Study of Dynamic Characteristics and Design Analysis of Bush & Spindle of Ultra-Precision Aerostatic Bearing

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Abstract: ***Aerostatic bearings have been adapted to develop spindles called ultra precision aerostatic spindles. Since most of the ultra precision machines require precision class spindle with higher running accuracy, stiffness and good thermal stability. Aerostatic bearings are in greater demand. Aerostatic bearing gives high rotational accuracy, thermal stability, stiffness and high operating speeds, compared to other types of bearings. Ultra-precision machines require spindles with nanometer accuracy in rotation, moderate axial and radial stiffness, and moderate load carrying capacity. Later various concepts like active air bearings and passive air bearings and others were developed. Accompanying this, further high precision is demanded for spindles and spindle supporting bearings that are elements of machine tools. In the present work an attempt has been made to develop an aerostatic spindle for ultra-precision machine tool which overcomes the drawbacks present in anti-friction bearing spindle which were used in precision machine tools. As problems like wear, thermal errors, lubrication problems, bearing failure, etc, were encountered in anti-friction bearings there was a serious research in the field of precision engineering. Different types of aerostatic bearings are analyzed and the best one is selected for design and further development. Detailed design of axial grooved journal bearings is done and groove parameters are studied and optimized. Then the concept of using aerostatic bearings was developed and it received a huge response from all organizations and research centers.***

Keywords: Aerostatic bearings, Aerodynamic bearing, Bush, Spindle, Design Analysis.

1. Introduction

A bearing is a machine element which supports another moving machine element. It permits a relative motion between the contact surfaces of the members, while carrying the load. A little consideration will show that due to the relative motion between the contact surfaces, a certain amount of power is wasted in overcoming frictional resistance and if the rubbing surfaces are in direct contact, there will be rapid wear. In order to reduce frictional resistance and wear and in some cases to carry away the heat generated, a layer of fluid (known as lubricant) may be provided. The lubricant used to separate the journal and bearing is usually a mineral oil. In earlier times anti-friction bearings were used for the development of precision machine tools, because of the problems like wear, bearing failure and other various factors there was a serious research in the field of precision engineering. Then the concept of using air bearings or gas bearings was developed and it received a huge response from all organizations and research centers. Later various concepts were developed like active air bearings and passive air bearings, externally pressurized air bearings and others.

Ultra-precision machines require spindles with nanometer accuracy in rotation, moderate axial, radial stiffness, and moderate load carrying capacity. Aerostatic bearings have been adapted to develop this type of spindles called ultra-precision aerostatic spindles. Since most of the ultra-precision machines require precision class spindle with higher running accuracy, stiffness and good thermal stability, aerostatic bearings are in greater demand. Aerostatic bearing gives high rotational accuracy, thermal stability, stiffness and high operating speeds, compared to other types of bearings.

The Basic Principles of an Air Bearing Spindle

The basic principle of operation of air bearings has been established for more than fifty years. An air bearing may comprise of a sleeve separated from a plain shaft by gap, typically 5–50 μm. High pressure air is fed through small orifices in the sleeve through the bearing gap where it flows along the gap and out of the ends of the bearing. Orifice size is matched to the bearing size so that under no load the pressure in the gap, just downstream of the orifice, is approximately half the supply pressure. When a radial load is applied, the gap on one side of the shaft closes down increasing its resistance to and causing pressure to rise. On the opposite side of the shaft, the larger gap has reduced resistance to airflow and allows pressure to fall. The pressure difference across the bearing gives it the capacity to support the applied load without incurring any metal –metal contact even if there is no shaft rotation.

