A Review on Design and Analysis of Machine Tool Spindle

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Abstract

The machine tool spindle provides the relative motion between the cutting tool and the workpiece which is necessary to perform a material removal operation. In turning, it is the physical link between the machine tool structure and the workpiece, while in processes like milling, drilling or grinding, it links the structure and the cutting tool. This work deals with design and analysis of Spindle in which the material used for the spindle is alloy steel. The machine tool spindle is one of the major mechanical components in any machining centre. The main structural properties of the spindle generally depend on the dimensions of the shaft, motor, tool holder, bearings and the design configuration of the overall spindle assembly. The forces which are affecting the machine tool spindle during machining are Tangential force (Fz), Axial force (Fx), radial force (Fy) will be estimated. Based on maximum cutting force incurred the analysis will be carried out. The spindle is modelled using CATIA software. The component is meshed and analysis is done in ANSYS software. It includes static and dynamic analysis of the spindle by considering different forces acting on the machine tool spindle during the turning operation. From static analysis stress and deformation of the spindle will be obtained and from dynamic analysis dynamic properties are obtained under vibrational excitation.

Keywords- *spindle, Catia, Ansys, deformations.*

LITERATURE SURVEY

Literature survey plays an imported part in formulating any work. There are many papers available for the analysis of spindle of which few are selected based on the relevance of the statement of this project. Based on these research papers, a different methodology will be chosen which is suitable for analysis of spindle. The referred papers are explained in brief as below.

Osamu Maeda*et.al* [1] discussed an Expert spindle design system strategy which is based on the efficient utilization of the laws of machine design, dynamics and metal cutting mechanics. The configuration of the spindle is based on the specification of the work piece material, necessary cutting conditions and commonly used tools on the machine tool. The spindle drive mechanism, driving motor, bearing type and spindle shaft dimensions were selected based on the required applications. They iteratively find out the Frequency Response Functions (FRF) of the spindle at the tool tip using the Finite Element Method (FEM).This work predicted the cutting operation at the required speed and depth of cut for different flutes of cutters. The arrangement of bearings was optimized using sequential quadratic programming (SQP).

Chi-Wei Lin *et.al*[2] diccused that Development of high speed spindle technology is critical to the implementation of High speed machining (HSM). As Compared to the conventional spindles, motorized spindles are equipped with a built-in motors for good power transmission but the built in motors produces large amount of heat into the spindle system as well as extra mass to the spindle shaft, thus it affect to the dynamic behavior of the spindle. The author presents an integrated model with experimental validation and sensitivity analysis for studying various thermo mechanical dynamic spindle behaviors at high speeds and the following effects are observed that is the bearing preload effects on bearing stiffness, and overall spindle dynamics, high speed rotational effects. The results of this paper shows that a motorized spindle softens at high speed because of the centrifugal effect on the spindle shaft.

Dr. S. Shivakumar *et.al*[3] discussed the Design and analysis of lathe spindle in which alloy steel material was used for the spindle. Two bearings were supported by spindle with different spans. Bearings consist of balls with the certain amount of stiffness, which acts as cushioning effect to the spindle so they considered the spring in the Ansys for the analysis and also carried out static analysis and dynamic analysis of a spindle supported by the front and rear bearing. Bearing stiffness

value was calculated by an iteration procedure and using numerical relations life of bearings was calculated.

Tobias Maier *et.al*[4] discussed modeling of the thermo mechanical process effects on machine tool structures, in machine tools thermally induced deviations are key issues specially when considering the actual trends of high performance and dry cutting. The interactions between the cutting process and the machine tool structure are significant boundary conditions for the numerical prediction of the thermo mechanical machine behavior. This paper presents an approach for the atomistic modeling of process effects, it includes process of heat, cutting forces and increased load on feed and main drives. Author provided an empiric data for the relation between cutting forces and active drive power.

A.Ertuk *et.al*[5] discussed the Effect analysis of bearing and interface dynamics on tool point FRF for chatter stability in machine tools by using new analytical model for spindle tool assemblies. It is observed that the bearing dynamics is controlled by rigid body modes of the assembly, where as the first mode is affected by spindle holder interface dynamics and second mode that is elastic mode is affected by holder tool interface dynamics. Individual bearing and interface translational stiffness and damping values control the natural frequency and the peak of their relevant modes respectively. From this paper it is concluded that rotational contact parameters do not affect the resulting FRF considerably. In this paper, the analytical method was presented for modeling spindle–holder–tool assemblies and predicted the tool point FRF. By using this model, the effects of bearing and interface dynamics on the tool point FRF were studied.

