A Gear Hobbing Attachment for Manual Milling Machines to Facilitate the Production of Exotic Gears for Full-Scale Working Prototypes

by

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ABSTRACT

This thesis aims to present the design, development, and fabrication of a gear hobbing attachment tailored for manual milling machines. The primary objective is to create a versatile, cost-effective tool that streamlines production of standard and exotic gears, with a specific focus on gears needed to create full-scale working prototypes, to test the performance of the gear train and to ready prototypes for pre-manufacture analysis. This approach seeks to replace the industry-standard prototyping method of manual indexing, which is time-consuming and error-prone, with a more efficient, reliable approach that mirrors the gear hobbing process used for industrial production.

The distinctive advantages of this gear hobbing attachment would be especially relevant for creating worm, helical, and screw gears. Because of their complex geometries, these gear types are effectively impossible to produce through conventional manual methods. Currently, producing such gears requires dedicated gear cutting machines and skilled operators, which drastically raises the cost of producing such gears for a prototype.

For startup designers and labs, while using a CNC machine with a 4th axis is a feasible option for creating certain gear components, this approach can be time-consuming and challenging to set up. It requires special CAM software packages and programming skills, along with the use of very small cutters, making it primarily viable for gears with larger modules, typically 1.5 and above. [9]

The proposed gear hobbing attachment would make the creation of production-accurate prototypes simpler, less costly and more accessible. This innovation would also make it practical to create gear aspect ratios typically unavailable in standard gear catalogs, such as large ring gears or thin worm wheels, providing greater design freedom and flexibility in prototype development.

The proposed gear hobbing attachment will consist of a spindle mounted to the bed of the manual milling machine with an AC servo motor for drive.

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1.INTRODUCTION

This thesis aims to present the design, development, and fabrication of a gear hobbing attachment tailored for manual milling machines. The primary objective is to create a versatile, cost-effective tool that streamlines production of standard and exotic gears, with a specific focus on gears needed to create full-scale working prototypes, to test the performance of the gear train and to ready prototypes for pre-manufacture analysis.

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This document describes the considerations that shaped the design and diagrams the final design of the gear hobbing attachment. It then details failure points in the system that still need to be resolved and proposes further tests to determine how to resolve them.

2.EXISTING GEAR CUTTING METHODS

Gears are a vital component of many current robotic systems, typically performing one of four essential mechanical functions: Power transmission, gear reduction, rolling joints and pulleys for belts.

In robotics and other fields that require mechanisms to be tightly packaged, when start-ups and academic labs need to prototype a potential product, they face a serious challenge when their designs require custom gears. Relying on off-the-shelf components typically results in systems that are impractically large and heavy, and not well tailored to the environment. Especially for machines with tight constraints on weight and space, custom gears are the preferred solution.

Unfortunately, while large corporations often have the expert staff and equipment to create custom gears in-house, academic labs and start-ups currently have three choices:

1. They can buy ready-made gears from a catalog;
2. They can order specific gears from a machine shop;
3. For low-speed applications, they can 3D print gears themselves.

All these options have significant drawbacks.

Limitations of off-the-shelf gears

Catalog gears are generally pre-hardened and have a standard aspect ratio, so they are ready to be pinned to a shaft, which makes them useful for replacing an existing part. They also arrive quickly, usually within a few days. However, when a prototype requires custom components – gears that are thinner, or have unusual dimensions or numbers of teeth, or are made of a specific material – ordering from a catalog can be prohibitively expensive or impossible. Moreover, because catalog gears are hardened, they are also difficult to modify.

Limitations of ordering custom gears

Many academic labs and start-ups therefore choose to order custom gears from a machine shop. However, for precision applications, this approach also presents challenges, starting with the cost, which is typically two or three times as expensive as off-the-shelf components. But even this added cost is no guarantee that the result will be workable. For example, machine shops typically produce gears using a CNC machine with a 4th axis. This achieves a generic tolerance of +/- 20 microns, which is not sufficient for proper gear tooth meshing, and requires significant hand-tuning after the fact to avoid unacceptable binding. In general, for precision applications, quality of gears from a machine shop that does not specialize in custom gears is not sufficient to answer the technical questions needed to assess the functioning of a prototype.

Ordering custom gears from a such a non-specialized machine shop is also slow, typically involving a turnaround time of 1-3 weeks, which significantly slows prototype development. It is common for an order to be sent back to a machine shop multiple times because the gears do not meet specifications, which magnifies the problem of slow turnaround time.

While it is possible to order from a machine shop that specializes in custom gears, the cost is typically several times greater, making this an unaffordable option for most startups or academic labs.

Limitations of 3D printed gears

For lower performance, low-weight and low-RPM applications, it is possible to produce certain custom gears for quick prototyping via 3D printing. However, this does not offer a path for most custom gear applications, which require steel gears.

3.SYSTEM DESIGN

The proposed design has similarities to four existing technologies for creating gears [3]:

Design references

- **CNC 4th axis**
  Apart from an industrial CNC gear hobbing machine, the system most similar to the proposed design would be a CNC machine with a 4th axis. The major difference is that a 4th axis generally cannot tilt its axis relative to the mill spindle. This makes it impossible to use a CNC to machine helical or screw gears. On the electrical side, most CNC machines do not have direct interrupt access to the mill spindle, which makes it impossible to properly synchronize their 4th axes with a gear cutting hob.

- **Dividing head**
  Dividing heads are one of the most closely related mechanisms to the proposed design. They are very similar to 4th axis machines, with an additional degree of freedom to allow them to rotate to cut gears via the manual indexing method. However, as with rotary tables, their worm drive means that cutting must be done only in one direction, as there is backlash between the worm and the worm wheel.

- **Rotary table**
  Rotary tables tend to have large axial contact surfaces which allow them to have large loads in the axial direction and relatively smaller radial plane bearing journals to take up the radial loads. In addition to a worm drive to drive their rotary motion, they are generally not very well adjusted for cutting that involves switching directions, as the worm drive is incapable of keeping track of the absolute position of the table.
- **Spindexer**

Spindexers tend to be used for dividing work into rotary positions and indexing with a tapered pin. They generally do not have any way to drive their rotary axes between these positions and so can only be taken as reference for spindle design.

