Design & Development of Short Benchtop Welding Positioner

by

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Submitted to the
Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

The spindle of a benchtop welding positioner is designed to meet a defined set of specifications. These particular specifications consist of dimensional optimizations for spindle height and thru bore diameter and performance requirements, such as speed. Preliminary static analyses are conducted on the subsystems with the heaviest design consideration to ensure they meet the spindle's requirements. The design takes into account the spindle's manufacturability, assemblability, components' overall cost, bearing protection, grounding cable path, and more important aspects. Ultimately, a welding positioner spindle is designed, and a prototype is manufactured to investigate the outcome of the design.

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Title: Technical Instructor at MIT D-Lab

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1. Introduction

Background

Welding is a process in which materials, usually metals or thermoplastics, are joined via high heat to melt the parts together and then cooled, which causes them to fuse into one part. It is an essential process that is prevalent in global industries, such as automotive, construction, aviation, consumer products, and many more. The metal joining process is responsible for the manufacturing of cars, aircrafts, pipelines, bridges, fences, kitchen utensils, and many more objects necessary to people's daily lives. Advances in welding techniques have led to the use of numerous energy sources to heat the workpieces, including a gas flame, an electric arc, a laser, friction, and ultrasound. Typically, two or more materials, or workpieces, are positioned in the orientation they are intended to be joined and then welded along the crevice formed by the edge profiles of the two workpieces. When welding circular profiles, such as pipelines, welders can experience difficulty having to navigate their wired weld gun in a circle around the workpiece, which typically would be resting on a welding table.

A welding positioner is a mechanical device that holds and rotates a workpiece to enable the person welding to work at a proper, safe, and suitable angle and position. The positioner spins the workpiece 360 degrees such that the welder does not have to move to create the weld around the circumference of the workpiece, and the positioner's table surface itself can adjust between vertical and horizontal orientations to attain a comfortable working angle for the welder. In both industrial and hobbyist environments, a welding positioner boosts productivity as it reduces the time it takes to position the workpiece in a suitable position, it allows for a consistent weld as it makes it easier to run complete weld without repositioning interruptions. In overall, with a welding positioner, a welder can experience higher quality, more consistent rotary welds, and less fatigue when welding.

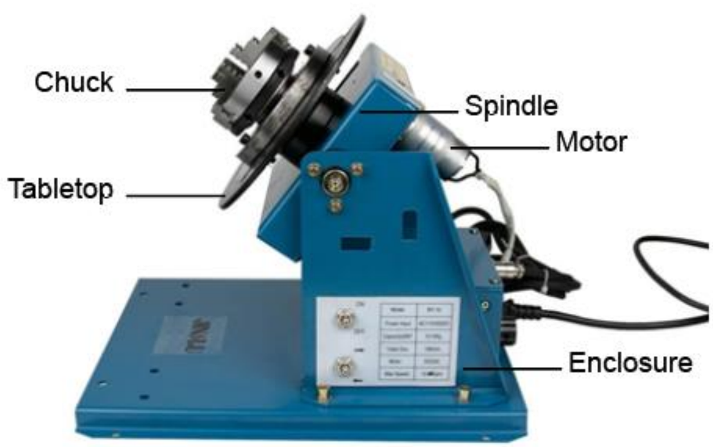

Figure 1: Annotated diagram of the basic parts of a welding positioner. [1]

A welding positioner consists of a spindle, which is responsible for providing the rotational motion of the workpiece, a motor to power the spindle, and a tabletop, which is designed to mate with other welding fixtures, like a chuck. A metal enclosure houses majority of the spindle, provides a stand to support the spindle and tabletop, and is designed to allow the entire spindle and tabletop assembly to rotate between horizontal and vertical orientations.

Purpose

The main purpose of this undergraduate thesis project is to design and develop a welding positioner spindle that will meet the design requirements listed and explained below. These requirements are defined based on the goals of a welder aiming to manufacture a distinguishable welding positioner as well as market trends.

