A Comprehensive Review on Static and Dynamic Response of Lathe Spindle

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Abstract — The lathe spindle is an essential component of machine tools and plays an important part in ensuring that machining operations are carried out in an accurate and time-effective manner. In the following examination, we will attempt to offer an overview of the design concerns, performance metrics, and new trends in lathe spindle technology. The first part of this analysis is devoted to a discussion of the fundamental concepts and needs of spindle design. These aspects of the design include rotational speed, power transfer, and structural integrity, among others. This article examines a variety of spindle designs, including belt-driven, gear-driven, and direct-drive spindles, and discusses the benefits, limits, and application areas of each. The performance characteristics of lathe spindles are the subject of the next section of this analysis. These features include spindle accuracy, thermal stability, vibration control, and dynamic balancing. It investigates the techniques that are used to monitor and enhance these performance criteria, such as cutting-edge sensor technologies, active control systems, and novel materials. In addition to this, the paper investigates recent developments and developing tendencies in the field of lathe spindle technology. The integration of intelligent sensors and data analytics for real-time monitoring and predictive maintenance of spindles is a topic that is covered in this article. It investigates the possibility of using modern materials, such as ceramics and composites, to improve spindle performance while simultaneously cutting weight. In addition to this, it investigates the possibility of incorporating high-speed and high-torque capabilities into spindle designs in order to meet the ever-changing requirements of contemporary machining procedures. In conclusion, the analysis outlines the problems and possibilities in lathe spindle research and development, putting an emphasis on the necessity for additional developments in areas such as energy efficiency, noise reduction, and scalability for large-scale industrial applications. This study is a significant resource for academics, engineers, and industry experts interested in the development and optimisation of lathe spindle systems since it provides a complete overview of lathe spindle design, performance characteristics, and developing trends. Additionally, this review serves as a helpful reference for readers. It provides insights into the present state of the art, highlights opportunities for improvement, and inspires additional study in this significant sector of machine tool technology.

Keywords: Natural Convection, Cavity, Nusselt Number

I. INTRODUCTION

The lathe spindle is an essential part of lathe machines since it acts as the machine's primary source of rotation and is in charge of both retaining and moving the workpiece when machining is being performed. In the operations of turning, facing, and drilling, as well as in other types of machining, it is an essential component in achieving precision, accuracy, and productivity. The design, performance, and technological improvements of lathe spindles have a direct influence on the level of quality in the machined components as well as the overall effectiveness of the production processes.

Historically, the majority of lathe spindles were propelled by belts that were attached to external power sources like steam engines or electric motors. On the other hand, as a result of advances in technology, a variety of spindle configurations have evolved to satisfy the requirements of various types of machining. The ease of use and low operating costs of belt-driven spindles have ensured their continued use in the manufacturing industry. They are adaptable to a wide range of cutting situations due to their variable speed choices, which are achieved by adjusting the size of the pulley. On the other hand, gear-driven spindles offer greater torque capabilities and are frequently used in situations that need a high level of physical strain. In more recent times, there has been a rise in demand for direct-drive spindles. These spindles offer higher accuracy, less noise, and increased energy economy.

When trying to achieve high-quality machined surfaces and accurate dimensions, the performance of a lathe's spindle is one of the most important factors. Spindle precision, thermal stability, vibration control, and dynamic balancing are just few of the factors that have a major impact on the overall performance as well as the productivity of the machining process. In order to achieve and maintain these performance standards, rigorous design considerations, the selection of appropriate materials, and control systems are required.

Over the course of the last several years, developments in technology have presented new opportunities for lathe spindle design, as well as for the optimisation of performance. Real-time monitoring of spindle conditions is made possible by the combination of intelligent sensors and data analytics, which also makes it easier to do predictive maintenance and cuts downtime. The utilisation of modern materials, such as composites and ceramics, improves spindle performance in terms of lowering the unit's overall weight as well as increasing its thermal stability and damping properties. Additionally, as a result of the demand for high-speed machining, spindles that are capable of generating greater rotational speeds and torque levels have been developed.

