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Design and Analysis of Bearing Arrangement for an Integrated Motor Milling Spindle

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Abstract

The necessity to increase productivity and to lower the cost of production, high speed machining tools has been widely utilized in the modern production facilities. High speed cutting is becoming more widely used and is possible by using a high speed integrated motor spindle, High speed integrated motor spindles are developed with a motor, integrated within the spindle housing, which eliminates the external power transmission components such as gears and belts. High speed motorized spindle systems are subjected to several effects during high-speed rotations that can cause substantial changes in their dynamic and thermal behaviours, leading to chatter, bearing seizure or premature spindle bearing failures, which affects the overall performance of the high-speed cutting. This paper discusses about modelling of a high speed integrated motor milling spindle and to optimize the factors influencing the stiffness of the high speed milling spindle running at 14000 rpm with power rating 15 kW by designing three bearing arrangement.

Keywords: *Integrated Motor spindle, Bearing Span, Deflection, Stiffness*

1. Introduction

The spindle is an important system of a machine tool since the dynamic properties of the spindle affect the cutting ability of the machine tool directly. The dimensions of the spindle shaft, location, bearing stiffness, bearing preload affects the vibration less operation of the spindle. The stiffness of the bearing depends on the bearing preload and during machining the stiffness is affected by the deformation of the spindle shaft. In most of the CNC machine spindles, angular contact ball bearings are most commonly used. These types of bearings have low-friction properties and are able to withstand both axial and radial external loads.

1.1 Motorized Milling Spindles

Modern technology to a great extent relies on the use of high frequency motorized spindle which is a competent technology for significantly ever-increasing productivity and plummeting production costs. Integrated motor spindles are developed to achieve high speed rotation. In this type of spindle, the shaft will have a built-in motor as an integral part, thus eliminating the need for external power transmission devices like gears and belts. In general, an integrated motor-spindle has a spindle shaft, including a motor and the tooling system. A set of high precision bearings which are lubricated by grease or oil, mounted on the shaft will hold it in position. The shaft will then rotate at maximum speed, depending on power characteristics of the motor used. The best performance of the spindle with required speed, power, stiffness and load capacity can be obtained by selecting suitable components.
A suitable size, capacity of the electric motor can be selected depending on the available space in the spindle.
The following parameters like loading capacity, Max speed, and stiffness are affected by the bearing size; hence the size of the bearing selected becomes critical. The bearing size se-

lected should also match the motor characteristics. But the high-speed rotation and built in motor generates a large amount of heat and introduces heavy rotating mass into the system. This needs to be regulated by precise cooling and lubrication methods. Extensive usage of Motorized milling spindles is made in present days in all types of machine tool for heavy duty milling. Compared to conventional spindles which are gear or belt driven by an external motor, the use of an integrated motor spindle is more convenient as it reduces vibrations and decelerations. In most cases, the high speed permitted by the integrated motor will provide maximum performance, flexibility and ensure optimum and economical machining for various sizes of work piece. These spindles can be successfully used for rough cutting and precise finish cutting. The arrangement for an integrated motor milling spindle is as shown in Figure 1.

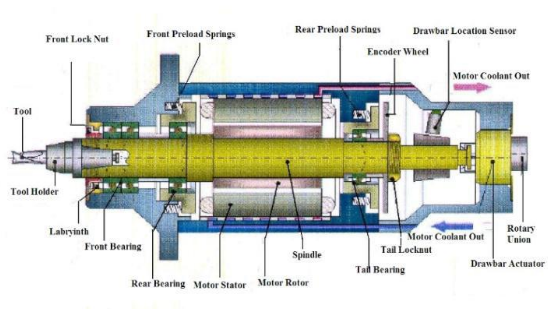


Figure 1: Motorized Milling Spindle.