1. *The bore hole through the spindle should be as large as possible*. Most commercial benchtop welding positioners either have no thru bore hole or have one up to 3” (76.2mm) in diameter. A larger thru bore will allow larger pipes and tubes to fit through the entirety of the positioner. This gives the welder more flexibility in positioning workpieces. The maximum diameter is limited by the internal diameters of suitable bearings and necessary wall thickness of the spindle shaft.
2. *The height of the spindle assembly should be as short as possible.* The welding positioner is intended to be used on top of a table and should be low enough from the tabletop such that a user of average height can comfortably use the device.
3. *The spindle should spin the workpiece up to 6 rpm.* This speed corresponds to typical maximum speeds of benchtop welding positioners. Within these constraints, the spindle should output as much torque as possible to support the highest possible work piece load.

2. Spindle Structure

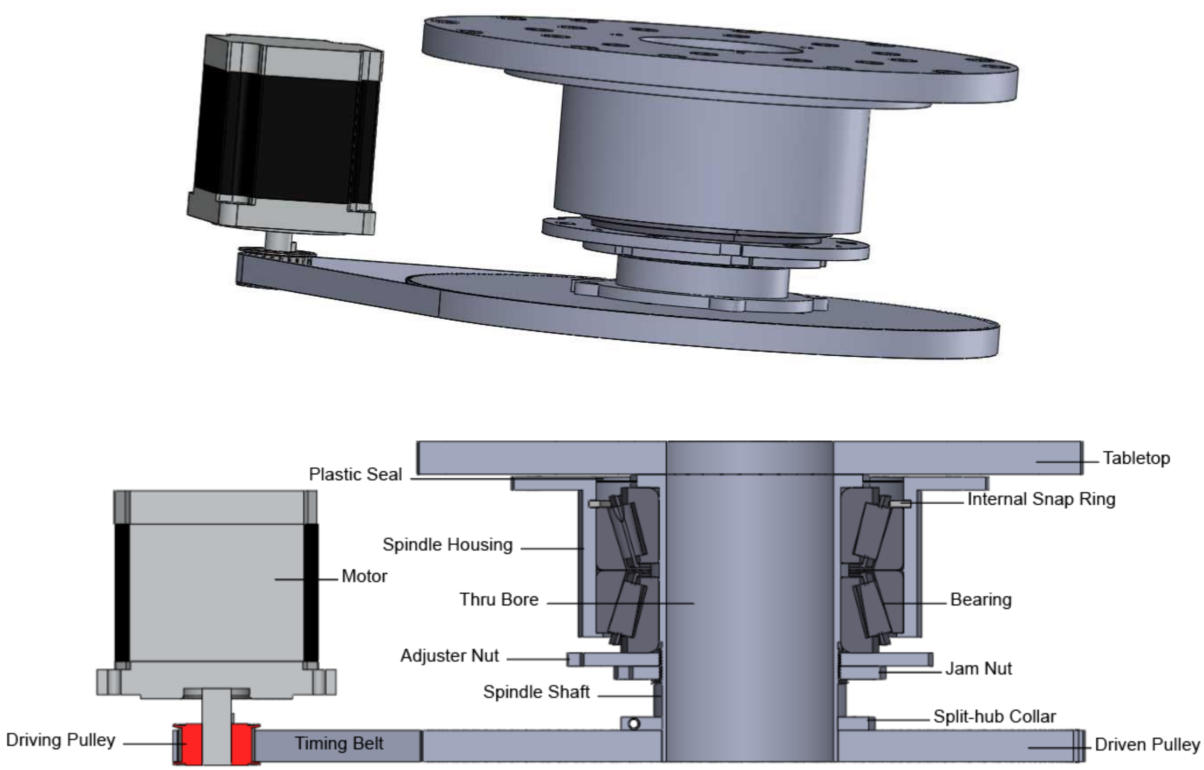

Figure 2: 3D models of the spindle system’s design in (top) isometric view and (bottom) annotated cross-section of front view.

