Analysis of Bearing Arrangement for an Integrated Motor Milling Spindle

Umesh B S[1], Shankara Murthy A G[2]
[1]Asst. Professor, Department of Mechanical Engg, Bapuji Institute of Engineering& Technology
[2] Professor, Department of Mechanical Engg, Bapuji Institute of Engineering& Technology

***Abstract*— With the increasing demand for higher productivity and lower production costs, high speed machining tools have been widely utilized in the modern production facilities. High speed cutting is becoming more widely used and is possible by using a high speed motorized spindle, High speed motorized spindles are equipped with a built-in-motor, so that power transmission devices such as gears and belts are eliminated. 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 discuss about modelling of a motorized high speed milling spindle and optimization of the parameters influencing the stiffness of the high frequency milling spindle running at 14000 rpm with power rating 15 kW by designing three bearing arrangement.**

***Index Terms*—Integrated Motor spindle, Bearing Span, Deflection, Stiffness**

I. INTRODUCTION

The machine spindle system is one of the most important system of a machine tool since its dynamic properties directly affect the cutting ability of the machine tool. The dimensions of the spindle shaft, location, stiffness of the bearings and bearing preload affect the vibration free operation of the spindle. The bearing stiffness is dependent on the preload and is also affected by the deformation of the spindle shaft with the housing during machining. Angular contact ball bearings are most commonly used in most of the CNC machine spindle due to their low-friction properties and ability to withstand external loads in both axial and radial direction

II 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. To achieve high speed rotation, motorized spindles have been developed. This type of spindle is equipped with a built in motor as an integrating part of the spindle shaft, eliminating the need for conventional power transmission devices such as gears and belts. In general, a complete motor-spindle is comprised of the spindle shaft, including motor element, and tooling system. The spindle shaft is held in position by a set of high precision bearings. The bearings require a lubrication method, such as grease or oil. The spindle shaft then will rotate up to the maximum speed, and exhibit the power characteristics of the motor type that is used. The selection of a particular component will, of course, depend upon the requirements of the machine tool. Also, compromises must be made in order to provide the best combination of speed, power, stiffness and load capacity. Integral motor spindles utilize an electrical motor as part of the rotor shaft. Therefore, the motor size and capacity will depend strongly upon the available space. Hence, bearing size is critical in a high speed spindle design, so the motor shaft will affect the bearing size that can be used. The bearing size also affects the loading capability, stiffness, and maximum speed, so the motor characteristics must match the bearing capability.

This design reduces vibrations, decelerations. However, the high speed rotation and built in motor also introduce a large amounts of heat and rotating mass in to the system, requires precisely regulated cooling and lubrication.

Motorized milling spindles are widely used today in all mill centers for heavy duty milling. There are some specially designed motorized spindles, solely used for hard core milling while there are other motorized spindles used in all types of machine tool applications including milling, drilling etc. The use of motor driven milling spindles is convenient compared to the gear driven or belt driven spindles in most cases and they are highly recommended for maximum milling performance and flexibility. The maximum speeds offered by the motor ensure optimum and economical machining from the small to the large work piece. They are suitable for both rough cutting and precise finish cutting. The arrangement for high frequency milling spindle is as shown in Fig.1

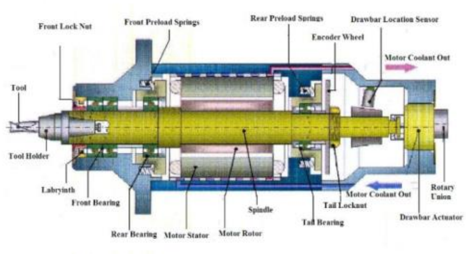

Fig.1: Motorized Milling Spindle.

II. 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 analyse 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..

