CRANFIELD UNIVERSITY

AROOP KUMAR SEN

ULTRA PRECISION AIR BEARING DEVELOPMENT FOR LOW COST MANUFACTURING

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING

M Res. In Manufacturing

Master in Research(M.Res.)

Academic Year: 2016 - 2018

Supervisor: Dr. Saurav Goel

Dr. Claudiu Giusca

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This thesis is submitted in partial fulfilment of the requirements for the degree of M.Res. in Manufacturing

ABSTRACT

Air bearings today are extensively used in the industry, the manufacturing processes involved in fabricating these bearings are complicated and have major drawbacks. The current research investigates the failure of aerostatic bearings based upon which a manufacturing process is developed which removes the correlation between the bearing surface and the effective gap between these surfaces. This results in low manufacturing errors due to the omission of repeated machining of the bearing surface.

The second factor that is novelty towards this research is the application of aluminium coated with hard nickel as suitable alternative to bearing base material instead to the current material for aerostatic bearings. This proposed material solution has low density, good wear resistance and good corrosion resistance. This allows the application of diamond turning instead of precision grinding as the bearing machining process. Reducing on majority of the manufacturing while achieving the form accuracy of the bearing surface.

The third novelty factor is the application of bi-conic configuration which would allow self-aligning capability and has a smaller packaging size as compared to any other fluid film mechanical configuration.

ACKNOWLEDGEMENTS

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Many thanks to my supervisors Dr. Saurav Goel and Dr. Claudiu Giusca

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$F \rightarrow$ Minimum force required for sliding motion between the bearing surfaces

$A \rightarrow$ Bearing Surface Area

$\nu \rightarrow$ Velocity of Fluid

$H \rightarrow$ Fluid Film Thickness

$\varpi \rightarrow$ Angular Velocity of the Bearing

$\mu \rightarrow$ Coefficient of Viscosity of Fluid

$R \rightarrow$ Outer Radius of the Bearing

$r \rightarrow$ Inner Radius of the Bearing

$L \rightarrow$ Length of the Bearing

$T \rightarrow$ Torque of the Bearing

$\delta_1 \rightarrow$ Increase in Diameter of a Hollow Shaft

$E \rightarrow$ Young's Modulus of Shaft

$\rho \rightarrow$ Density of Materials

$t \rightarrow$ Shaft Wall Thickness

$D \rightarrow$ Normal journal diameter

$K \rightarrow$ Radial Stiffness of Journal Bearing

$h_o \rightarrow$ Effective Bearing Gap

$W \rightarrow$ Bearing Load

$P_0 \rightarrow$ Supply Pressure

$P_a \rightarrow$ Atmospheric Pressure

$P_1 \rightarrow$ Pressure in Region 1

$P_2 \rightarrow$ Pressure in Region 2

$P_3 \rightarrow$ Pressure in Region 3

$K_1 \rightarrow$ Ratio of flow between Inlet and Outlet

$K_2 \rightarrow$ Ratio of width of the groove to the width of the rib of the bearing

$K_3 \rightarrow$ Ratio of the volume liquid flow between groove and rib of the bearing

1 Introduction

Air bearings use air as medium of fluid between two bearing surfaces. While using air as a fluid seems inexpensive as a process yet the manufacturing of a single high precision air bearing requires high amount of process control, long production hours and huge complexity towards design of an aerostatic bearing. While the result of this prolonged process seems suitable, yet the operations of these bearings isn't as smooth as its counter parts like hydrostatic, roller element bearings, etc. Simplification of the manufacturing process would allow broader application of these bearings and would help in understanding the behaviour of these bearings in different manufacturing environments.

There are researches for example by Xiao Hang et. Al. which has investigated better manufacturing techniques for aerostatic bearings studies the application of these bearing in high speed precision micro spindles [1]. The research by Chen at.al which discusses greatly towards the variation in the performance of an aerostatic journal bearing due to the geometric variation of the bearing surface [2]. The simpler methodology towards aerostatic bearing manufacturing is yet to be discovered. There are major drawbacks in the current manufacturing process of these aerostatic bearings. Some of these key issues have been mentioned below:

- Corrosion of bearing surface
- The limitation towards the packaging size of these bearing
- And the correlation between form accuracy and gap generation of the between the bearing.

This research primarily investigates the current drawbacks and performance requirements towards the manufacturing of aerostatic bearing and then fulfilling these requirements through modification of design and economical manufacturing techniques.

1.1 Aim

Developing an ultra-precision air bearing considering low cost manufacturing/ fabrication techniques. To fulfil the aim of this research certain objectives have been drawn upon:

1. Analysis of failure of fluid film bearing (Formulation)
2. Design development of Ultra precision aerostatic bearing design based upon failure analysis. (Proposed Design Specification)
3. Developing a low-cost fabrication process for Ultra Precision aerostatic bearing. (Process Development)

1.2 Structure

To achieve the above-mentioned objective, the report has been broken into 6 sections.

In the first section a brief introduction towards the research has been presented including the novelty towards this research. The Aims and Objectives are established based upon the knowledge gaps in the current research of aerostatic bearings.

In the second section the literature review covers the previous research and literature in the manufacturing and design of aerostatic bearings. It discusses the differentiation of both types of fluid film bearings and how the performance of an aerostatic bearing differentiates from other hydrostatic bearings. It further discusses the different mechanical configurations that are applied in aerostatic bearings. Lastly it covers the metrological concepts and manufacturing processes applied in the fabrication of these bearing including the materials that are commonly used for hydrostatic and aerostatic bearings.

The third section of the report investigates the methodology of the research and analysis of the current aerostatic bearing failures and performance requirement. Which creates a pathway or a research map for the future research in these bearing systems.

The fourth section analysis the current drawbacks and performance requirements of these aerostatic bearings. And proposes a suitable detailed solution from the design and manufacturing perspective of the bearing.

The fifth section cover the result and discussions which looks towards the requirements and proposed solution for these bearing configurations.

The sixth section of this research covers the future work that could be performed to further improve and simplify the manufacturing process.

2 Literature Review

2.1 Fluid Film Bearing Systems

Over the years fluid film bearings are used extensively in the industry. They are applied across numerous fields which includes machine tools, hard disk drives, turbine, rotor dynamics, etc [3]. With the research performed by Zhang et.al. [4] And Xiao et.al. [1]. There is considerable amount of research towards the performance of these fluid film bearings that is still needed to be explored. To further understand these bearing systems, they would be required to be studied in detail by expanding the application of these bearing which is possible through simplification of the manufacturing techniques involved towards the development of fluid film bearings [5]. Before this research jumps into detail it is suitable to study about the physical characteristics of these bearings.

In fluid film bearings the opposing or the mating bearing surfaces are completely separated by a layer of fluid or gaseous lubricant [6]. The viscosity of the fluid film is the most significant characteristic in case of fluid-film bearings. As an advantage, it controls or limits the exit flow from the bearing and as a disadvantage, the lubricant shear causes consumption of power in the bearing [6]. Fluid film bearing systems are categorized based on the source of pressure generation between the bearing surfaces. Externally pressurized bearing is called hydrostatic in liquids and Aerostatic in gaseous fluid film bearing systems, whereas internally pressurized or self-acting bearings called hydrodynamic in liquids and aerodynamic in air bearing system [3]. This study would be exclusively discussing about aerostatic bearing system. While in case of externally pressurized fluid film bearings, they are further categorized by constant supply pressure system and constant flow system. Constant supply pressure system can be applied to both hydrostatic and aerostatic bearings and in this case the flow of the liquid or air is restricted so that the pressure developed between the bearing systems over a period is constant. In case of constant flow system, the flow of fluid is kept constant between the bearing surfaces without restricting the flow of the fluid, hence it can only be applied to hydrostatic bearing system as compared to aerostatic bearing system [7].

The rate of change of film thickness with increase of the load on a fluid film bearing is referred to as the stiffness of the bearing. In the case of fluid film bearings to be statically stable, it is necessary that the pressure in the fluid film between the bearing surfaces increases as the bearing clearance is reduced i.e. the gap between bearing surface is inversely proportional to the working pressure of these fluid film. An analogy to this fact could be that the force that is required to compress spring increases as the spring is compressed [8].

2.1 Comparison between Liquid and Air Film Bearing System

Fluid film bearing system performance greatly depends on the viscosity of the fluid used. There are two major characterization of fluid film bearing system based on the viscosity of the different fluid. Liquid or hydrostatic bearing system and gaseous or aerostatic bearing system. Below are some of the most important physical aspects of these systems concerned to fluid film bearing study.

1. The compressibility of liquid with respect to gas can be considered next to negligible.
2. Liquids have higher viscosities as compared to gas.
3. The behaviour of viscosity of both the fluid system with respect to temperature is opposite that is with rise in temperature the viscosity of the liquid decreases whereas that of gas increases.
4. Due to the compressibility of gas more energy is spent in raising a given volume of gas to a certain pressure, as compared to raising the same volume of liquid to the same pressure.
5. Because of the above-mentioned point and the reduced volume when compressed, a certain volume of gas at high pressure contains more energy as compared to the same volume of liquid at similar pressure.
6. Much of the energy spent in compression of gas is spent in raising the temperature [7].

Table 1 below covers a general summary towards both bearing platforms.

	Liquid (Oil, Water)	Gas (Air, Nitrogen)
Type	Capillary, orifice, slot or diaphragm restricted	Porous, orifice, or slot restricted
Typical applications	Large machining forces (Milling machines, etc.)	Moderate forces (Measuring equipment, grinding spindles, diamond turning)
Load capacity	Very high	Moderate
Stiffness	Very high	High
Damping	Very high	Moderate
Friction	Low at low speeds	Very low at all speeds

Table 1 Comparison Liquid and Gas Bearing

The coefficient of viscosity of fluid is given by

$$\mu = Fh/A\nu \qquad \textbf{(1)}$$

Where ***F*** is, the minimum force required for sliding motion between the bearing surfaces ***A*** with velocity ν separated by a fluid film of thickness ***h.*** Where ***F/A*** is viscous stress and ν/h is the viscous gradient of the film. To get a similar equation for torque for journal and thrust bearing systems the angular velocity ω rad/sec, for journal bearing system could be written as:

$$\mathbf{T = 2\pi\mu\omega R3L/h}$$

(2)

And in case of thrust bearing could be written as:

$$\mathbf{T = \pi\mu\omega(R^3 - r^4)/2h}$$

(3)

[8]

The lower viscosity of air results in lower frictional resistance as compared to hydrostatic bearings and can rotate at very high rotational speed without developing neither excessive drag torque nor rise in temperature.

While going into the detail of these bearings, the research would be focussed towards externally pressurized bearings. Both the hydrostatic and aerostatic bearings have their own advantages and disadvantages. Which makes them suitable certain distinctive applications. The performance specification had been drawn in earlier researches testing all different types of bearing under similar parameters.

In this study for fluid film bearings we would be comparing the performance of hydrostatic and aerostatic bearing systems. As the current research studies, the constraints of manufacturing for these two types of systems. Below is graph giving an overview into different bearing load capacities with respect to the frequency of rotation. The sample that has been chosen for testing for generation of this graph is of diameter of 2inch and the length of 2 inch except in the case of roller bearing which is smaller in size. The mineral oil used in the hydrodynamic bearing is assumed to be medium viscosity. It is based on the I.Mech.E. Data sheet No. 65007 [9].

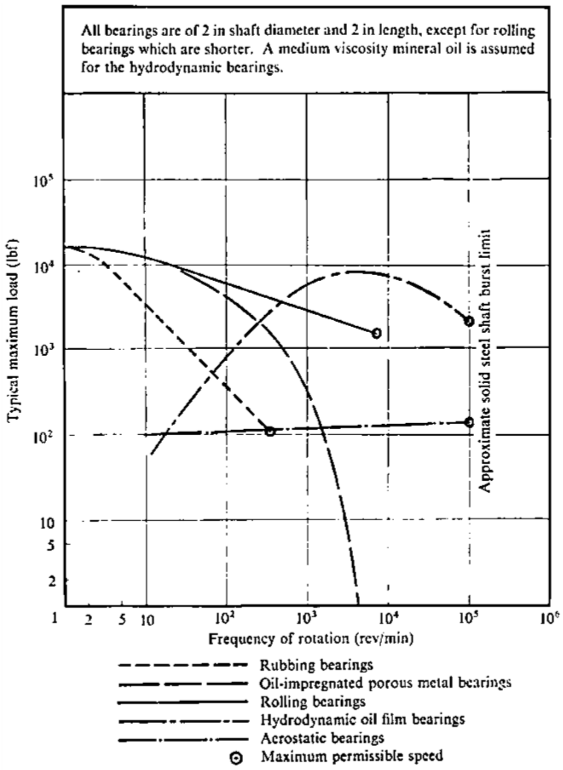


Figure 2 General comparison of bearing types [9]

Certain observations about hydrostatic and aerostatic bearing system could be drawn out from the graph mentioned above:

- Hydrostatic bearings system can carry more load than an aerostatic bearing at speeds of 300 rev/min and 1500 rev/min respectively.
- As the frequency of revolution is increased the air bearing system slightly increase or maintain the same load capacity whereas in case of hydrostatic bearing the load capacity drops drastically due to the shear of the fluid film.