Because of their very low RPM requirements, these four systems all consist of large plain bearing surfaces that are either hand scraped or ground with oil films that manage friction between parts.

If these systems were adapted for gear cutting, the RPMs required would be too great for their bearings. This drives the requirement for the proposed gear hobbing attachment to use rolling element bearings, as opposed to plain bearing surfaces.

How subsystems of the proposed design will meet functional requirements

Meeting the functional requirements of the gear hobber depends on three subsystems

1. The **spindle** is the rotary axis around which the gear blank will rotate and is required to take the axial and radial loads of the gear cutting process.
2. Similar to a dividing head, the **trunnions** make it possible to rotate the gear cutting axis to match the helix angle if cutting helical gears.
3. The **motor gear train** is what synchronizes the mill and hopping spindle axes and governs the stiffness requirement around the rotary axis.

Functional requirements

The proposed gear hobber must meet functional requirements in three areas:

1. Functions directly related to holding and manipulating the gear blank
   In order to cut gears with accuracy, the machine must be able to
   - Hold the gear blank concentrically with the gear cutting axis and easily mount the blank after it is roughed out on the lathe
   - Coordinate the gear blank with the milling spindle, with respect to the number of teeth to be cut
   - Incline the gear cutting axis to cut helical and screw gears
2. Functions related to user ergonomics and typical machine shop environments
   To be a worthwhile addition to a lab or start-up shop, the machine must
   - Be movable by a typical machine shop user without injury
   - Mount easily and quickly to a manual milling machine
   - Allow for continued motion of the quill
   - Operate in a dirty shop environment

3. Functions related to cutting forces and reactions

   In order for gear cutting to proceed with sufficient accuracy, the device must be stiff enough when subjected to the machining loads. The system's stiffness needs to be analyzed in terms of

      - Maintaining linear position under cutting forces
      - Maintaining angular position under cutting forces
      - Providing sufficient angular resolution for useful involute.

Design parameters

The proposed machine would respond to these functional requirements via the following design parameters.

1. Work holding and manipulation
   - The gear blank will be held in a modified three-jaw chuck with added set true adjustment screws.
   - Although traditionally sub axes for gear hobbing would have been physical gear trains, the layout of knee mills (moving tables) available in prototyping shops and the need for many gear ratios means that electric coordination is the only reasonable option.
   - A trunnion type design was chosen to allow for the axis to be inclined without adjusting the vertical height of the cutting by a large amount.
2. Ergonomics and machine shop environment
   - Ideally the hobbing attachment should be movable easily by a person without requiring special lifting equipment, comparable to a 6in-8in rotary table's weight, ~ 13kg
   - The device must be compatible with Bridgeport and Bridgeport-clone knee mills T-slots 64mm centers, with alignment keys for quick mounting without needing for tramming in.
   - To protest the bearing in dirty manufacturing and shop environments, they need to be sealed. Lip seals were chosen for low friction and easy press-in installation.
3. Reaction to cutting forces and system stiffness
   - A dual taper roller bearing spindle was chosen for its relative simplicity and easy of manufacture. [3]
   - Angular stiffness about the driven axis should be analyzed via reference to stepper motor characteristics.

Analysis of requirements for reactions to cutting forces and system stiffness

- **Cutting forces**

  In designing a spindle, the main consideration is its working loads. These loads govern the bearing selection, as well as the arrangement and preload. The literature on gear hobbing cutting forces is an area of rich academic study but the main focus tends to be on complicated models involving modeling of chip formation. While these papers are useful for the design of industrial machines, they are less useful for the proposed design as they tend to characterize very large hobbs and very stiff machine. For this project, the two paths pursued for a first order estimate of cutting forces were a very useful paper that simplified industrial cutting models and the standard practice of cutting power estimation and dividing out cutting speed, as described in the Machineries Handbook. These produced an upper estimate for cutting force that can be used to estimate stiffness.

- **Gear cutting accuracy requirements**
  While one would love to imagine that a manual milling attachment could produce industrial quality gears, that requirement would be very hard to meet and unnecessarily high for early prototypes. Industry standards for gear cutting tend to apply to finished and hardened gears and not gears right after machining. To meet the demands of lab and start-up prototyping, this project aims to produce gears within the JIS standard 7-to-8 range, which is generally deemed to be useful for industrial equipment drive trains and consumer appliances. [4] These standards have a tooth profile accuracy of 11.2 module + 35.5 microns and tooth lead accuracy of 3.15 (0.1b + 10) microns where b is the tooth width. [4] These accuracy requirements, along with our cutting force requirements, can provide a lower bound for the stiffness requirements.

- **Stiffness requirements**
  Stiffness requirements can be seen as the allowable deflection under the load of forces applied. In this case, the gear standard provides us with the maximum allowable deflection while the cutting forces provide us with the expectations of the forces involved. This stiffness requirement can then feed into the proposed system design. The linear combination of all sources of deflection must be added together to inform the design.

- **Spindle stiffness design**
  The spindle is the largest and most well characterized of the subsystems to be considered. Its design can greatly affect the system's overall stiffness. Fortunately, in low-speed applications, the selected spindle design – a dual tapered roller bearing – reduces the major risk of thermal effects which can cause huge forces and reduce spindle life. The main functional requirements of our spindle will be stiffness, easy of manufacture, and absolute load. In high-speed applications, the spindle design would be less suitable.

$$K_{spindle} = \frac{1}{\frac{a^3}{3EJ_a} + \frac{La^2}{3EJ_L} + \frac{1}{K}(1+\frac{a}{L})^2 + \frac{1}{K}(\frac{a}{L})^2}$$

EQ1. Spindle stiffness equation [11]
a = spindle over hang, E = Young's modulus,Ja = moment of inertia of overhanging spindle, Jl = moment of inertia of spindle running thought bearings, K = bearing stiffness, K spindle = spindle bending stiffness

$$\theta_{spindle} = \frac{z}{2\pi} * sin\left(\frac{T_a}{T_h}\right)$$

EQ2. Stepper motor stiffness equation [5]
Theta spindle = deflection of stepper motor, z = stepper motor circular pitch, Ta= expected torque on stepper motor, Th = stepper motor holding torque

- **Stiffness around rotary axis**
  The stiffness around the rotary axis is dominated by the stepper motor holding torque, the gear ratio and the belt stiffness. The belt drive was chosen for its zero backlash capabilities.