Tugrul Ozel, Taylan Altan[6]presented paper titled Process simulation using finite element method prediction of cutting forces, tool stresses and temperatures in high speed flat end milling. End milling of die mold steels is a highly demanding operation because of stresses and temperatures generated on the cutting tool due to high hardness of work piece. Modeling and simulation of cutting processes have ability for selecting optimum conditions and improving cutting tool designs, especially in an application such as high-speed milling. The main objective of this study was to develop a methodology for simulating and predicting chip flow, cutting process in flat end milling, operation cutting forces, temperatures and tool stresses using finite element analysis (FEA). It was used in the application for machining of P-20 mold steel
with 30 HRC hardness by using the commercially available software DEFORM-2D.

Mr. Sahil, Mr. Jiten Saini[7]has written a paper on Static, fatigue and modal analysis of
connecting rod under different loading conditions. Connecting rod is an important link between crankshaft and piston, and its primary function is to convert reciprocating motion into rotary motion of crankshaft. Connecting rod is subjected to many stresses than any other Engine components. In this paper static and modal analysis was performed on the connecting rod and the S-N approach by modified Goodman criterion for predicting fatigue life of the connecting rods is presented. The model was created using Solid
modeling software-Solidworks2013. Further author conducted finite element analysis using Ansys14 Workbench to determine the von-mises stresses and strains, fatigue life and modal frequencies under different loading conditions.

R. A. Gujar, S. V. Bhaskar [8]presented paper on Shaft design under fatigue loading by using modified Goodman method. In this paper, shaft was used in an inertia dynamometer rotated at 1000 rpm. Considering the different parameters like torque acting on a shaft, forces it helps to calculate the stresses induced. With the help of FEA stress analysis carried out and the results which were obtained from FEA compared with the
theoretical values. Consider the stress concentration factor to find the fatigue life.

Wojciech Stachurski, Stanis law Midera*et.al* [9] discussed the effect of processing conditions on the value of the cutting force (*Fc*), during straight turning operation. The process is based on equations in the form of power polynomials which were obtained from the results of experimental tests. The tests were conducted while turning C45 carbon steel metal with and without the use of cutting fluid. Here cutting forces were determined by using three-component piezoelectric dynamometer.

Haci Saglam, Suleyman Yaldiz*et.al* [10] presented paper on the effect of tool geometry and cutting speed on main cutting force and tool tip temperature. In this paper, the effects of rake angle and entering angle in the tool geometry and cutting speed on cutting force components and the temperature generated on the tool tip in turning operation were investigated. The data used for the investigation were derived from experiments conducted on a CNC lathe. During the tests, the depth of cut and feed rate were kept constant. They found that rake angle was effective on all the cutting force components, while cutting speed was effective on the tool tip temperature. They got average deviation between experimental measured and calculated force results were found as 0.26%.

R. A. Gujar, S. V. Bhaskar [11]presented paper on Shaft design under fatigue loading by using modified Goodman method. In this paper, shaft was used in an inertia dynamometer rotated at 1000 rpm. Considering the different parameters like torque acting on a shaft, forces it helps to calculate the stresses induced. With the help of FEA stress analysis carried out and the results which were obtained from FEA compared with the theoretical values. Consider the stress concentration factor to find the fatigue life.

Haci Saglam, Faruk Unsacaret.al [12] presented a paper titled investigation of the effect of rake angle and approaching angle on main cutting force and tool tip temperature. This author also done the same work as [10] and same experiment setup was used, this paper differs in selection of parameters during turning operation. They considered effect of rake angle and approaching angle on cutting forces and tool tip temperature. They got average deviation between experimental measured and calculated force results were found as 0.37%. Here author has an empirical approach to calculate cutting main force. The cutting forces were assumed to be linearly proportional to the uncut chip area Ac. The relationship between main cutting force Fc and uncut chip area Ac and specific cutting stress ks is expressed by Kienzleas

Fc = Acks Where, Fcis the main cutting force in N, Ac is the chip crosssection in mm2 and ksis the specific cutting force in N/mm2 .