2.2 Mechanical Configuration in Aerostatic Bearing System

These sliding fluid film bearings (aerostatic bearings) are of different mechanical design configurations which as stated below Figure 1

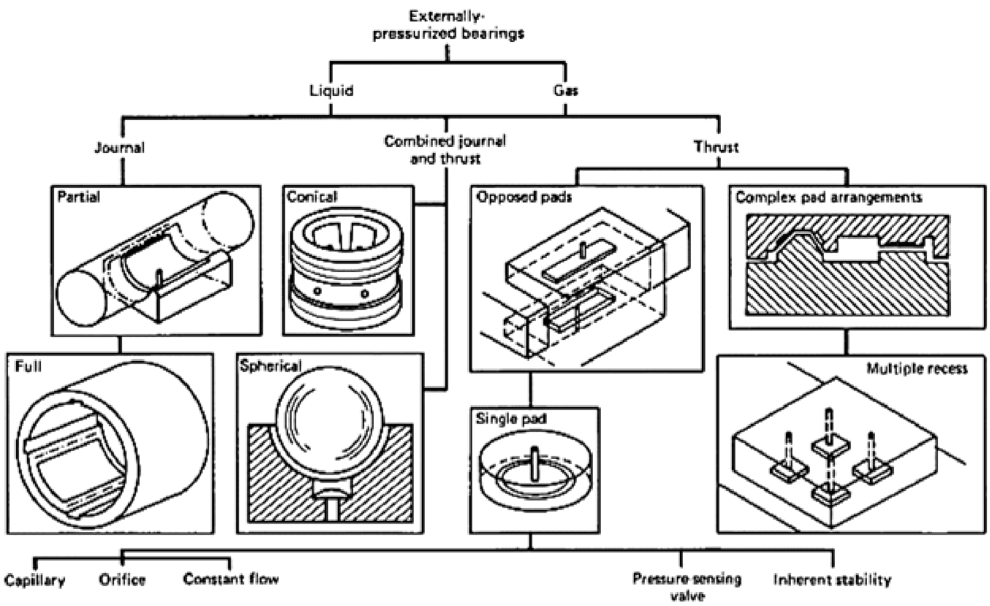


Figure 1 Types of configurations of fluid film bearing systems

Most of these bearing configurations are named after the geometrical shape of the fluid film. The selection of the bearing configurations is based upon the type the forces being experienced by the bearing. Hence radial, Thrust and combination (radial and axial) are developed and focus separate areas of application.

Every one of these configurations are universe in themselves and to stream line this research we would primarily be focusing towards Radial and journal Combination configurations, which could be modified into their standalone version of journal or thrust bearings. There are three basic configurations that could be used if a combination of both configurations (radial or thrust) is required. These configurations are:

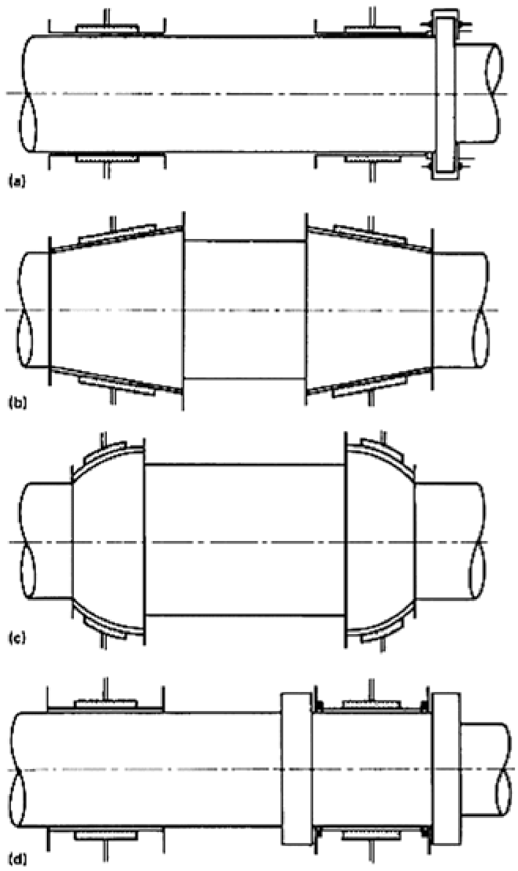


Figure 2 Combination Bearing Configurations [5]

A. Cylindrical Journal with Opposed Thrust
B. Conical Journal
C. Partial Spherical Bearings
D. Yates Bearings

In case of Configurations A and D, both bearings use both the radial and journal bearings to provide axial and radial load capacities. The load capacities in radial direction are calculated by studying the radial bearing surface of the fluid film. Similarly, the thrust capacities are studied by calculating the bearing surface in the direction of thrust. Since these bearings are designed to handle radial and axial forces, this configuration has very low tilt stiffness [10].

The complexity towards these configurations increases with the Configurations B and C. Which also has combination of radial and thrust load capacities as compared to other configurations but requires much smaller packaging size and lower flow rates [11].

The spherical bearings require high amount of the manufacturing precision. As the form accuracy which is required in these bearing is higher as compared to other configurations. The major advantage towards these bearings is that the fluid film is able to achieve more area of contact and as the fluid film thickness is dependent upon the average of the gap size along the bearing surface, hence these bearings are capable of achieving better stability and stiffness as compared to Configuration A and D [12].

The conical bearings are one of the simpler and less explored areas of the air bearing configurations. The reason behind the gap in the development of these bearing configuration in the practical application is due to the manufacturing complexity to achieve the form accuracy on the bearing surface. But with the current manufacturing techniques these bearings have started to become one of the most optimal solution towards combination bearings.

2.2.1.1 Bi-conical aerostatic Bearings

In this bearing configuration, the bearing surface is conical which allows the bearing to be capable of handling radial and axial load capacities. This bi-conic design configuration has been around for quite long period but substantial amount of research into these bearing configuration is still required. The bi-conic bearing has been discussed earlier by Stansfield where he discusses in brief about different bi-conic bearing configurations and their capabilities [13]. Rowe discusses in detail about flow in conical bearings with respect to capillary or orifice restrictors [5].

A bi-conic configuration based aerostatic bearings have earlier been developed by an American organisation P.I. Instruments. Which uses steel as the base material and the grinding as the finishing process to achieve the required form geometry [14]. These bearings are designed in similar package sizes as the block head design as they wanted it to be a suitable replacement from the combination radial journal bearings which is the design of their block head bearings.

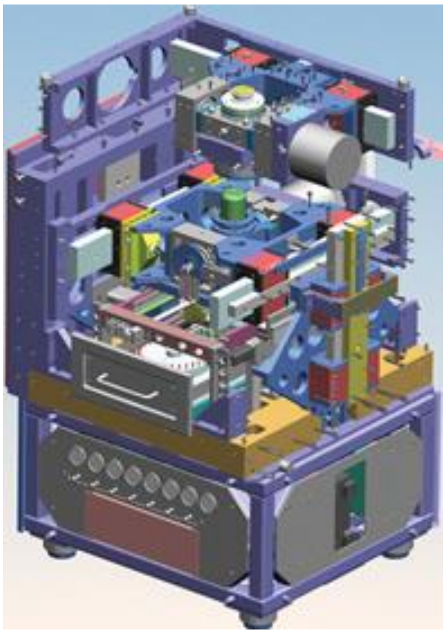


Figure 4 Loxham Precision Micro 4 [15]

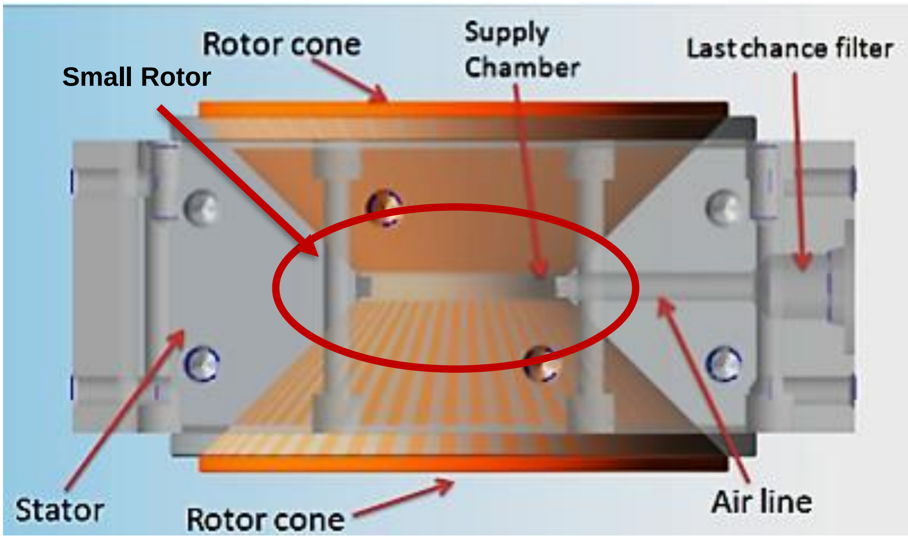


Figure 5 CAD Model Bi-Conic Air Bearings [12]

These bearing were used by Loxham Precision in Cranfield University in µ4 machine which is a meso scale six axis diamond turning and micro milling platform.

These bearing are self-compensated, i.e. they compensate for uneven fluid film thickness which could arise from geometrical form errors between the rotor and the housing. To select the between the families of combination and bi-conic bearings configuration, we investigate studies which have performed earlier in similar area of research.

Comparison between the Combination (Radial and Axial) Bearings vs Conical Bearing Design

In Stansfield's work the advantages of using bi-conic bearings in place of combination bearings have been discussed. He studies this by creating bearings with similar specification in both configurations, which can be seen in Figure and Figure .

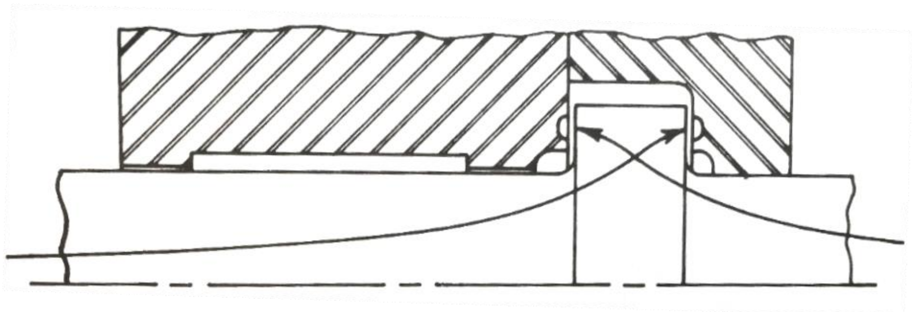


Figure 6 Radial and Journal Combination bearing [13]

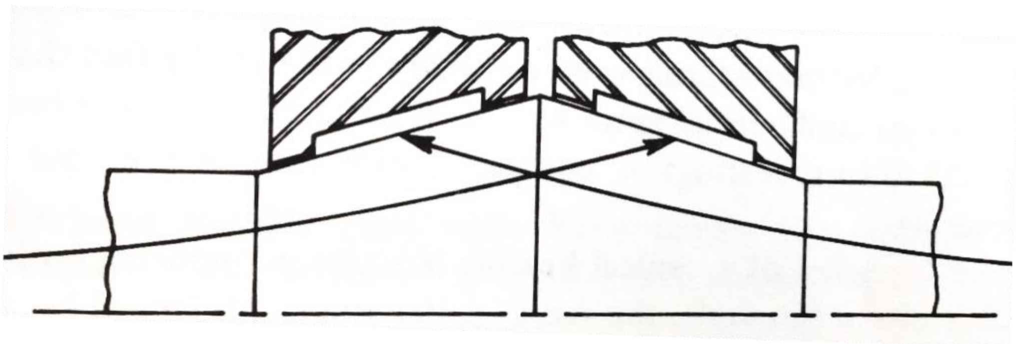


Figure 7 Bi-Conic Configuration [13]

The radial and journal load capacities are similar of both the bearing configurations, and certain study could be interpreted out of this:

a. The space required by the bi-conic bearing is less as compared to the combination bearings
b. There would be less loses on the shaft power in the bearing as the bionic requires fewer lands area to function
c. With lesser area in function, the machining required on the surface is less
d. The bi-conical bearings are much stiffer as compared to combinations bearings as the radial and axial bearings are integrated into one bearing surface.

Taking this study into consideration, bi-conic bearings outperform the combination bearings. There are different types of bi-conic configurations. These are five most common bi-conic configurations:

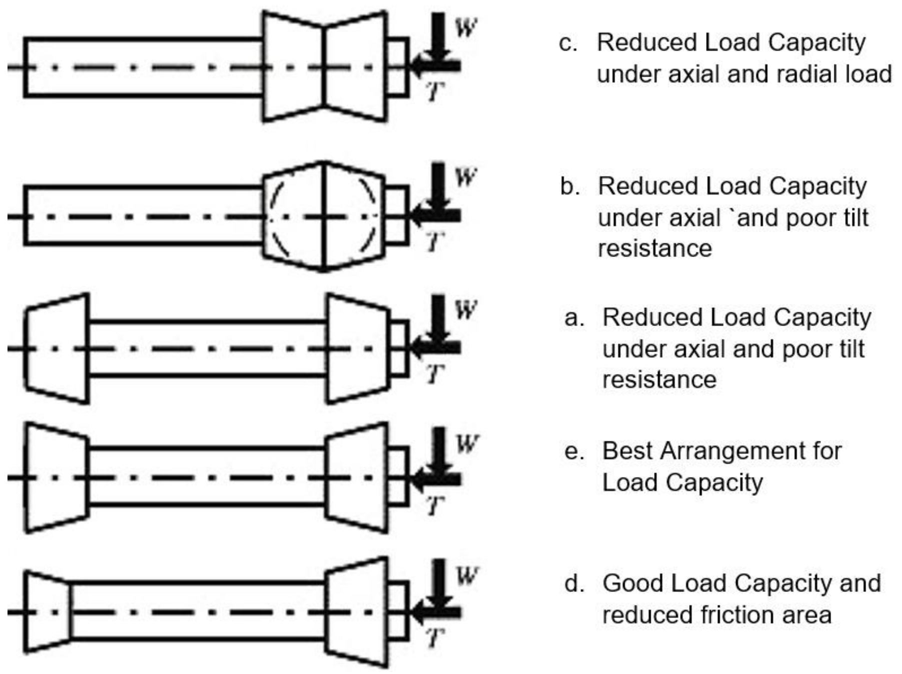


Figure 3 Bi-Conic Bearing Configurations [3]

The configurations above discuss in brief the performance of these bearings. But the application of these configurations would shed more detail into their actual performance. In the current research only, configuration E from Figure 3 has been worked upon due to its high tilt stiffness capabilities. Yet these bearing have their own drawbacks. Factors like thermal expansion, manufacturing simplicity, etc. have not been considered into this study.

