Design and Analysis of Machine Tool Spindle

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Abstract

Abstract-The power utilization capacity of machine tool spindles depends mainly on stiffness at tool point. It is known in machine tools for instance in machining centers the spindle system could alone account for about 30 to 40% of stiffness at cutting point between tool and work piece.

Even though there are 2 or more bearings as a pack at each front or rear location even then an approximate or equivalent stiffness is given at front and rear locations. This is because it is not possible to compute shaft deformations supported on more than 2 supports on a shaft it is not represented further each bearing has a number of rolling elements like ball or roller around 15 to 20.It is possible to predict the stiffness of a bearing by computing hertizian contact stresses at each rolling element going through nonlinear procedure In view of above it is necessary to develop a simplified methodology for modeling spindle system with bearings in a machine tool spindles. The methodology should facilitate 3D modeling the bearing in a large machine tool mesh at the same time the methodology should ensure precise results.

Keywords*- spindle, stiffness, bearing, shaft, deformations*

I Introduction

I-A Machine Tool Structure

The machines commonly used to perform material removal operations are known as machine tools. The principle of a machine tool is to generate required surface by providing requisite motion between the cutting tool and the work piece. The most commonly used machine tool applications are turning, milling, drilling, grinding etc**.**

1) Purpose of machine tools

The basic purpose and principle of machine tools are:

- To provide the relative motion between the cutting tool and the work piece.
- To provide the stiffness required for the cutting operation.
- To control the vibrations caused during cutting.
- As a source of power for the cutting operation.
- To facilitate accuracy and surface finish.

2) Machine Tool Spindles

Spindles are rotating drive shafts that serve as axes for cutting tools or 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**.**

The design of the spindle and the quality of the components inside the spindle are major factors that contribute to the spindle's durability and longevity. The spindle should be designed in such a manner so that features that keep chips and coolant are kept out of the spindle's bearing system, like in an air purge system and wipers that use positive lubrication pressure to protect the spindle from contaminants

Spindles: A key to improve manufacturing productivity and machine tool performance.

There is no doubt about the fact that today the manufacturing industry has become more and more globalized. Manufacturers are constantly looking for various ways and means to improve the productivity of machine tools through improved power densities, higher speeds, greater flexibility, and more multitasking of operations. One important method to achieve this is by continual innovation and improvement of spindles. Spindles play a vital role in the quality of the final product and enhance the overall productivity and efficiency of the machine tool itself. Today's spindle designs offer the manufacturers and machine builders much greater performance and reliability than ever before. Users can increase productivity in any industry by properly applying the advanced spindle technologies in specific applications. The powerful, flexible and faster machine tool spindles can reduce the number of cuts and making holes in manufacturing by half.

3) Design of Spindle

In modelling and analysing the FEM model of machine tool structure there will be number of elements as shown in Fig 1 in view of this it is difficult to analyse the each part of structure separately

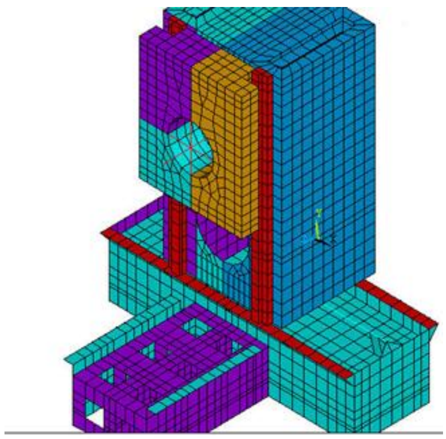


Fig1 FEM model of machine tool structure

To model, analyse spindle with bearing having all the rolling elements and to calculate stiffness of bearing is possible by computing hertizian contact stresses at each rolling element going through non linear procedure. but if FEM mesh of complete machine tool is to be done than it becomes very complex because, to model each rolling element and calculating stresses becomes complex with the application of load on different roller will have different point of contact at each location a typical load distribution model of ball bearing before contact and after contact is as shown in Fig 2

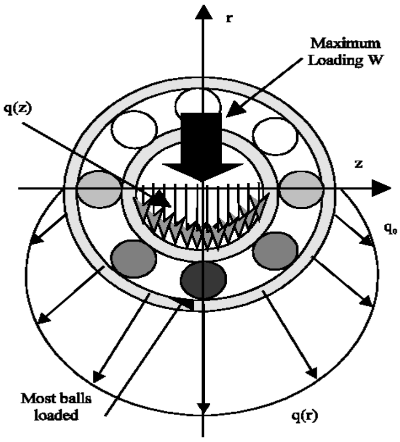


Fig2 Loads distribution model on ball bearing before contact q(Z) and after contact q(r).