The overall design of the spindle assembly consists of a spindle shaft, spindle housing, and two tapered roller bearings, in which the inner race is spinning with the shaft and the outer race is stationary with the housing. The flange of the spindle shaft expands into the tabletop surface of the positioner. An adjuster nut and a jam nut are threaded onto the spindle shaft to keep the bearings in pre-load. A split-hub collar is clamped onto the shaft and is fastened to a driven pulley, which is connected to the power transmission system and motor that drives the spindle.

Spindle shaft

The spindle shaft is the main rotating component of the assembly. The entire length of the shaft—beyond the bearing section—is home of the other components that are in the assembly. As the main rotating component, it is first to experience the loading during operation, so its stiffness will be key in the response of the spindle system.

Spindle bearings

The spindle system consists of two bearings to hold the spindle and carry the necessary loads, one in the front and one at the back. The bearings are the transition elements between the spindle and its housing which acts as the support elements to withstand against the reaction forces generated by both the motor and the device's operation. The internal diameter of the bearings also needs to be large enough to accommodate the large thru bore hole diameter and cheap enough to minimize the expense of the device.

Spindle housing

The primary function of the spindle housing is to support the bearings. Because all the forces generated on the spindle during machining are transferred to machine body through the housing, the housing must be stiff enough to withstand the experienced loads. [2] The flange of the spindle housing contains clearance holes to fasten to the welding positioner enclosure.

Motor

Majority of welding positioners are driven by electric motors. The motor needs to have enough power to spin the workpiece fast enough and up to a load that is within the motor's supported torque range. The motor's rated torque capacity is directly related to the spindle's load capacity. The body dimensions of the motor also must be considerate of the of the overall spindle system's size within the positioner enclosure.

Other parts

Above the bearings, an internal snap ring is fitted to constrain the vertical displacement of the bearings. A thin disc of nylon plastic is press fitted onto the spindle shaft above the snap ring as a plastic seal to mitigate the entry of debris, of which the build up will lead to reduced bearing life.

Below the spindle, a nut and jam nut are threaded along the spindle shaft to maintain the bearings' pre-load in their position. The holes in the profiles of these nuts need to match wrenches used to tighten them against each other.

A space between the nuts and the split-hub collar is designed to hold the grounding strap, which will wrap around the shaft.

The split-hub collar is clamped around the shaft via a bolt screwed into a threaded hole. The diameter of the hub must be sized correctly to support the driven pulley and provide enough clamping force around the spindle shaft.

3. Spindle Design Considerations & Decisions

Motor

The motor provides the spindle system the power to provide enough torque to support the spinning of a workpiece and enough speed to spin the workpiece at a suitable rate for the welder. There are four main types of electric motors: stepper, servo, DC, and AC. The key considerations for the motor selection were motor power, body dimensions, price, and ease of programmability and control.

Among the four groups, stepper motors a good balance of precision and load bearing in its typical application. Additionally, out of the four, the stepper motors are the most convenient to wire up and program for the purpose of prototyping. For the reasons just mentioned, stepper motors were selected as the primary type of motor to search for to power the system. Because the required torque to support the metal workpieces expected to be used in this welding positioner is higher than the rated torques of commercial electric motor, a mechanical power transmission system is necessary for the spindle system's operation. Thus, motors with different torque ratings will yield different gear reduction ratios, and ultimately different sizes of pulleys needed. These gear reductions increase the output torque at the spindle and decrease the output speed. Numerous motors were found and compared against each other, and the considerations for motor comparison were the gear reduction needed (constrained by the maximum allowable driven pulley diameter), the motor's cost, and the body dimensions—particularly the height.