2.3 Restrictor and Compensation Designs in Air Bearings

Restrictor and compensation mechanism is required in aerostatic bearings to maintain uniform pressure across the bearing surfaces. In a normal fluid flow the pressure of the fluid drop as it moves away from the point of inlet. The restrictors depending upon inlet or outlet are responsible for restricting the flow to the bearing surface and is responsible for the inlet/ outlet stiffness of the bearing. The drawback towards these restrictor is the restricted flow which in turn restricts the load capacity of the bearing.

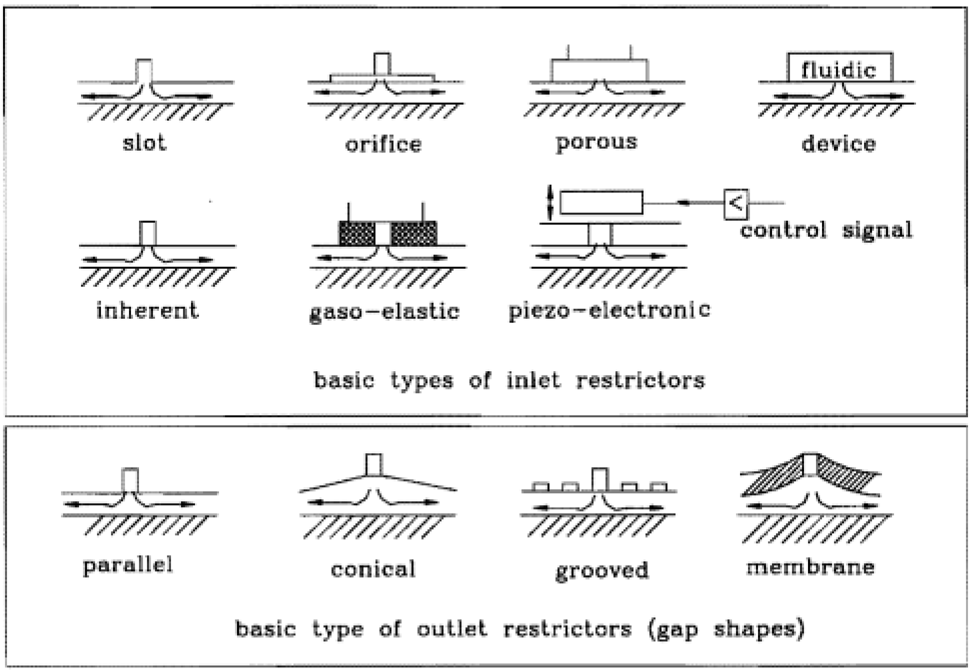


Figure 4 Different restrictor designs for aerostatic bearings

Another method maintaining stiffness in the fluid film of the between the bearing surface is by using compensation mechanism which allow the uniform flow across all the cross-section between the bearing surface. In case of aerostatic bearings, due to the low viscosity of air the restrictor design becomes complicated and hence compensating mechanism play an important role towards the stiffness of these aerostatic bearings. Below are the most commonly developed compensation mechanisms.

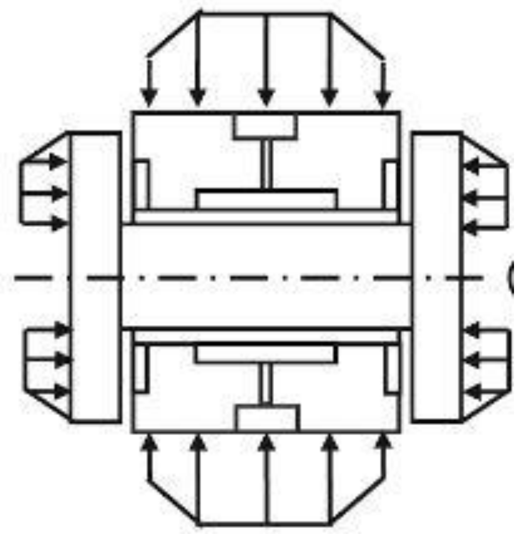


Figure 5 Orifice/ Capillary based bearing example [12]

a. Orifice or capillary – It one of the most commonly applied restrictor mechanisms, this design was first introduced by FW Hoffer and was later improved upon by Hedberg. In this design opposing pads were used to regulate flow to pockets on the opposite side of the fluid film bearing.

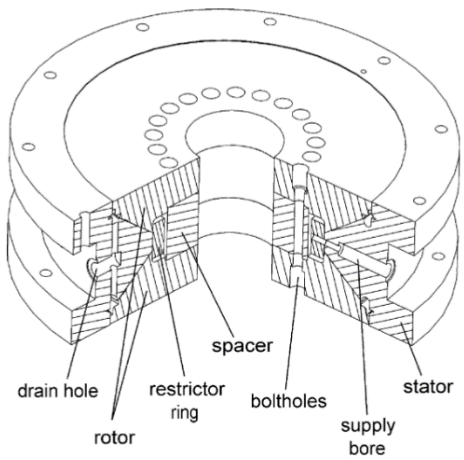


Figure 6 Section of rotary bearing with angled surface self-compensation [16]

b. Angled surface self-compensation – This approach Figure 6 was introduced by N.R. Kane et.al. The restrictors are not directly opposing, and neither are they on the face, but they are rather on face that is preferably at an acute angle for better feed efficiency [16]. The manufacturing complexity of these bearings is high due to the combination of restrictor and compensation mechanism. This compensation mechanism was used in hydrostatic bearings and so far, there has been no application of this compensation mechanism in aerostatic bearings.

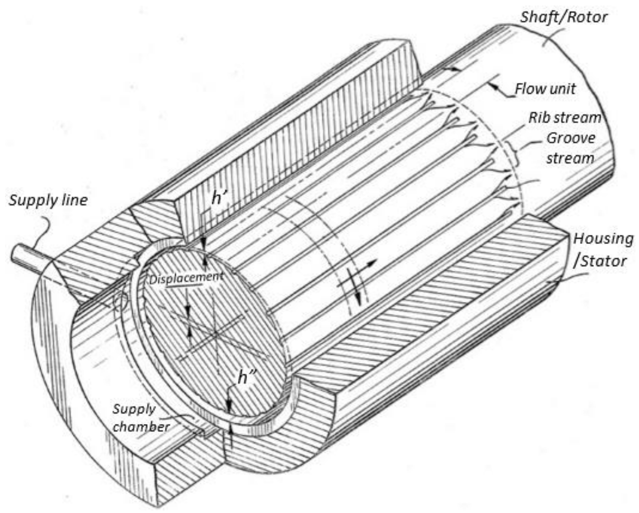


Figure 7 Groove Restrictor

c. Groove restrictors – This restrictor design approach was introduced HEG Arneson, which achieved compensation by using groove on the bearing surface with precision depth which also performed as flow restrictors. The groove must etched/ machined to a very precise depth and width with reference to the clearance between the bearing surfaces. There is a certain advantage towards this approach as the restrictors don’t have to separately install with the bearing as they become integral with the bearing surface.

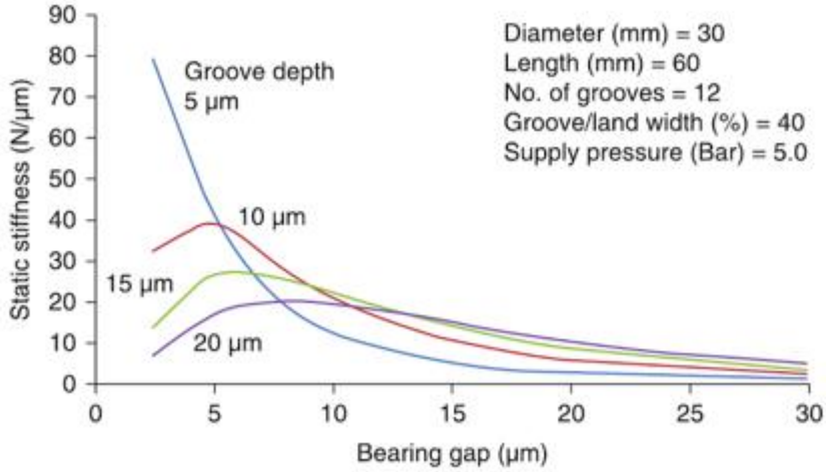


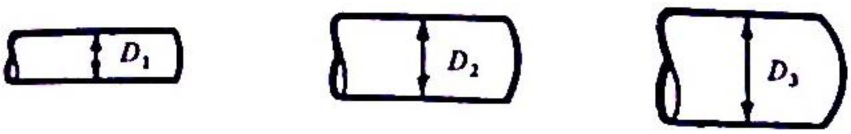
Figure 8 Static Stiffness characteristic for Groove Compensated Bearing [17]

Static stiffness is more easily achievable through groove compensated bearings as compared another restrictor design [17].

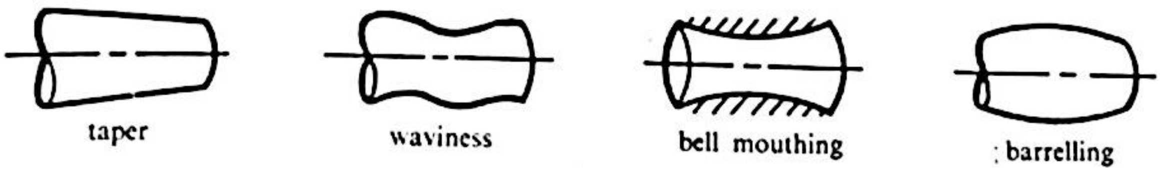
2.4 Bearing Manufacturing Errors

In case of bearing manufacturing certain common factors are studied during the metrology study of the bearing components to understand the performance of the bearing with respect to the form errors on the bearing surface. These errors are:

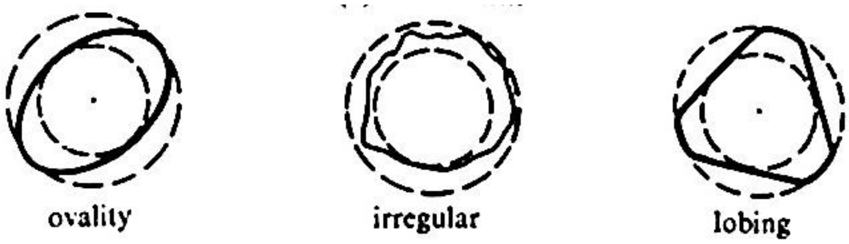
- Errors of the bearing system,
  - Absolute Size Error



  - Parallelism Error

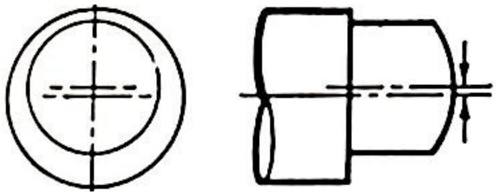


  - Roundness Error

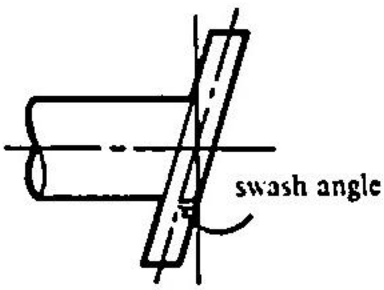


- Straightness Error

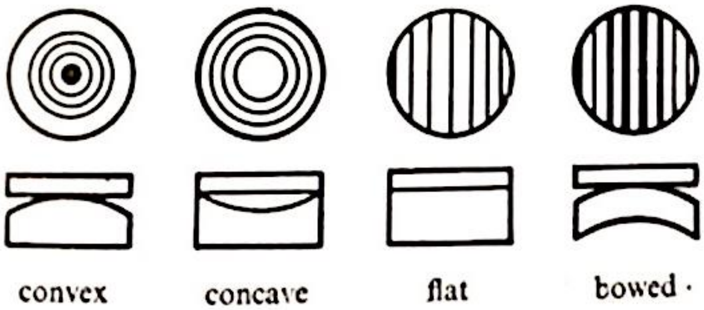
- Concentricity Error



- Squareness of faces to axis of rotation Error



- Flatness Error



- Surface finish Error

Talysurf trace with high vertical magnification

These errors could be summarized into four categories:

1. Variation in bearing clearance

Variation in bearing clearance is due to the inaccuracies of the manufacturing process and the complexity towards maintaining the gap size between these bearing surfaces. It is difficult with current design and manufacturing techniques to precisely maintain the bearing gap sizes.

2. Variation in restrictor or compensator dimensions

With the low viscosity of air with small deviation in the dimension or accuracy of the compensator or restrictor, it results in huge deviation in the performance of the bearing. For example, the step/ groove compensated mechanisms could only function with maintenance of the precise depth of the groove on the bearing surface. Something that has been perfected by P.I. Instruments over a period [12].

3. Form errors

The geometry of the fluid film which is primarily responsible for the performance of the bearing is dependent upon the form accuracy of the bearing surface. The form accuracy is required to be studied into detail. As the gap between a bearing surface in inversely proportional to the pressure exerted by the fluid on the bearing surface. Low form accuracy could result with the bearing having different pressure gradient along the bearing surface resulting in the failure of the fluid film bearing [11].

4. Local Burring

Local burring are the chips that are developed during the manufacturing process, this error arises due to the lack supervision across the manufacturing process. If the machined surface isn't cleaned properly after machining, then these burrs could chip-off and damage the bearing surface during operations. Which further develops into form error on the bearing surface [11].

5. Misalignment

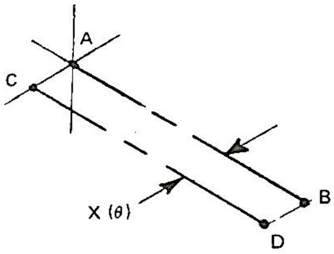
The misalignment of the bearing is due to the uneven pressure distribution along the surface. The uneven pressure could be the result of the error of manufacturing of the compensator/ restrictor or the form error on the bearing surface. To avoid misalignment the pressure between the bearing surfaces must be equalized actively by an external system or the bearing gap and compensators/ restrictors must be manufacturing with higher precision [18].