<u>Manufacturing considerations</u>

The design of the parts was informed with an awareness of how they would be manufactured. Each part was machined via a combination of CNC milling and turning. Tolerances were selected based on bearing catalog suggestions and load path considerations.

- **Bearing fits**
  Locational clearance tolerances were selected for the outer race of the tapered roller bearings, and locational interference fits were selected for the inner race mounted to the spindle well.

- **Tolerance and sizing**
  A torque transmitting press fit was used for the main face plate to the spindle. The material – 1144 medium alloy steel – was chosen for its relatively low price and high machinability.

- **Fitment**
  After initial machining of many of the parts, some dimensional adjustments had to be made for the pieces to properly fit together. Clearances between the trunnions and the side plates were very small, which made adjustment of the mechanism hard, so these tolerances had to be loosened. In hindsight, the closeness of these uncritical dimensions was unnecessary and increased manufacturing time.

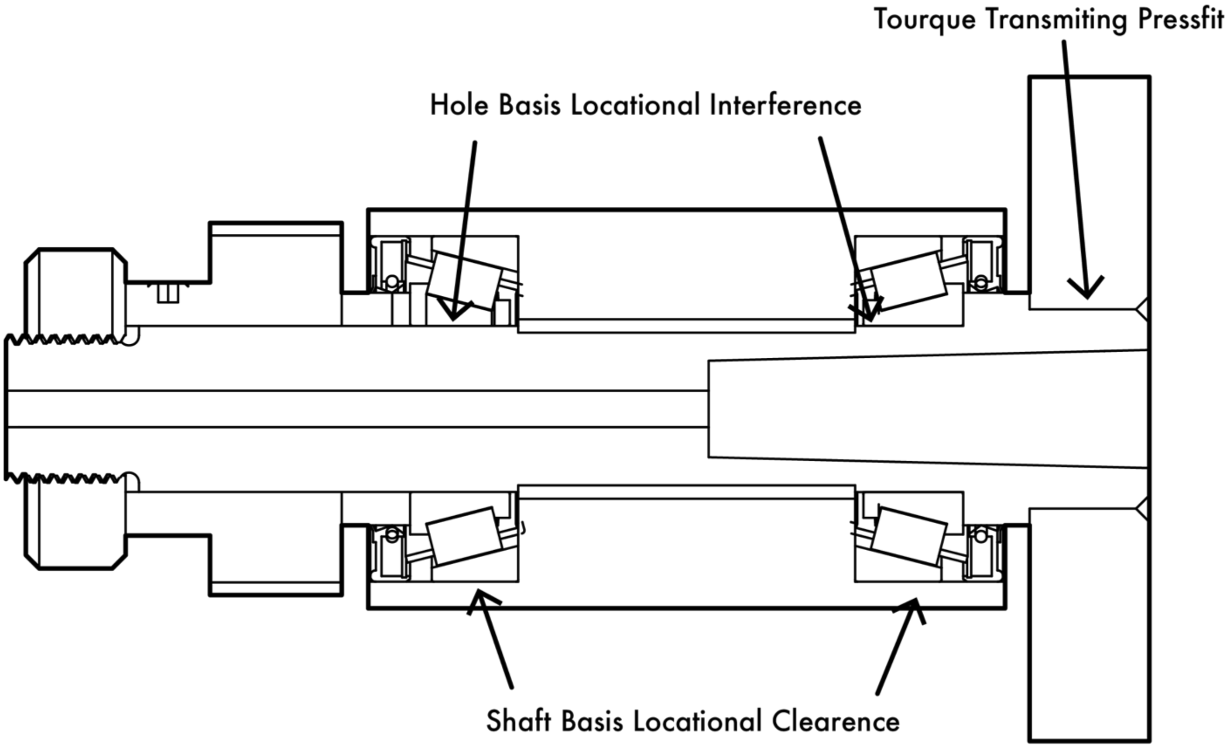

Figure 1. Cross section of the spindle design

- **Material choice**
  For cost and time reasons, no parts will be cast for this project, so therefore the sub parts must be made out of billet pieces of stock. While casting would produce a continuous part, the chosen approach produces parts that are broken into multiple sections with a bolted connection.

- **Machining and assembly**
  A very substantial part of the time required for this project was devoted to milling and turning individual components by hand. This was appropriate for this variety of research project, which seeks to explore whether such a gear hobbing machine could perform the desired functions. However, to determine whether this design could realistically become a manufacturable product would require a redesign in which every part did not need to be milled or turned by hand.

Control system design

Functional requirements for the control system

The gear hobber's accuracy depends on the ability of the control system to

- Maintain angular position under cutting forces
- Provide sufficient angular resolution for useful involute.

CNC gear cutting machines

In terms of control system design, the most conceptually similar machine to this manual gear hobber would be a servo-synchronized gear cutting machine; instead of having a physical gear train between the milling spindle and the gear blank, it synchronizes the movement between the two using a servo motor drive and an encoder.

The proposed design uses a similar approach because it does not need to synchronize other axes.

- **Servo vs. stepper motor**

  The initial design included a servo motor, because servos have the potential for higher resolution and they have feedback control so they do not experience step loss when they are overdriven. However, after testing with the Nema 23 package size, it became clear that servo motors do not have enough torque to provide sufficient stiffness. Switching to a comparable size stepper motor demonstrated that it could provide substantially higher torques while reducing the complexity of the control system.