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**.**

spindle technologies in specific applications. The powerful, flexible and faster machine tool spindles

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 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

can reduce the number of cuts and making holes in manufacturing by half.

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.

Special Purpose Machines

Special purpose machines (SPM) are designed to perform special machining operations or testing of components, as per the requirements. Examples include milling machines, boring machines, broaching machines, lapping and honing machines, test rig for fuel injection pump calibration, profile checking equipment for camshafts, axial play testing for gear box testing auto electric test rig for motors and alternators, nozzle testers and so on.

The SPM"s are developed by Bosch Limited and is being supplied to various renowned customers depending on their requirements. The SPM"s consists of base, drive systems, mechanism, slides, machine tool spindle and so on. They are manufactured to carryout special particular tasks like mass production, super finishing operations, testing rigs, inspection benches and so on with at most accurately.

In a milling machine the cutter having one or more cutting teeth is mounted on the spindle shaft, which rotates at different speeds and machines the workpiece held on the machine table. Thus, the spindle speed, the direction of rotation of the cutter, the depth of cut and the table feed becomes the key parameters of the milling process. Thus good results of machining a workpiece can only be achieved in the milling process with a well-balanced setting of these parameters.

Among all the component of a machine tool, the spindle system is the most important critical part, since its dynamic properties directly affects the cutting ability of the whole machine tool. Spindle is the major key component of all the machine tools. The productivity and the finish quality of the workpiece directly depend on the structural properties of the spindle. The dimension of the shaft, bearings, tool holder and the overall spindle assembly plays a crucial role in the structural properties of the spindle. A Precision machine tool spindle that will be used must be designed to provide the required performance features. The important performance features include:

1. Achieving the desired Spindle Power, highest and Continuous.

2. Capable of withstanding the Maximum Spindle load both axial and radial.

3. Reaching the Maximum Spindle Speed Allowed.

4. Tooling Style, Size and Capacity for Automatic Tool Changer.

5. Belt Driven or Integral Motor-Spindle Design.

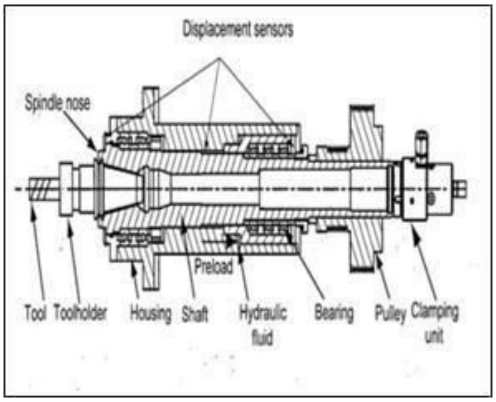

Fig: A Spindle System

Although these standards may seem evident, for the spindle designer to design they represent a broad range of needs that are rather demanding to meet and improve in one design. As we will determine, many of these conditions are inconsistent to one another, and in due course a compromise must be selected to achieve the best design. Earlier the spindle researches were concentrated mainly on static and quasi-static analysis, However the current research is been extended to optimize the design by utilizing the dynamic analysis. The spindles are generally designed based on the accumulated experience, the metal cutting mechanics, and the basic laws of machine design.

Design of spindle

The geometric model of the machine tool spindle is created with CATIA software. Geometric modeling is a branch of applied mathematics and computational geometry that discusses the mathematical methods behind modeling the realistic objects for computer graphics and computer aided design. The software helps in geometric modeling of critical components and structural assemblies. Components that are classified as Critical components in the machine tool spindle are Spindle shaft, bearings, spacers, Tenons, front cover, front arrester, rear cover, rear arrester, labyrinth cover, spindle housing, screw nut, screws.