2.5 Error Motion of the Bearing System

To study the metrology of the bearing system ANSI/ASME B89.3.4M-1985 standards. The standards specify error motions based on:

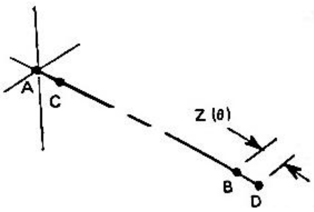
i. Structural Error Motion
   It is referred in place of vibration between the relative motions of the rotating unit the stationary unit. The error could be cause by any no. of reasons from mechanical to environmental.
ii. Thermal Drift
   In case of relative motion between two surfaces, there is always the generation of heat system. The temperature variation in the system results in thermal expansion and contraction in the system which is termed as thermal drift
iii. Error Motion Geometry

The error motions in the spindle of the bearing system are termed into these below mentioned categories:



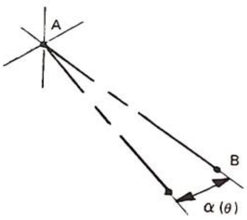
1. Pure Radial Error

   In this error motion the actual spindle axis is parallel but moves perpendicular to the true axis of rotation.



2. Pure Axial Error

   In this error motion the actual spindle axis is coaxial with the true axis of rotation and moves parallel to it.



3. Pure Tilt Error

   In this error motion the actual spindle axis moves angularly with respect to the true axis of rotation.

iv. Synchronous and Asynchronous Error Motions

When the error generated is cyclic in nature i.e. error motion repeats periodically then the motion is referred to as synchronous error motion.

When the error generated is non-cyclic in nature i.e. error motion repeats non-periodically then the motion is referred to as asynchronous error motion.

The result of the error motions is shown below with an example of the effect on surface roughness to different error motions.

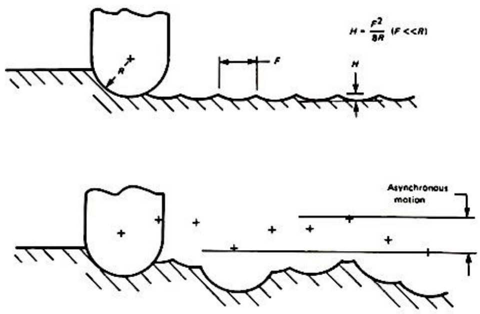


Figure 9 Synchronous and Asynchronous error motion effect on surface roughness

2.6 Material Selection

Material which covers all the materials in the manufacturing are:

- Metals
- Ceramics
- Composites
- Natural
- Polymers
- Polymer Foams

Materials selection for fluid film bearing is studied based on certain physical characteristics:

- Stiffness (GPa):
  The primary factor in choosing a material for mechanical assembly is the stiffness of the material. Young’s modulus/ Elastic modulus of the material would define the stiffness of the material. Fluid film bearings are chosen due to its high stiffness capabilities. Material with low stiffness capability, tend to deform under high pressure and stress conditions. The selected material would be applied in aerostatic bearings in which the fluid between the bearing bearings surfaces function at very higher-pressure conditions. As the bearing

gaps are smaller, a small deviation in the form of the bearing surface would result in performance variation with the fluid film bearing.

- Machinability:

  The current research works around finding an economical manufacturing process for fluid film bearings. Hence, we would be looking into materials that would be considered under this process have to be Machinable under a traditional machining facility which includes, milling, turning, grinding, etc. The manufacturing process should can achieve tight tolerances under processes. To achieve high surface finish and good form accuracy, machining is the most economical choice.

- Corrosion:

  With respect to air bearings, environmental factors like corrosion do affect the performance of the bearing in the longer run. The most common type of bearing which faces issues with corrosion are aerostatic bearings. As they require dry air to function, and any moisture in the air flow leads to corrosion and blocking the air inlet ports and destroys the bearing surface. Coating the bearing surfaces is still a possibility but the air inlet ports are still exposed to corrosion. Hence it is of best of interest to select materials which are corrosion resistant.

- Thermal Conductivity or thermal resistivity:

  Aerostatic bearings fluids function at very high pressure which as a result increases the temperature of the fluid. No matter how much a material is thermally resistive, yet without the proper thermal conductivity, the dissipation of heat is difficult, and the system ends up working at higher temperature which leads to form inaccuracies because of thermal expansion in the system. Hence, the material should be thermally conductive to dissipate the heat as it is being generated in the fluid film system.

- Dilation Factor:

  This phenomenon is studied in cases the where hollow shafts are studied. In case of air bearings, due to the low viscosity of the liquid, it is advisable on the design perspective to optimize the weight of the rotor or the moving slide. Material with larger dilation factor result in higher form error under high pressure conditions. From the formula below, E/ρ is inversely proportional to the dilation of the journal diameter of the shaft.

Based on the dilation formula [9]:

$$\delta_1 = \frac{\rho\omega^2}{4gEX}\left(D^3X - tD^2 + t^2D^2\right) \tag{4}$$

Where, δ_1 → **increase in diameter of a hollow shaft, E→young's modulus of shaft, ρ→Density of materials, t→shaft wall thickness, D is the normal journal diameter.** [9]

- Density:
  While working with mechanical system with rotation and sliding components. It is always advisable to use materials with small density as these mechanical systems would be dealing high reaction forces. Light weight assemblies have lower masses in the system. With reference to the 11 principals of precision engineering, it is always more beneficial for the mechanical system to work with small inertial forces. Hence light weight assembly not only put less load on the fluid film system but also have better capability in precision motion

Several materials are currently being used in the industry which have been studied in hydrostatic and aerostatic. The prime reason behind looking for hydrostatic bearing is similarity of both bearing platforms which could increasing the family for material selection towards the field of air bearings. Due to very low viscosity of the fluid only bearing bodies with low inertia have been applied in air bearing manufacturing.

2.6.1 Hydrostatic Bearing

Hydrostatic bearings used in areas where load capacities are to be managed by the bearing system. The primary reason for using hydrostatic bearings in these applications is due to the viscosity of the fluid as discussed above. With higher viscosity of the fluid, higher pressure gradients are achieved in the system. As the system functions under high temperature and high-pressure conditions, the materials preferred should be capable to functions under these conditions. Hydrostatic bearings have been applied in many applications over its lifetime and a lot of different materials have used to study the suitability of these materials for hydrostatic bearings. Some of these materials are mentioned below:

Steel Alloys

One of the widely used materials in hydrostatic bearings is Steel. The reason behind using steel is the convenience of procession steel to its required tolerance requirements and maintaining the form accuracy. Even though steel is widely used into these applications, yet it has its own drawbacks which includes low corrosion resistance, higher density and limitations towards economical precision manufacturing processes [19].

Aluminium with coatings like Hard Chrome, Nickel and SiC

Aluminium with hard coatings like Chrome, Nickel and SiC has been well researched as suitable material for hydrostatic bearings. As aluminium has all the desirable physical properties as suggested above and low wear resistance is compensated with using hard coating like Nickel, Chrome and SiC. But further research is required to establish it as a suitable manufacturing material for hydrostatic bearings [20].

Copper Alloys

Copper Alloys are have applied in hydrostatic bearings, it has its own advantages like good stiffness capabilities, low density, and good heat conductivity. It is one of the best material for hydrostatic bearings, but the cost of these materials is relatively higher than other materials which makes it less desirable towards bearing applications with economical limitations [21].

Bronze with Lead/ Phosphorous

Bronze with Lead/ Phosphorous has been analysed as the material has high corrosion resistance and is one of the most economical solution with respect to other materials with similar physical properties [22].

Tungsten Carbide

Tungsten Carbide has high wear resistant and is suitable for hydrostatic bearings which under harsh conditions or in conditions replacement of bearing arrangement due to wear is not possible. A paper by K. Cheng and W.B. Rowe discusses the application of this material in hydrostatic bearing [11].

With the possibility of numerous for hydrostatic bearings, further research and proper methodology should be built up which would be studied in this research.

2.6.2 Aerostatic Bearing

Like hydrostatic bearings, aerostatic bearing material family is quite similar. The certain differences which allows further difference from the hydrostatic bearing is due to the viscosity of the fluid. As dry air has very low viscosity as compared to fluids, the functioning tolerances are much tighter to achieve similar load capacities as compared to hydrostatic bearing. Even though hydrostatic bearings could achieve much higher load capacity, yet the maximum motion speed of these bearings are much smaller aerostatic bearings. There are have been numerous materials that have applied in aerostatic bearings, the family of these materials have been classified under following groups:

Steel Alloys

As discussed above in hydrostatic bearings, similarly in case of aerostatic bearings the most extensively used material for application is steel. The application and drawbacks of steel has been discussed. In air bearings, one of major cause for the failure of air bearings is due to corrosion which occurs due vapour in air supply, non-functioning of bearings over a long period, vice versa. Coating could be used to prevent this corrosion in steel but in aerostatic bearings, the hole diameters for air inlet are quite small which are hard to be coated and when these holes get corrosion, then they stop functioning altogether [23] [24].

Titanium Alloys

Titanium alloys have wear and corrosion resistance. Which makes it ideal for aerostatic bearings, but the machining of titanium alloys is very difficult and expensive which it difficult for using titanium as an economical alternative to its other counterparts [25].

2.6.2.1 Bronze Alloys

Bronze is a suitable choice as a material for aerostatic bearings. As it has corrosion resistance and is quite economical for machining. Bronze alloy has been used for aerostatic bearings for W.B. Rowe and K. Cheng in their research and could be researched further [11].

2.6.2.2 Silicon Carbide Composites

Silicon Carbide composites are used in a special condition and are not used for high load conditions. The major reason behind the application for this is because the machining cost of silicon carbide is quite high. Hence application into economical processes is burdensome [26].

2.6.2.3 Carbon Fibre Composites

As air bearings are more suitable in application into areas where motion speed requirement is higher as compared to load the capacity. Which requires the rotor or the slide unit to have very low mass and handle high load capacities. The development of carbon fibre-based components is still considered in its infancy period as the knowledge gap to work this material is quite high. Hence the cost of manufacturing is high [27].

2.6.2.4 Ceramic Composites

Ceramic components are considered under light load capacity application. Ceramic components have brittle nature and would require advanced manufacturing techniques to be used in as a material for aerostatic bearings [28].

2.7 Fabrication Technique

The manufacturing process adapted to manufacture fluid film bearing system are selected based the metrological report of each component. Selecting ultra-precision processes for manufacturing of components with high tolerance ranges (0.1mm-1.0mm) ends in increasing the manufacturing cost rather selecting crude manufacturing processes and expecting high precision results in the failure of the mechanical system. Hence of the manufacturing process is greatly dependent on the required accuracy of the spindle error motions, surface roughness and form accuracy of the bearing surface.

An economical manufacturing process is not only about bringing the manufacturing cost of the mechanical system but rather it also must investigate maintaining if not betters the quality of the manufactured component by studying on the basic requirements to achieve the desired results. Which includes achieving the metrological requirements while maintaining the quality of mechanical system.

2.7.1 Manufacturing Processes

Since air film gaps are of the magnitude ~ 5μm. Hence proportionally we are looking at processes which create the part geometry around 0.05μm to 0.5μm of form accuracy. The processes are

i. Diamond Turning/ Machining
ii. Ultra-Precision Grinding

Considering the manufacturing processes that are currently available or have been used in similar manufacturing conditions. We are studying the capabilities of these manufacturing processes and selecting a suitable manufacturing process that can achieve the required precision. These manufacturing processes are:

2.7.1.1 CBN Hard Turning

With respect to the traditional turning process which is suitable for turning softer materials. CBN Hard Turning deals with using Cubic Boron Nitride tools which can turn Hard Materials or surfaces (58 to 70 HRC) to the desired dimensions. The achievable surface finish and form accuracy is quite limited in this process. Hence, it’s suitable for processes that require moderate precision. Like every manufacturing process, CBN turning has its own limitations over materials. We have studied its limitations based on our consideration as suitable material for the manufacturing process. These materials are alloys of steel, titanium, Carbon fibre composites, etc [29] [30] [31].

2.7.1.2 Precision Grinding

It is the most widely used process for manufacturing of fluid film bearing system in a regular production system with high volume. Over the last era of development of manufacturing processes precision grinding has had its own growth. The capability of removing small amount of material and achieving the dimensional metrology at ultra-precision, has helped in the manufacturing industry precision components with ease. Generating free form surfaces with high form accuracy can very economically be achieved by precision grinding. The biggest advantage is certainly at times also turns to become the major drawback which in case precision grinding is the low material removal rate of the manufacturing process. Even though availing precision grinding is more accessible compared to other manufacturing processes, the achievable precision through this process is very high as material removal rate of this process is very small. As a result, it is less economical as compared to Hence, it results with being one of the most expensive processes. But its cover wide area of materials that can be machines by this process which are steel alloys, Titanium alloys, Silicon Carbide composites, carbon fibre composites, aluminium, etc [32] [33] [34] [35].

2.7.1.3 Diamond Turning

The tip of the tool in this process is diamond. The advantage of this process is that due to the strong crystalline structure of diamond, small tool radius of the scale of Nano-meters can be created and maintained for a long period of time. But diamond tools have certain disadvantages as compared other turning operation. They are susceptible to more wear when used into cutting of materials with carbon in their composition as it results in reacting and creating bond with the carbon atom of the diamond tool. Which results in more wear of the cutting tool radius of the diamond tool. Hence materials like Steel, Carbon fibre composites, sintered graphite cannot be diamond turned without compromising the cutting tool radius of the diamond tool. But due to low cutting tool radius which can be generated in these diamond tools, it is one of the fastest and the most accurate processes in turning and the form accuracy is at par with that of cylindrical grinding. Research has been performed over years to replace cylindrical grinding process with diamond turning processes. It can be used to process a lot different materials like Titanium alloy, bronze alloy, silicon carbide alloy, ceramic composite, sintered materials like silica porous, etc [36] [37] [38] [39].

2.7.1.4 Electrical Discharge machining

It is also known as EDM is used widely in the industry in creation of slots, groove and other special impressions on the surface of different materials with high precision. The patterns created with this process are very accurate, but due to small amount of material removal over a long period of operation it is one of the most expensive processes. It can be used for softer and harder materials hence could applied in manufacturing with wide variety of materials. It is specifically suitable for processes which are manufactured under tight tolerances [40] [41] [42] [43].

