materials employed in this technology are silicon, silicon oxide, metallic films (mainly aluminum), and piezoelectric materials like quartz. These micro-devices applications are encountered in many industries such as the automotive, the biomedical, electronics, computer, etc.

The manufacture of micro-components employing micro-mechanical systems (micro-factories) was proposed in the 90's as a new alternative to cover some of the micro-world applications where MEMS could not be applied. A research group from Japan proposed the development of tools that allow generating other kind of application which can be made from different materials and can have 3-D geometry shapes. The main goal was to create MMTs, micro-manipulators (MMs), etc. at a scale comparable with the size of the produced micro-components. Their proposal consisted of transferring the conventional mechanical methods to the micro-world and to develop micro-factories able to produce micro-devices. A micro-factory contains several systems: a manufacturing system, an assembly system, a quality control system, a transport system, a maintenance system, and others. The micro-factories allow a decrease in the consumption of energy, space, and resources [16]. The produced micro-components can be used in the watch industry, the automotive industry, medical facilities, biology investigations, etc. [16] and [17]. For example, in the medical field, the micro-equipment demands are: microscopy, diagnosis, non-invasive surgery, etc. in the industrial field for the development of micro-robots to inspect inaccessible or dangerous places, pipe inspection, transportation machinery, archeological research, etc. Another interesting application field is the development of micro-actuators, for example: micro-grippers for manipulation with living cells, micro-generators, micro-motors, etc. [13].

The first micro-machine tool was developed in the National Institute of Advance Industrial Science and Technology of Japan in 1996 [12]. Nowadays, there are many groups in different countries around the world such as Germany, Korea, Switzerland, Mexico, USA, etc. interested in this field [18],[19] and [20]. Researchers from the National Institute of Advance Industrial Science and Technology of Japan developed an automated micro-factory to produce components for micro-bearings in 2000 [21]. The assembly of micro-bearings was made in the same micro-factory with a semi automated process.

Particularly, in Mexico, investigation in micro-mechanics began in 1999. The main goal is to create technology for automated micro-mechanical devices for production based on low-cost and high efficiency equipment and instrumentation. To achieve this goal, it was proposed to work out the micro-equipment as sequence of generations where the first generation of micro-equipment is produced by conventional machine tools. The micro-equipment of this generation will be able to produce the second generation of micro-equipment having smaller overall sizes than the previous one. Employing the second generation, it would be possible to produce the third generation of micro-equipment, and so on. The sizes of each new generation devices are smaller than the sizes of the precedent ones. This process can be repeated until the micro-machines with overall sizes of some micrometers have been obtained [14].

Studies on improvement in the performance of machine tool structures are the major area of research. The two important functional requirements for precision machine tools are high structural stiffness and high damping, which cannot be satisfied simultaneously if conventional metallic materials are used for structures because conventional high stiffness metals have low damping and vice versa. Although the stiffness of machine tool structures can be increased either by employing higher stiffness materials or by increasing the sectional modulus of structures [22].

High static stiffness against bending and torsion, good dynamic characteristics as reflected by high natural frequency and high damping ratio, ease in production, good long term dimensional stability, reasonably low coefficient of expansion, low cost and low material requirements are the basic properties of machine tool structures that engineers look for designing and fabricating. However, from user's point of view, machine tool vibration is an important factor because it adversely affects the quality of a machined surface. To improve both the static and dynamic performances, the machine tool structures should have high static stiffness and damping. Using either higher modulus material or more material in the structure, the static stiffness of a machine tool may be increased. But, it is difficult to increase the dynamic stiffness of a machine tool with these methods and increase in the static stiffness cannot increase its damping property. Material distribution is the important in the structural strength and using material in required place can increase static stiffness with less mass. Faster cutting speeds can be facilitated only by structures which have high stiffness and good damping characteristics. The deformation of machine tool structures under cutting forces and structural loads are responsible for the poor quality of products and also aggravate the problem by introducing noise and vibration. In many a situation, it is the level of deformation and vibration that determines the upper limit on the ability of the machine to produce components with high precision. All these above said deleterious effects greatly necessitate constant innovations and increasing amount of research to keep them under check. Increasing structural stiffness could help in avoiding such problems. To increase the static stiffness and damping, alternative materials can be used for machine tool bed. The high speed machining process requests completely new demands for the mechanism of such processing equipment, as due to the process, path speeds exceeding 50m/min can be achieved. In this field, potential capacities of manufacturing processes require a dynamic behavior ten times higher than conventional machine tools and increased accuracy. This can be solved by the systematical evaluation of suitable machine kinematics, by the application of linear direct drives as well as by mass reduction of the axis through light weight components of sheet metal. The requirements of high speed machining and ways to improve the performance of machine tool have been studied [23].

