Influence of Bearing Arrangements for Static Stiffness Analysis of High Frequency Milling Spindle

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Abstract:- **The objective of this work is to optimize the parameters influencing the stiffness of the high frequency milling spindle. The analysis has been carried out to evaluate the spindle stiffness and to minimize deflection at the nose by varying the Bearing arrangement and Overhang of spindle nose from the front bearing. The static analysis was also carried out using ANSYS and there is a good correlation between the results obtained by theoretical approach and ANSYS.**

Keyword : Bearing, Spindle, FAG, Rigidity, Stiffness.

1. PREAMBLE

1.1 Introduction

The spindle is the main mechanical component in machining centers. The spindle shaft rotates at different speeds and holds a cutter, which machines a material attached to the machine tool table. The static and dynamic stiffness of the spindle directly affect the machining productivity and finish quality of the workpieces. The structural properties of the spindle depend on the dimensions of the shaft, motor, tool holder, bearings and the design configuration of the overall spindle assembly. The bearing arrangements are determined by the operation type and the required cutting force and life of bearings.

1.2 High Speed Spindles

Spindles are rotating drive shafts that serve as axes for cutting tools or to hold cutting instruments in machine tools. Spindles are essential in machine tools and in manufacturing because they are used to make both parts and the tools that make parts, which in turn strongly influence production rates and parts quality.

High speed spindles have emerged today as the most important component of any kind of high machining process. For all kind of machining tasks, whether in the CNC, tool machining center and other process components, the use of high speed spindles always optimizes productivity. To achieve high speed rotation, motorized spindles have been developed. This type of spindle is equipped with a built-in-motor as an integrated part of spindle shaft, eliminating the need for the conventional power transmission devices such as gears and belts. This design reduces vibrations, achieves high rotational balance and enables precise control of rotational accelerations and decelerations. However, the high speed of rotation and the built-in-motor also introduce large amounts of heat and rotating mass into system, requiring precisely regulated cooling, lubrication and balancing.

1.3 Motorized Milling Spindles

Motorized milling spindles are widely used today in all mill centers for heavy duty milling. There are some specially designed motorized spindles, solely used for hard core milling while there are other motorized spindles used in all types of machine tool applications including milling, drilling etc. The use of motor-driven milling spindles is convenient compared to the gear driven or belt driven spindles in most cases and they are highly recommended for maximum milling performance and flexibility. The higher maximum speeds offered by the motor ensure optimum and economical machining from the small to the large work piece. They are suitable for both rough cutting and precise finish cutting.

1.3.1 Features of motorized milling spindles

- A basic feature of this type of spindle is that it can help in reducing the cycle time
- Consider especially for complete machining in a single clamping setup.
- This type of spindle is also available with multifunctional unit for turning, drilling and milling.
- The spindle also has connection with automatic tool change providing functionality and flexibility.
- The motorized spindles ensure machining of a wide range of workpieces without changeovers.
- Integrated motor design eliminates the problems of gears and pulleys.
- The rotary motion in such spindles is accomplished by means of a torque motor as direct drive.
- Higher speed milling.
- Higher overall rigidity.

2. MAJOR COMPONENTS

The major components required for Precision Spindle design include:

- **Spindle Style**- Integral Motor-Spindle.
- **Spindle Bearings**- Type, Quantity, Mounting and Lubrication Method.
- **Spindle Shaft**- Including Tool Retention Drawbar and Tooling System Used.

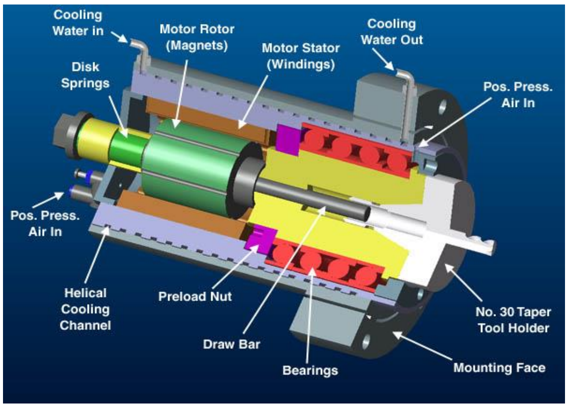

Figure: 2.1 Major Mini-Spindle components and layout.[15]

2.1 Spindles with Integral Motors

The spindle is the main mechanical component in machining centers. The spindle shaft rotates at different speeds and holds a cutter, which machines a material attached to the machine tool table. The structural properties of the spindle depend on the dimensions of the shaft, motor, tool holder, bearings and the design configuration of the overall spindle assembly. For design optimization of spindles, static stiffness is considered to optimize the bearing span using two bearings. In addition, most of the optimize design parameters such as shaft diameter, bearing span and bearing preload are considered to minimize the static deflection.