2.7.1.5 Deep Hole Drilling

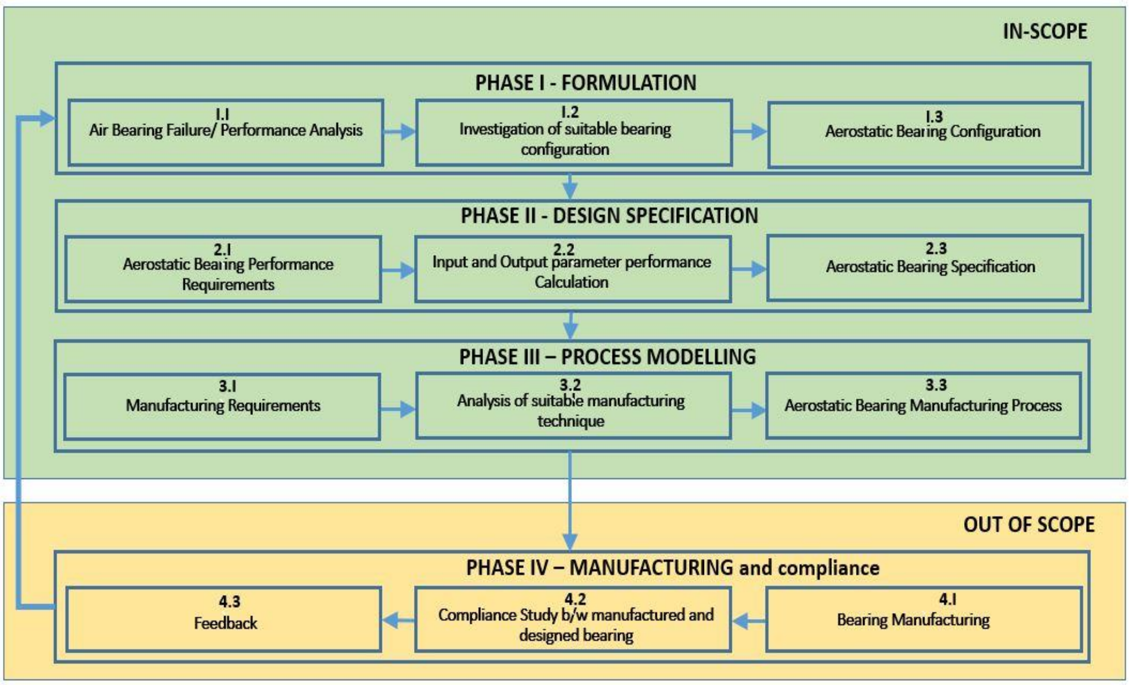
It is specifically performing in areas where the tool radius extremely small as compared to the shank length of the tool. Due to high difference in size between the length and diameter of the tool, it is normally assumed that during the drilling operation the chips created might result in breaking the tool. Hence vacuum tube is installed over the drill which would extract the chips during the cutting process. Since it's a specialized drilling operation hence it requires a lot of arrangements before the operation. The accuracy of the process is high and the process cost is moderate as compared to other processes [44] [45] [46].

2.7.1.6 Milling

One of the most widely used manufacturing process. In this context, I would be using milling operation to create slots and groove on the bearing surface. The process cost and the accuracy that could be achieved is very low. It is applicable to a large set material for manufacturing of these on the bearing surface. It can be applied materials like Steel alloys, titanium alloys, bronze alloys, aluminium alloys, etc. [47] [48].

3 Methodology

To achieve the above-mentioned Aim and Objectives I have broken my research into 3 phases. These three phases could be covered into the scope of this research and the fourth phase (out of scope) could be performed to study compliance of the results with the current research and then recalibrated to further develop this ultra-precision bearing manufacturing system.



3.1 Phase 1 - Formulation

1-1 Air Bearing Failure/ Performance

In this section the current failure in performance of aerostatic bearing would be studied. The common performance characteristics would be noted. This draws performance requirements for aerostatic bearing. The analysis would present clarity towards the do’s and don’ts of current design and manufacturing process of aerostatic bearing.

1-2 Investigation of suitable bearing configurations

The configuration selection would draw its inputs from the earlier processes and would be helpful in selecting a suitable configuration for the aerostatic bearings.

All the configurations discussed in section 2.2 and section 2.3 would be studied further and would present better clarity over the advantages and disadvantages of these configurations.

1-3 Aerostatic Bearing configuration

The configuration selection would be a basic layout of the aerostatic bearing. Which would include the type of mechanical configuration, the type restrictor/ compensator, and other factors.

3.2 Phase 2 – Proposed Design Specification

2-1 Aerostatic Bearing Performance Requirements

In this the brief performance requirement for the bearing would drafted that would also refer to section 1-1 and section 1-3. Relevant literature review will be conducted to explore the mathematical basis of performance calculations.

2-2 Input/ Output parameter performance calculations

In this section the previous empirical formulas derived from the works of Rowe and Powell would be used to find the performance specifications of the bearing.

Journal Bearings

$$\text{Radial Stiffness } K = \frac{2W}{h_o} \tag{5}$$

$$\text{Tilt Stiffness } = \frac{KL^2}{16} \tag{6}$$

$$\text{Load Coefficient} = \frac{W}{(P_0 - P_a)LD} \tag{7}$$

Where K is the radial stiffness of a journal bearing, W is the load in the radial direction, h_o is ideal gap between the bearing surfaces. L is the length of the journal bearing. P_o is the supply pressure of air and P_a is the atmospheric pressure.

Thrust Bearings

$$\text{Axial Stiffness} = 1.44\frac{W}{h} \tag{8}$$

$$\text{Tilt Stiffness}=\frac{K(b+a)^2}{8} \tag{9}$$

Where W is the load in axial direction, h is the gap between the bearing surface, b and a are extreme ends of the aerostatic bearing and K is the axial stiffness of the bearing.

Calculation for groove compensation for aerostatic bearings:

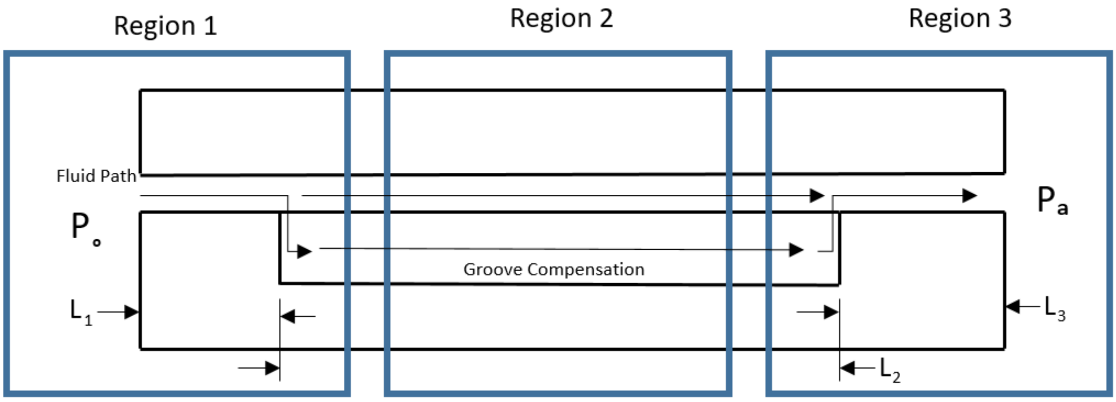


Figure 10 Groove Restricted Bearing Nomenclature

$$\frac{K_1}{K_1 + \lambda} = \frac{P_2 - P_3}{P_1 - P_3}$$

(10)

$$K_1 = \frac{C_g + C_r}{C_s}$$

(11)

$$K_2 = \frac{b_g}{b_r}$$

(12)

$$\lambda = \frac{l_{1,2} - \Delta}{l_{2,3} - \Delta}$$

(13)

$$\Delta l \cong 0.5 b_r [K_2 \frac{K_1 - 1}{K_1}]^{\frac{1}{3}}$$

(14)

$$t = \frac{h_g}{h_r}$$

(15)

$$K_3 = (\frac{h_g}{h_r})^3 = t^3$$

(16)

$$K_3 = K_1 K_2 + K_1 - K_2 \tag{17}$$

$$b_g \geq 5h_g \tag{18}$$

Where K_1 is the ratio of flow between inlet and outlet, K_2 is the ratio of width of the groove to the width of the rib of the bearing and K_3 is the ratio of the volume liquid flow between groove and rib of the bearing.

h_g is the between the groove and the bearing surface and h_r is the height rib and bearing surface.

b_r is the width of the rib and b_g is the width of the groove of the bearing.

Conditions for the bearing to function based upon Navier-Stokes equation

- L>500h
- $L_{2,3}$>20h
- $L_{2,3}$>0.25b_r

Where L is the Length of the groove, h is the bearing gap and $L_{2,3}$ is the length of the second passage of the restricted bearing.

2-3 Aerostatic Bearing Specifications

In this section the final bearing specification would be drafted. Upon which the bearing would be designed.

3.3 Phase 3 – Process Development

3-1 Manufacturing Requirements

Based upon section 2-3 the specification of the bearing would be taken as input to further understand the manufacturing requirements of the bearings. The inputs from section 1-1 would also be studied in this section as a lot of the failure might be due to the manufacturing processes.

3-2 Analysis of suitable manufacturing technique

Suitable manufacturing technique for the fabrication of the aerostatic would be investigated. The deciding factor into these sections would the physical properties of the material and the precision of the manufacturing techniques.

3-3 Aerostatic bearing

A final design of the air bearing would be developed including the manufacturing drawings with reference to section in the earlier sections of the analysis.

4 Analysis

4.1 Phase 1 – Formulation

In this section the current problems and performance characteristics with the development of aerostatic bearings would be studied. Based upon which the concept bearing developed with the suitable mechanical configuration which suits the design requirements.

4.1.1 Air Bearing Failure/ Performance Requirements

The aerostatic bearings have been applied across a lot of platform and a lot of the research into this platform has been performed which has been discussed in Section 1.1 of this research thesis. In this section the bearing failure criterions and certain more performance characteristics have been studied.

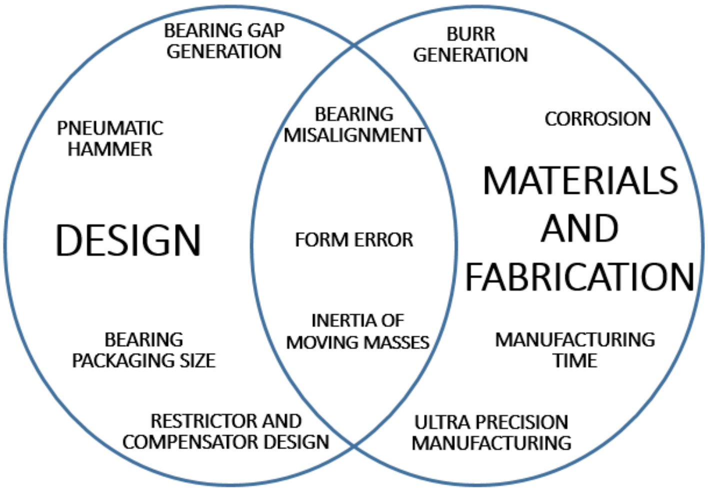


Figure 11 scope of work to be looked upon design and manufacturing

Looking into the current research into aerostatic bearings, below mentioned are the major issues that are currently faced with manufacturing and operation of aerostatic bearings:

a) Bearing Misalignment

Misalignment of the centre axis with respect to the rotor of the bearing housing [49].

b) Form Error/ irregularity in Fluid Film Thickness

The form accuracy of the bearing surface is responsible for the bearing stiffness and load capacity. The thickness of the bearing film is inversely proportional to the pressure applied. With low form accuracy the bearing surface would have variable pressure gradient across the surface. Resulting in low stiffness and low load capacity of the bearing.

c) Bearing Gap Generation

The working bearing gaps in these aerostatic bearings as discussed in section 2.2 of this thesis would require very high precision manufacturing as the gap generation in most of the mechanical configuration is correlated to the form accuracy of the surface [50].

d) Burr Generation

Burr from the manufacturing of aerostatic bearing if not cleaned properly enters different air paths and then damages the bearing surface and creates distortion in the performance of aerostatic bearings [51].

e) Corrosion

In case of aerostatic bearings, since the working bearing gap and the feed-hole sizes are very small, a small amount of corrosion of the material due to the moisture in the air supply results in distortion in the fluid film thickness [52].

f) Pneumatic Hammer

Pneumatic Hammer is a self-excited instability which occurs in aerostatic bearing during low supply pressures. It results in damaging the bearing surface and hence is avoided in most conditions [53].

g) High manufacturing time/ cost

As relation between bearing gap and form accuracy of the bearing must be maintained. The large amount of time and cost is spent generating the bearing gap size while maintaining the form accuracy of the bearing surface. Which leads longer processing time. During period the parts must loaded and unloaded to be checked for the tolerance after every cutting cycle.

A lot of these issues are correlated i.e. they are related by a cause and effect relation. The form error could be the cause for bearing misalignment which could also be the cause for low stiffness and lower load capacity.

There are other factors that would be categorized under performance characteristics and would be important characteristic towards the development of an aerostatic bearing. These are:

a) Packaging Size of the bearing

The size of these bearing systems is quite limited as by increasing the size of these bearings, the manufacturing complexity also gets increased. Hence, most of these aerostatic bearings are applied under smaller packaging sizes and achieving high precision under these sizes is much simpler as compared large sizes.

b) Ultra-precision Manufacturing

The ultra-manufacturing of these bearings requires ultra-precision application. The major reason is the requirement of high form accuracy and smaller gap sizes. Which as discussed above creates huge complexity towards the manufacturing of these aerostatic bearings.

c) Restrictor or compensator design

Dealing with air as a fluid is difficult as the fluid flow follows turbulent flow models with very high flow velocity as compared to hydrostatics. Simplicity towards the design is required where simpler processes could be incorporated that would be suitable for maintaining stiffness across the bearing surface.

d) Bearing surface sensitivity towards wear

As these bearings systems are very sensitive to wear on the bearing surface. Hence during processing of the bearing surface, great care is required to clean the burr from the manufacturing processes. Wear resistance is required for these bearings to operate in regular conditions.

e) Inertia of moving masses.