2. Design and Modeling

Design and modeling of the BT-40 milling spindle for a rated speed of 14000 rpm, was developed, by making use of precision bearings and different bearing arrangements. Keeping the requirements in mind, three assemblies with different bearing arrangements will be modeled using SOLIDWORKS 3D modeling software. The model is shown in Figure 2.

The design of a high-speed integrated milling spindle includes following major components

- Spindle Style: Integrated Motor Spindle
- Spindle Motor: Capacity, Size
- Spindle Housing: Mounting Style, Housing Size, Capacity
- Spindle Bearings: Bearing Type, Number, Mounting method, Lubrication Method
- Spindle Shaft: Tool Retention Drawbar and Tooling System Used

The BT-40 CNC Milling spindle is designed to satisfy the required specifications. The design is optimized by proper selection of spindle components and simplifying the design of the spindle parts from the machining point of view.

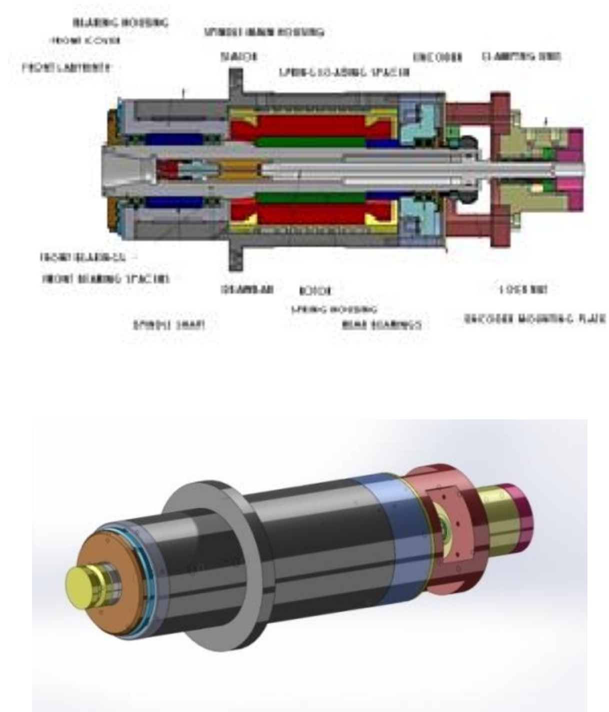


Figure 2: Model of Integrated motor spindle assembly design

2.1. Spindle Material Selection

Considerations for better damping capacity, High wear resistance, machinability, lower specific gravity, high strength was given in selecting suitable materials. The materials for the various components listed in Table.1, below were selected based on their properties which were adequate to meet the design requirements and service conditions.

Table 1: List of Components Of BT-40 Spindle Assembly And Materials Selected

Part number	Part name	Material
	Spindle main housing	SG Iron 500/7
2	Spindle shaft	EN24
3	Bearing housing	EN8
4	Front cover	EN8
5	Front labyrinth	EN8
6	Bearing spacers	EN24
	Spring housing	EN8
8	Rear labyrinth	EN8
9	Spring loaded spacer	EN8
10	Encoder mounting plate	C45
11	Drawbar	EN24

2.2. Selection of Electric Motor

Selection of electric motor becomes the main factor as it is integrated with the rotor shaft. The motor for the spindle is selected depending on the requirements of speed, torque, cooling arrangement type, dimensions of the motor, etc. The size and capacity of the motor selected depends upon the available space. The size of the bearing used depends upon the motor shaft, and it affects the loading capability, stiffness, and maximum speed achieved by the spindle. The characteristics of the electric motor must also match the bearing capability.

An AC induction motor is used in high-speed integrated motor spindles. In this design, the rotor is attached to the spindle shaft during assembly by thermal clamping. The bearings mounted on front and rear end of the shaft. The shaft is then assembled into the spindle housing. The spindle shaft can then rotate at high speeds due to transfer of power from the integrated motor to the cutting tool. The shaft must locate and support the bearings and contain the complete tooling system as well.