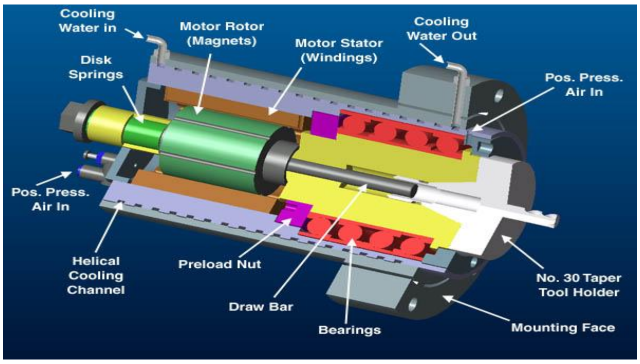

Figure 1: Cut section of an Air Bearing Spindle

Air Spindles

Air spindles employ two or more cylindrical journal bearings to support radial loads and an opposed pair of flat, annular thrust bearings to support axial loads. A practical design of air spindle also has an integral drive motor and means of work holding. In a typical spindle compressed air enters through a port on the rear face and is fed through drillings to reservoirs surrounding each journal bearing and reservoirs positioned either side of the thrust bearings. From the reservoirs, air is fed through rows of orifices into the bearing gaps. Exhaust air from the ends of the journal bearings, inner and outer edges of the thrust bearings is vented to atmosphere .Cooling water enters the spindle through a port on the rear face. From here it is typically ducted along the spindle where it flows through a reservoir surrounding the front bearing. The cooling water is then fed back along the spindle where it passes through a reservoir surrounding the rear journal bearing before exiting through a port on the spindle’s rear face.

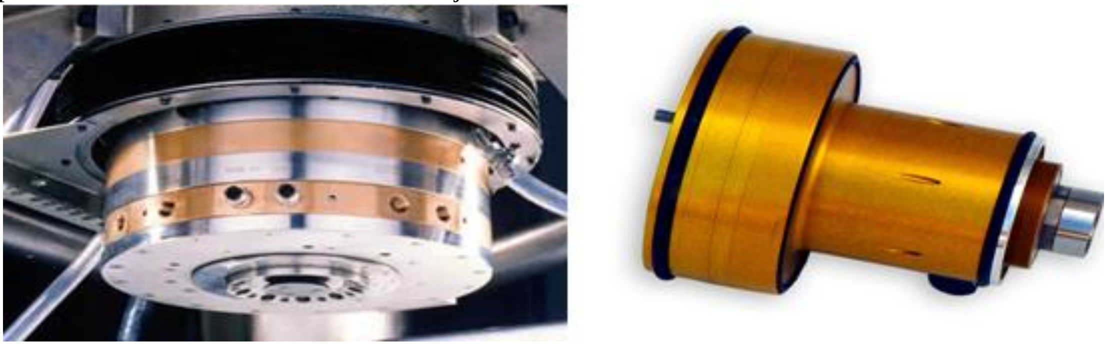

Figure 2: Aerostatic Spindles for ultra-precision machines

Figure 2a: Aerostatic Spindles for ultra-precision machines

2. Types of Air Bearing Technology

There are two basic types of precision bearings:

Aerostatic Bearing

Aerostatic bearings require an external pressurized air source. This air pressure is introduced between the bearing surfaces by precision holes, grooves, steps or porous compensation techniques. Because aerostatic bearings have a pressurized air source they can maintain an air gap in the absence of relative motion between the bearing surfaces. Air bearings offer a solution for many high-tech applications where high-performance and high accuracy is required. Aerostatic bearings require an external