2.1.1 Spindle Features

The spindle is water cooled to allow very robust control of its temperature (thereby minimizing thermal errors and bearing wear). The robust cooling system also allows the use of an aluminum alloy as the housing material.

2.2 Spindle Bearings

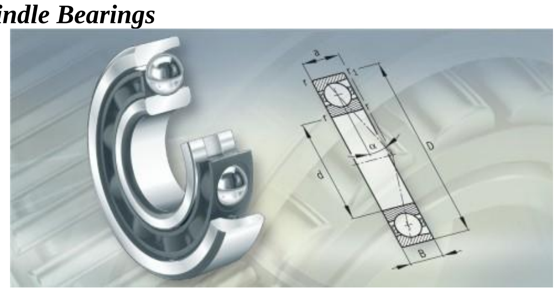

Figure:2.2 Bearing cut section[5]

In construction of main spindle, the most important factors are the choice of bearings and basic geometry. Some of the famous bearing manufacturers, such as FAG has recently produced modular main spindles as a assembly and place it on market.

Spindle bearings are most important element in spindle unit because it locates the spindle axially as well as radially. It carries the load acting on the spindle and also supports the spindle. The selection criterions for spindle bearings are

- Speed
- Torque
- Spindle nose size / tool size / power
- Axial and radial stiffness
- Lubrication
- Preload
- Life.

2.2.1 Bearing Selection

The very short length of the spindle shaft means that an unconventional bearing arrangement can be used. In our spindle shaft is held by a single assembly (of three bearings) that are mounted at the front end of the shaft (between the nose and motor) and a set of two bearings are mounted at the rear end.

2.2.2 Bearing Speeds

Once the operating speed of the spindle has been determined bearings are sized and selected. Then it is decided to run the bearings in grease rather that oil because this eliminates need for oil feed/filtering equipment. To achieve a spindle speed of 12000 rpm we are looking for bearings with a maximum speed more than that of the spindle speed between 14000 rpm and 16000 rpm.

2.2.3 Bearing Arrangement

Often, if a bearing is subjected to large loads or if a high degree of rigidity is required then two or more bearings are used. The bearing arrangements can be combined from universally matched bearings or produced at sufficient lot sizes.

The different bearing arrangements are

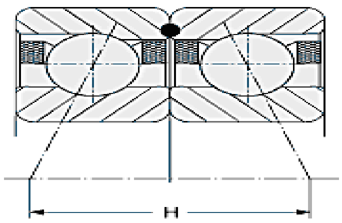

Figure:2.3 Back-to-Back arrangement(DB)

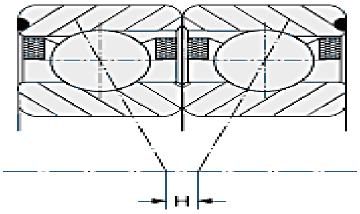

Figure:2.4 Face-to-Face arrangement(DF)

2.2.4 Bearing fit

The machining quality and the correct selection of the fits for the bearing sets are of great importance for a satisfactory operation of precision bearing applications.

2.2.5 Bearing Lubrication

The correct choice of lubricant and method of lubrication is as important for the proper operation of the bearing as the selection of the bearing and the design of the associated components. The function of lubrication is to provide a microscopic film between the rolling elements to prevent abrasion and skidding.

Grease lubrication should be used if the maintenance-free operation over long periods of time is desired, the maximum speed of the bearings does not exceed the speed factor of the grease.

Oil lubrication should be used if the high speeds do not permit the use of grease and the lubricant must simultaneously serve to cool the bearing.

Hence grease is most preferable over oil lubrication at higher speeds.

2.2.6 Spindle Cooling

Both air cooled and water cooled spindle options are available. An air cooled spindle would offer the advantage of requiring a water source and pumping equipment. However, given the limited time allotted for the development of the spindle, we choose the water cooled design because it is much more robust in controlling the temperature of the housing.

3. STATIC STIFFNESS ANALYSIS

3.1 Introduction

Static stiffness is one of the important performances of machine tools. Hence it must be correctly defined and related parameters of spindle must be properly determined. The concepts of "influence factors" in mechanics is made use to discuss the definition of static stiffness (referring to radial stiffness) and to minimize the displacement at the spindle nose in the selection of the structure and related parameters.

