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Improving Kinematic Accuracy of Radial Drilling Machines through Servo-Driven Modernization

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ABSTRACT: The growing demand for precision and productivity has increased interest in modernizing legacy machine tools. Radial drilling machines commonly exhibit kinematic inaccuracies caused by mechanical wear, structural deformation, and outdated transmission systems. This study examines a modernization approach based on servo-driven feed systems, improved structural stiffness, and thermal–dynamic compensation. Analytical, numerical, and experimental results show that servo-driven feeds enhance positioning accuracy, reduce backlash, and improve dynamic performance, thereby extending machine lifespan and improving machining efficiency.

KEY WORDS: Radial drilling machine, kinematic accuracy, machine tool modernization, servo-driven feed system, structural stiffness, finite element analysis (FEA), thermal deformation, dynamic modeling, positioning accuracy.

I. INTRODUCTION

Radial drilling machines (RDMs) occupy an important niche in manufacturing because they can machine large and medium-sized components that are difficult or uneconomical to mount on conventional machining centers. Their radial arm and swivelling column allow the spindle to reach multiple positions over a fixed workpiece, making them suited for operations on heavy castings, welded frames, and large structural parts in shipbuilding, energy, mining, construction and general fabrication industries [1-3]. In such environments, RDMs are routinely used for drilling, reaming, boring, countersinking and tapping, often under high torque and intermittent loading conditions. However, the majority of RDMs installed in legacy plants were designed decades ago, with mechanical architectures optimized for robustness and manual operation rather than high-precision, high-speed performance. Their feed and spindle systems typically rely on stepped gearboxes, cone pulleys, clutched transmissions and manually actuated feed levers, which inherently introduce backlash, stick–slip effects, limited feed resolution and poor controllability [4-7]. Over time, wear of gears, splines, bearings and slideways further degrades kinematic accuracy and repeatability, especially when the arm is extended and structural deflections become significant. Industrial surveys show that used high-speed radial drilling machines are still widely traded and kept in service, underscoring the practical need for cost-effective modernization rather than full replacement.

II. KINEMATIC ACCURACY IN MACHINE TOOLS

Kinematic accuracy in machine tools describes the degree to which the actual motion of the tool center point (TCP) coincides with the commanded or nominal trajectory defined by the control system. It is a fundamental indicator of machining precision and directly affects dimensional accuracy, surface integrity, and process repeatability. Unlike static geometric accuracy, kinematic accuracy reflects the combined influence of machine structure, motion transmission elements, control system behavior, and environmental conditions during operation. Thermal expansion of structural components represents one of the dominant and most complex sources of kinematic error. Heat generated by motors, bearings, cutting processes, and ambient temperature variations causes non-uniform expansion of machine components. Because radial drilling machines often feature large columns, long arms, and extended quills, even small temperature gradients can result in measurable displacement of the

tool center point. Thermal-induced kinematic drift is typically slow but persistent, making it particularly harmful in long machining cycles.
Axis misalignment and structural deformation under load further degrade kinematic accuracy. In multi-axis machines, perfect orthogonality between axes is difficult to maintain due to assembly errors, wear of guideways, and elastic deflection under cutting forces. In radial drilling machines, the cantilevered arm and spindle head are especially susceptible to bending moments, causing angular deviations that translate into significant positional errors at the tool tip. Such errors are load-dependent and therefore vary with cutting conditions.

III. METHODOLOGY

Analytical Kinematic and Dynamic Modeling

Analytical kinematic and dynamic modeling forms the theoretical foundation for evaluating and improving the motion accuracy of radial drilling machines (RDMs). The primary objective of this modeling stage is to quantify how mechanical imperfections, structural flexibility, and dynamic effects influence the deviation between commanded and actual tool motion. In a radial drilling machine, the position of the tool center point (TCP) is defined by the combined motion of multiple translational axes. For a three-axis system, the nominal TCP position vector P_n can be expressed as:

$$P_n = \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

However, due to kinematic imperfections, the actual TCP position $\mathbf{P_a}$ deviates from the nominal position. This deviation can be represented as:

$$[P_a = P_n + \Delta P]$$

where

$$\Delta \boldsymbol{P} = \begin{bmatrix} \delta x \\ \delta y \\ \delta z \end{bmatrix}$$

is the kinematic error vector. For each linear axis, the positioning error can be decomposed into systematic and load-dependent components:

$$[\delta x = \delta x_g + \delta x_b + \delta x_t]$$

where: δx_g – geometric error (lead screw pitch error, straightness error), (δx_b) – backlash-related error, (δx_t) – thermally induced displacement.