Based on this study, the prototype of LabVIEW controlled Micro-lathe is developed for production maximized education efficiency, it can be learned easily and a disjoining and assembling are possible and attempt has been made to fabricate an E-Glass/Epoxy bed. Dynamic analyses were done on the micro lathe bed structure to compare between the steel and Glass/epoxy materials. Compared with damping factors of steel, the E-Glass/Epoxy bed exhibits superior damping characteristics. The final Exploded and assembly view of Micro-lathe is shown in Figure 1 & 2.

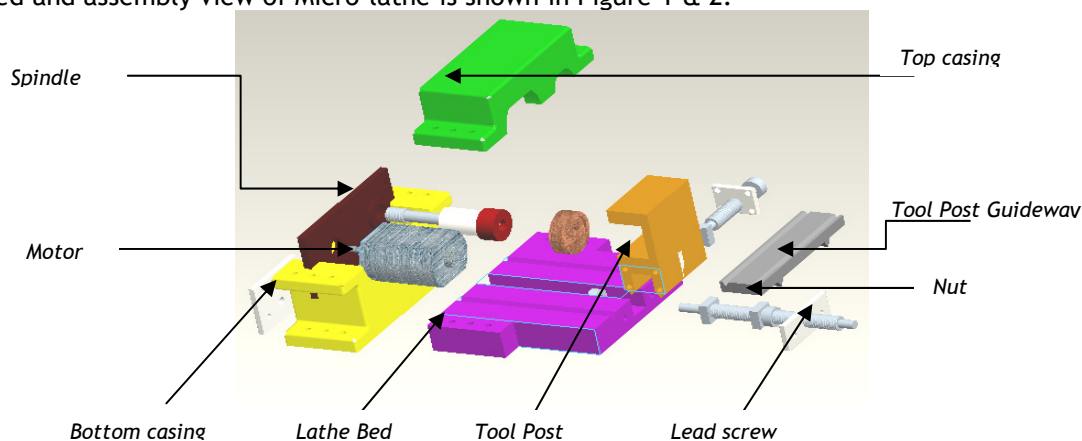


Fig. 1. Exploded view of microlathe

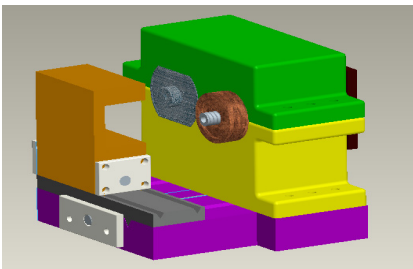


Fig.2. Assembly view of Microlathe

❖ **STATIC AND DYNAMIC ANALYSIS ON THE MICRO LATHE BED. STRUCTURES AND MATERIALS**

Both static and dynamic analyses were done on the micro lathe bed structure to compare between the steel and Glass/epoxy materials [24]. On the static analysis part, the deformation of the bed due to the weight of headstock and tool post have been investigated through FEA and also verified experimentally. And on the dynamic analysis part, modal analysis using finite element software for finding natural frequencies and corresponding mode shapes of the machine bed was performed and it was compared with the experimental modal analysis that can find out the modal parameters by measuring the frequency of an existing structure by using LabVIEW software. Finally the results of both the materials are compared and best suitable one is chosen. Hand layup process is selected to fabricate composite machine bed in order to understand composite manufacturing [25,26,27]. It has the following steps. Molds are made from a master pattern. The master pattern could be a steel or wood. The bed should be glossy and defect free to reduce the amount of sanding and buffing on the mold. Once the master mold is ready, it is waxed with release agent for easy removal of the mold. The master is coated with release wax three or four times in alternate directions and allowed to harden after each layer is applied. The next step is to apply a tooling gel coat on the surface of the bed. The tooling gel coat provides a hard, glossy and long-lasting surface on the mold. It is applied using a brush or spraying equipment. The gel coat is allowed to gel before applying any laminating material. To make sure the gel coat has properly gelled, the surface is lightly touched with a finger. If the finger does not stick or does not leave slight fingerprint mark on the gel surface, it is ready for lamination.