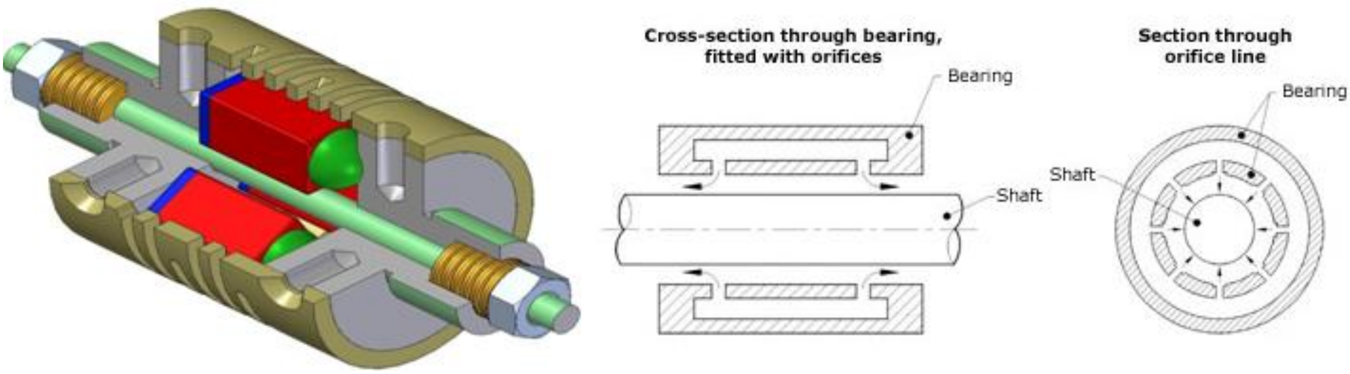

Figure 3: Aerostatic bearing

Pressurized air source due to which aerostatic bearings are also known as passive air bearings. High stiffness can be achieved. The aerostatic bearing is able to support higher load than the aerodynamic bearing, but it requires continuous power supply for supplying pressurized air. Overall, aerostatic bearings perform well in most aspects such as having long life, noise-free operations and are free from contamination Since air has a very low viscosity, the bearing gaps need to be small, of the order of 1- 10 μm. As the object floats on a thin layer of air, the friction is extremely small and even zero when stationary.

Aerodynamic bearing
Aerodynamic bearings depend on relative motion between the bearing surfaces and usually some type of spiral grooves to draw the air between the bearing lands. This bearing action is very similar to hydroplaning in our automobile on a puddle of water at high speed. At a lower speed our tire would cut through the water to the road. In just this way, aerodynamic bearings require relative motion between the surfaces, when there is no motion or when the motion is not fast enough to generate the air film the bearing surfaces will come into contact. Aerodynamic bearings are often referred to as foil bearings or self-acting bearings. Examples of this type of bearing include the read-write head flying over a spinning disk, crankshaft journals, camshaft journals, and thrust bearings for electrical generator turbines.

3. Classification of Aerostatic Bearing

There are five basic types of aerostatic bearing geometries as follows: single pad, opposed pad journal, rotary thrust and conical journal or thrust bearings.
It can be classified again as follows:
- Journals—basically cylindrical surfaces
- Thrust bearings—circular or annular flat surfaces which are designed for rotation
- Slider bearings—flat surfaces of any boundary shape which are designed for obtaining a sliding motion
- Spherical bearings

4. Principle of Aerostatic Bearing

Figure. 4 shows that, how gas at a supply pressure, Ps is admitted into the clearance through a restricting device, which reduces the supply pressure. The pressure drop is due to the acceleration of the gas as it expands. The air will flow through the bearing and back to the atmosphere where the pressure further reduces to atmospheric pressure, Pa. A smaller clearance will reduce the pressure drop that gives a higher load capacity. It is desirable to achieve an optimum condition at which a maximum stiffness occurs where the rate of change of load when divided by the rate of change of clearance is a maximum.

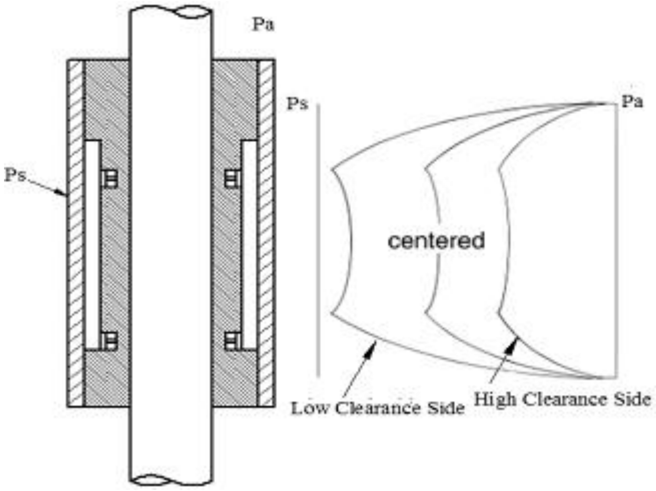

Figure 4: Principles of Aerostatic Bearings

5. Advantages of Air Bearing Spindle

As compared to other types of spindle, air spindles have a number of performance advantages:-
- **High Rotational Accuracy** – Bearing air films average any surface features to a low level enabling error motions of less than 0.05 µm TIR to be achieved.
- **Cleanliness** – Not requiring any liquid lubricants air spindles are suitable for use in clean rooms.
- **Ease of Maintenance** – Air spindles do not require servicing. Air supplies must however be maintained. Bearings and low vibration, air spindles use in machining applications can produce
- **High Dimensional Stabilit**y – Low bearing friction and water cooling enables negligible thermal growth to be achieved.
- **High Speeds** – Again low bearing friction and the use of water cooling allow bearings to operate at extremely high surface speeds.
- **High Stiffness** - The small clearances inherent to air bearings enables them to be designed with high static stiffness. Air bearings also enable large shaft diameters to be used which enhances the stiffness of spindle assemblies.
- **Improved Surface Finish** – Due to the inherently high accuracy of rotation of air
- **Increased Bearing Life** – The absence of metal-metal contact ensures an unlimited bearing life provided the air supply is maintained clean and free from oil and water.
- **Low Vibration** – All air spindles are balanced to better than 0.001 gm cm.