The purpose of this article is to give readers with an in-depth understanding of lathe spindles, including their fundamental design principles, performance characteristics, and new trends. The purpose of this article is to shed light on the relevance of lathe spindles in machining operations and to inspire future research and development in this essential area of machine tool technology by examining the different configurations, performance concerns, and developments in technology. In doing so, this article intends to explore the

numerous configurations, performance considerations, and advancements in technology.

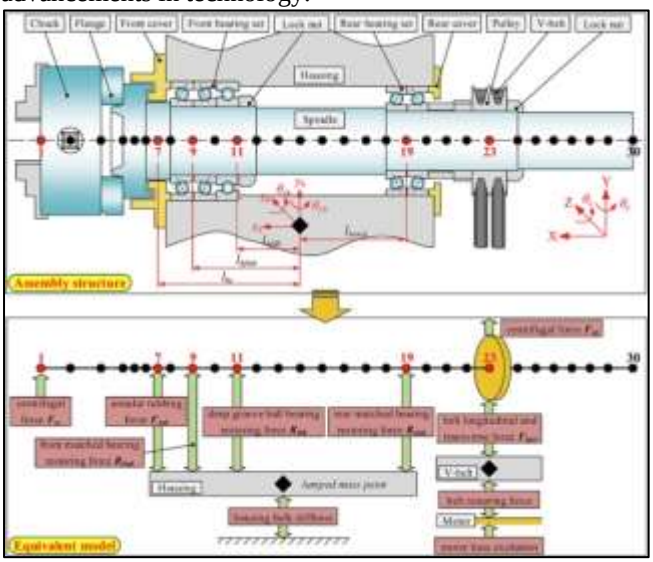

Fig. 1: Structure diagram and equivalent model for spindle-housing-belt system. (Xu et al. 2023)

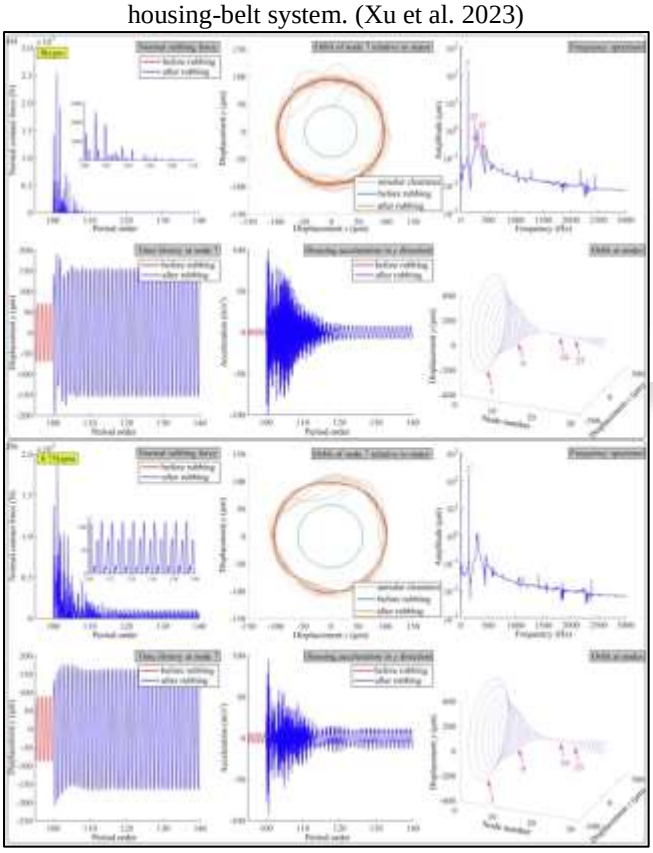

Fig. 2: Detailed vibration response windows when sudden unbalance excitation is used at the 100th period moment and rubbing occurs(Xu et al. 2023)