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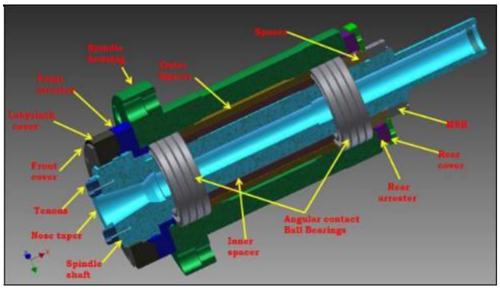

Fig: Assembly Drawing of the Spindle

The above figure illustrates the assembly drawing of the machine tool spindle. Each part was created individually according to the calculated dimensions and their standard specifications. The standard parts such as screws, bearings are got from the library in-built in the software. The spindle shaft is modelled considering the standard specifications provided by the spindle manufacturers. Further static analysis is carried out on the critical components as, spindle shaft, Tenons, and spacer to predict the resulting deformations and stresses present in the elements.

Finite Element Analysis

Meshing of the model is generated to approximate the geometry and reduces the degree of freedom from infinite to finite. This meshing process is vital in the finite element analysis as the quality of the results generated directly depends on the quality of the mesh. At the same time the computation time will be affected depending on the number of elements (number of nodes).

Static Structural Analysis

Project Objective:

In this project, we will be able to define total deformation and stress, etc

- Create the static structural analysis system
- Apply different types of materials
- Applying of boundary conditions
- Apply a different type of constraints
- Apply different loads
- Generate the results as per required
- Generate project reports

In this project, we imported the geometry of the component show the dimensions for the component with respect to the load applications. The material to be applied on the model is Steel. Next, you will run the analysis under two conditions and evaluate the Total Deformation, Directional Deformation, Equivalent Stress, Maximum Principal Stress, and Minimum Principal Stress.

The Static Structural analysis is one of the important analyses in ANSYS Workbench. It is available as Static Structural analysis system under the Analysis System toolbox in the Toolbox window, This system analyses the structural components for displacements (deformation), stresses, strains, and forces under different loading conditions. The loads in this analysis system are assumed not to have damping characteristics (time dependent). Steady loading and damping conditions are assumed in this type of analysis system.

To start a new Static Structural analysis system, double-click on Static Structural in the Analysis Systems toolbox in the Toolbox window; the Static Structural analysis system will be added to the Project Schematic window. To start an analysis, first you need to specify the geometry on which the analysis is to be done. To do so, you can import the geometry from an external CAD package, or you can create the geometry in the ANSYS's Design Modeler software. After the model is specified for an analysis, you need to double-click on the Model cell of the Static Structural analysis system to open the Mechanical window. In this window, you can specify the parameters and run the analysis.

Dynamic Analysis

Project Objective:

In this project, we will be able to study the dynamic properties of the spindle under the vibrational excitation.

- Create the dynamic analysis system
- Apply different types of materials
- Applying of boundary conditions
- Apply a different type of constraints
- Apply different loads
- Generate the results as per required
- Generate project reports

In contrast to Static Analysis, where code is not executed, dynamic analysis is based on the **system execution**, often using tools.

Dynamic program analysis is the analysis of computer software that is performed with executing programs built from that software on a real or virtual processor (analysis performed without executing programs is known as static code analysis).

Dynamic program analysis tools may require loading of special libraries or even recompilation of program code.

The most common dynamic analysis practice is executing Unit Tests against the code to find any errors in code.

In both Static and Dynamic Analysis apply the boundary conditions consisting of force and rotational velocity. In the static structural analysis the main concern is with the total deformation and stress acting on the spindle. Equivalent stress and total deformation acting on the spindle is determined.

CONCLUSION

The topic of this study focus on the reviews of static and fatigue analysis of machine tool spindle during the turning process. By the results obtained from this review it is found that:

- The configuration of the spindle is based on the specification of the work piece material, required cutting conditions and commonly used tools on the machine tool.
- A motorized spindle will soften at high speed because of the centrifugal effect on the machine tool spindle shaft.
- It was found out that the optimum bearing span to support the spindle is having length 240 mm and has got minimum deflection.
- During the cutting force measurement, it was found that rake angle was effective on all the cutting force components, while cutting speed was effective on the tool tip temperature.
- It was observed that all cutting forces were increased when the feed rates were increased. Optimum machining condition was obtained at rake angle = 00 , approaching angle = 750 .
- Cutting forces during turning operation can be measured experimentally and analytically by using empirical relations, at this cutting force condition analysis of machine tool spindle can be done.

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