6. Disadvantages of Air Bearings Spindle

The rest of the disadvantages are listed below:
- The surfaces must have an extremely fine finish.
- The stability characteristics are poor
- The speed must be high.
- The loading must be low.
- The design is more empirical since the flow relationships are almost impossible to solve.
- The alignment must be extremely good.
- More power is required to pressurize a compressible fluid.
- Dimensions and clearances must be extremely accurate.
- Careful filtering is required to avoid scoring and binding...
- Careful designing is required to avoid vibration due to compressibility of the fluid.
- A very small film thickness is required to confine the fluid flow to reasonable values, thus requiring very precise machining in manufacturing.

7. Air Bearing Applications

Air Bearings are used in a variety of applications including: Coordinate Measuring Machines, Precision Machine Tools, Semiconductor Wafer Processing, Medical Machines, Optical Lens Production Equipment, Digital Printers, Lithography Precision Gauging, Diamond Turning Machines, Materials Testing Machines, Crystal Pulling, Rotary Tables, Spindles, and Friction Testing. New Way air bearings offer distinct advantages for different industries and markets as outlined below.

8. Material Selection

In aerostatic spindle it is important to select carefully the materials used for the shaft, bearing and restrictors. The following considerations should always be considered for the material selection.

- Corrosion resistance
- Mach inability
- Material stability
- Thermal conductivity
- Thermal expansion

For the bearing bush material, lead bronze is best suited. Lead bronze is corrosion resistant, can be easily machined and easily soldered or brazed so that the pressure tight fixing of the numerous feed jets is a relatively simple procedure. They are readily suited for use in combination with austenitic stainless steel body material. The coefficients of thermal expansion are well matched theory avoiding thermal stress problems and the electrochemical potentials are identical so that no electro-chemical corrosion can occur. In the process of analytical calculations three assumptions are made:

1. The film thickness h0 is uniform over the bearing element
2. A one dimensional axial flow is assumed
3. The pressure drops in axial direction.

9. Materials of the Air Bearing Spindle

The blank for a machine tools spindle may be:

1. Rolled stock in the case of spindles having diameter < 150 mm.
2. Casting in the case of spindles having diameter > 150 mm

It should be kept in mind that if the spindle blank is cut from rolled stock, the cutting must be done by cutting tools to avoid additional distortion of the material microstructure. In machine tools spindle design the critical design parameter is not strength but stiffness. If we compare the mechanical properties of various steels, then their modulus of elasticity should be more or less equal, although the strength of the alloyed steels can be considerably greater than of mild steel. Since stiffness is primarily determined by the modulus of elasticity of the material, it may be concluded that no particular benefit accrues from using costly alloyed steels are required to make spindles.

10. X Scope, Objectives and Methodology

Scope

In earlier times anti-friction bearings were used for the development of precision Machine tools, because of the problems like wear, bearing failure and other various factors there was a serious research in the field of precision engineering. Then the concept of using air bearings or gas bearings was developed and it received a huge response from all organizations and research centers. Later various concepts were developed like active air bearings and passive air bearings, externally pressurized air bearings and others.

Objectives

The main objectives of the present study are:-

1) To come up with a design of an aerostatic spindle capable of having Load carrying capacity > 500 N.
2) To come out with the design in which the spindle is running at a speed range of 30-10,000 rpm.
3) To come up with a design of an aerostatic spindle capable of having a radial stiffness of greater than 90N/μm and axial stiffness of greater than 200N/μm.

Methodology

The methodology adopted during the process of design is given below:

- Analysis is carried out on various components by using FEA Package ANSYS.
- The detail design was carried out on the selected type of aerostatic bearing.
- Various types of aerostatic bearings with different types of restrictors are studied and the type which best satisfies from the point of performance of the spindle and manufacturability is selected.