4) Contact rolling bearings for machine tools

Since the contact rolling bearings are frequently used for machine tool spindles, there are a number of bearing types for machine tools. The spindle speed range has been speedily increasing for high speed machining. Only the bearings suitable for high speed spindle, such as angular ball bearings and cylindrical roller bearings, are used for machine tools, especially for drilling machine spindles.

Angular Contact Ball in the machine tools, This type of bearing has balanced essential properties for the high speed and high accuracy spindle. Because of the structure, it only supports an axial load inone direction; thus it has to be applied to at least two angular bearings in the spindles. Also, the stiffness of the angular contact ball bearing it self is not high enough for the milling operations.Therefore, designers may need to use a multiple number of bearings in order to compensate for the disadvantageBearings are the most suitable and most frequently used.

Fig3 Angular contact ball bearing

Usually bearing structure will have no of roller elements around 15 to 20 as shown in Fig 3 and to model each rolling element and carry out FEM analysis in a spindle structure will be a difficult task so it is needed to develop a simplified method of modelling spindle which should take care of bearing structure and the method should ensure that correct results are obtained when analysis of spindle structure is done. The results should match with the literature papers presented earlier or with the analytical calculation carried out using standard relations used in machine tool structures.

II Statement of the Problem

In the present work the static analysis and dynamic analysis is carried out for spindle supported on two front bearings and a rear bearing. For the analysis of structure the minimum deflection region near loading point is considered. Bearing stiffness value will be calculated by an iteration procedure, life of bearings is calculated using numerical relations and this paper also describes the modifications required to correct the bearing span so as to get more stability for spindle.

II- A Optimization Bearing Span

After selecting on the components of the spindle, designers concentrate on the design details such as the dimensions and positions of the parts. Recently, finite element (FE) analysis techniques have become popular, which allow designers to predict part properties, such as static and dynamic stiffness. For example, the designers can analyze the static stiffness of a part many times by changing the part dimensions until a satisfactory design dimensions are achieved. However, the designers can never know if the design is an optimum or not. The need to optimize part dimensions and locations has increased, and some commercial optimization software is in fact available.

In order to apply the optimization to the spindle design, an objective and design variables must first be identified. The chatter vibration is an important issue for machine tool operators, as it may cause the spindle to break, resulting in expensive repairs. Therefore, designing a chatter free spindle is the main objective selected in this research.

In a spindle design, there are many design parameters, such as the dimensions of the spindle shaft, housing, and collars. However, it is not realistic to optimize all of these dimensions because the process is time consuming and there is no guarantee that the results will converge due to too many variables. Therefore, in practice, there should not be too many design variables, and most efficient design parameters need to be selected to optimize the objectives. There are numerous constraints on the geometric design of spindle parts, and design dimensions are usually coupled with each other; if the diameter of the spindle shaft changes, the bore diameter of the housing also has to be changed. In this case more parameters need to be taken into account, and the iterative optimization result may not be accomplished with a convergence. The dimensions that are independent from other parts and affect the dynamic properties of the spindle for a chatter free spindle are bearing positions. A detailed explanation of why the bearing spans are important in regard to the chatter property of the spindle will be detailed later. From the design principle, the front end bearing must be as close as possible to the spindle nose in order to increase the static stiffness of the spindle at the tool tip. While it is the most critical bearing in terms of the dynamic stiffness of the spindle, changing the position of the front end bearing is practically now viable

II-B Bearing life calculations

The life expectancy of bearing used in machine tools depends on several varying factor and definite rule cannot be applied. It depends upon kind of machine tool, whether it is a special purpose machine working under constant working conditions or universal machine tool where the machining conditions are regularly varying. It also depends upon the position in which the bearings is used and ease with which it can be replaced. The life expectancy of the bearing may coincide with life expectancy of the machine or be only part of it. For example it may be equal to the overhauling period decided by experience. However the life expectancy of bearing used in machine tool working continuously for 8 hours a day at constant load and speed is chosen between 20000 to 30000 hours. A value between 50000 to 60000 hours is selected for a machine working continuously all 24 hours of the day.