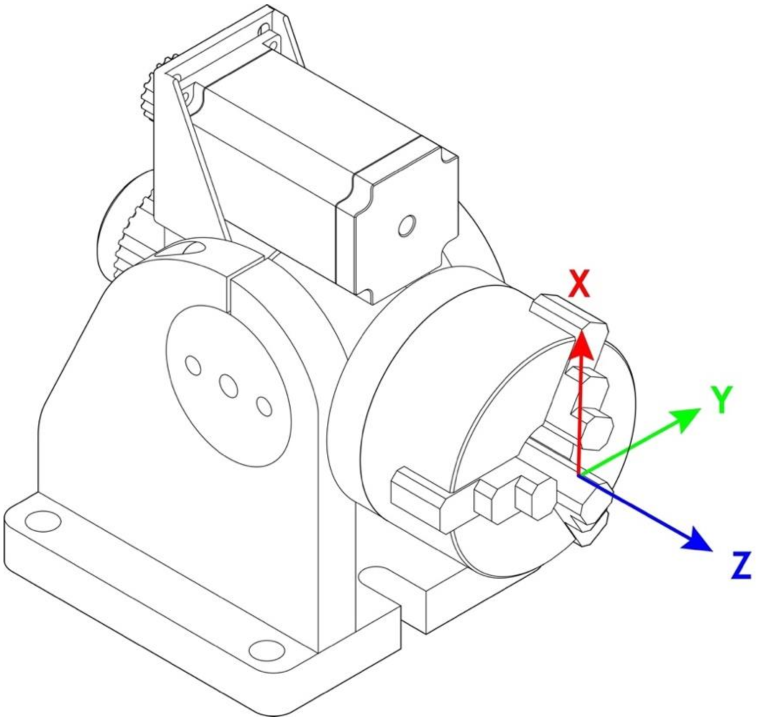

Figure 2. Third-axis projection of gear hobbing attachment showing main axis labels

- **Spindle encoder and implied tooth accuracy**
  To synchronize the gear hobbing spindle and the mill spindle, an encoder is required. The number of counts per revolution on this encoder is a somewhat important parameter as it defines the accuracy between the synchronization of the milling spindle and the gear hobbing axis. The upward bound on the spindle encoder counts is governed by the maximum interruption rate the microcontroller can handle along with the number of steps the stepper motor takes in one revolution. If the number of encoder counts is not divisible by the number of stepper motor steps per revolution, then there will be a small rounding error that will make it impossible for the system to continually cut gear teeth.

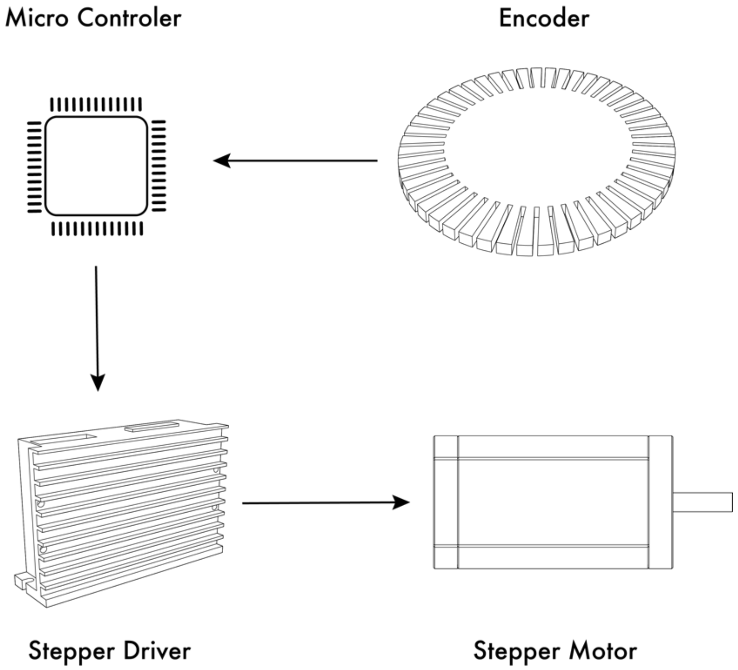

Figure 3. Design of control system

4.TESTING

Once the prototype was created, initial testing revealed some faults in the design that need correcting.

Once the bearings are preloaded, the main limitation comes from the choice of gear reduction. The rotational stiffness is governed by the gear reduction and by the stepper motor current. A belt was chosen to produce no backlash in the gear train, so it could be driven in either direction. However, this requires the stepper motor to have a high level of stiffness. Since the gear reduction is relatively low, this means that the gear hobbing is coming around the cutting forces, causing the gear blank to hop around significantly.

This limits the materials that can be cut. In addition, as the radius of the gears gets larger, the cutting forces are amplified through that radius. This means that the tooth profile was less accurate to the proper involute.

Shortcomings

- **Unreliable electrical system**
  The main problems with the electrical system so far have been related to noise. The encoder reading is very sensitive to the rising edge and falling edge. The microprocessor interrupts are very sensitive to the encoder signal, which includes these rising and falling edges. It appears that the stepper motor pulses coming out of the stepper motor driver are causing interference that is disrupting the encoder signal and throwing off the synchronization between the milling spindle and the gear blank.

- **Belt motor stiffness**
  The current design does not include an adequate system for applying sufficient tension against the belt. This is causing further stiffness losses in addition to those coming from the stepper motor. This became clear in testing and would require some redesign to the gear ratio or belt-tensioning systems.

- **Locking load**
  The initial approach relied on an AC servo motor instead of a stepper motor. A problem that emerged in testing was that throughout its torque speed curve, the servo motor has relatively lower holding power than a stepper motor. Therefore, at very low RPM, the servo motor would have quite a lot of phase lag relative to the milling spindle, which causes huge inaccuracies in the tooth profile. This required switching to a very large stepper motor which, because of the clogging of the rotor and stator, offers much higher holding power for the same current and therefore increases the accuracy of the gear hobbing.

- **Control system**
  In cutting the initial gears, some rounding errors appeared in the control system. Once the machine started to cut a gear, if left to cut continuously, it would slowly remove all the gear teeth until the blank was left to just the root diameter. This may be attributed to some level of overcounting of spindle encoder ticks.

  A possible remedy was tried involving a small capacitor. This reduced the counting of RPMs by dropping the voltage sufficiently at high RPMS, so the capacitor had to be removed. More testing and analysis would have to be done to pinpoint the particular kind of miscounting and remedy the problem.

- **Proposed design adjustments**
  This problem with the control system, as well other limitations discovered around stiffness and belt adjustment, argues for switching to something like a preloaded worm drive, which would offer more stiffness. In terms of a long-term redesign,

the current electrical system could be made to be reliable given the right kind of shielding and filtering.

In terms of rotational stiffness, the spindle's stiffness around its unconstrained axis (on which the motor turns) is much lower than one would like, meaning that for larger diameter gears, the forces multiplied through that lever arm are pretty high for the cutting force, producing a bit of slop back and forth with the motor and belt, which reduces the accuracy of the teeth cut. One remedy would be preloading the belt, as would increasing the gear ratio.