Motor	Price [$]	Total Height [mm]	Stall Torque [Nm]
NEMA 34 12 Nm	69	187	12
NEMA 34 8.2 Nm	51	151	8.2
NEMA 34 7 Nm	55	135	7
NEMA 34 4.8 Nm	34	112	4.8
NEMA 24 4 Nm	46	121	4

Table 1: Table of shortlisted stepper motors comparing the motors' retail prices from available outlets, total height of the motors' bodies and shaft lengths, and their rated stall torques.

The ideal motor will have a combined body height and shaft length that fit in between the bottom of the driven pulley at the bottom of the spindle and the flange of the spindle housing, which is 127.25 mm. For any motors with heights greater than that distance, the gap where the grounding strap is wrapped around the spindle shaft will have to be increased to accommodate the motor's height. That increase in length should be minimized, if not avoided. The driven pulley should not be larger than the tabletop of the spindle, otherwise that would force the overall size of the enclosure to be larger, which would hinder the ease of the entire spindle assembly rotating 90 degrees. The only motors identified within the minimized gap are NEMA 24 4 Nm and NEMA 34 4.8 Nm stepper motors. However, the NEMA 34 7 Nm motor only increases the height of the assembly by 7.75 mm, while increasing the torque capacity of the system by 45.8% compared to the NEMA 34 4.8 Nm, which is the highest rated motor that does not necessitate the increase of the assembly's height.

Power Transmission System

Mechanical power transmission is the transfer of power from one component to another in machines and is often seen when converting one rotational movement into another, in which the torque and speed of the driven motion differs from those of the driving motion. There are numerous types of rotational power transmission methods, namely chain drives, gear drives, and belt drives. The drawbacks of chain drives are their noisiness, causing vibrations hence power loss, potential chain skipping and constant need of lubrication to operate. The drawbacks of gear drives are their tendency to cause noise and vibrations, frequent need of lubrication, and primarily its higher cost than the other transmission methods. The drawbacks of belt drives are their relatively shorter service life, the potential for the belt to slip, and the need to maintain tension in the belt. [3] For the application of the welding positioner spindle, the cheapest and easiest to maintain drive is desired. As a result, a belt drive was selected for this system.

The belt drive system consists of a driving pulley, timing belt, and driven pulley. To spec the system, the tooth ratio between driving and driven pulleys and the profile, width, and length of the belt had to be determined. Equations and figures used to determine and validate the specs of the belt drive were obtained from SDP/SI's technical datasheet for timing belts, pulleys, chains, and sprockets.

The peak design load must be determined first to understand the load capacity of the belt drive system, and it is obtained by multiplying the maximum driving torque by a service factor, which generally lie between 1.5 and 2.0 for small pitch synchronous drives.

$$T_{peak} = T \times SF \tag{1}$$

T is the pull-out torque of the motor, which is the expected maximum torque to be produced by the motor at any given time during consistent and smooth operation, and SF was chosen to be 2 for higher reliability. For a T of 5.6 Nm, T_{peak} was 11.2 Nm.

The belt's pitch was selected in consideration of the maximum size of the pulley and belt system within the spindle. As various pitches can satisfy the same torque requirements, smaller pitches tend to require wider dimensions to do so. The selection was also guided and validated by Figure 41, a speed-torque pitch rating diagram, in SDP/SI's technical datasheet. As a result, the selected pitch was 5mm as it met both our sizing limitations and the power requirements.

The tooth count for each pulley is needed to determine the drive's speed ratio and each pulley's pitch diameter. The speed ratio is the ratio of the number of teeth on the driven pulley to that of the driving pulley. The driven pulley has more teeth to decrease the output speed at the spindle and increase the output torque. To maximize the load capacity of the spindle, the fewest teeth in the driving pulley and highest number of teeth in the driven pulley were sought. The driving pulley's tooth count was constrained by the availability of parts from distributors that both matched the selected pitch and internal bore dimensions that fit onto the shaft of the selected motor. As a result, the smallest pulley that could be found had 24 teeth. Through consultation with a distributor of timing pulleys, it was determined that it is not recommended to use a pulley with over 200 teeth due to the tolerance stack up that could aggravate belt misalignment. Additionally, to maintain the compact nature of the welding positioner, the pulley cannot be wider than the spindle's tabletop, which has a diameter of 320 mm. The pitch diameter of a pulley is determined from the formula