Aerostatic bearing maintains the gaps between the bearing surfaces even during static conditions. To further improve the performance of these by further reducing the masses of the rotor while keeping the stiffness of the bearing constant. Which could be achieved by maintaining the form accuracy and bearing gap size while lowering the density or the basic mechanical structure of the rotor.

Out of the above sections certain factors are covers by the design factor of the bearing and certain factors are controlled by the material and fabrication processes.

In the above Figure 11 the scope of work for the design and manufacturing is covered. In the next following sections the selection processes in page 49 investigation of suitable bearing configuration and in page 45 the analysis of suitable manufacturing process would be governed by the factors notified into this section of research

4.1.2 Investigation of suitable bearing configurations

There has been a lot of research towards bearing configuration. The selection process in this case has been derived by the selection strategy developed by W.B. Rowe.

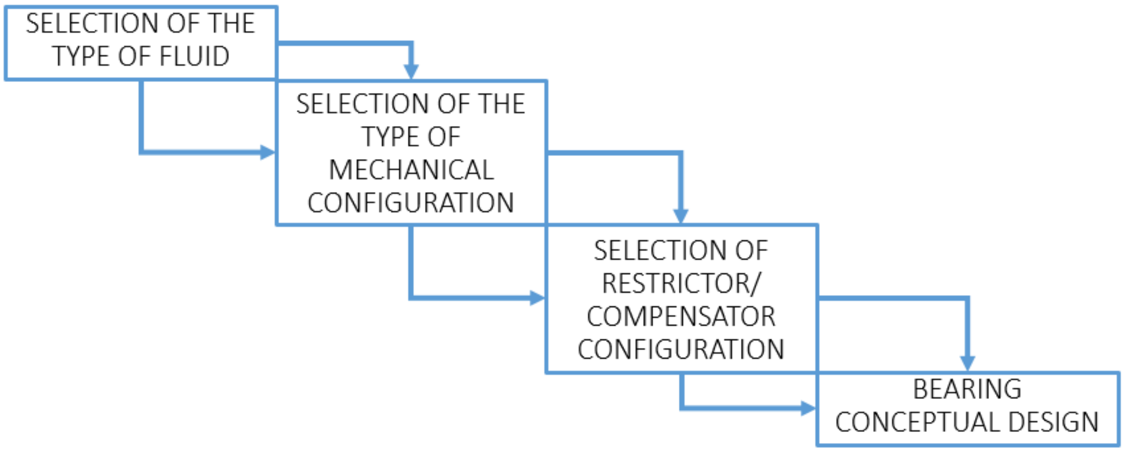


Figure 12 Configuration Selection Strategy [11]

In the configurations selection the mechanical configuration in Figure 12 which includes the shape of the fluid film and the restrictor design would be selected. In the above section 4.1.1 the problems with the current problems from manufacturing, operations and performance factors where discussed. The mechanical configurations that would be covered in this section of the research would be combination of radial and axial bearing. As the combination configuration would can cover a larger area of application they could be could be modified/ scaled to the desired journal and thrust bearing configuration.

As discussed in section 2.2 there are 3 types of combination bearings.

- Radial and journal combination
- Spherical bearing
- Bi-conical Bearings

These bearings can now be compared against these factors based upon the research by K. Cheng and W.B. Rowe [11] and could be summarized under a simplified table:

FACTORS	COMBINATION	CONICAL	SPHERICAL
LOAD CARRYING CAPACITY IN AXIAL DIRECTION	HIGH	HIGH	HIGH
LOAD CARRYING CAPACITY IN RADIAL DIRECTION	HIGH	HIGH	HIGH
POSITIONAL ACCURACY IN AXIAL DIRECTION	MEDIUM	HIGH	HIGH
POSITIONAL ACCURACY FOR ANGULAR DIRECTION	MEDIUM	HIGH	HIGH
POSITONAL ACCURACY IN RADIAL DIRECTION	LOW	HIGH	HIGH
STIFFNESS IN RADIAL	MEDIUM	MEDIUM	MEDIUM
STIFFNESS IN AXIAL	HIGH	HIGH	MEDIUM
MANUFACTURING COST	LOW	LOW	HIGH
DESIGN COMPLEXITY	LOW	MEDIUM	HIGH
SELF ALIGNING ABILITY	MEDIUM	HIGH	LOW
FLOW RATE OF FLUID	HIGH	LOW	HIGH
PRECISION GAP GENERATION	LOW	MEDIUM	HIGH

Table 2 summary of different mechanical configurations [11]

In the above Table 2 a general specification sheet is drawn which summarizes the performance of these mechanical configurations.

Based upon the section mentioned above, these aerostatic bearings would require primarily three factors to be considered:

- The bearing gap generation
- The form error of the bearing surface
- The bearing Misalignment

Generating bearing gap is much simpler in bi-conical and spherical bearing which would allow aerostatic bearing to be manufactured to the desired size with less errors and manufacturing defects. Further the combination and the spherical configuration is more susceptible to bearing misalignment as compared to bi-conic design a bi-conic configuration has a self-aligning capability due to the location in a conical structure.

Based upon the Table 2 presented above the bi-conic configuration has certain advantages:

- Smallest packaging size as compared to other configurations
- Lower manufacturing cost due to modern stiffer fabrication processes
- Self-aligning capability
- Has better precision in positional capability.

This might also be an opportunity to explore the bi-conical configuration which would bring zero correlation between the form accuracy of the surface and gap generation between the bearing surfaces. Maintaining the form accuracy of the bearing surface requires high precision manufacturing which results in employing manufacturing techniques that require a longer period due to low material removal rates. In the current research a configuration could be developed through bi-conic design that that would have low correlation between the form accuracy and gap generation.

In case of the restrictor design discussed in the case of aerostatic bearing in the above section 2.3. Dealing with air as the fluid between the bearings surfaces, controlling the flow of the air require high precision orifices to be generated. Which would also limit the load capacity of the bearing.

A brief representation of the restrictor and compensator designs have been discussed. These configurations also bring a level of manufacturing criticality towards their selection as these restrictors/ compensators are responsible for the internal stiffness of the fluid film bearing. While a lot of these configurations are suitable for experimentation, a very few of these configurations are currently being applied in the industry due to the manufacturing difficulties that are presentation towards the design and manufacturing.

Research has been performed towards the comparison of the most suitable restrictor/ compensator design. Belfort Guido et.al. [54] Experimented to study the load carrying and stiffness capabilities of groove compensated bearings in relation to orifice restricted bearings. The research showed that the groove compensated bearings have far better load carrying and stiffness capabilities as compared to simple orifice restricted bearings. Research presented by Frank Wardle [17] towards the comparison of groove restricted self-compensated and orifice restricted bearing shows that the groove restricted bearings are suitable for achieving better load capacity. The two graphs reported Frank Wardle showing the magnitude of static stiffness of the bearing shows the superiority of the groove compensated bearings to orifice compensated bearings.

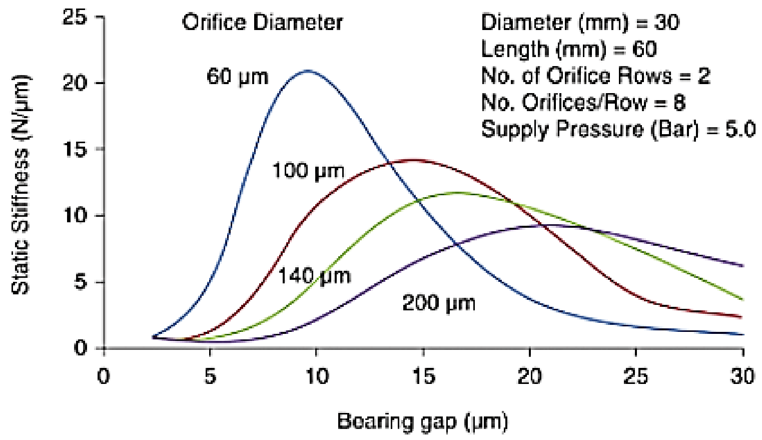


Figure 13 Orifice Restricted Bearing [17]

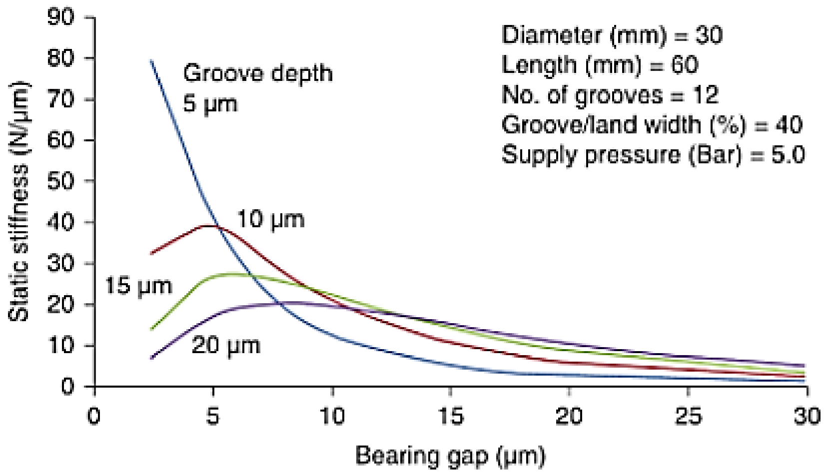


Figure 14 Groove Restricted Bearing [17]

Hence, looking towards the data above it is suitable for the selection of groove restricted self-compensating bearing configuration.

4.1.3 Novel Aerostatic Bearing configuration

Looking towards the above-mentioned work in section 4.1.2, a conceptual design of the bearing could be generated which would be suitable for three major factors:

1. Isolating the gap generation from the form accuracy of the bearing surface.

2. A biconic configuration which could be scaled or modified towards application in most applications of these bearings.

3. Using groove restricted self-compensating design to achieve better stiffness capabilities.

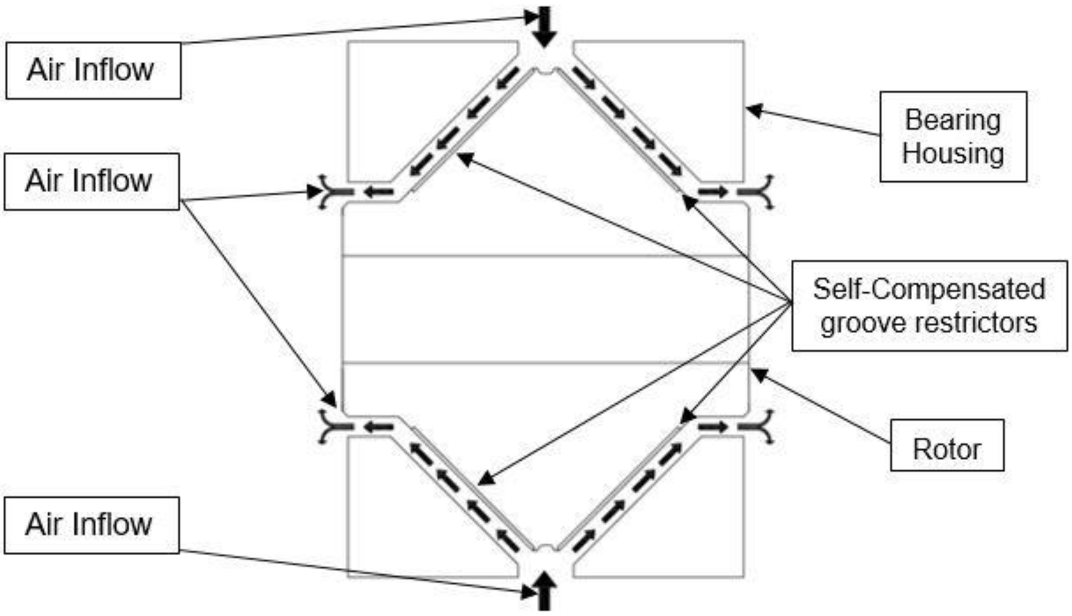


Figure 15 Biconic Design Developed (Schematic)

In the above configuration in Figure 15 the conceptual design has been developed based upon the selection in section 4.1.2. The bearing would be a 3-piece bi-conic bearing.

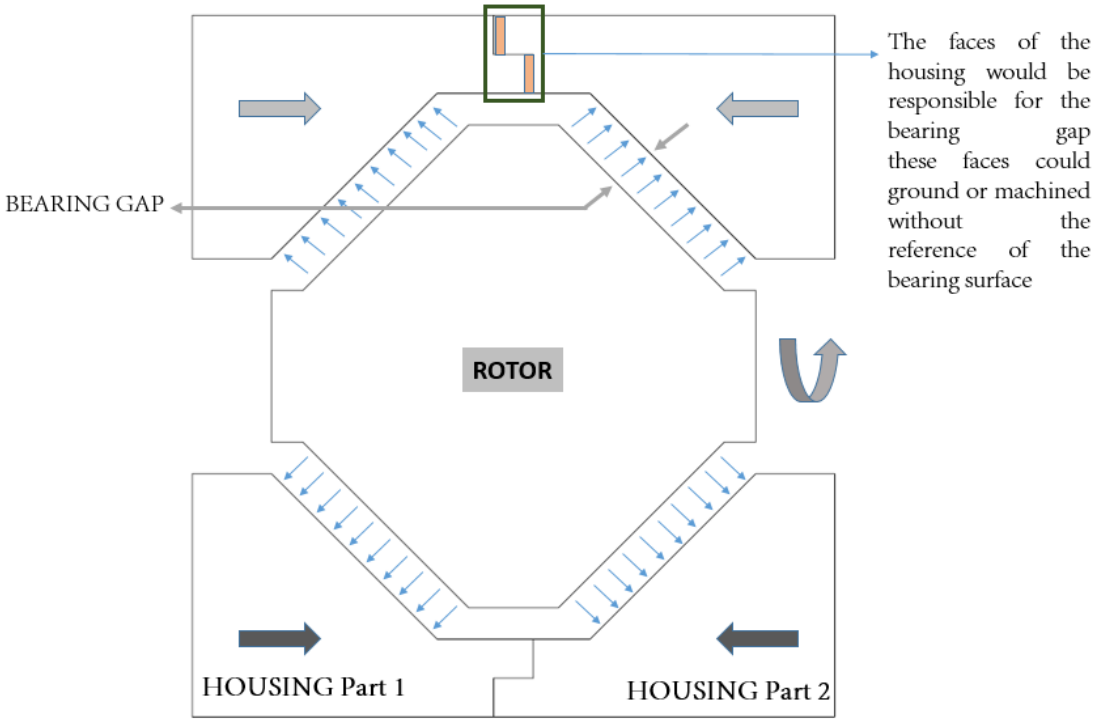


Figure 16 Bi-conical Gap Generation

- This configuration of bi-conical design has not been worked developed into application before this period. Rotor would be a single piece and it would be able to carry better load capacities as compared to other bi-conic configurations due to better cross-sectional area at the middle of the rotor.
- As seen in Figure 16 the second novel factor would be that the gap generation in this bearing would be dependent upon the housing mating faces. Which could be ground or turned without having a relation from the centre of the bearing. Hence it would make the gap generation completely independent to the form accuracy of the bearing surface.
- The third factor would be using the groove restrictor self-compensated configuration in this biconic design.