Backlash and Transmission Error Modeling

In conventional mechanical feed systems, backlash introduces a dead zone during direction reversal. The backlash error (δ_b) can be approximated as:

$$\delta_b = \begin{cases} 0, & \text{unidirectional motion} \\ \pm b, & \text{directional motion} \end{cases}$$

where b is the backlash magnitude. For lead screw or ball screw transmissions, pitch error introduces a periodic positioning deviation:

$$\delta_p(x) = A_p \sin\left(\frac{2\pi x}{p}\right)$$

where: A_p – amplitude of pitch error, p – screw pitch, x – axis displacement. Servo-driven ball screw systems significantly reduce (b) and (A_p), thereby minimizing transmission-related kinematic errors. Structural deformation under cutting forces is a major contributor to kinematic error, especially in radial drilling machines with cantilevered arms. The elastic displacement δ_s at the tool tip can be approximated using linear stiffness theory:

$$\left[\delta_s = \frac{F}{k}\right]$$

where: F– resultant cutting force, k – equivalent structural stiffness of the kinematic chain. For a cantilever beam representing the radial arm, bending deflection at the tool location is given by:

$$\left[\delta_b = \frac{FL^3}{3EI}\right]$$

where: L – arm extension length, E – Young's modulus of the material, I – second moment of area. This relationship highlights the strong dependence of tool deflection on arm length, emphasizing the importance of stiffness enhancement in extended working positions.

Dynamic Modeling of Feed Axis Motion

To analyze dynamic behavior, the feed axis is modeled as a lumped mass–spring–damper system. The equation of motion is:

$$[m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t)]$$

where: m – equivalent moving mass, c – damping coefficient, k – stiffness, F(t) – actuator force input. The natural frequency of the system is:

$$\left[\omega_n = \sqrt{\frac{k}{m}}\right]$$

and the damping ratio is:

$$\left[\zeta = \frac{c}{2\sqrt{km}}\right]$$

A higher natural frequency and adequate damping are desirable to prevent resonance and reduce dynamic positioning error during acceleration and deceleration phases.

Servo Control Influence on Dynamic Error

For a servo-driven axis, the closed-loop position control system can be approximated by a second-order transfer function:

$$\left[G(s) = \frac{K}{s^2 + 2\zeta\omega_n s + \omega_n^2}\right]$$

where K represents the controller gain. The dynamic tracking error $e(t)$ is defined as:

$$[e(t) = x_r(t) - x(t)]$$

where $x_r(t)$ is the reference trajectory and $x(t)$ is the actual position. Proper tuning of the proportional–integral–derivative (PID) controller minimizes $e(t)$, improving contouring accuracy and reducing overshoot.

Combined Kinematic Error Model

The total positioning error of the tool center point can be expressed as a superposition of individual error components:

$$[\delta_{total} = \delta_g + \delta_b + \delta_s + \delta_t + \delta_d]$$

where: δ_g – geometric error, δ_b – backlash error, δ_s – structural deformation, δ_t – thermal displacement, δ_d – dynamic tracking error.

Structural Optimization Using FEM Analysis

The CAD models created were exported to ANSYS Workbench to create finite element models.

Table 1.
Material properties

Density	7850
Young's modulus	2×10^{11}
Poisson's ratio	0,3

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The analysis of contact zones within the machine tool structure shows that element size varies according to local geometric complexity. In regions with detailed features such as holes and recesses, a refined mesh with element sizes of 1–3 mm is applied, while less critical areas are meshed more coarsely with element sizes of 5–10 mm. This approach provides an effective balance between computational efficiency and numerical accuracy.

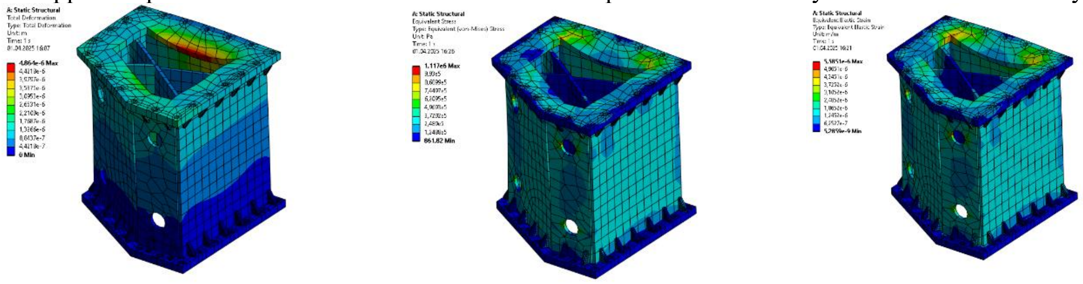

Figure 1. ***Full deformation representation, stress analysis, and equivalent elastic deformation (left column)***

Figure 1 shows the results of the ANSYS Total Deformation analysis for the machine tool bed model. The main data of this study are Static Structural, Total Deformation. The results show that the maximum deformation is 4.8604e-6 m, or 4.8604 micrometers. As can be seen from the model, the upper part of the bed is subjected to loading from the portal and the spindle, and the grooves reduce the rigidity of the structure. This is a very small value, indicating a high rigidity of the structure.