$$PD = \frac{pN}{\pi} \tag{2}$$

where p is the pitch and N is the number of teeth. For a pulley with 200 teeth and a 5mm pitch, the pitch diameter is 318.31 mm, which is less than the diameter of the tabletop. Therefore, the driven pulley was chosen to be 200 teeth. And, for the driven pulley, the pitch diameter is 38.20 mm. The speed ratio for the pulley system is, as a result, 8.33.

The speed of the belt must be checked to ensure it does not require special reinforcements to operate. Belts that travel at speeds greater than 6,500 fpm generally require special materials and dynamic balancing for the pulleys. The belt speed is expressed as follows

$$v = 0.262 \times PD1 \times \omega \tag{3}$$

where $PD1$ is the pitch diameter of the driving pulley in inches and ω is the speed of the motor in rpm. With a maximum motor speed of 40 rpm and driving pulley pitch diameter of 38.20 mm, the belt's speed is 131.33 fpm, which is significantly below the 6,500 fpm threshold.

The length of the belt is dependent on the pulleys' layout, primarily the center distance between them. The minimum center distance between the pulley, which ensures enough teeth on the belt are engaged with the pulleys, is expressed as

$$C_{min} = \frac{N1+N2}{2\pi} \times p \tag{4}$$

where $N1$ and $N2$ are the number of teeth on the driving and driven pulleys, respectively. The minimum center distance for the pulley configuration is 178.25 mm. From this, the number of teeth NB in the belt can be specified as

$$NB = \frac{N1+N2}{\pi} + \frac{N1-N2}{\pi} - \sin^{-1}\left[\frac{(N1-N2)p}{2\pi C}\right] + \sqrt{\left(\frac{2C}{p}\right)^2 - \left(\frac{N1-N2}{\pi}\right)^2} \tag{5}$$

where C is the center distance. Using the minimum center distance for this pulley configuration, the minimum number of teeth the pulley should have is 206. The available belt configurations above 206 teeth are 210, 230, 254, 260, and 290 teeth. The number of teeth needs to yield a center distance that ensures there is enough clearance between the motor and other components of the spindle as well as comfortably engage enough teeth on the driving pulley. Through iterative calculation to ensure enough teeth on the belt are engaged on the pulley (which is discussed subsequently), the configuration with 230 teeth was selected, and the consequent center distance and belt length as a function of NB can be determined by

$$C = \frac{p}{4}\left\{NB - \frac{N1+N2}{2} + \sqrt{\left[NB - \frac{N1+N2}{2}\right]^2 - \frac{2(N1-N2)^2}{\pi^2}}\right\} \tag{6}$$

$$L = p \times NB \tag{7}$$

which are 256.81 mm and 1,150 mm.

The width of the belt affects if torque capacity. Based on the pitch diameter of the driving pulley and the speed of the faster shaft, which is the motor, the torque rating T_a is located in Table 35 in the technical datasheet for the base width of the belt. The final rated torque must be multiplied by a length and width factor based on the dimensions of the belt. This final torque must be greater than the T_{peak} to verify that all the specifications of the belt render a strong enough belt for the application. For the given specifications, the thinnest width that met the torque requirements was 15 mm. Thus, the belt's width is 15 mm.

To verify an appropriate center distance and, consequently, belt length, the number of teeth engaged with the smaller pulley must be checked. The number of teeth engaged with the smaller pulley at a given time should not be less than 6 to ensure reliable performance. The number of teeth engaged can be determined by

$$T = \frac{Arc \times n}{360} \tag{7}$$

where n is the number of teeth on the smaller pulley and Arc is

$$Arc = 180 - \left[\frac{60(PD - pd)}{C}\right] \tag{8}$$

where PD and pd are the pitch diameters of the larger and smaller pulleys, respectively. For the specifications of the belt and pulley system, the number of teeth engaged is 7, which is above the required threshold.