11. Results and Discussions

Analysis of Bearing Bush:

The analysis of the bearing bush has been carried out and the below figure shows the various results like radial stress, hoop stress and shear stress induced in the long cylinder subjected to an internal pressure of 0.8 N/mm2 and the radial stress is maximum0.699851N/mm2 at inner diameter and minimum 0.632E-4 N/mm2 maximum shear stress is 0.1669E-10N/mm2 and maximum deflection is 0.001487mm or 1.487μm which is allowable deflection to maintain the accuracy of the spindle since the bearings are designed for the radial stiffness more than 90N/μm.

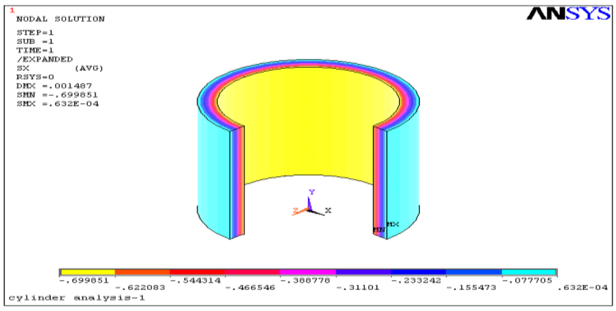

Figure 5a: Radial Stress Plot

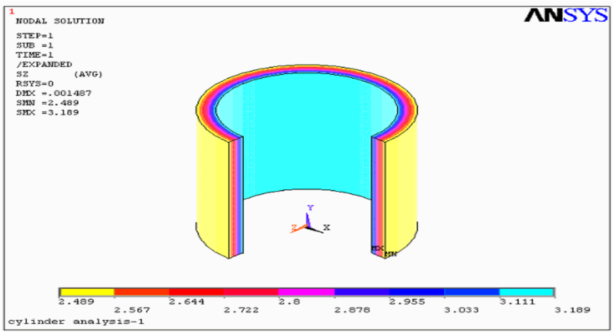

Figure 5b: Hoop stress plot

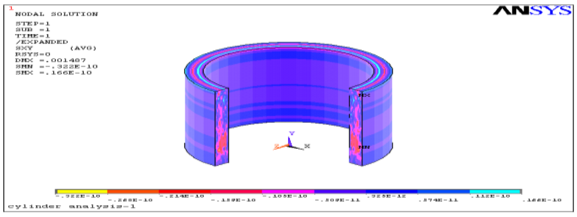

Figure 5c: Shear Stress Plot in xy Direction

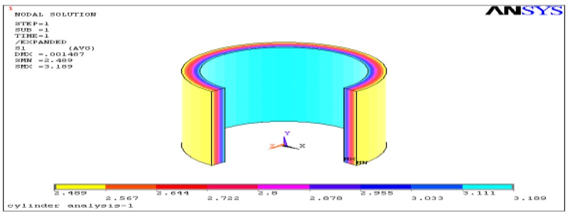

Figure 5d: Principal Stress

Static Analysis of Spindle

From the FEA result, it shows that the shear stresses are well within the permissible limits and the deformation is 0.219nm, the deflection obtained in analytical method is 2.896E-8mm. Thus the designed spindle shaft can be used for precision machine applications.