4.2 Phase 2 – Proposed Design Specification

4.2.1 Aerostatic Bearing Performance Requirements

Based upon the results from section 4.1.3, the bearing would now be set for performance specifications based upon the empirical formula discussed in section 2.6 on this research.

To simplify the manufacturing process the bearing volumetric size that has been taken upon for sample for testing the parameter study is 38x60x60 (L x B X H) mm^3. The reason for small packaging size of the bearing is the manufacturing limitations in the Cranfield University and with a larger size, certain more factors must be taken into consideration which would complicate the results and would compromise the main purpose of research of these aerostatic bearings.

The angle between the conical surface must maintained at 45 degrees to achieve three planes of symmetry.

The bearing would function at 5 Barr pressure conditions and would require dry air as in case normal air supply the water droplets tend to get deposited on the bearing surface and would destroy the functioning of the aerostatic bearing.

The performance specifications that would be studied in to establish a practical working design of the aerostatic bearing are:

- Load Capacities – Axial and Radial load capacity
- Stiffness – Axial, Radial Stiffness
- The working gap between the bearing surface
- The size of the groove on the bearing surface

4.2.2 Input / Output parameter performance calculations

As these biconic air bearings are still new to their development path, there are no empirical formula to derive the performance of these bearing in their bi-conical configuration. Hence to further learn about these bearing in cases of tilt stiffness and tilt load capacity, practical experimentation would be required. In the current scenario, the bi-conic bearing could be broken to its radial and axial bearing forms and their load capacity and stiffness calculations could be performed based on journal and thrust bearing equivalence.

Based on the empirical formulas discussed above in section 2.6, the outer dimension of the bearing was decided based upon the current manufacturing capability available at Cranfield University. To understand the performance of the bearing (Load Capacity and Stiffness) the formula from Section 2.6. have been used to

These specifications are drawn through the excel sheet:

RADIAL BEARING CALCULATIONS		
DIAMETER (inch or mm)	0.79 inch	20 mm
LENGTH (inch or mm)	0.89 inch	22.6 mm
RADIAL LOAD @ (100 lbf/sq.in or 6.9 Barr)	16 lbf	7.26 kgf
PRESSURE DIFFERENCE (lbf/sq.in or Barr)	58 lbf/sq.in	4 Barr
ECCENTRICITY RATIO ε	0.5	0.5
ACTUAL LOAD CAPACITY W^R (lbf or kgf)	9.28 lbf	4.2 kgf
RADIAL CLEARANCE (inch or mm)	0.0001 inch	0.005mm
RADIAL STIFFNESS K (lbf/in or kg/mm)	97684 lbf/ in	1683.737 kg/ mm

THRUST BEARING CALCULATIONS		
INNER DIAMATER	0.79 inch	20mm
OUTER DIAMETER	1.8 inch	45mm
AXIAL LOAD @ (100 lbf/sq.in or 6.9 Barr)	63 lbf	28.6 kgf
PRESSURE DIFFERENCE (lbf/sq.in or Barr)	58 lbf/ sq.in	4 Barr
ACTUAL LOAD CAPACITY W^A (lbf or kgf)	45.7 lbf	20.7 kgf
AXIAL CLEARANCE (inch or mm)	0.0001 inch	0.005mm
AXIAL STIFFNESS K (lbf/in or kg/mm)	1315440	990668

Groove Size CALCULATION			
INLET PRESSURE	P1	5	BARR
WORKING PRESSURE	P2	3.5	BARR
OUTLET PRESSURE	P3	1	BARR
FLOW RATIO	k1	14.5	
LENGTH RATIO BETWEEN FIRST AND SECOND PASSAGE	λ	8.7	
WIDTH OF THE RIB	br	1.04	mm
WIDTH OF THE GROOVE	bg	0.08	mm
RATIO OF WIDTH B/W RIB TO GROOVE	k2	13	
FLUID FILM GAP AT GROOVE	hg	0.03	mm
FLUID FILM GAP AT BEARING SURFACE	hr	0.005	mm
CUBE OF RATIO BETWEEN THE FLUID FILM GAP AT GROOVE AND BEARING SURFACE	k3	216	
LENGTH OF THE GROOVE	L	15.68	mm
LENGTH OF THE THIRD PASSAGE	l2,3	1.3	mm

4.2.3 Aerostatic Bearing Specifications

Based on the above specification air bearing detailed design of the aerostatic bearing is developed as shown below:

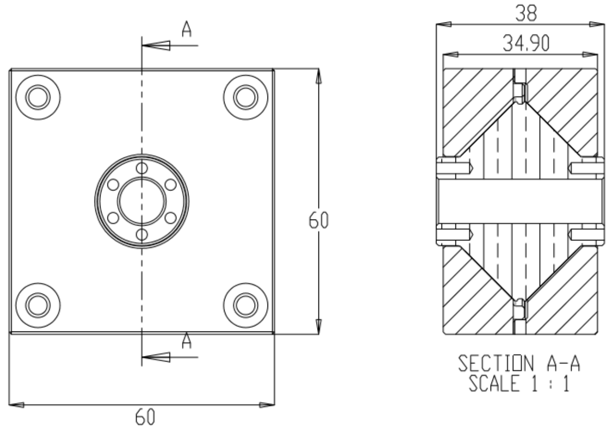


Figure 17 Package Size of the aerostatic bearing

The detailed rotor has been developed with respect to the calculation and specifications developed in section 4.2.1 and 4.2.2

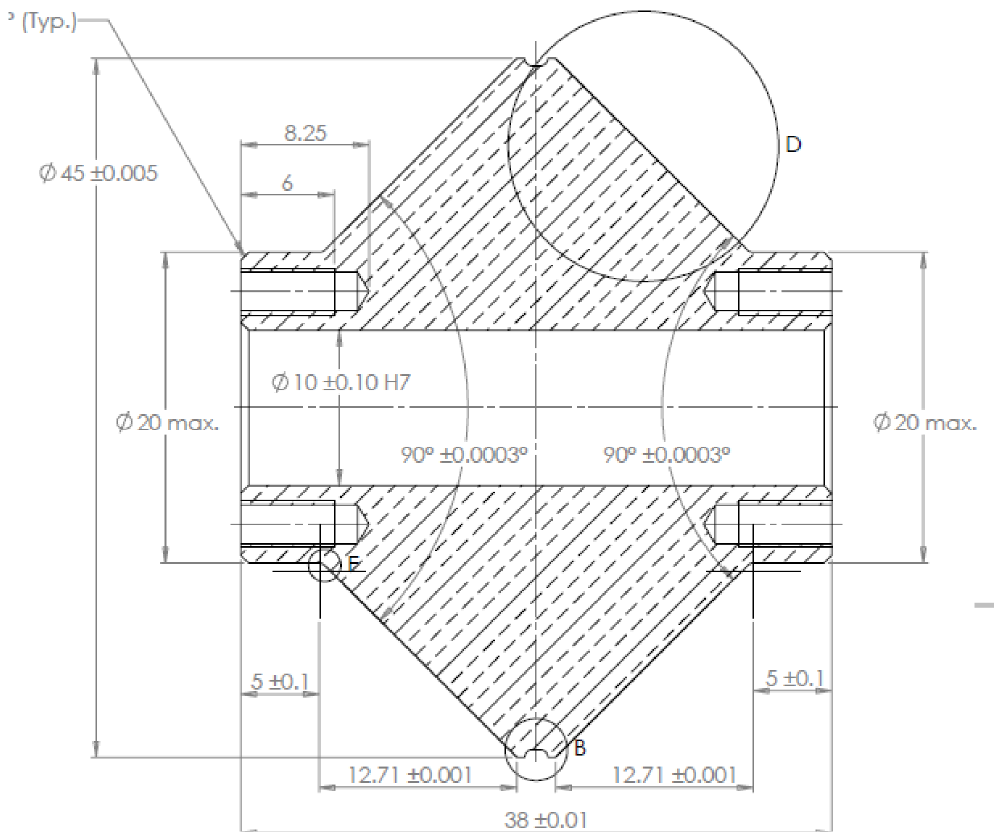


Figure 18 Detailed aerostatic bearing rotor CAD Drawing

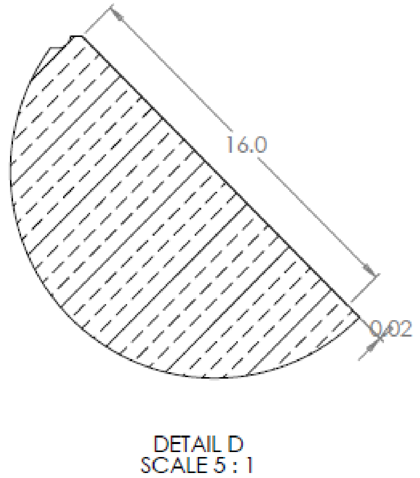


Figure 19 Detail of the groove generated on the rotor

One of the major design developments that have been performed are on the bearing housing of these aerostatic bearing which has a collar based design as shown in Figure 21 New developed in bi-conic aerostatic bearing that allows precise generation of bearing gap without disturbing of the form of the bearing surface. By machining the collar marked in Figure 21 New developed in bi-conic aerostatic bearing, the distance between the both the outer cones reduces which in turn allows more control over the gap generation of the bearing.

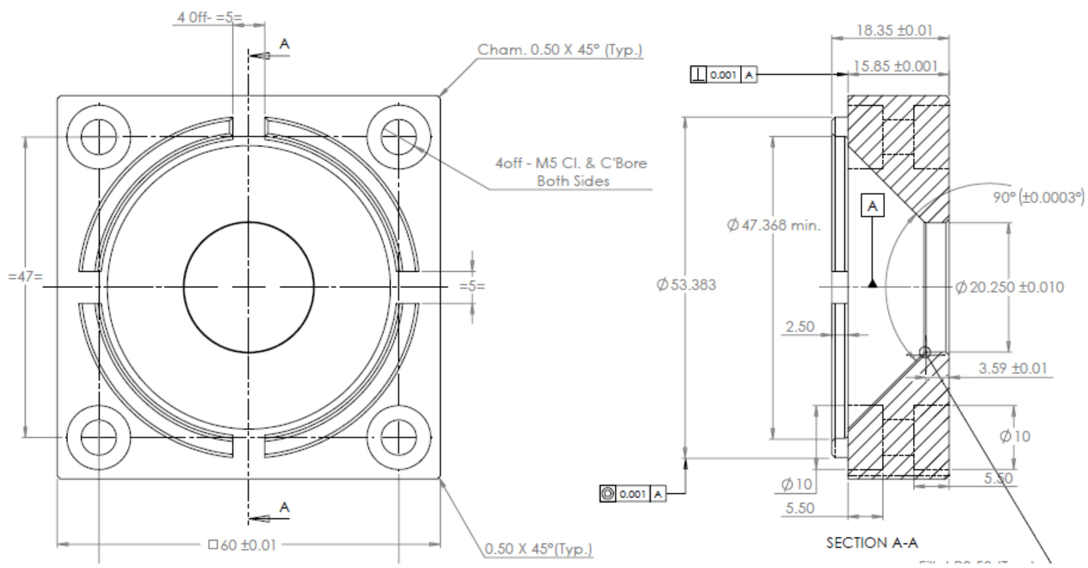


Figure 20 Detailed bearing housing

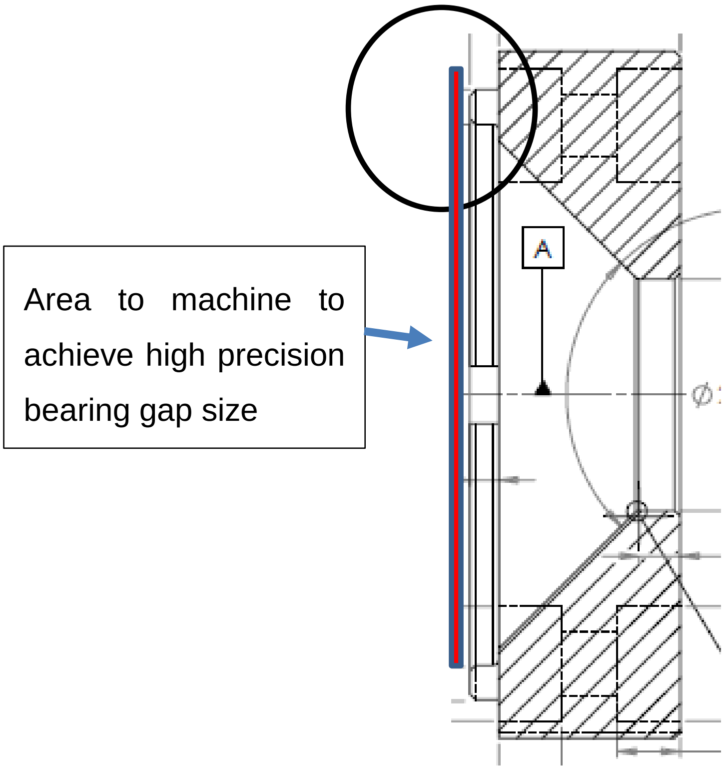


Figure 21 New developed in bi-conic aerostatic bearing

4.3 Phase 3 – Process Development

4.3.1 Manufacturing Requirement

After the detail drawings of the aerostatic bearings have been developed. This would help in deciding on a suitable manufacturing technique and material.