Since power loss will be there in terms of mechanical efficiency, but as compared to conventional belt drive system where around 20-30%, here it has been reduced to 10-15%. Hence the available power at the spindle is assumed to be around 8.5 to 9 KW.

Stiffness of the spindle is defined as its ability to resist deflection under the action of cutting force. In general "correlation stiffness" is used as the definition of the static stiffness of the spindle. As shown in fig.3.2 when a force exerted on the spindle nose is F_z, the displacement at the spindle-nose in the same direction as that of F_z is '**δ**' and correlation stiffness is defined as $\mathbf{K = F_z/\delta}$.

3.2 Features of High frequency milling spindle to be designed

The designed spindle operates at 12000 rpm with maximum power rating 10 KW. 25^0 angular contact ball bearings are used for mounting the spindle. In analysis of the stiffness of the spindle the outer diameter of the spindle is nothing but the bearing diameter of the inner bearing race. In general, high speed spindles that utilize grease lubrication do not allow for replacement of the grease between bearing replacements.

3.3 Analysis of Rigidity

Machine tool spindles are subjected to dynamic excitation during machining. While static stiffness is of fundamental importance in geometric accuracy and also the dynamic characteristics of the spindle play a very important role in machining since they affect surface finish, chatter, tool life, bearing life and noise. If the excitation frequency becomes close to one of the natural frequencies of a spindle system, the spindle will undergo an excessive vibration and can produce an unacceptable surface finish. Furthermore, it can drastically shorten the life of the bearings and the tools and can lead to the premature failure of other machine tool components.

The static stiffness or "spring rate" of a system is defined as the ratio of the amount of load, to the deflection of the spindle at the point of load and is expressed in N/mm. The important parameters that need to be considered to determine the spindle stiffness are overhang distance from the nose bearing to the load, bearing speed and bearing stiffness.

The static rigidity is the force required to obtain a unit deflection of the spindle due to its own bending under the force in addition to the deflection caused due to bearing elasticity.

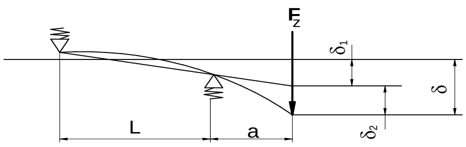

Figure: 3.1 Deflection of the spindle nose

The deflection of the spindle nose 'δ' for an unloaded spindle due to load F_z is given by [2]:

$\delta = \delta_1 + \delta_2$

$$\delta = F_z\left[\frac{1}{S_A}\left(\frac{a+L}{L}\right)^2 + \frac{1}{S_B}\left(\frac{a}{L}\right)^2 + \frac{a^2}{3E}\left(\frac{L}{I_L} + \frac{a}{I_a}\right)\right]$$

---eqn.3.1

where,

δ_1= Deflection due to radial yielding of the bearings in mm

δ_2= Deflection due to elastic bending of the spindle

in mm
a= Length of overhang in mm
L= Bearing span in mm (varying)
E= Young's modulus of Spindle material in N/mm^2
P= Cutting force in N
S_A=Stiffness of the front bearing in N/mm
S_B=Stiffness of the rear bearing in N/mm
I_L= Mass moment of inertia of the shaft at the bearing span in mm^4
I_a= Mass moment of inertia of the shaft at the overhang in mm^4

Two different bearing arrangements 'A' and 'B' are considered for the design. Angular contact ball bearings

The stiffness of the measuring rod can be calculated from a beam model. It consists of steel with a Young's modulus of 2.1×10^5 N/mm²

The front bearing set should be positioned to minimize the overhang of the spindle nose. It is required to optimize the bearing spacing 'L_0' for maximum spindle stiffness. This requires examination of relative combinations to deflection, which arise from both bearing deflections and spindle bearing. By using bearings with a smaller cross section, larger spindle diameters can be used without changing the housing bore diameter or slightly increasing the housing bore diameter. This increases the bending rigidity of spindle and leads to increase in overall rigidity. Initially optimum bearing span is calculated using following eqn. (3.2) for each configuration. Details of different bearing arrangements [08] and calculated optimum bearing span length (L_0) are listed in table 3.2.