(Xu et al. 2023) uses finite element approach is utilised in order to carry out the vibration response analysis for the lathe spindle-housing-belt system with rubbing. The advent of free-running abnormal noise in inexpensive commercial lathes inspired the merger of the annular rubbing model and the spindle-housing-belt system. This was possible due to the fact that there is a tiny space between the front bearing cover and the shaft in order to achieve adequate sealing. When the geometric and material properties, as well as the starting tension of the belt, are included into the belt's stiffness coefficient, the longitudinal and transverse dynamic equations for the tight and loose sides of the V-belts are constructed. In order to characterise the interaction between the shaft and the housing, the Lankarani-Nikravesh contact model, which is dependent upon the incursion and rotation speeds, is utilised. The computed value of the suggested model coincides rather well with the outcomes of the modal and harmonic excitation tests, as well as the findings of the measurement of the free-running rotor orbit signal and the housing acceleration data with rubbing. It demonstrates that the model has potential to accurately forecast the aberrant noise produced by the laboratory lathe. Based on the results of numerical simulations, it appears that the dynamic characteristics of the belt have a minor impact on the vibration form and amplitude of the system. When the rubbing force is applied, there is a higher probability that the bigger imbalanced excitation will cause nonlinear behaviour to be initiated. Because the Lankarani-Nikravesh model is speed-dependent, increasing the rotational speed results in an increase in the interaction load.

(Subbarao and Dey 2020) demonstrates a model of the spindle in three dimensions, which has been created. There are a total of four distinct materials that are up for consideration, including AISI 1045 carbon steel, AISI 4140 alloy steel, AISI 304 stainless steel, and grey cast iron. The static and dynamic studies, which are both based on FEM, are carried out independently under cutting pressures and while the cutting tool is rotating. Modal shapes can be derived by the use of dynamic analysis. Computational simulation is carried out in ANSYS 15.0 workbench, and static structural analysis is carried out using a range of values for cutting force and speed. In order to determine which material is best suited for the application, total deformation, equivalent stresses, and strains were all considered. In each and every scenario, the AISI 1045 carbon steel exhibits the lowest possible values of total deformation and equivalent stress. A consistent stress pattern can be seen across all of the materials, with the location of the highest stress remaining the same despite the fact that its magnitude varies. In every material, the spindle face area is where the total deformation is found to be at its greatest, while the spindle bearing section is where it is at its least. Maximum equivalent stress is created in the housing area of the spindle, whereas the least amount of stress is experienced at the tail end. Additionally, the corresponding strain is noted to be at its greatest at the spindle housing area and its least extreme at the tail end location. There is less of an impact from the spindle's rotating speed on the accumulation of stresses and strains in the spindle. The critical velocity may be determined with the use of the Campbell diagram, which can then be used to select the most appropriate material. As a result, this paper examines both the static and dynamic evaluations of the lathe spindle for a variety of materials.

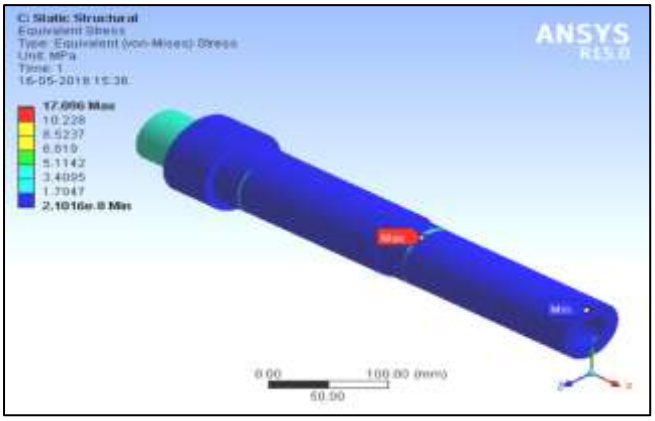

Fig 3: Equivalent (von-Mises) stress in AISI 1045 carbon steel.(Subbarao and Dey 2020)

(Segonds et al. 2007) solved the issue with the type of dilatation measures that need to be repartitioned. The results of a Khi-2 test performed on dilatation measures indicate that these measures propagate in accordance with a regular repartition rule. As a result, a model is provided that may be used to compute the confidence interval associated with the dilatation prediction. The creation of this model is made possible by the legislation of repartitioning the samples of dilatation. After that, an approach to calculating an upper bound on the standard deviation of the dilatation repartition law is given as the next step. The confidence interval of the spindle dilatation phenomena is something that can be determined with the help of the model that was proposed. Because of this determination, it is now possible to attach a confidence interval to the dilatation estimate, which makes it possible to make an accurate prediction of the process.