2.2.1. Siemens1FE1 standard built in motors

Siemens1FE1073-4WT11, shown in Figure3.is selected depending on the requirements of the spindle. It is built-in synchronous motors suitable for high-performance motor spindle is selected. It has the Rotor and stator ready for installation and has a cooling jacket for liquid cooling. The motor is suitable for the highest demands on machining quality, accuracy, and smooth running.

Figure 3: SIEMENS 1FE1073-4WT11Motor

The specifications of the SIEMENS 1FE1073-4WT11 motor are shown in Table 2.

Table 2: Specifications of SIEMENS 1FE1073-4WT11 Built in Spindle Motor

Rated Power	kW	15
Rated Speed	RPM	3200
Rated Torque	Nm	45
Rated Current	A	30
Maximum Current	A	60
Moment of inertia	kg m^2	0.00287
Maximum Rotational Speed	RPM	14000
Stator weight with cooling jacket	kg	12.5
Rotor weight	kg	2.2

The dimensions of Siemens 1FE1073– 4WT11 built in spindle motor is shown in Figure 4.

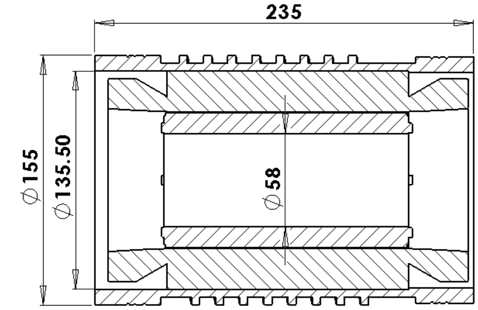


Figure 4: Dimensions of SIEMENS 1FE1073 – 4WT11 built in spindle motor.

2.3 Bearing Selection

Rolling element bearings are available in a variety of types, configurations, and sizes. It is important to consider following factors, mounting space, bearing loads, Speed requirements, bearing tolerances, Rigidity requirements, Misalignment considerations, Mounting and dismounting considerations and analyze in various means before selecting the suitable Bearing for Integrated motor spindle.
The inner diameter of the rotor is 58 mm. Hence the outer diameter of the shaft is restricted to 58 mm where the rotor is fitted. Therefore, for the shaft designed for this condition, front bearings of bore 65 mm and rear bearings having bore of 55 mm is chosen.
For the purpose of selection of optimum bearing arrangement, three bearing arrangements are designed considering the bearing data from four different manufacturers, NSK, Timken, SKF and FAG.

2.4 Encoder Selection

The ERM modular encoders from Heidenhain 2400 series encoder shown in Figure 5, was selected. It consists of a magnetized scale drum and a scanning unit with magneto resistive sensor. Their magnodur measuring standard and the magneto resistive scanning principle make them particularly tolerant to contamination.

Figure 5: Heidenhain 2400 series encoder

2.5 Adjustable locknut Selection

Adjustable locknuts are used to apply preload on the bearing sets. KLS precision locknuts shown in Figure 6 are selected. This locknut applies required preload to secure bearings and other machine components on shafts and spindles with a high degree of stiffness.

Figure 6: KLS precision Locknut - YHB type

2.6 Draw Bar

A clamping mechanism is provided to secure the tool holder in the taper during machining operations. During cutting process the forces created will tend to pull the tool out of spindle and hence the drawbar must provide sufficient pulling force to overcome all forces. The end of the drawbar grips the tool holder retention knob, and holds the tool holder in position in the taper. When a tool change must occur, a hydraulic or pneumatic cylinder compresses the drawbar, and the tool holder is released. ES series spindle drawbar is shown in Figure 7

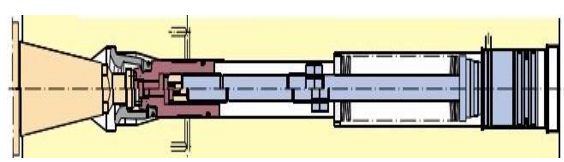


Figure 7: E S series spindle drawbar

2.7 Mechanical clamping systems

The mechanical clamping system offers the highest pull forces. Special features of the power drawbar are the amplification mechanism for transmission of the pull force and locking the universal spindles inside shape. After the locking mechanism is in place, all cutting forces are directed against the solid steel shaft, not against the Belleville washers. This system provides very high holding force and rigidity, which is critical to the high-speed cutting process.