❖ **EXPERIMENTAL MODAL ANALYSES**

The vibration response of the bed was obtained using impact testing, where an instrumented hammer was used to excite the bed. The resulting vibration was measured using a low mass accelerometer. The experimental setup consisted of an impact hammer, a charge accelerometer, signal conditioner, LabVIEW software and data acquisition Figure 3. This experimental setup was used to find the modal characteristics of the micro lathe bed. The natural frequencies were tabulated in and table 1.

Table 1. Experimental modal analysis

Mode No.	Steel	Natural frequency(Hz)	
		E-GLASS/ Epoxy bed	Percentage increase in natural frequency (%)
1	100	152	0.52
2	106	225	1.122642
3	120	294	1.45
4	175	296	0.691429
5	184	400	1.173913

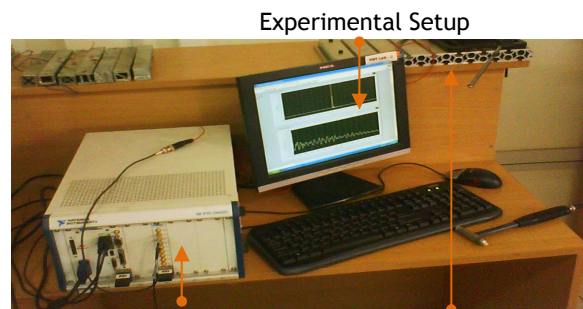


Fig. 3. Experimental setup

The vibration test results for steel bed are shown in figure 1. By using the half-power band width method, we can find the damping factor of the each beam from the response curve.

$$\eta = (f_2 - f_1) / f_r \tag{1}$$

Where, (f2-f1) and fr represent the half power band width and the corresponding natural frequency, respectively [28]. From this method, the natural frequency and damping ratio can be calculated. The calculated damping ratio is 0.01111 and the natural frequency of the steel bed is 104 Hz. The amplitude data of the steel bed is shown in figure 4.

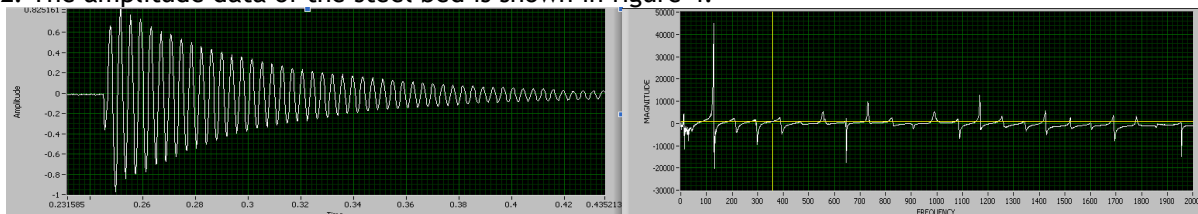


Fig.4. Free vibration test result showing amplitude and frequency response for Micro-lathe steel bed

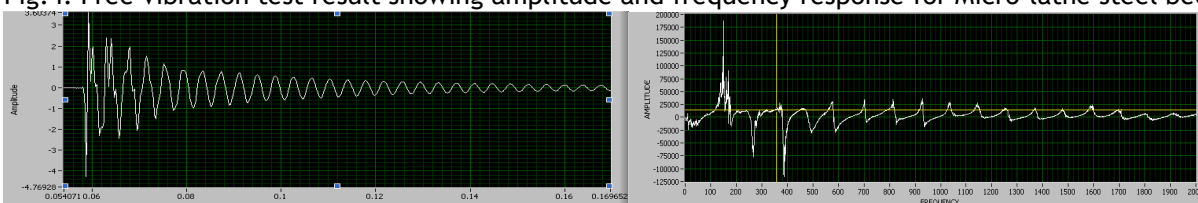


Fig. 5 Free vibration test result showing amplitude and frequency response for Micro-lathe E-Glass/Epoxy bed

Again the natural frequency and damping ratio for glass/epoxy bed can be calculated by using the same method. The calculated damping ratio is 0.01398 and the natural frequency of the steel bed is 161Hz. The amplitude data of the glass/epoxy bed is shown in figure 5.