Following this method of selecting and validating belt and pulley specifications, [4] the timing belt drive system was specified and implemented in the design on the welding positioner spindle.

Bearing Selection

The bearings were selected driven by minimizing cost and attaining a large bore hole through the spindle shaft. The selected roller bearings have a bore of 95.25 mm and have a retail price of approximately $40 per pair. This met two of the core design considerations.

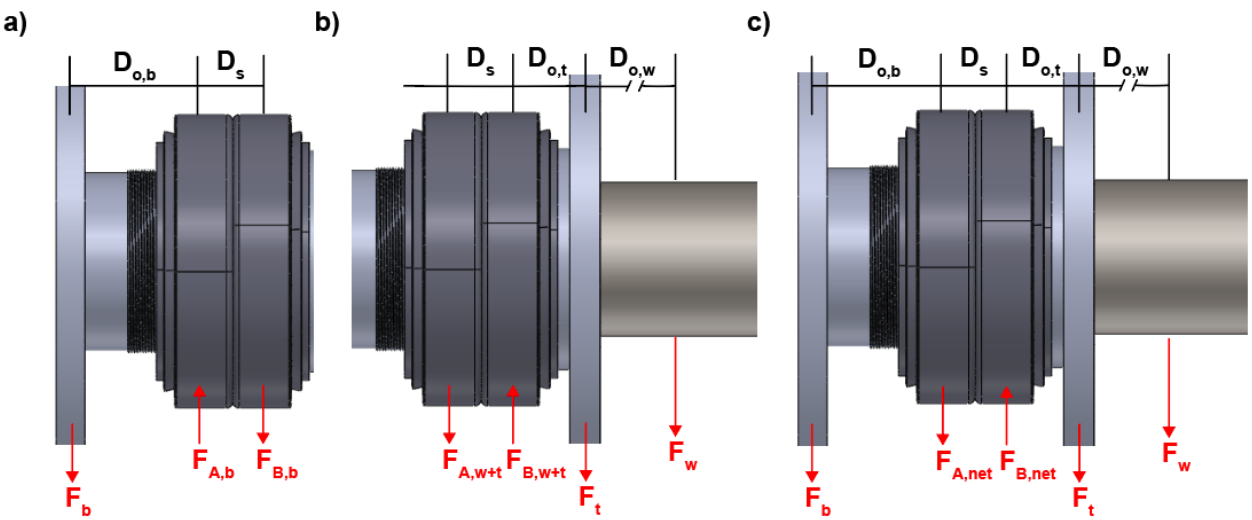

Figure 3: Free-body diagram of spindle shaft showing (a) the load force from the timing belt tension F_b, the bearings' radial forces due to the belt tension, $F_{A,b}$ and $F_{B,b}$, the overhang distance between bearing A and the belt $D_{o,b}$, and the bearing spacing distance D_s, (b) the load forces from the weights of the tabletop and workpiece, F_t and F_w, the bearings' radial forces due to the tabletop and workpiece, $F_{A,w+t}$ and $F_{B,w+t}$, the overhang distance between bearing B and the tabletop $D_{o,t}$, the distance between the tabletop and the workpiece's center of gravity $D_{o,w}$, and the bearing spacing distance D_s, and (c) the combined loading

scenarios with load forces from the timing belt tension F_b, the tabletop F_t, and the workpiece F_w, and the net radial forces due to all loading forces, $F_{A,net}$ and $F_{B,net}$.