3. Analysis of Bearing Arrangement

Since operating conditions and machine components vary depending on the application, bearing performance, and bearing mounting arrangements need to be varied. For the purpose of selection of optimum bearing arrangement, three bearing arrangements are designed considering the bearing data from four different manufacturers, NSK, Timken, SKF and FAG and analysed

3.1 Bearing arrangement - 1

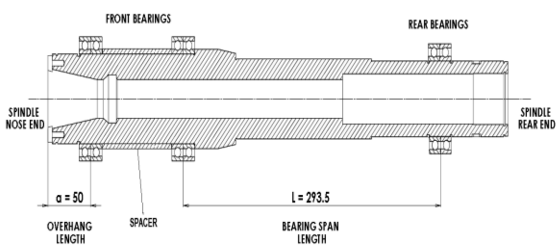


Figure 8: Bearing arrangement- 1

In Bearing arrangement-1 shown in Figure 8, two sets of bearings are arranged as quadruplet back-to-back (DBTT) at the front separated by a spacer. One pair of bearings are arranged as tandem with respect to each other and the other pair of bearings are arranged in tandem with respect to each other and back-to-back with respect to the first set of bearings. This arrangement is able to take the load applied at the spindle nose from both directions. Better rigidity is also provided with the proper preloading. The speed reduction of the bearings is less due to large bearing distance due to this a better stiffness can be obtained along with higher speeds and resistance to tilting moments. The rear end of the spindle is provided with one set of bearings as back-to-back (DB) mounting arrangement so that the spindle can be radially supported. The dimensions of the bearings used for arrangement 1 are shown in Table.3

Table.3: Bearing Dimensions for Arrangement-1

Bearing	*Bore (mm)*	*OD (mm)*	*Width (mm)*
Front bearings	*65*	*90*	*13*
Rear bearings	*55*	*80*	*13*

3.2 Bearing arrangement -2

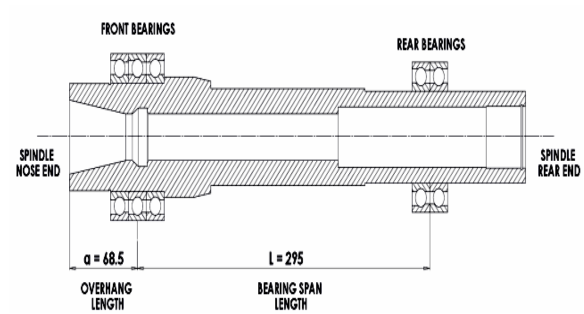


Figure 9: Bearing arrangement- 2

In Bearing arrangement-2 shown in Figure 9, one set of bearings are used at the front and rear end of the spindle. The front end of the spindle is arranged as tandem back-to-back (DBT) in which a pair of angular contact ball bearings is arranged in tandem with respect to each other and back-to-back with respect to a single angular contact ball bearing. Tandem bearing pair will carry both radial and axial loads equally. The speed reduction is more in this arrangement due to triplet arrangement at the front. The rear end of the spindle is supported by one set of bearings arranged in back-to-back (DB) fashion.