III. 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

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A. Bearing arrangement -1

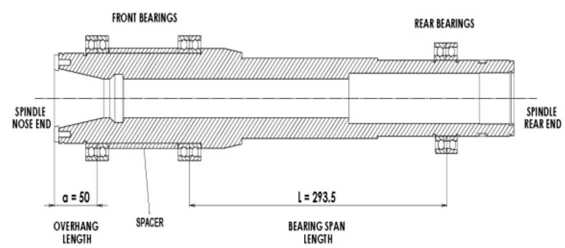


Fig.2: Bearing arrangement- 1

Fig.2 shows the bearing arrangement-1. In this arrangement there are 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. With this arrangement the bearings will be able to take loads from both directions. By using four bearings at the front better rigidity is provided with the proper preloading. The load applied at the spindle nose will be completely carried by the front set of bearings. The speed reduction of the bearings is less due to large bearing distance and hence 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.1

Table.1: Bearing Dimensions For Arrangement 1

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

B. Bearing arrangement -2

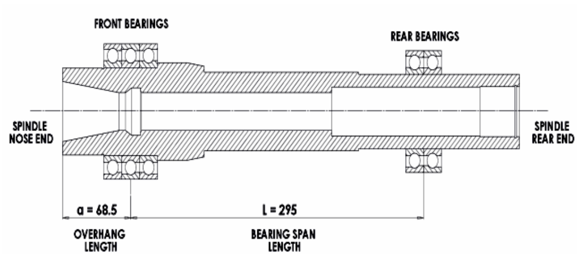


Fig.3: Bearing arrangement- 2

Fig.3.shows the bearing arrangement-2. In this arrangement 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 one pair of angular contact ball bearings are 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. However, axial loads can be carried in one direction and therefore the single angular contact bearing which has been arranged in a back-to-back fashion will oppose the tandem bearing set in-order to accommodate any axial loads in the reverse direction. 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.

C. Bearing arrangement -3

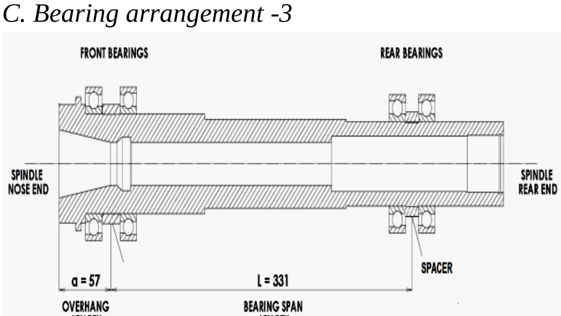


Fig 4: Bearing arrangement-3

Fig.4 shows bearing arrangement-3. In this arrangement 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-2

Table.2: Bearing Dimensions For Arrangement- 2&3

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

D. Determination Of Cutting Forces Acting On The Spindle Nose

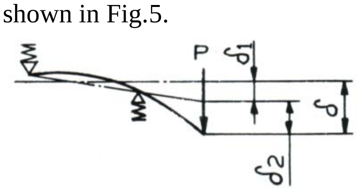
Theoretical cutting forces acting on the spindle nose for different machining process, are calculated by a standard procedure. The cutting data obtained from cutting force calculations is listed in Table.5

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

Table.3 Cutting Data

IV 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 Fig.5.



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

Fig.5. Spindle deflection diagram and Expression

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

A. Deflection obtained for Bearing arrangement 1

a = Length of overhang = 50 mm

L = Bearing span in mm = 293.5 mm

E= Young's modulus of Spindle material = 210000 N/mm^2

P = Radial force in N = 1217 N

S_A= Stiffness of the front bearing = 1248000 N/mm

S_B= Stiffness of the rear bearing = 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 δ = 4.019 × 10^{-3} = 4.019 µm

B. Deflection obtained for Bearing arrangement 2

a = Length of overhang = 68.5 mm

L = Bearing span = 295 mm

E= Young's modulus of Spindle material = 210000 N/mm^2

P = Radial force in N = 1217 N

S_A= Stiffness of the front bearing = 955400 N/mm

S_B= Stiffness of the rear bearing=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 δ = 7.21 × 10^{-3} mm = 7.21 µm

C. Deflection obtained for Bearing arrangement 3

a = Length of overhang = 57 mm

L = Bearing span in mm = 331 mm

E= Young's modulus of Spindle material = 210000 N/mm^2

P = Radial force in N = 1217 N

S_A= Stiffness of the front bearing = 702500 N/mm

S_B= Stiffness of the rear bearing = 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 δ = 6.12 × 10^{-3} mm = 6.12 µm.