Calculation to find Optimum Bearing Span Length (Eqn.3.2):

$$Lo = \left[6EI_L\left(\frac{1}{S_A}+\frac{1}{S_B}\right)+\left(\frac{6EI_a}{aS_A}\right)Q\right]^{1/3} \quad ---3.2$$

where,
L_0= Static optimum Bearing Span Length in mm
E = Young's modulus = 2.1x10^5 N/mm^2
a = Length of overhang = 65 mm
S_A=Stiffness of front bearing = 485x10^3 N/mm (for dia. 65mm)
S_B = Stiffness of rear bearing = 318.4x10^3 N/mm (for dia. 55mm)
I_a = Moment of inertia of the shaft at the overhang is found to be 375.5x10^3 mm^4
I_L =Moment of inertia of the shaft at the bearing span is found to be 814.4x10^3 mm^4
Q = Trial value for iterative determination of L_0=4xa = 4x65 = 260 mm

Theoretical analysis has been carried out to evaluate spindle stiffness and to optimize the design to have maximum spindle nose deflection. Here the span length is varied from 140 mm to 230 mm. The variation of span length may become essential to accommodate the integral motor rotor. By considering spindle nose size BT-40

with 25° contact angle are used with medium preloading. The bearing arrangement 'A', with triplet bearing set at the front, in which one pair of angular contact ball bearings are arranged in tandem with respect to each other and back-to-back with respect to a single angular contact ball bearing and the duplex bearing set at the rear mounted in back-to-back fashion. The bearing arrangement 'B', with duplex bearing set at the front, in which a pair of angular contact ball bearings is arranged in back-to-back and the duplex bearing set at the rear mounted in back-to-back fashion.

For diameter 65 mm front bearing, axial rigidity(C_a) for medium preloading condition is C_a=178.3 N/µm [5]

taper and also the flange, the overhang of the spindle is around 65 mm from the front bearing center. The diameter of the spindle at the front bearing is changed to find out its influence on the spindle stiffness. The diameter of the spindle at the front is varied from 60 to 70 mm to evaluate its role in imparting the stiffness to the spindle system. Deflection and stiffness for bearing arrangements A & B for different span lengths and for different front bearing diameters are listed in tabe.

Calculation to find Defection i.e .$\delta = \delta_1 + \delta_2$ (From Eqn.3.1):
where,
a = Length of overhang = 65 mm
L = Bearing span = 200 mm
E = Young's modulus of Spindle material = 2.1x10^5 N/mm^2
F_z = Cutting force =4500 N
S_A= Stiffness of the front bearing = 485x10^3 N/mm (for dia. 65mm)
S_B=Stiffness of the rear bearing = 318.4x10^3 N/mm
I_L= Moment of inertia of the shaft at the bearing span is found to be 814.4x10^3 mm^4
I_a=Moment of inertia of the shaft at the overhang is found to be 375.5x10^3 mm^4

δ = 30.41x10^{-3} mm
or **δ = 30.41 µm**
and, Stiffness, **K=F_z/δ**
=4500/30.41
K =147.97 N/µm

Variations of deflection and stiffness values for bearing arrangements 'A' and 'B' are given in the following table.

Table: 3.1 Variations of Deflections and Stiffness for bearing arrangements 'A'& 'B'.

Sl. no	Span length mm	Overhang mm	Front bearing dia. mm	'A'		'B'	
				Δ µm	K N/ µm	δ µm	K N/ µm
1	140 to 230	65	60	31.81 to 32.88	141.46 to 136.86	37.29 to 38.93	120.69 to 115.60
2	140 to 230	65	65	30.07 to 31.26	149.64 to 143.95	35.28 to 36.70	127.56 to 122.63
3	140 to 230	65	70	28.16 to 29.53	159.79 to 152.38	32.94 to 34.08	136.61 to 132.05

The diameter of the spindle between the bearings has more influence on the rigidity as is evident from the tables 3.3 to 3.5. This diameter could be varied to the extent of a maximum of 65 mm from the practical considerations. To accommodate the integral motor rotor of 10 KW power rating, the span length of the spindle shaft is taken as 200 mm and the maximum diameter of 65 mm.If the diameter of the spindle is increased, than the motor power may have to be increased and the bearing arrangements have to be reshuffled. Therefore at the spindle diameter of 65 mm, the attainable speed is 15000 rpm which falls in-between the range of 14000-16000 rpm, so that the required spindle can run at the speed of 12000 rpm. Hence at the available optimum values, the stiffness of the arrangement 'A' has a value of around 147.97 N/µm and the deflection of the spindle nose based on static analysis is around 30.41 µm. From the point of view of static analysis, bearing arrangement type 'A' is chosen as an optimum design.The variation of deflection and the stiffness of the spindle nose with varying span lengths are plotted in fig.3.2 and 3.3. The hatched part shows the optimum region of bearing span length.