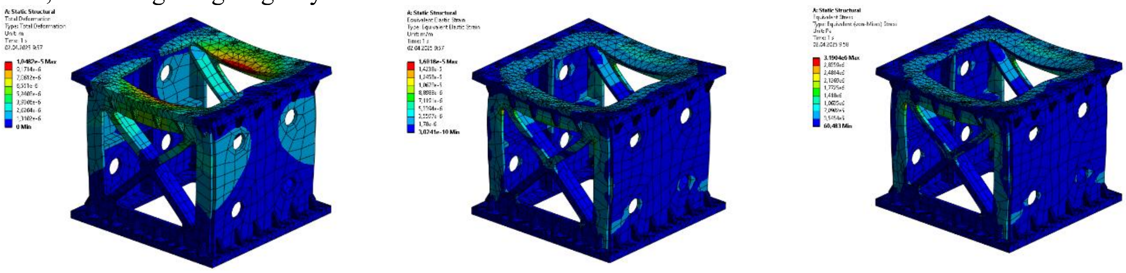

Figure 2. ***Full deformation representation, stress analysis, and equivalent elastic deformation (right column)***

Red (maximum, 5.9851e-6 m/m) - areas with the greatest deformation. Blue (minimum, 5.2895e-9 m/m) - areas with the least deformation. We calculate the stress in the region of maximum deformation: $\sigma = E\varepsilon = 2 \cdot 10^{11} \cdot 5.9851 \cdot 10^{-6} = 1.197 \cdot 10^{6} Pa = 1.197\ Pa$

3.7 Thermal Modeling of the Spindle System

The spindle system was modeled using transient thermal analysis available in SolidWorks software. The initial temperature for the entire structure was set to 21°C, and the transient analysis duration was set to 3 hours, which is consistent with the experimental time. The previously obtained boundary conditions were used to obtain the temperature field of the spindle system in the FEA model. The back of the head was set to be constrained, and then the thermal deformations of the spindle system along the Y and Z axes were obtained based on the temperature gradient field. The results for the X axis were ignored because the error in this direction is negligible due to the symmetry of the machine. Figure 3 shows the simulated temperature of the FEA model. The simulated displacement data were obtained from nodes located at the same positions of the displacement sensor used to control the Y and Z axes.

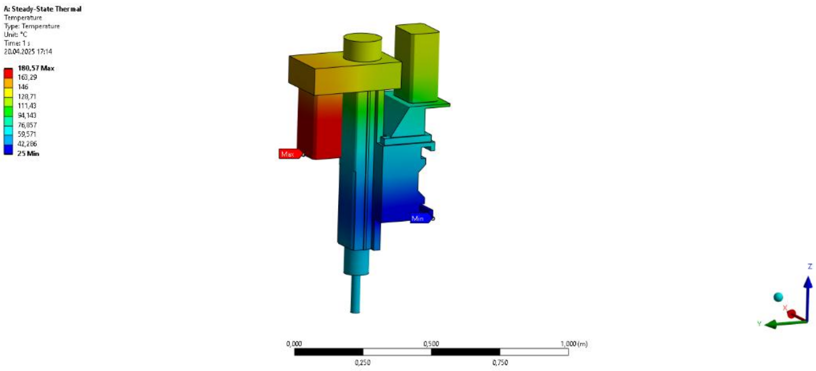

Figure 3. ***Thermal modeling results for the spindle system***

IV. RESULTS

The analytical and numerical results confirm that the main sources of kinematic error in radial drilling machines are backlash, structural compliance, dynamic effects, and thermal deformation. Servo-driven feed systems significantly reduce backlash and improve positioning accuracy and repeatability. Dynamic modeling shows that increased stiffness raises the natural frequency of the feed axis, reducing vibration and tracking errors. Finite element analysis indicates high structural rigidity of the machine bed, with a maximum deformation of 4.86 µm under load, confirming elastic behavior within safe limits. Stress levels remain well below the material yield strength. Thermal analysis of the spindle system reveals non-uniform temperature distribution during extended operation, leading to measurable displacement along the Y and Z axes, while deformation along the X axis is negligible due to structural symmetry.

V. CONCLUSION AND FUTURE WORK

This study demonstrates that modernizing radial drilling machines using servo-driven feed systems, structural optimization, and thermal modeling effectively improves kinematic accuracy and dynamic performance. The proposed approach reduces positioning errors, enhances stability, and extends machine service life without full replacement. These results confirm that targeted modernization is a practical and cost-effective solution for upgrading legacy radial drilling machines to meet modern precision requirements.

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