III Results and Discusion

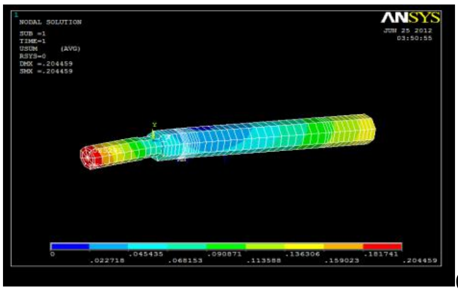
III-A Introduction

Different modifications on the basic geometries were investigated to obtain the required stiffness at the end of spindle structure where load is applied. An attempt was made to reduce the deflections by varying bearing span. The model undergoes through all iterative procedures, and evaluation is performed by using the output results. The objective of this chapter is to present and discuss the output results of static and dynamic analysis and also to plot graph of bearing span v/s deflection.

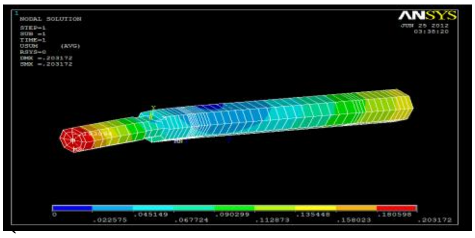
III-B Results of Analysis

. The Finite Element Model with the boundary conditions is submitted in ansys for Static Analysis. As for output request FEM model results of spindle are obtained which include mainly deflection. For checking the deflections of spindle in axial and radial direction go for sub grid solution under query results mode.

1] First begin with bearing span of 90 mm



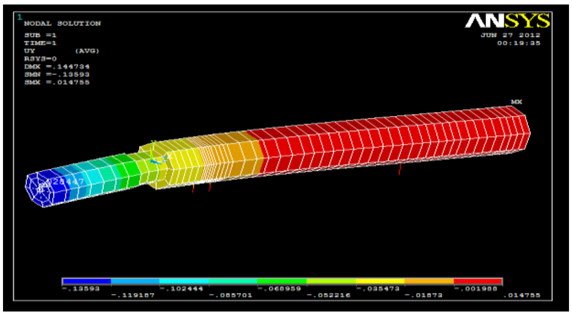
(a)Axial



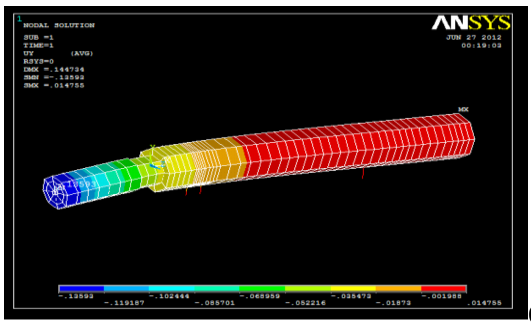
b)Radial

Fig 4 Showing deflection for 90mm in (a) Axial and (b) Radial direction

2] Bearing span of 250mm



(a)Axial



(b)R adial

Fig 5 Showing deflection for 250mm in (a) Axial and (b) Radial direction

III-C Modal Analysis

Modal analysis is used to determine the vibration characteristics (natural frequencies and mode shapes) of a structure or a machine component while it is being designed. It can also be a starting point for another, more detailed, dynamic analysis, such as transient dynamic analysis, a harmonic response analysis, or a spectrum analysis.