Shown in Figure 3, the belt's downward tension force F_b, which is derived from the motor's torque and the driven pulley's pitch diameter in addition to the belt's static pre-tension, must be balanced out by the two bearings supporting the shaft with reaction forces $F_{A,b}$ and $F_{B,b}$. Additionally, in the horizontal orientation, where the gravitational forces of tabletop and workpiece, F_t and F_w, act perpendicular to the spindle's axis of rotation, the bearings will experience their most intense radial loading condition, in which the experienced radial forces, $F_{A,w+t}$ and $F_{B,w+t}$, act in opposite directions to the respective radial forces experienced due to the loads of the belt tension. Therefore, the net radial forces experienced in the bearings, $F_{A,net}$ and $F_{B,net}$, are the respective net forces of the radial forces due to the belt only and the radial forces due to the tabletop and workpiece only. Per static moment and force balances, the radial forces experienced by each bearing can be expressed as:

$$F_{B,b} = \frac{F_b D_{o,b}}{D_s} \tag{9}$$

$$F_{A,b} = F_{B,b} + F_b \tag{10}$$

$$F_{A,w+t} = \frac{F_t D_{o,t} + F_w (D_{o,t} + D_{o,w})}{D_s} \tag{11}$$

$$F_{B,w+t} = F_{A,w+t} + F_t + F_w \tag{12}$$

$$F_{A,net} = F_{A,b} + F_{A,w+t} \tag{13}$$

$$F_{B,net} = F_{B,b} + F_{B,w+t} \tag{14}$$

where $D_{o,b}$, $D_{o,t}$, $D_{o,w}$, and D_s are the overhang distance from bearing A to the driven pulley, the overhang distance between bearing B and the tabletop, the overhang distance between the tabletop and the workpiece's center of gravity, and the spacing distance between the bearings, which are 64.61 mm, 34.13 mm, 200 mm, and 39.69 mm, respectively. The belt's static pre-tension can be found with the below equation:

$$T_{st} = \frac{0.812DQ}{d} + mS^2 \tag{15}$$

in lbf and where DQ is the motor driving torque, d is the driving pulley's pitch diameter, m is the belt's mass factor found in Table 9 of the SDP/SI technical datasheet, [4] and S is the belt speed/1000. For the pulley design and belt selection of the belt drive system, the belt's static pre-tension T_{st} per span is 2.5 lbf, which is 11.12 N. The force T_d transmitted through the belt from the motor to the driven pulley is 17.61 N, therefore the total downward force of the belt, $2T_{st} + T_d$, is 39.85 N. The gravitational force due to the weight of the tabletop F_t is 86.57 N. F_w is selected as an arbitrary load of 1000 N (224.81 lbf), which exceeds the expected maximum weight that the welding positioner will support (based on its size and use case) and is used to safely overestimate the expected bearing load. $D_{o,w}$ is selected as an arbitrary distance of 200 mm, which corresponds to a overhang of 400 mm from the tabletop to the workpiece's tip and also exceeds the expected overhang distance supported by the welding positioner. As a result, the radial loads experienced by the bearings, $F_{A,net}$ and $F_{B,net}$, are 6,078.13 N and 7,124.85 N, respectively. These forces are both significantly lower than the bearings' static radial load rating of 319,000 N, and the thrust force resultant from the workpiece spinning is negligible in any positioner orientation due to the positioner's very slow operating speeds. Therefore, the bearings selected are rated well enough and beyond the specifications of this spindle.

Height Minimization

To design the spindle assembly to be a short as possible, heights and vertical thicknesses of parts were minimized, and compact assembly of parts were sought after. The gap between the tabletop and the top of the spindle housing flange is only 2 mm to provide clearance; the small gap both reduces overall height and reduces the pathway for debris to reach the bearings inside the housing. The bearings were arranged in a face-to-face duplex arrangement to not only to diffuse the radial and thrust loads but to also eliminate the distance between bearings. The thickness of the bearing adjuster nut, jam nut, and split-hub collar were selected based off stock thicknesses. The gap for the grounding strap was designed to be big enough to accommodate the cable thickness of large 200 A cables used in welding.