By comparing the modal parameters of steel and glass/epoxy beds, it can be seen that glass/epoxy is a better material in terms of dynamic performance. It has high natural frequencies and damping ratios. The first resonance of glass/epoxy bed occurs at almost twice the frequency of steel and damping ratios of glass/epoxy are almost twice of those for steel. Thus glass/epoxy bed will be more stable when compared to steel bed.

❖ NUMERICAL MODAL ANALYSIS

The modeling of Micro-lathe bed was done in ANSYS. Applying the same conditions used in static analysis, the modal analysis was done using Subspace method to find first five natural frequencies and mode shapes [29]. The mechanical properties of steel and glass epoxy are shown in table 2 and 3 respectively.

The modal analysis was performed on the bed structure using both steel and composite to determine the natural frequencies and mode shapes of the bed structure. From these results, the natural frequency is compared with experimental and found that third natural frequency of the mode shapes is same so it is in resonance level. The mode shapes of the steel and glass/epoxy beds as shown in figure 6.

Table 2. Mechanical Properties of Steel

S.NO	Property	Unit	Steel
1.	Young's Modulus (E)	GPa	210
2.	Density ( $\rho$ )	Kg/m <sup>3</sup>	7850
3.	Poisson ratio ( $\gamma$ )	-	0.3

Table 3. Mechanical Properties of E-Glass/Epoxy

S.NO	Property	Unit	E-Glass/Epoxy
1.	E11	GPa	49
2.	E22	GPa	8
3.	G12	GPa	2.78
4.	$\gamma$ 12	-	0.245
5.	$\rho$	Kg/m <sup>3</sup>	1915

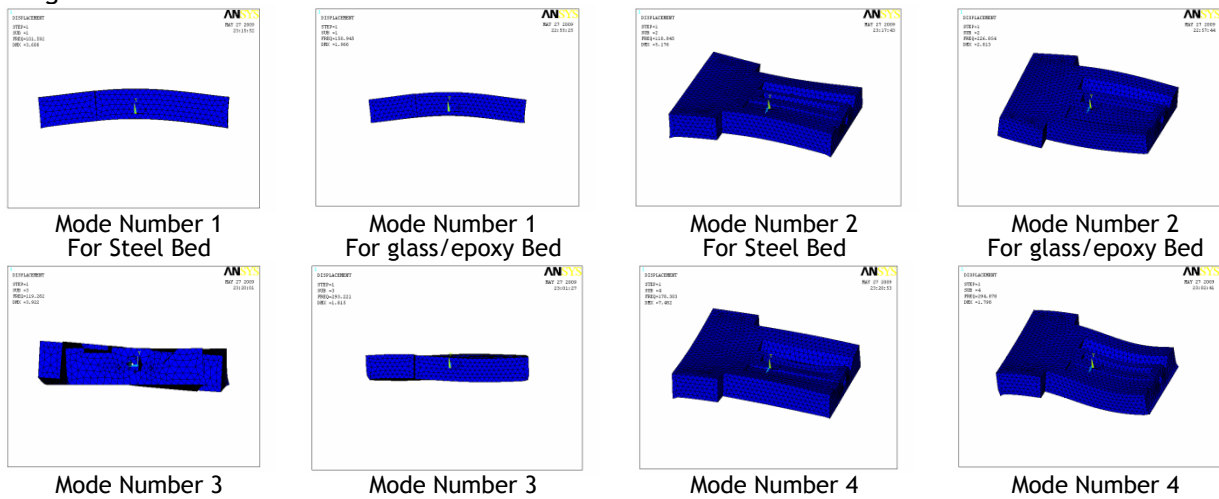


Fig.6. Various mode shapes of the Micro-Lathe bed structure

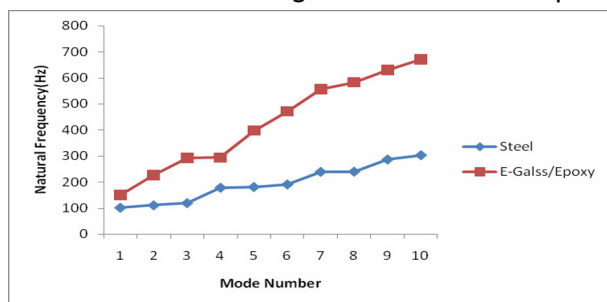


Fig.7 Comparison between Steel and E-Glass/Epoxy micro-lathe bed- Numerical analysis

The results obtained from modal analysis of both composite and steel bed structures were shown in figure 7. It was found that natural frequencies were higher when composite bed was used using FEM analysis. Table 4 shows the Comparison of Natural frequency between steel and E-glass/epoxy bed.