The procedure for a modal analysis consists of four main steps:

1) Building the model
2) Applying loads and obtaining the solutions
3) Expanding the modes

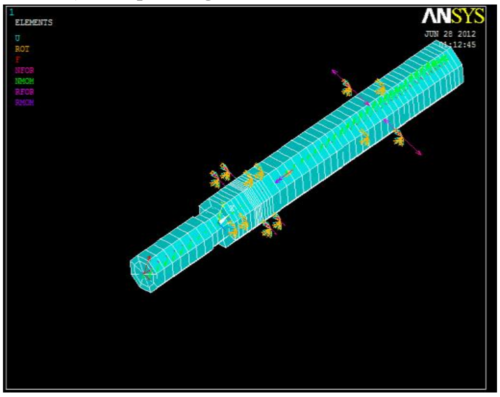


Fig 6 3D spring model with boundary conditions applied

1) *Mode shapes*

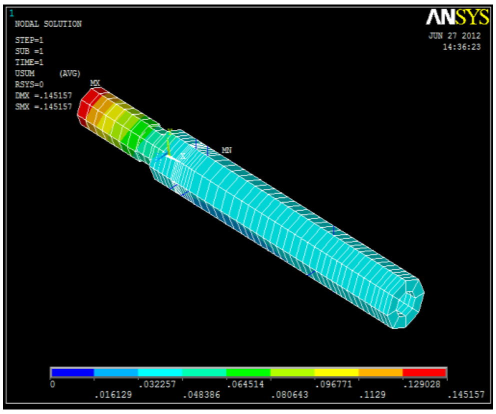


Fig 7 Mode shape 1

Fig 7 shows the mode shape 1 at freq 201.6Hz. It can see from the Fig that the mode shape is only in axial direction

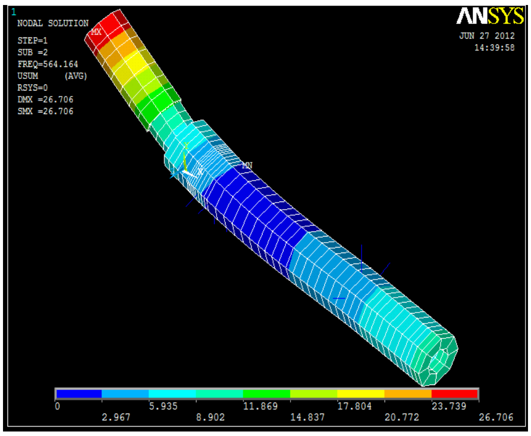


Fig 8 Mode shape 2

Fig 8 shows the mode shape 2 at freq 564.16Hz It can be seen from the Fig that there is bending mode in vertical direction at loading point

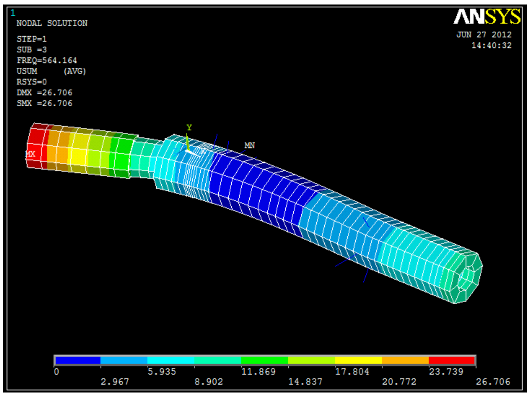


Fig 9 Mode shape 3

Fig 9 shows the mode shape 3 at freq 564.16Hz. It can see from the Fig that there is bending mode in horizontal direction at loading point even though frequency at step 2 and 3 is same the mode shape is different this is mainly due to symmetry of spindle structure.

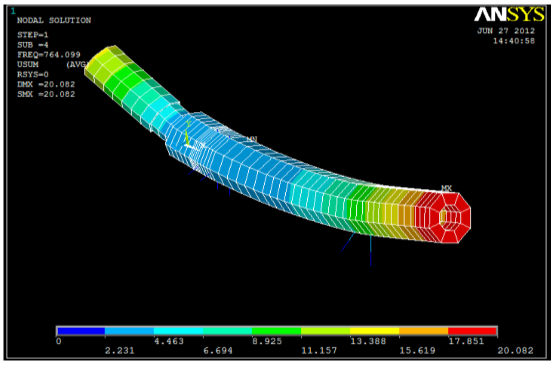


Fig 10 Mode shape 4

Fig 10 shows the mode shape 4 at freq 764.16Hz. It can see from the Fig that there is bending mode vertical direction at both ends