Results

To implement changes suggested in the Shortcomings section, the gear ratio of the system was adjusted, going from a drive ratio of 2:1 to 3.6:1. This modification in the gear ratio improved general spindle stiffness and made it possible to use a more professional encoder, at 360 counts per revolution instead of only 200. A belt tensioning idler was also added, which made it possible to clamp down on the belt with sufficient force to achieve the preloads required to reduce the backlash in the belt drive system. A shielded wire was used to replace the spindle encoder wire, which reduced the influence of noise in capturing false encoder ticks that was impairing the spindle coordination. These improvements are shown in Figure 4.

Once the machine was cutting gears of sufficient quality to inspect, many module 1 and module 2 gears were cut to try to understand the influence of cutting force on tooth profile. The resulting gears were analyzed in two main ways: through image analysis and a composite gear inspection test. (Figures 5 and 7)

To inspect the machine's performance with respect to the gear cutting standard, an optical image analysis was performed. This involved plotting the true expected involute against an image of a gear tooth cut by the machine. (Figure 5)

The results of this image analysis can be seen in Figure 6, which shows the error between the expected profile and produced profile. Generally these deviations are greater than what would be desirable, but they do fall within the JIS standard 6-7. The composite testing apparatus (Figure 7) quantifies the major run out of the gear around its shaft and the one pitch running error. The one pitch running error is well within the JIS standard 6-7. The one turn error falls outside of that specification, but with some adjustment to the machine could be expected to conform.

To quantify the spindle stiffness as it relates to cutting force, tests were performed with the gear hobber mounted to a tensile testing machine, as seen in Figures 10 and 11. The bending stiffness of 6 Newtons per micron is similar to the stiffness of a prototype milling machine such as a Bridgeport, generally 10 to 15 Newtons per micron.

By contrast, as shown in Figure 11, the spindle torsional stiffness is very nonlinear. This is related to the nonlinearities represented in stepper motors' stiffness characteristics.

Subjectively, the gears produced by this machine would be useful for prototyping but further improvements would have to be made before they could reflect true manufacturability.