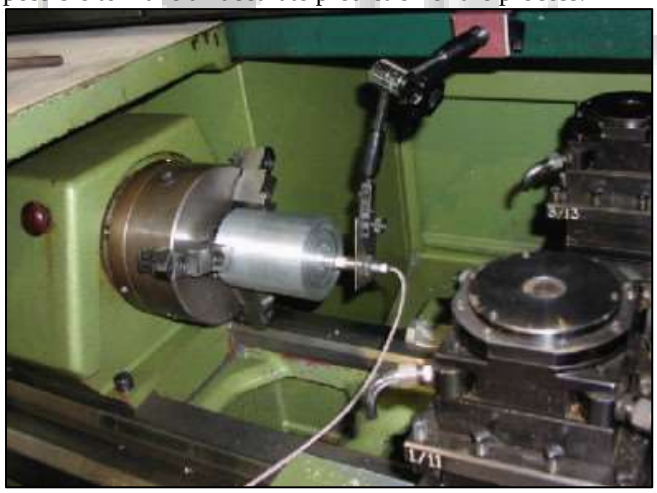

Fig. 4: Experimental set-up. Measuring of spindle elongation. (Segonds et al. 2007)

(Yang, Ren, and Du 2002)The homogeneous coordinate transformation approach provides a one-of-a-kind form of the error synthesis model. This model incorporates both the geometric and thermal errors of the NC twin-spindle lathe, making it ideal for modelling error synthesis. Through the process of estimating the variance in the slopes of the error profiles, it is possible to separate the geometric mistakes from the thermal errors. For the purpose of modelling various kinds of thermal error components in accordance with their attributes, a set of modelling methodologies has been proposed. 16 thermal sensors are used to provide continuous monitoring of the temperature field within the machine. Empirical models that have already been constructed can estimate the thermal error components in real time using the temperatures that have been observed and the coordinates of the slides. After that, the kinematic model will perform a synthesis of the estimated values for the thermal and geometric error components in order to calculate the planar error for the machine in its current state. The computer, having identified the extent of the machine's planar error, then sends correction signals along to the controller of the machine. The controller performs a cyclical pick-up of the compensation signals about every 10 millisecond and then shifts the reference origin of the slides in order to rectify the planar error. The success of this procedure was tested during the compensating cutting test. During this test, the size variations of the workpieces were able to be reduced from 60 to 14 m, and the taper was able to be decreased from 50 to 15 m/cm.

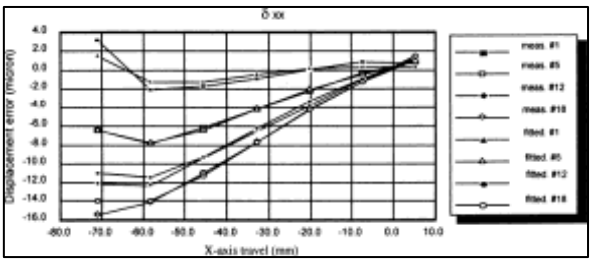

Fig. 5: Linear displacement error of the X-axis(Yang, Ren, and Du 2002)

(Arugolanu, Borra, and Mamilla 2023)On the lathe bed, at maximum stress conditions, static structural and mode forms analysis is carried out. These simulated results are utilised to lighten the lathe bed without losing its structural integrity or its capacity to absorb vibrations. This is accomplished by inserting ribs and lowering volume in areas where loads and deflection are created to occur less frequently. Cast iron, mild steel, and CFRP, which is a combination of epoxy resin hardener and granite, are used in the FEA analysis of a redesigned lathe bed as an alternative material. The study was carried out using a computer programme. Comparisons are made between the two materials in terms of the stresses and deformations that they cause, as well as the amount of weight they save. Lathe bed CAD Models were developed with the help of the CATIAV5 Modelling programme. In order to construct the FE Model, ANSYS 16.2 was utilised. In order to carry out the analysis, ANSYS was utilised. After calculating the observations and presenting them in the form of contour plots, one analyses the influence of weight reduction on the structural strength of the machine bed both before and after the weight reduction, and then one comes to a conclusion on the best design.