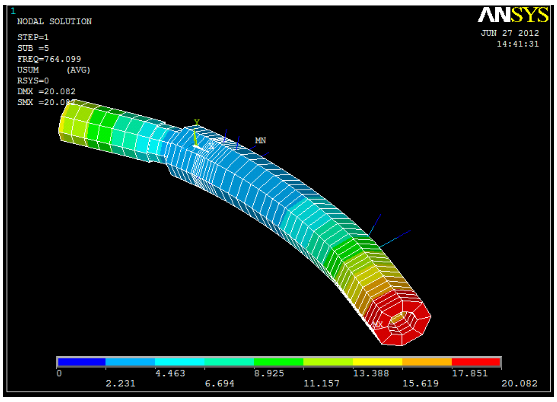


Fig 11 Mode shape 5

Fig 11 shows the mode shape 5 at freq 764.16Hz. It can see from the Fig that there is bending mode horizontal direction at both ends this is again due to symmetry of structure.

2)Rigidity Calculations

A spindle provides drive to either the work piece or the tool depending upon the type of machine tool. The accuracy with which a spindle runs affected by elastic deformation of the spindle its bearings the housing and other components of arrangement. The stiffness of the spindle diameter all have an influence on the overall stiffness of spindle system while stiffness of housing is an important factor the overall stiffness of spindle system, normally the housing when compared to other elements of spindle arrangement are quite stiff and hence its effect is not discussed here.

The overhang has a great influence on the stiffness of spindle, lesser the overhang better it is. The influence of front bearing stiffness on overall stiffness is quite considerable. Hence a bearing with higher stiffness could be located at front. Ignoring effects of housing deformations on the spindle, the total deflection of the spindle unit is due to the elastic deformation δ_2 of the spindle itself together with δ_1 the deflection caused by elastic deformation of the bearings. The total deflection of the bearing system due to load `P` at the point of applied load is given by

$$\delta = \delta_1 + \delta_2 = P\left[\frac{1}{S_A}\left(\frac{a+L}{L}\right)^2 + \frac{1}{S_B}\left(\frac{a}{L}\right)^2 + \frac{a^2}{3E}\left(\frac{L}{I_L} + \frac{a}{I_a}\right)\right]$$

In the above equation it is assumed that the bearings, the diameter of spindle and overhang of spindle are fixed, it can be seen that the stiffness becomes a function of bearing span only. Thus the optimistic distance between bearings is based on consideration of static deflection which gives the maximum stiffness to the spindle system which is given by

$$L_0 = \left[6EI_L\left(\frac{1}{S_A} + \frac{1}{S_B}\right) + \left(\frac{6EI_L}{aS_A}\right)Q\right]^{1/3}$$

The equation for optimum bearing span could be solved by iteration by first taking Q=4a and then equal to the derived value of L_0 for subsequent iterations. It has observed that effect of change in stiffness of spindle system is less when bearing span exceeds the optimum than when it is less than optimum. An increase of about 20% on the bearing span reduces the spindle stiffness by 4%. It is recommended to maintain the bearing span within these limits because of other design considerations in such cases a third bearing will have to be used despite the system becoming statically indeterminate structure combined with increased misalignment of bore.

IV Conclusion and Future Scope

IV-A Conclusion

Usually spindles are mounted in antifriction bearings such spindles are often found in several machine structure including machine tools especially if number of bearings are more than two analytical calculation of stiffness becomes difficult because the beam becomes a continuous beam.

The FEM analysis of practical machine tool structures is complicated with several thousands of nodes and elements, the model of spindle with bearings becomes part of this since each bearing contains several The simplified approach has been developed for 2D and 3D analysis of spindle supported on multiple bearings is developed an iterative procedure is presented for computing reactions of bearings under load and also for calculating bearings stiffness in general 3 to 4 iterations are sufficient to get convergent results. The procedure makes use of beam element for spindle and matrix 27 for springs. In 2D model each bearing is represented by a single matrix 27 element where as in 3D it is represented by four springs this matrix 27 element represents elastic deformation of all rolling elements in the bearing and sleeves as well rolling elements it is not possible to make exact bearing model.

IV-B Scope of future work

- The study effect of spinning of the rolling elements, which is applicable at high speeds.
- The thermal analysis of spindle structure can been carried out.

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