Figure 4. The process of gear cutting

Figure 5. Gear tooth image analysis

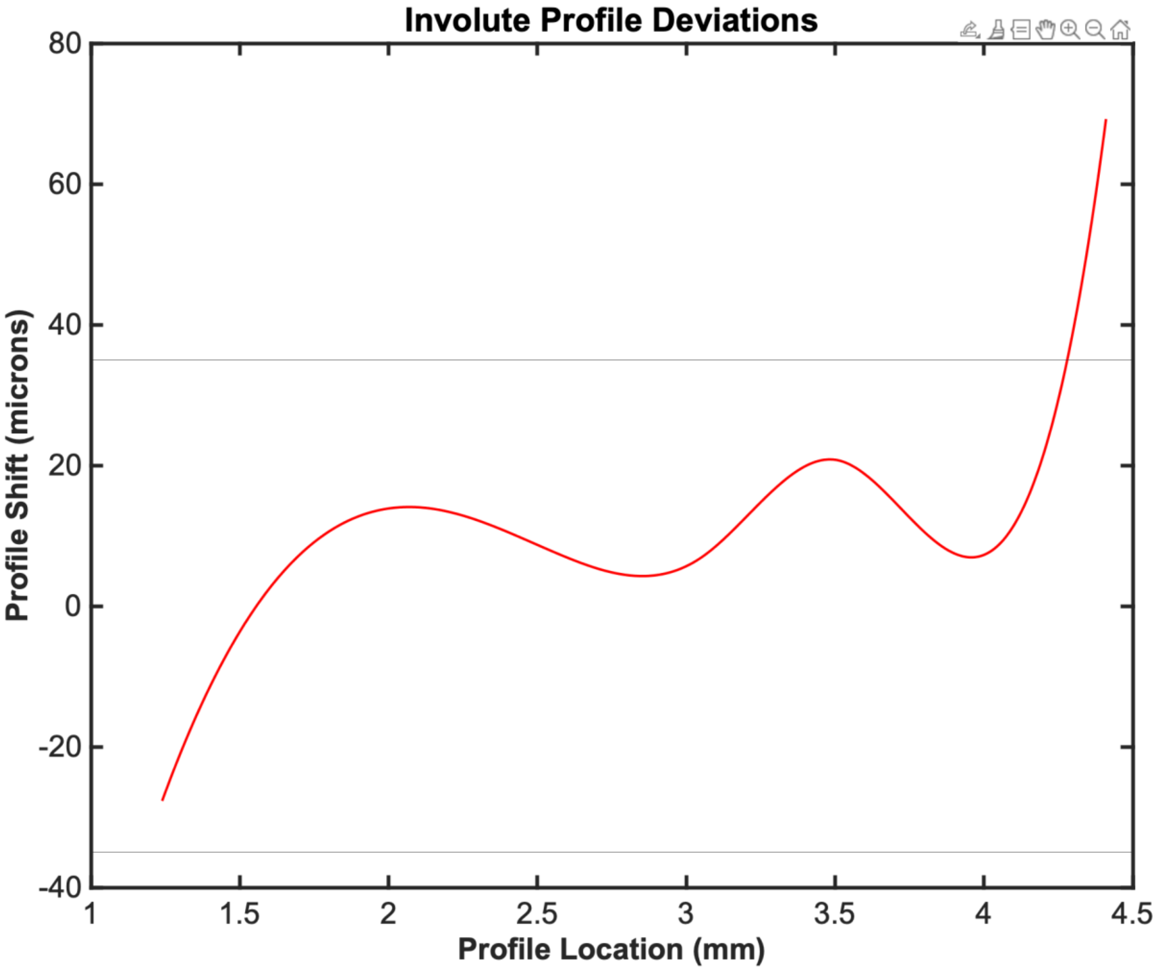

Figure 6. Gear tooth profile comparison from image inspection

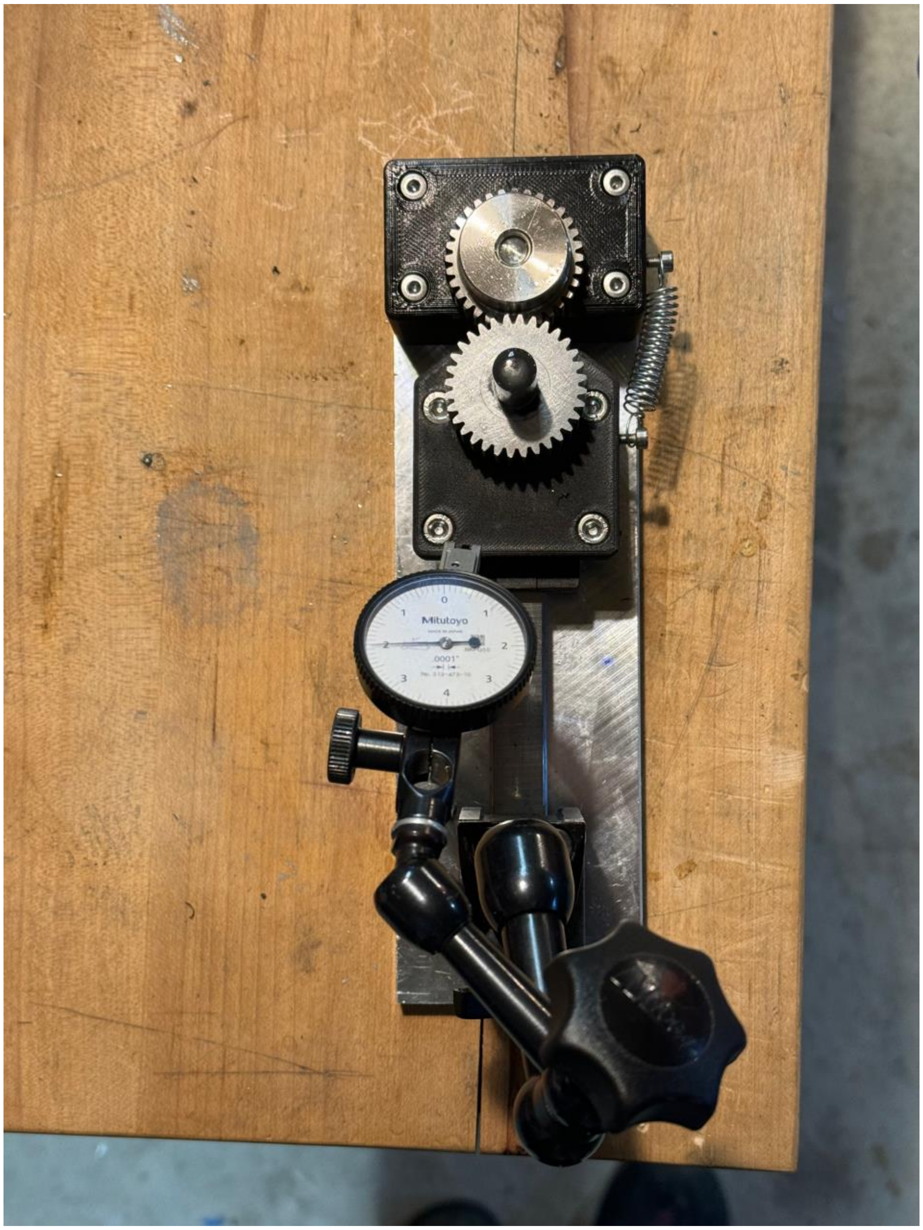

Figure 7. Composite gear inspection testing apparatus [4]

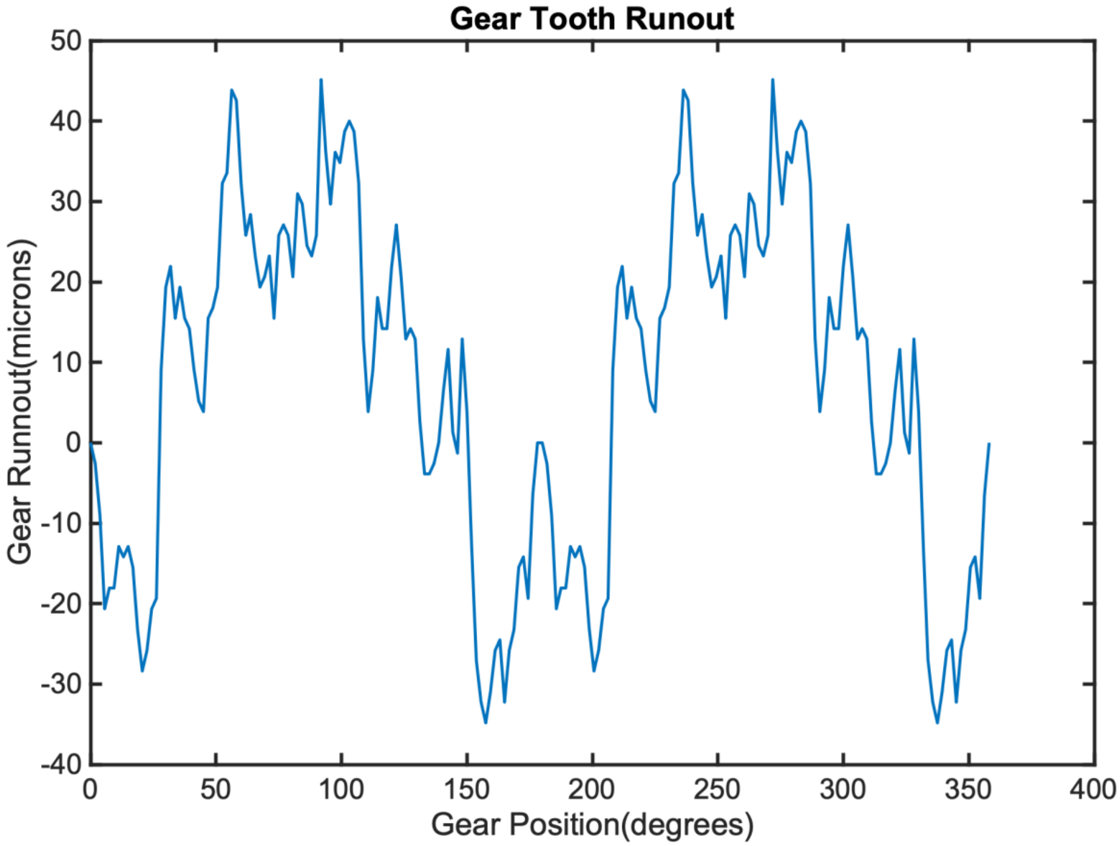

Figure 8. Gear tooth runout measurement via composite inspection [4]

In the composite inspection test, the major amplitude is called the one turn running error, which can be adjusted out. The small fluctuations are called the one pitch running error, which is more indicative of the cutting performance.