3.3 Bearing arrangement -3

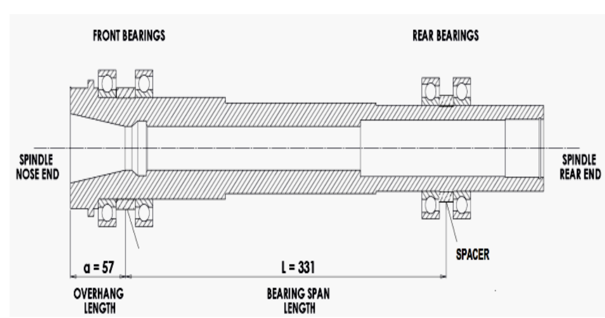


Figure 10: Bearing arrangement- 3

In Bearing arrangement-3 shown in Figure 10, one set of bearings is arranged at the front in back-to-back (DB) fashion. The bearings are separated by a spacer. The bearings will be able to carry loads from both the directions. The bearings should be preloaded from the rear side. The speed reduction in this arrangement is more due to the small bearing distance. The rear end of the spindle is provided with one set of bearings arranged in back-to-back (DB) fashion.

The dimensions of the bearings used for arrangement 2 & 3 are shown in Table 4.

Table 4: Bearing Dimensions for Arrangement- 2, 3

Operation	Tangential Load (N)	Radial Load (N)	Axial Load (N)	Speed (rpm)	Torque (Nm)
Face Milling	1441	504.35	793	318	57.75
End Milling	2213.87	1217	553.5	1274	22.18
Drilling	1214.5	0	4100	319	24.29

3.4 Determination of cutting forces acting on the spindle nose

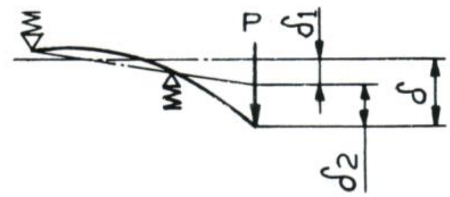
Theoretical cutting forces acting on the spindle nose for different machining process are calculated by a standard procedure. The cutting data obtained from cutting force calculations is listed in Table.5

Table.5 Cutting Data

Bearing	Bore (mm)	OD (mm)	Width (mm)
Front bearings	65	100	18
Rear bearings	55	90	18

3.5 Theoretical calculation of spindle deflection for bearing arrangements.

Spindle deflection calculations have been carried out under the assumption that the housing deformation is of no consequence. The total deflection of the spindle is therefore due to the elastic deformation of the spindle and elastic deformation of the bearings. Ignoring the effects of housing deformation on the spindle, the total deflection of the spindle unit is due to the elastic deformation δ_2 of the spindle itself together with δ_1 the deflection caused by elastic deformation of the bearings. The total deflection of the bearing system due to load P at the point of application of load is shown in Figure 10.



$$\delta = P\left[\frac{1}{S_A}\left(\frac{a+L}{L}\right)^2 + \frac{1}{S_B}\left(\frac{a}{L}\right)^2 + \frac{a^2}{3E}\left(\frac{L}{I_L} + \frac{a}{I_a}\right)\right]$$

Figure 10: Spindle deflection diagram and Expression

Using above expression Spindle deflection for three bearing arrangement is calculated.

3.5.1 Deflection obtained for Bearing arrangement 1

a = Overhang Length = 50 mm
L = Bearing span in mm = 293.5 mm
E= Young's modulus = 210000 N/mm^2
P = Radial force in N = 1217 N
S_A= Front bearing Stiffness = 1248000 N/mm
S_B= Rear bearing Stiffness = 540000 N/mm
I_L= Second moment of area of the shaft at the Span = 605113.53 mm^4
I_a= Second moment of area of the shaft at the Overhang = 780010.53 mm^4

By substituting the above values in spindle deflection equation, the magnitude of deflection $\delta = 4.019 \times 10^{-3}$
$\delta = 4.019$ μm

3.5.2 Deflection obtained for Bearing arrangement 2

a = Overhang Length = 68.5 mm
L = Bearing span = 295 mm
E= Young's modulus = 210000 N/mm^2