Table 4. Comparison of Natural frequency between steel and E-glass/epoxy bed

Mode No.	Natural frequency(Hz)		Percentage increase in natural frequency (%)
	Steel	E-GLASS/Epoxy bed	
1	101.59	150.54	0.48
2	110.84	226.85	1.04
3	119.28	293.22	1.45
4	178.30	294.87	0.65
5	181.23	398.25	1.19
6	191.11	472.16	1.47
7	239.44	557.66	1.32
8	240.14	583.42	1.42
9	286.92	631.20	1.19
10	303.28	672.02	1.21

❖ RESULTS AND DISCUSSIONS

Design and fabrication of a prototype of an inexpensive LabVIEW controlled micro-lathe was developed. The results obtained from modal analysis of both steel bed and E-Galss/Epoxy bed structures were analyzed. It was found that natural frequencies were higher when E-Galss/Epoxy bed was used. The first resonance of glass/epoxy bed occurs at almost twice the frequency of steel and damping ratios of glass/epoxy are almost twice of those for steel. Thus glass/epoxy bed will be more stable when compared to steel bed. This implies that the machine with composite bed can operate at

much more higher speeds without any resonance. In case of steel bed resonance will occur at a speed of 6000 rpm whereas this is raised to 9000rpm in case of composite bed. From the experimental work, E-galss/epoxy micro lathe bed was high stiffness and high damping ratio. The error of numerical results compared to experimental results is less than ten percent.

#### ❖ CONCLUSIONS

In this research we developed Micro-lathe for education institute by using LabVIEW software. This developed Micro-Lathe will contribute to Micro-factory education and Micro-machine domestic production for education, and to prototype FMS for education by combining Micro-Lathe, Micro Milling, Micro grinding, Micro cutting, micro-manipulator, micro-machine tool and Micro-Factory system. Typical E-Glass/Epoxy micro lathe bed was designed and fabricated. Experimental setup was designed and developed for testing of beds. The static deflection characteristics and modal characteristics of beams were found experimentally. The numerical modeling and analysis of beds were done in ANSYS and numerical results were taken and validated against experimental results. Damping and natural frequencies also found for both beds. E-Glass/Epoxy micro lathe bed were found to be best for replacing steel to increase the stiffness of structures.