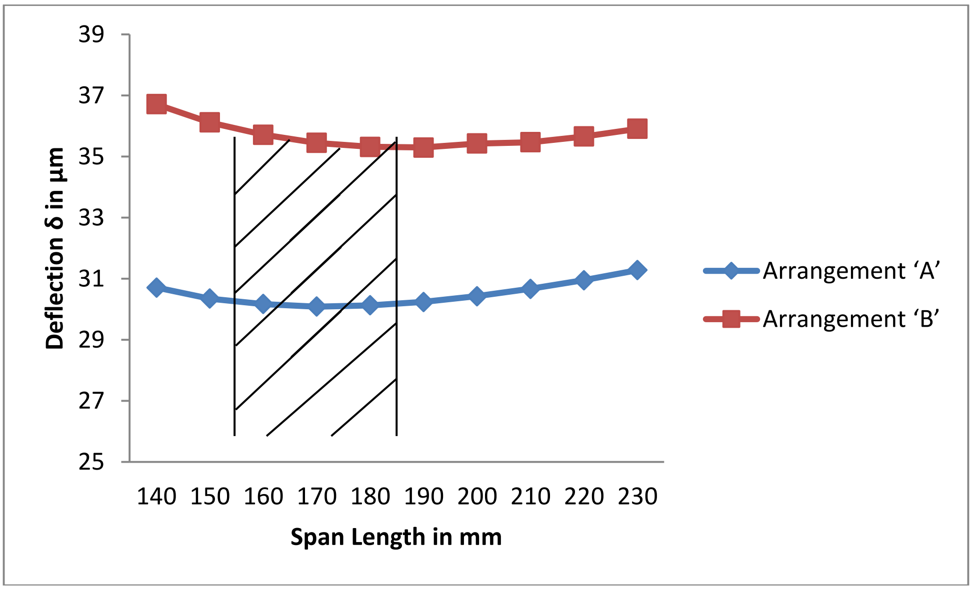

Figure: 3.2 Deflection at the nose for bearing arrangements (front bearing dia. 65mm)

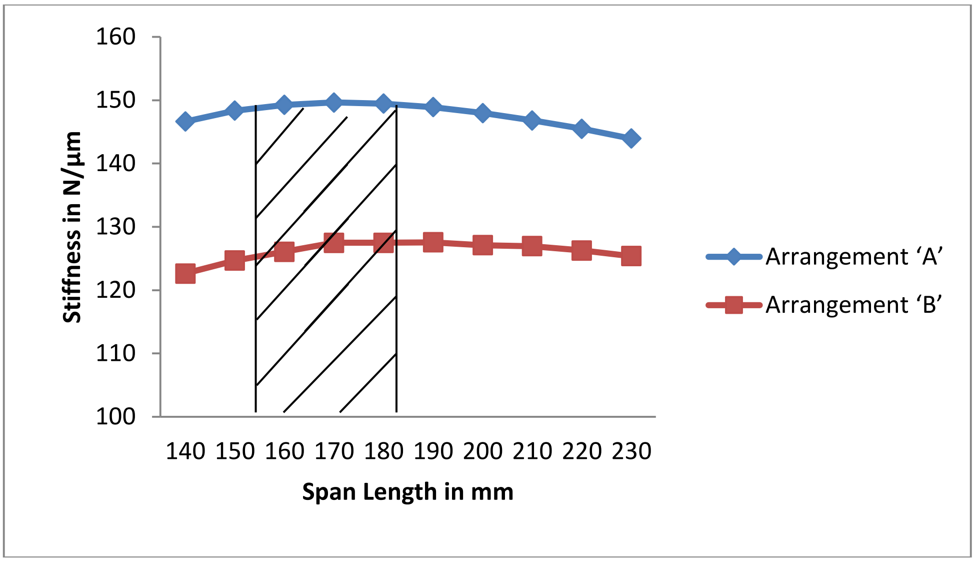

Figure: 3.3 Stiffness variations for bearing arrangements (Front bearing dia. 65mm)

The above figures show the effect of spindle elasticity and spindle deflection on the overall rigidity. The hatched part shows the optimum region of bearing span length. Variation of deflection and the stiffness when the bearing span is changed from 140 to 230 mm is not significant. This gives the designer flexibility in sizing the span to accommodate the integral induction motor.