P = Radial force in N = 1217 N
S_A= Front bearing Stiffness = 955400 N/mm
S_B= Rear bearing Stiffness =540000 N/mm
I_L= Second moment of area of the shaft at the span = 600195.7 mm^4
I_a= Second moment of area of the shaft at the overhang = 774803.56 mm^4

By substituting the above values in spindle deflection equation, the magnitude of deflection $\delta = 7.21 \times 10^{-3}$ mm, $\delta = 7.21$ µm

3.5.3 Deflection obtained for Bearing arrangement 3

a = Overhang Length = 57 mm
L = Bearing span in mm = 331 mm
E= Young's modulus = 210000 N/mm^2
P = Radial force in N = 1217 N
S_A= Front bearing Stiffness = 702500 N/mm
S_B= rear bearing Stiffness = 540000 N/mm
I_L= Second moment of area of the shaft at the Span = 598991.8mm^4
I_a= Second moment of area of the shaft at the Overhang = 1183653.15 mm^4

By substituting the above values in spindle deflection equation, the magnitude of deflection $\delta = 6.12 \times 10^{-3}$ mm
$\delta = 6.12$ µm.

3.6 Theoretical deflection results for three bearing arrangements

The theoretical deflection results obtained for three bearing arrangements and for bearing from four different manufacturers, NSK, Timken, SKF and FAG are listed in Table.6 to Table .8.

Table.6: Deflections for Arrangement 1

	Preload		
	Light	Medium	Heavy
Bearings	Deflection (µm)		
NSK	4.37	4.01	3.74
Timken	5.93	4.80	4.31
FAG	6.20	5.07	4.36
SKF	4.97	4.34	3.84

Table.7: Deflections for Arrangement 2

	Preload		
	Light	Medium	Heavy
Bearings	Deflection (µm)		
NSK	7.52	7.21	6.82
Timken	9.24	7.98	7.39
FAG	10.3	8.39	7.64
SKF	8.02	7.20	7.05

Table.8: Deflections for Arrangement 3

	Preload		
	Light	Medium	Heavy
Bearings	Deflection (µm)		
NSK	6.57	6.12	5.62
Timken	8.61	7.10	6.37
FAG	9.85	7.61	6.62
SKF	7.11	6.12	5.37

It is observed that the deflection of the spindle for bearing arrangement 1 is much lesser compared to that of other two bearing arrangements. In many of the applications medium preloading of the bearings is preferred and hence the results obtained for NSK bearings is considered and optimum bearing span length is calculated for three arrangements with medium preloaded NSK bearings.

3.7 Computing the Bearing Span Length which is Optimum for three Bearing Arrangements

Optimized bearing span for bearing arrangement 1, 2 and 3 for medium preloaded NSK bearings is determined by calculating the deflection and Stiffness for different span lengths, shown in Table.9 to Table.11

Table.9: Deflection & Stiffness Values for Different Span lengths In Bearing Arrangement 1

Span (mm)	Deflection (µm)	Stiffness (N/µm)
150.0	3.48	349.71
160.0	3.47	350.53
170.0	3.49	348.71
180.0	3.51	346.72
190.0	3.53	344.75
200.0	3.56	341.85

210.0	3.60	338.05
220.0	3.64	334.34
230.0	3.69	329.89
240.0	3.74	325.40
250.0	3.79	321.10
260.0	3.85	316.10
270.0	3.90	312.65
280.0	3.96	307.32
290.0	4.02	302.73
300.0	4.08	298.28
310.0	4.15	293.25
320.0	4.21	289.07
330.0	4.28	284.34

Table.10: Deflection & Stiffness Values for Different Span lengths In Bearing Arrangement 2