D. 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.4 to Table .6.

	Light Preload	Medium Preload	Heavy Preload
Bearings	Deflection (µm)	Deflection (µm)	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.4: Deflections For Arrangement 1

	Light Preload	Medium Preload	Heavy Preload
Bearings	Deflection (µm)	Deflection (µm)	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.5: Deflections For Arrangement 2

	Light Preload	Medium Preload	Heavy Preload
Bearings	Deflection (µm)	Deflection (µm)	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

Table.6: Deflections For Arrangement 3

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.

E.Optimum bearing span length for three Bearing Arrangement

Optimum 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.7 to Table.9

Span (mm)	Deflection (µm)	Stiffness (N/µm)
150	3.48	349.71
160	3.47	350.53
170	3.49	348.71
180	3.51	346.72
190	3.53	344.75
200	3.56	341.85
210	3.60	338.05
220	3.64	334.34
230	3.69	329.89
240	3.74	325.40
250	3.79	321.10
260	3.85	316.10
270	3.90	312.65
280	3.96	307.32
290	4.02	302.73
300	4.08	298.28
310	4.15	293.25
320	4.21	289.07
330	4.28	284.34

Table.7: Deflection & Stiffness Values For Different Span lengths In Bearing Arrangement 1

Span (mm)	Deflection (µm)	Stiffness (N/µm)
150	3.48	349.71
160	3.47	350.53
170	3.49	348.71
180	3.51	346.72
190	3.53	344.75
200	3.56	341.85
210	3.60	338.05
220	3.64	334.34
230	3.69	329.89
240	3.74	325.40
250	3.79	321.10
260	3.85	316.10
270	3.90	312.65
280	3.96	307.32
290	4.02	302.73
300	4.08	298.28
310	4.15	293.25
320	4.21	289.07
330	4.28	284.34

Table.8: Deflection & Stiffness Values For Different Span lengths In Bearing Arrangement 2

Span (mm)	Deflection (µm)	Stiffness (N/µm)
150	5.53	220.07
160	5.45	224.95
170	5.38	226.21
180	5.36	227.05
190	5.39	225.78
200	5.41	224.95
210	5.44	223.71
220	5.48	222.08
230	5.52	220.47
240	5.57	218.49
250	5.63	216.16
260	5.69	213.88
270	5.75	211.65
280	5.82	209.10
290	5.89	206.62
300	5.96	204.19
310	6.04	201.49
320	6.11	199.18
330	6.19	196.60

Table.9: Deflection & Stiffness Values For Different Span lengths In Bearing Arrangement 3

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

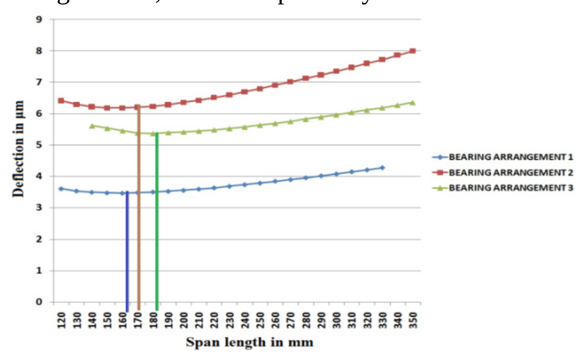


Fig-6 Variation of deflection with respect to span length

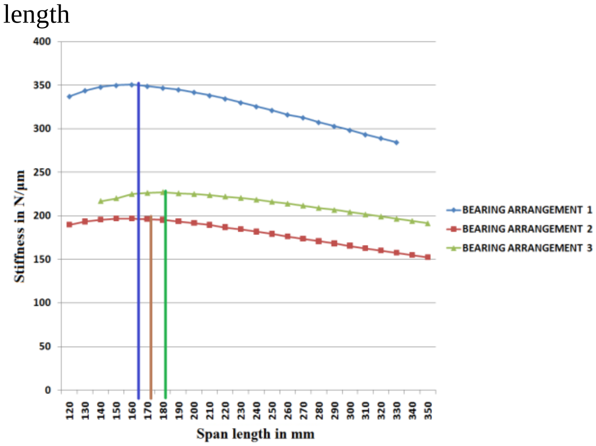


Fig-7 Variation of stiffness with respect to span length

It is observed that, the stiffness value increases as the span length increases and reaches a maximum value at the optimum span length.

V 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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