In this we consider Triplet bearing set arrangement 'A' for the front end of the spindle, in which one pair of angular contact ball bearings are arranged in tandem with respect to each other and back-to-back with respect to a single angular contact ball bearing. Tandem bearing pair will carry both radial and axial loads equally shared. However, axial loads can be carried in one direction and therefore, the single angular contact bearing which has been arranged in a back-to-back fashion, will oppose the tandem bearing set in-order to accommodate any axial loads in the reverse direction. The overall bearing arrangement will provide good axial and radial stiffness. Thus the results obtained by both the methods agree with each other to the maximum extent with good correlation.

4. CONCLUSIONS

- Variation of stiffness and deflection when the bearing span is changed from 140 to 230 mm is not significant. This gives the designer flexibility in sizing the span to accommodate the integral induction motor.
- The diameter of the spindle between the bearings has more influence on the rigidity as is evident from the results. This diameter could be varied to the extent of a maximum of 65 mm from the practical considerations of the bearing speeds. At this diameter the stiffness of the arrangement 'A' has a value of around 147.97 N/µm and the defection of the spindle nose based on static analysis is around 30.41 micron meter for the above arrangement. From the point of view of static analysis, bearing arrangement type 'A' is chosen as an optimum design.
- For a given overhang of 65 mm, it is evident that the bearing arrangement A, with triplet bearing set at the front, in which one pair of angular contact ball bearings are arranged in tandem with respect to each other and back-to-back with respect to a single angular contact ball bearing and the duplex bearing set at the rear mounted back-to-back shows the maximum stiffness of the spindle arrangement and is equal to 147.97 N/µm.
- The overhang has great influence on the stiffness of the spindle; lesser the overhang the better is the stiffness of the spindle. The influence of the front bearing stiffness on the overall stiffness is quite considerable. Hence, the bearings with higher stiffness should be located at the front.
- Analysis of rigidity was also carried out using ANSYS and there is a good correlation between the results obtained by theoretical calculation and ANSYS.

REFERENCES

1. B.Denkena, H.C.Mohring, J.C.Will, Tool defection compensation with an adaptronic milling spindle, Institute of Production Engineering and Machine Tools (IFW),Hannover Center for Production Technology, Hannover Leibniz University.
2. Book of Spindles, www.dynospindles.com.
3. CMTI Hand Book, Machine Tool Design Hand Book, Tata McGraw-Hill Company Limited, 1983,421-588
4. Dr.Sinan Badrawy, Dynamic Modeling and Analysis of Motorized Milling Spindles, Moore Nanotechnology Systems, LLC, 2003.
5. FAG Spindle Bearings Catalogue, AC 41 130/7 EA · March 2008, www.fag.com.
6. INA-FAG BEARINX®-online Spindle Calculation-SCHAEFFLER GROUP Industrial.

7. Lipka I, Harkany, Determination of the optimum bearing distance of cantilever shafts with two supports, Mach. Tool Research Transactions, 45 (1964) 65-80.
8. Machine Manual, VMC 1000, The Mysore Kirlosker company, Harihar.
9. Matti Rantatalo, P. Norman, K. Tatar, Non-contact measurements of tool vibrations in a milling machine, SVIB vibrations Nytt, 22 (2) (2004) 22-29.
10. Mehdi Sherafati Zangeneh, Seyed Saleh Hosseini Yazdi, High Revolving Speed Spindles Definition Due to Transient Vibration Conditions, Sharif University of Technology, Tehran, Iran.
11. Modal analysis using ANSYS, www.mece.ualberta.ca/tutorials/ansys.
12. Momir Sarenac, Stiffness of Machine Tool Spindle as a mainfactor for treatment accuracy-UDC 62-113,624.046, Mechanical Engineering Vol.1, No 6, 1999, pp. 665 – 674.
13. Osamu Maeda, Yuzhong Cao, Yusuf Altintas, Expert spindle design system, International Journal of Machine Tools & Manufacture, 45 (2005) 537–548, October 2004.
14. Spindle Basics, 2008, www.spindlesworld.com.
15. Spindle Concepts and Design-Spindle Motors, literature KAE-S626-7.3, Yaskawa Electric Corporation, Tokyo, Japan.
16. Technical Specifications for IBAG-Motor Spindles, IBAG Switzerland AG, 1999, www.ibag.ch.
17. TIMKEN, Machine Tool Spindle, 1M-07-02 No. 5911, www.timken.com.
18. Yung C. Shin, Analysis of bearing configuration effects on high speed spindles, International Journal of Machine Tools & Manufacture, 44 (2004) 347–364.83, 421-588.