4. Development of Spindle

The process of fabrication started with the spindle housing, which consisted of the flange and the tube. The flange was cut from a large plate of 0.25"-thick mild steel stock using the waterjet. The waterjet cutting process was used to cut out the flange shape as well as the holes within it. The tube was cut off from a longer tube of mild steel stock. The outer diameter of the tube and the inner diameter of the flange were welded together to fuse the two components into one part. The welds were subsequently faced off on the milling machine. As one part, on the lathe, the housing was turned down to its desired dimensions and features—such as the internal groove for the snap ring, chamfer at the base of the flange for bearing entry, and lip at the bottom of the bearings—were added. Per the specifications for the stationary housing designed for industrial use of the bearings, the G7 tolerance class was selected, [5] which yielded a desired clearance of +0.014-0.054 mm for the inner diameter of the housing.

The spindle shaft was fabricated in a similar process. The shaft's flange, which is the spindle tabletop, was cut with the waterjet from a plate of mild steel, and the tube was cut from a longer tube stock of mild steel. On the lathe, the shaft was turned down to its desired dimensions and was threaded in the section above the bearings, where the adjuster and jam nuts thread onto. Per the specifications for the stationary housing designed for industrial use of the selected bearings, the m6 tolerance class was selected, [5] which yielded a desired interference of +0.013-0.035 mm for the outer diameter of the shaft. Unlike with the housing, the flange and tube were welded after the tube's lathe operations as the flange was too large to fit onto the chucks of the lathe.

The adjuster and jam nuts were cut on the waterjet and were internally threaded on the lathe so that they thread onto the spindle shaft. The split-hub collar was cut on the waterjet, and the clamp screw hole and mounting holes for the pulley were tapped. The driven pulley was cut with the waterjet out of a plate of aluminum stock. Lastly, the plastic seal was laser cut out of a thin sheet to its desired dimensions to achieve a press fit onto the spindle shaft.

The timing belt, driving pulley, and stepper motor were off-the-shelf parts purchased from third-party distributors. For this project, the motor was powered by an external DC power supply and programmed using an Arduino microprocessor and motor controller.

5. Discussion & Conclusions

Discussion

Setting the minimization of the spindle's height as the driving design requirement has its drawbacks from a performance perspective when also limited by cost. A larger, more expensive motor could have been selected to provide more torque to the system and increase the positioner's overall load capacity as well as reducing the diameter of the driven pulley. The bearings could also have been more spaced out to reduce the individual radial load that each bearing incurs. Additionally, the requirement for making the thru bore as large as possible necessitated the selection larger bearings, which are generally more expensive as well.

To minimize the accumulated material removed during machining, stock tubes with nominal outer and inner diameters should be selected. On small lathes in particular, the lathe spindle speed and tool feed rate should be carefully monitored to mitigate the deflection and damage of the tool, especially with such large workpieces being machined.

Conclusions

As a result of this thesis, a welding positioner is designed and fabricated with the following specifications:

1. It has a thru bore with a diameter of 88.75 mm.
2. The total spindle package height, from the top of the tabletop to the bottom of the pulley, is 166 mm.
3. At no load, it can spin up to 7.5 rpm.
4. It outputted a torque of 20 Nm.
5. It is designed to run with a stepper motor connected to a timing belt drive power transmission system.
6. The radial loads experienced by the bearings are much lower than their static radial rating of 319,000 N.

The design and fabrication of the first prototype of this welding positioner spindle showcased the ability of its design to develop a spindle that is as short as possible and has a thru bore as wide as possible. The desired numbers were not met due to lack of time available in the scope of this project to tune the motor drive.

6. Further Work

The following are potential ideas for further work:

- Design of the welding positioner enclosure can be done.
- Analysis of the dynamic loading conditions of the bearings can be conducted.
- Bearings of different geometries or materials can be investigated.
- Tolerance stack-up and its effects of the spindle's rigidity can be investigated.

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