#### ❖ REFERENCES

- [1] Takayuki H. Future prospect of micro-machine, Technical article, Micromachine Center Japan; 1999. p. 6.
- [2] Ishikawa Y, Kitahara T. 1997 Present and future of micromechatronics. International Symposium on Micromechatronics and Human Science, Japan; p. 13–20.
- [3] N.Kawahara,T.Suto,T.Hirano,Y.Ishikawa,T.Kitahara,N.Ooyama,T.Ataka,1997.Technical papers ;Micro system Technologies Micro factories; new applications of micro machine technology to the Manufacture of small products .p.37—41 Springer-Verlag 1997
- [4] Kitahara.T, Ishikawa.Y, Terada.K, Nakajima.N, and Furuta K., 1996 Development of Micro-lathe. Journal of Mechanical Engineering Lab, Vol.50, p.117-123.
- [5] Okazaki.Y, Mishima.N, and Ashida.K, 2004 Microfactory -Concept, History and Developments . Journal of Manufacturing Science and Engineering, Vol.126, November p.837-844.
- [6] Dornfeld.D, Min S., Takeuchi.Y, 2006 Recent Advances in Mechanical Micromachining. Annals of the CIRP, Vol. 55, February.
- [7] Ashida.K, 2000 Development of a micro press machine. Journal of Mechanical Engineering lab, Vol.54 (6), p.16-20.
- [8] E. Kussul, D. Rachkovski, T. Baidyk and S. Talayev, 1996 Micromechanical engineering: a basis for the low-cost manufacturing of mechanical microdevices using microequipment. *J Micromech Microeng* 6, p. 410–425.
- [9] Trimmer WS. Micromechanics and MEMS, classic and seminal papers to 1990. IEEE; 1996.
- [10] Kussul E, Baidyk T, Ruiz L, Caballero A, Velasco G, Makeyev O. 2006 Techniques in the development of micromachine tool prototypes and their applications in microfactories. In: Leondes, Cornelius T, editor. MEMS/NEMS Handbook – Techniques and Applications, vol. 3. Springer Publications;. p. 1–61. ISBN: 0-387-24520-0.
- [11] E. Kussul, T. Baidyk, L. Ruiz, A. 2006 Caballero and G. Velasco, Scaling down of microequipment parameters. *Precision Eng* 30, p. 211–222.
- [12] Okazaki Y, Kitahara T. Micro-lathe equipped with closed-loop numerical control. In: Proceedings of the 2nd International Workshop on Microfactories, Switzerland; 2000. p. 87–90.
- [13] T. Fukuda and W. Menz, Handbook of sensors and actuators, micro-mechanical systems, Elsevier 1998.
- [14] Kussul E, Ruiz L, Caballero A, Kasatkina L, Baidyk T. CNC machine tools for low-cost micro-devices manufacturing. The First International Conference on Mechatronics and Robotics, Russia 2000; 1: p.98–103.
- [15] E. Kussul, T. Baidyk, L. Ruiz-Huerta, A. Caballero, G. Velasco and L. Kasatkina, 2002 Development of micromachine tool prototypes for microfactories. *J Micromech Microeng* 12, p. 795–813.
- [16] MicroMachine Center. Application of micromachine technology. MicroMachine magazine (reference webpage: <<http://www.mmc.or.jp/e/>>); p. 7–20.
- [17] Yu-Chong T. MEMS manufacturing at the Caltech micromachining lab. M<sup>4</sup> Workshop on Micro/Meso Mechanical Manufacturing, USA 2000. (Reference webpage: <<http://www.mech.northwestern.edu/MFG/AML/M4/M4-Files/Tai/index.htm>>.).
- [18] Lauwers TB, Edmondson LZK, Hollis R. Progress in agile assembly: free-roaming planar motors. In: Proceedings of the 4th International Workshop on Microfactories, China; 2004. p. 7–10.
- [19] Brand U, Kleine-Besten T, Schwenke H. Development of a special CMM for dimensional metrology on microsystem components. ASPE 15th Annual Meeting, USA; 2000. p. 542–46.
- [20] Driesen W, Varidel T, Régner S, Breguet J. Micro-manipulation by adhesion with two collaborating mobile micro-robots. In: Proceedings of the 4th International Workshop on Microfactories, China; 2004. p. 17–22.
- [21] Okazaki Y, Mishima N, Ashida K. Microfactory and micro-machine tools. Reported in The 1st Korea-Japan Conference on Positioning Technology, Korea; 2002.
- [22] Jung Do Suh and Dai Gil Lee, 2008 Design and manufacture of hybrid polymer concrete bed for high-speed CNC milling machine. International journal of Mechanical Material Design, volume 4, p. 113-121.
- [23] Heisel, M Gringel, 1996 Machine Tool Design Requirements for High Speed Machining”, in CIRP Annals-Manufacturing Technology, volume 45, Issue 1, p. 389-392.
- [24] D.I. Kim, S.C. Jung, J.E. Lee, S.H. Chang, 2006 Parametric study on design of composite-foam-resin concrete sandwich structures for precision machine tool structures,” Composite Structures 75 , p.408–414.
- [25] Ju Ho Kim, Jae Eung Lee, Seung Hwan Chang, 2008 Robust design of micro factory elements with high stiffness and high damping characteristics using foam-composite sandwich structures, Composite Structures 86 , p. 220–226.
- [26] J. D. Suhl and D. G. Lee’ “Composite Machine Tool Structures for High Speed Milling Machines,” Korea Advanced Institute of Science and Technology, ME3261, 373-1, Guseong-dong, Yuseong-gu, Daejeon-shi, p. 305-701, Republic of Korea.
- [27] Ju Ho Kim, Jae Eung Lee, Seung Hwan Chang, 2008 obust design of micro factory elements with high stiffness and high damping characteristics using foam-composite sandwich structures,” Composite Structures 86 , p.220–226.
- [28] Dai Gil Lee , Jung Do Suh, Hak Sung Kim, and Jong Min Kim, “Design and manufacture of composite high speed machine tool structures”, in Composites Science and Technology”, volume64, 2004, p.1523-1530.
- [29] Michael R Hatch, Vibration Simulation using ANSYS and Matlab.