Span (mm)	Deflection (μm)	Stiffness (N/μm)
150.0	3.48	349.71
160.0	3.47	350.53
170.0	3.49	348.71
180.0	3.51	346.72
190.0	3.53	344.75
200.0	3.56	341.85
210.0	3.60	338.05
220.0	3.64	334.34
230.0	3.69	329.89
240.0	3.74	325.40
250.0	3.79	321.10
260.0	3.85	316.10
270.0	3.90	312.65
280.0	3.96	307.32
290.0	4.02	302.73
300.0	4.08	298.28
310.0	4.15	293.25
320.0	4.21	289.07
330.0	4.28	284.34

Table.11: Deflection & Stiffness Values For Different Span lengths In Bearing Arrangement 3

Span (mm)	Deflection (μm)	Stiffness (N/μm)
150.0	5.53	220.07
160.0	5.45	224.95
170.0	5.38	226.21
180.0	5.36	227.05
190.0	5.39	225.78
200.0	5.41	224.95
210.0	5.44	223.71
220.0	5.48	222.08
230.0	5.52	220.47
240.0	5.57	218.49
250.0	5.63	216.16
260.0	5.69	213.88
270.0	5.75	211.65
280.0	5.82	209.10
290.0	5.89	206.62
300.0	5.96	204.19
310.0	6.04	201.49
320.0	6.11	199.18
330.0	6.19	196.60

The optimum bearing span was found to be L = 166.9 mm, L = 173.72 mm and L = 180.55 mm Bearing arrangement 1, 2 and 3 respectively

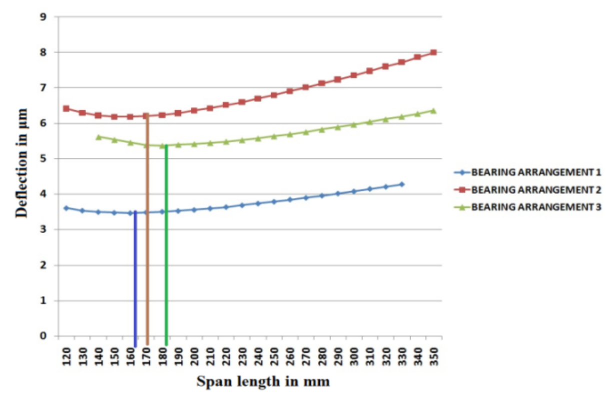


Figure 11: Variation of deflection with respect to span length

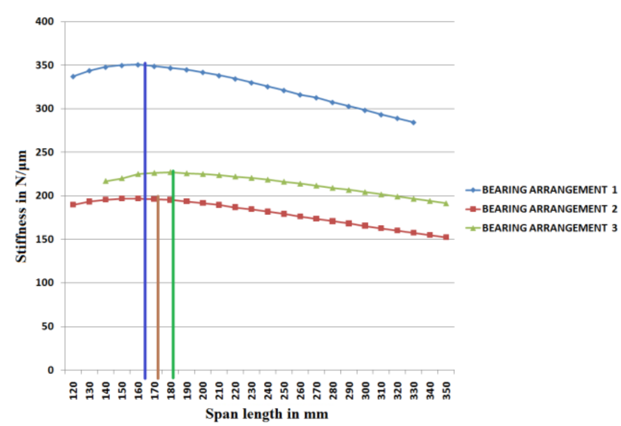


Figure 12: Variation of stiffness with respect to span length

Figure 11 to Figure 12 show the variation of deflection and stiffness with respect to span length respectively It is observed that the stiffness value increases as the span length increases and reaches a maximum value at the optimum span length.

4. Conclusions

The BT-40 CNC Milling spindle is designed to satisfy the required specifications. The design is optimized by proper selection of spindle components and simplifying the design of the spindle parts from the machining point of view. Three Bearing Arrangements with different bearings and preload configurations. are designed and spindle deflection is calculated theoretically and an optimum span length is determined by calculating deflections and Stiffness for varied span length. for three bearing arrangements

Bearing arrangement 1 with medium preloaded NSK bearings can be considered as optimized configuration. with optimum deflection of 4.01 μm, and Stiffness 303.49 N/μm.

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