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(Liu et al. 2020) carries out an exhaustive investigation into the geometric inaccuracy of the ultra-precision drum roll lathe that has a dual-spindle symmetrical construction and a cross slider arrangement. First, the volumetric error model for the dual-spindle ultra-precision drum roll lathe (DSUPDRL) is established based on the combination of the homogeneous transfer matrix (HTM) theory and the multi-body system (MBS) theory. This model accounts for all of the geometric errors that are associated with the DSUPDRL. Second, a sensitivity analysis for the volumetric error model is carried out in order to determine the sensitive geometric error components of the DSUPDRL. This analysis is carried out with an updated version of the Sobol technique that is based on the quasi-Monte Carlo algorithm. The conclusion of the sensitivity study served as the basis for the following geometric error calibration. After that, a laser interferometer and a pair of inductance displacement probes are utilised in order to calibrate some sensitive error components that are located along the X and Z directions. In addition to the volumetric error model, a concentricity error model that is induced by a dual-spindle symmetrical construction has been suggested and calibrated by the on-machine measurement employing a traditional reversal approach. This model is utilised to determine the volumetric error. Following the completion of the calibration process, the DSUPDRL is used to produce a large-scale roller mould having a diameter of 250 mm and a length of 600 mm. The experimental result demonstrates that an accuracy of 1.4 m/600 mm may be achieved, which validates the efficiency of the geometric error analysis and calibration.

(Vadgeri, Patil, and Chavan 2018) The influence of approach angle, feed, depth of cut, and nose radius on the components of cutting force was studied. The tests were carried out on a PSG 124 lathe machine with carbide coated cutting tools on material that had been hardened to EN9. For the purpose of optimising the testing, the orthogonal array of L-16 was utilised. The three-axis lathe tool dynamometer was used to measure the cutting forces that were created during the turning operation of the lathe. In order to explore the maximum cutting force that was created, a statistical regression analysis technique was employed. The results of this investigation revealed that the greatest cutting force was obtained at an approach angle of 450, a feed of 0.3 mm, a depth of cut of 1 mm, and a noseradius of 0.8 mm. Analyses of static stress and fatigue have been performed numerically by taking into account the various forces that are exerted on the lathe spindle. The findings of this investigation indicate that the existing configuration of the spindle is risk-free.

(Sharan, Sankar, and Sankar 1987) As part of this body of work, a dynamic analysis and an optimal design of lathe spindles have been developed. The design factors that were used for these endeavours include the bearing stiffness, bearing spacing, and the diameter of one of the sections of the spindle. It has been investigated how changing the mass of the chuck and the slenderness ratio of the workpiece affects the dynamic responsiveness of the system. There is also discussion over the potential incorporation of a third bearing support for the spindle.

II. Conclusion

As a result of the limitations imposed by two sets of supporting bearings, the two overhanging ends of the lathe spindle system are the sites at which the vibration response is at its highest. When the vertical stiffness of the housing is greater than the horizontal one, the response amplitude of two radial directions acts in a manner that is distinct from one another. The vibration peak-to-peak value increases as the rotation speed increases, and the greater speed makes it easier for a non-circular form of orbit to be created at the back end of the spindle.

AISI 4140 alloy steel has stresses and deformation less than AISI 304 stainless steel. Overall, AISI 1045 carbon steel showed good results as less stresses and deformation.

Knowing the equation of spindle's dilatation, standard deviation value and average value as a function of time, it is thus possible to predict dimensional change of the spindle and the specific confidence interval associated for a given machining cycle taking in account time and rotational frequency.

Geometric and thermal planar error synthesis models are given, which include 23 error components of geometric and thermal errors.

Different types of models are proposed for different kinds of thermal error components. The separation of the geometric and thermal error components is done by estimating the variation of the slopes of the error profiles.

1By applying forces recorded by a machine tool dynamometer and strain gauges at the maximum load conditions of the lathe machine, the structural analysis result of the lathe bed may be more accurately determined.

It is possible to broaden this investigation to incorporate dynamic and thermo-structural evaluations. FE may also be used to study composite materials like High Modulus Carbon Fiber Reinforced Polymer.

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