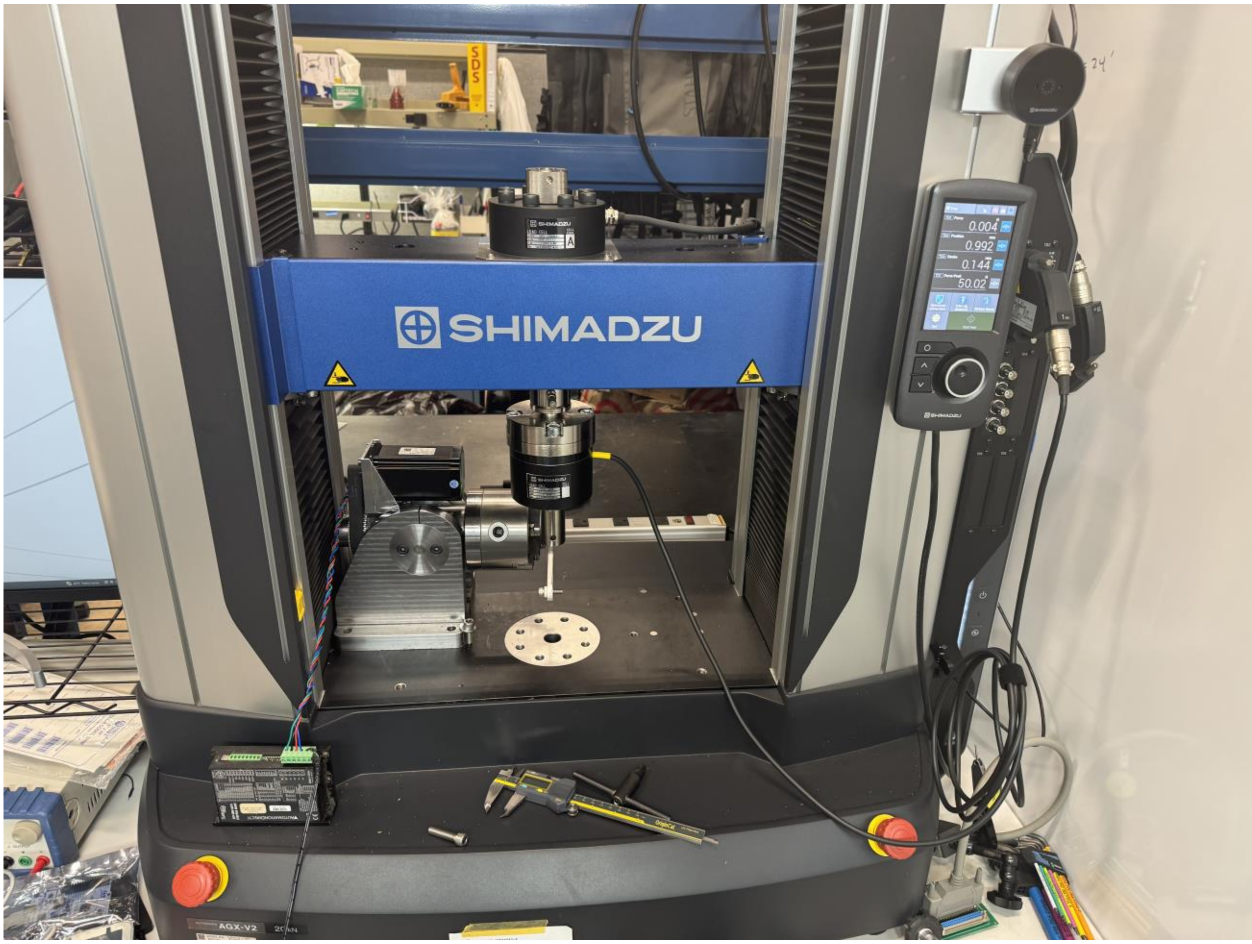

Figure 9. Stiffness testing on Shimadzu testing machine

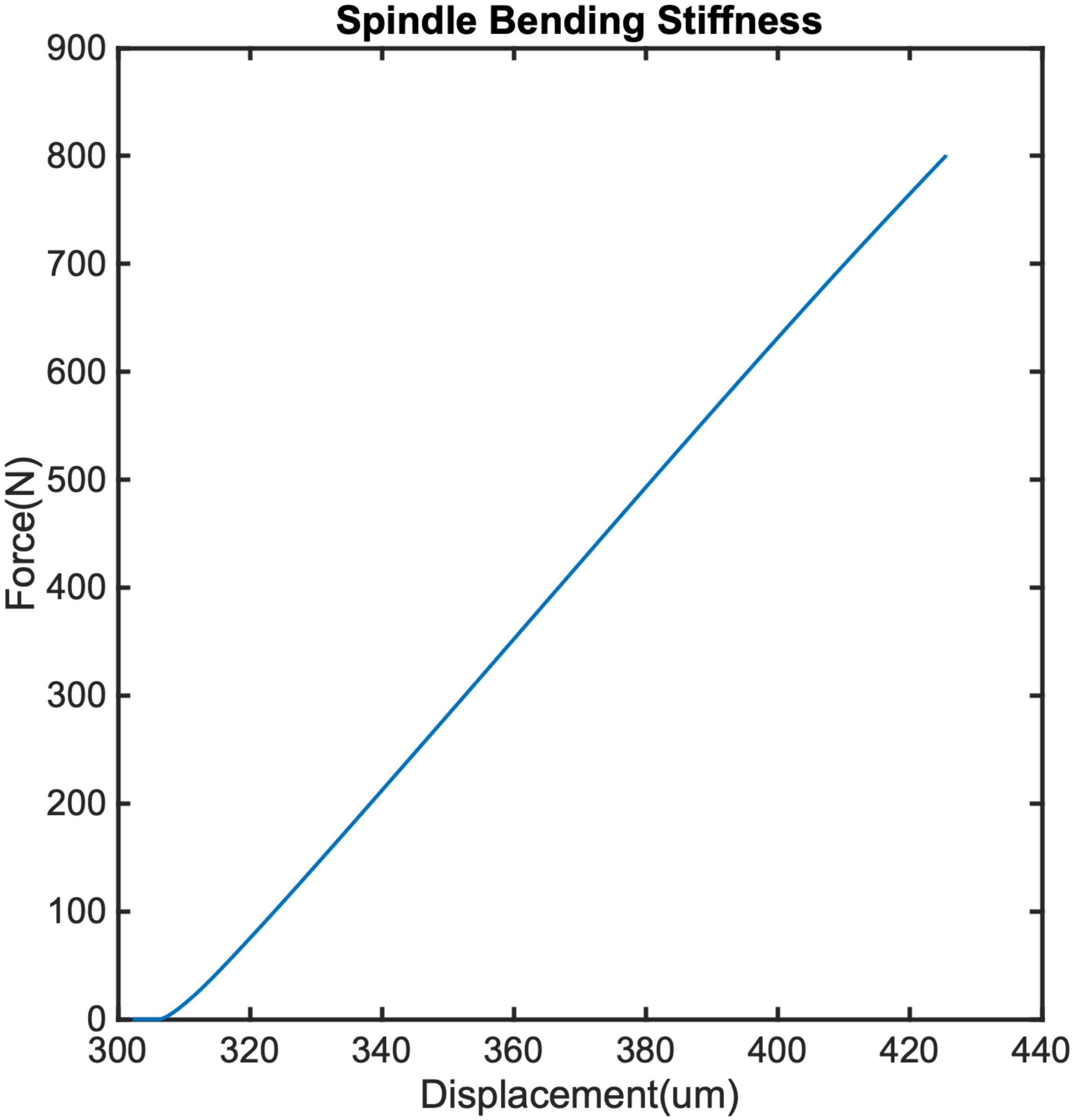

Figure 10. Spindle bending stiffness

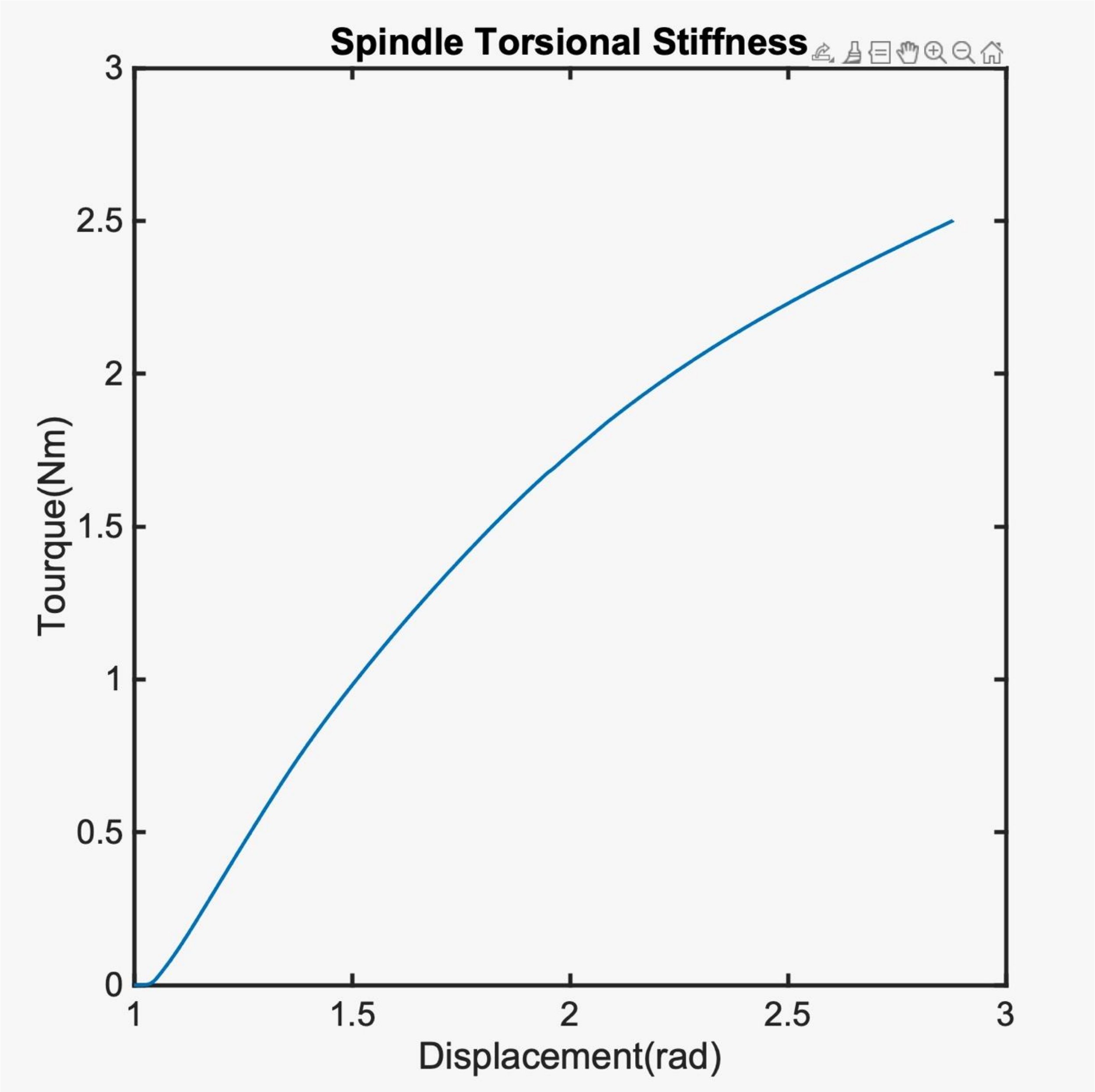

Figure 11. Spindle torsional stiffness

5.CONCLUSION

The project was very useful as a design exercise, and the fact that the machine was able to produce gears that are very close to the JIS standard suggests that it would be feasible, without a great deal of additional tuning, to create a hobbing attachment for manual milling machines that could produce useful gears very quickly.

Some unexpected difficulties, including electrical noise problems and the challenge of achieving a sufficiently high gear ratio without overwhelming the microprocessor, indicate that more optimization would be required to satisfy the practical needs of prototyping engineers in academic labs and start-ups.

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