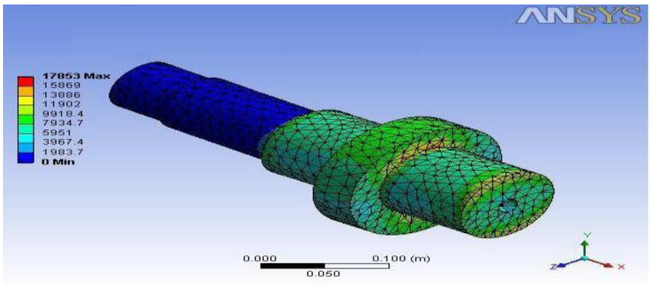

Figure 6a: Maximum Shear Stress Distribution

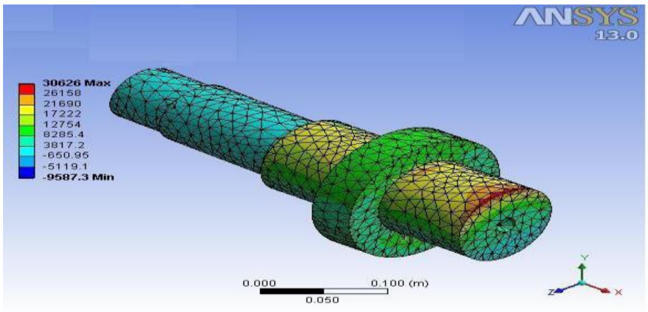

Figure 6b: Maximum Principal Stress Distribution along the Length of the Shaft

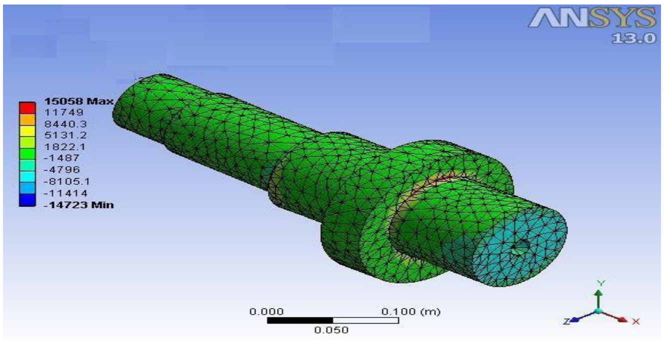

Figure 6c: Shear Stress Distribution

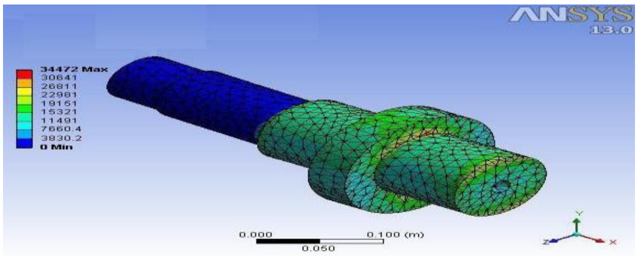

Figure 6d: Von-Mises Stress Distribution

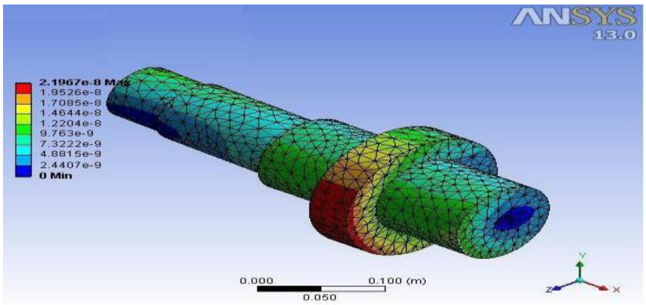

Figure 6e: Total Deformation in the Shaft

The objective of this project is to come up with a design of an air bearing spindle having radial stiffness greater than 90N/μm and axial stiffness greater than 200N/μm so that spindle can be used for the ultra precision turning or grinding machine. The design process included different steps. Methodology adopted in this project work included selection of inlet restrictor according to our required bearing stiffness and flow considerations.

Table 1: Optimized Values of the Aerostatic Bearings

Sr. No.	Bearing Parameter	
1	Supply Pressure ratio	0.5- 0.7
2	Groove dimensions 1.Width ratio(B') 2.Depth ratio(n) 3.Length ratio(L')	 0.26 3.5 0.9
3	Number of grooves(k)	13
4	Radial Clearance(Cr)	8 μm
5	Load Carrying Capacity (F)	523 N
6	Stiffness(K)	117 N/μm

12. Conclusions

Following conclusions can be drawn on completion of the current work:

- The analysis on the spindle and bush revealed the stresses developed and the deformation. The load acting on the shaft and bush are well within the acceptable limits.
- The analysis was carried out on aerostatic bearings with even number of from 2 to 20. The analysis reveals that the load carrying capacity varies having grooves from 2 to 6. In bearings with number of grooves above6the load carrying capacity is constant.
- The developed air bearing spindle is having radial stiffness greater than 90N/μm and axial stiffness greater than 200N/μm so that spindle can be recommended for use in the ultra-precision turning or grinding machine.
- Turbulence which causes instability in the system is overcome by providing grooves on the bearing surfaces.

13. Scope for Future Work

A future work on this project has been identified and can be summarized as follows:

1) The aerostatic spindle designed will operate at speed range of 30-10000 rpm; designing a spindle for still more speed range up to 60000 rpm and still higher values of stiffness and load carrying capacity for high speed machine applications can be taken as future work.
2) The effect of number of grooves after 6 numbers on load carrying capacity was found to less, hence designing a bearing with 6 or 8 numbers of grooves and testing the performance and also analyzing the spindle for thermal effect. This part can be considered for optimization of the spindle so that the cost of manufacturing the spindle and accuracy is increased.

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