Based upon the current manufacturing drawing, high precision bearing surfaces must be machined but the gap the generation is independent of the bearing surface generation.

The material for the bearing must be economical and should have the physical characteristics discussed in section 4.1.1.

The fabrication technique should can achieve good form accuracy and surface finish. The manufacturing period of these bearing must be lower as well which would help in developing the manufacturing economically.

4.3.2 Analysis of suitable manufacturing technique

Based on the analytical study above the material would be required to have physical characteristic properties as discussed in section 2.7 and section 4.1.1 i.e.

- Good Stiffness Capabilities
- Better Machinability
- Corrosion Resistance
- Thermal Resistivity
- Lower Density
- Wear Resistance

Based upon the material families mentioned above in then literature review, my research would be focussing on primarily into metal due to their good stiffness capability and machinability.

The factors mentioned above are all the materials that were screened. A summary of the screening method is mentioned below in Figure 22 Material selection methodology

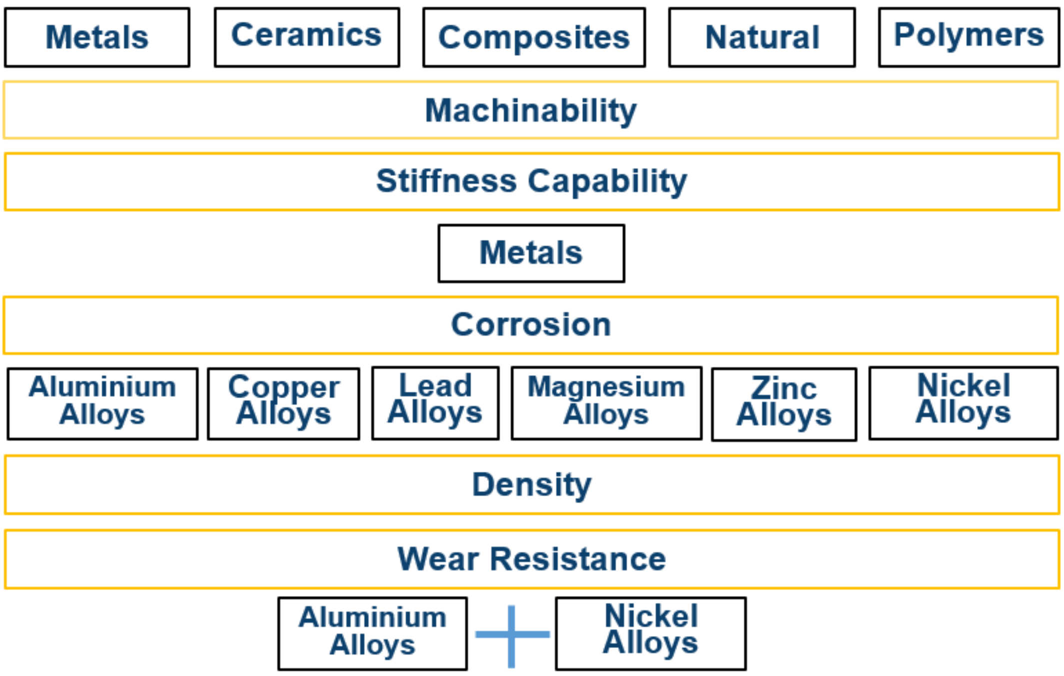


Figure 22 Material selection methodology

- Materials were first screened based upon the stiffness and machinability criteria. Through this process materials that could be commercial processed through common manufacturing techniques and are commonly available with good stiffness capabilities got selected.
- In the next section metals that have low corrosion resistance were removed as this would result in damaging the aerostatic bearing surface in a longer operation cycle.
- The metals that had good corrosion resistance were then studied for low density and good wear resistance. A certain issue in this process was noticed i.e. Aluminium had very low density as compared to other materials in consideration, but it also had low wear resistance whereas the material Nickel had good wear resistance among other materials but had very high density as well.
- In recent research by Gang Zhao hard nickel coating over aluminium as base material in hydrostatic bearings were used [55]. An application of this could be applied into these bearings. As the material would be light and the Hard Nickel coatings would give good wear resistance to the material.

Selecting a suitable fabrication technique is straight forward as far as it comes to rough fabrication. In the finished fabrication processes certain amount of study could be performed to make the process of aerostatic bearing manufacturing more economical.

In the current scenario using aluminium as base metal limits the amount of manufacturing techniques that could be applied towards the bearing surface generation. While processes like grinding are rare to be used in aluminium based materials. Diamond turning would be much more suitable and economical based upon the findings of Gang Zhao his research [55].

Further this application towards precision air bearing manufacturing would be first of its kind in application. The material removal rates in diamond turning process are much higher as compared to the traditional grinding process. And the bearing surface generation of hard nickel on an aluminium base material are acceptable for a bearing to function.

Hence this manufacturing process should be adapted for these aerostatic bearings.

4.3.3 Aerostatic bearing Manufacturing

A final layout of the manufacturing process would be discussed which shall cover the manufacturing process of these bearing from rough to finish point.

- Final Material Selection

Aluminium has a lot of alloy families which are 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000 series. A research on machining and machinability of aluminium alloys by V. Songmene material was used into the aluminium industry V. Songmene et.al have investigated the most suitable materials for machining Aluminium alloys. The materials that have high machinability are series 6000 and 7000 aluminium alloys [56].

In case of 6000 series, aluminium is alloyed with silicon and magnesium. The materials have earlier been applied into the aerospace and automotive sector. The material also has moderate high strength and is coupled with extremely good corrosion resistance. Series 7000 is primarily applied into aerospace industry and has similar advantages as that in the case of series 6000. The only difference is the tensile strength of the materials. 7000 series have high tensile strength.

The materials that we would be considering are Aluminium 6061 and Aluminium 7075. The mechanical properties are quite similar except as discussed, the tensile strength of 7075 alloy is higher than 6061. Yet the manufacturing and processing cost of Aluminium 6061 is much lower than Aluminium 7075 as 6061 is most commonly used for mechanical components in the industry. For the selecting the most suitable material, we would be working with AL 6061 as our material.

All assemblies would be manufactured first through rough machining and 0.15 mm of on all controlled surface as shown in the figure 12, 13 and 14 shown above.

The bearing surface of the housing on these controlled surfaces would be finished by the diamond turning process. As diamond turning is the finishing operation and is capable to going for higher resolution, similar machine configuration is not suitable rough machining where the precision requirements are lower. To rough machine the components, traditional process like carbide tool based turning and milling operation would be performed. The acute angled surface of the rotor towards the supply end must be kept sharp for the bearing function properly.

- Final Fabrication Process

The finished machining process would be shifting the component from diamond turning, then to micro milling machine and then back to diamond turning for finished machining.

The initial diamond turning process would to bring the material to the desired geometry but would keep some material on the bearing surface. The depth would be maintained to the desired size by milling process but after the micro milling process the bearing surface would be damages by the chips from the micro milling process. To remove these indentation, the bearings surface would have to be cleaned by diamond turning, then carefully the removing the burr form the groove.

The groove must be left with sharp corners on the bearing surface. As damaging the sharp edges of the groove on the bearing surface fails the groove compensation mechanism.

The groove compensation on the rotor surface, requires precision depth of groove across the surface. To create this groove EDM or milling operation could be performed. In this case, based on the time of the process, the groove of the rotor surface must be created with a serial pattern. In which the opposite groove would be created and then groove at 90^0 must be created in a similar manner. This process considers the tool wear, creating opposite grooves simultaneously provided better probability for balanced pressure distribution across surface for the bearing to be stable at static and dynamic conditions.

The tool pattern is mentioned below in:

The sequence here compensates for tool wear and tool change during operation. As the depth on all the opposite grooves must be precisely equal for the compensation system to function.

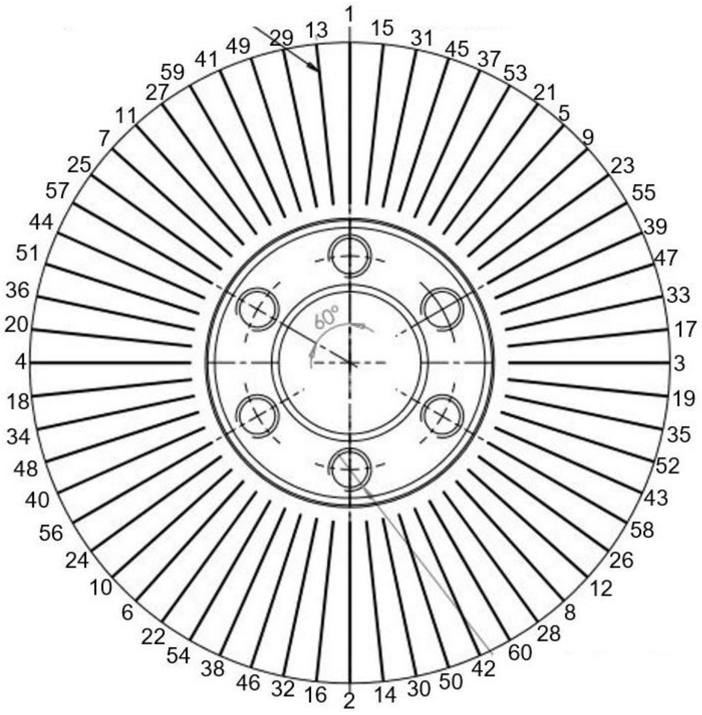


Figure 23 Groove Generation Tool Path

Bearing Base Material	AL6061
Coating on the Bearing Surface	Nickel Boron Coating
Bearing Surface Fabrication	Diamond Turning
Bearing Groove Generation	EDM or Micro Milling
Bearing housing gap generation	Diamond turning on Mating Face of the bearing housing

5 Results and Discussions

The above analysis first covered current manufacturing issues and performance requirements of these aerostatic bearing and then proposed a design configuration and manufacturing technique based upon the initial analysis of the system. The Table below summarizes the solutions proposed towards drawbacks and performance requirements.

- Bearing Gap Generation

The novel research towards this bearing configuration allows a simplistic approach towards bearing gap generation.

- Bearing Misalignment

The bi-conic configuration selected in this configuration allows self-aligning of the rotor w.r.t the bearing housing. The conical surface aligns the bearing towards the centre. This solves the issue towards bearing misalignment. Even in case of acute or obtuse angle w.r.t. to desired angle, the bi-conical configuration allows capability towards aligning the bearing by adjusting housings w.r.t. the rotor’s axis of rotation.

- Burr Generation

As the majority towards burr generation is dependent on factor of material handling. Tackling this issue towards manufacturing could not be dealt at the fabrication process stage.

- Corrosion

The material selection process during this research involved selection of material with high corrosion resistance. The final material Aluminium coated with hard nickel have high corrosion and wear resistance.

- Form Error

The factor involved in generation of form error due to manufacturing which is bearing gap generation and burr generation have been discussed in the sections above. Another factor that prevents form error in the bearing surface through improving the metrological study of the bearing surface during manufacturing which could be incorporated in the current manufacturing technique.

- Inertia of moving masses

The material selection process investigated materials with low density and chose aluminium but then used hard nickel coating due to the low wear resistance of aluminium

- Manufacturing Time

The manufacturing time in these bearings would be reduced further due to two developments. First is the change in the bearing design configuration that removes the correlation between the bearing gap generation and the form accuracy of the surface. The second is for using diamond turning instead grinding in the manufacturing of the bearing surface, which could generate required form accuracy and surface finish with higher material removal rate as compared to precision grinding.

- Ultra-precision Manufacturing

The ultra-precision manufacturing techniques as discussed above has been modified based upon the requirements of the bearing manufacturing process. With the new manufacturing technique, the generation of bearing surface becomes economical.

- Pneumatic Hammer

To avoid pneumatic hammer in aerostatic bearing, the gap generated between the bearing surfaces must be controlled high precision and the stiffness of the bearing must be compromised to a point by increasing the flow of the fluid which is further possible through the new manufacturing technique.

- Bearing Packaging Size

Biconic bearing have one of the most compact sizes that incorporates journal and thrust bearing.

- Restrictor and Compensator Design

The simplify the manufacturing of the restrictor, instead using the external restrictor self- compensating groove restrictors were manufactured on the bearing surface that would allow better load capacity and stiffness of the bearing

Aerostatic Bearing Failure and Performance Requirements	Results
Bearing Gap Generation	The novel research towards this bearing configuration allows a simplistic approach towards bearing gap generation.
Bearing Misalignment	The bi-conic configuration selected in this configuration allows self-aligning of the rotor w.r.t the bearing housing.
Burr Generation	As the majority towards burr generation is dependent on factor of material handling. Tackling this issue towards manufacturing could not be dealt at the fabrication process stage.
Corrosion	The final material Aluminium coated with hard nickel have high corrosion and wear resistance
Form Error	Diamond Turning as a manufacturing process reduces the form error of bearing surface
Inertia of Moving Masses	The low density of the rotor allows lower inertia of moving masses
Manufacturing Time	The novel bearing design and the application of diamond turning allows lower manufacturing time
Ultra-Precision Manufacturing	The precision capability is completely dependent upon diamond turning as the fabrication process
Pneumatic Hammer	The Novel bearing design allows better control over bearing gap generation
Bearing Packaging Size	The Bi-conic configuration selected has the smallest packaging size compared to other configurations with similar capabilities
Restrictor and Compensator Design	The self-compensation groove restrictor design allows better load carrying capability as compared to orifice restrictor-based designs

Table 3 Summarized Results

6 Future Research

6.1.1 Bearing Manufacturing

In future research the aerostatic bearing could be manufactured based on the manufacturing drawing and processes developed in section 4 of the research.

6.1.2 Compliance Study between manufactured and designed bearings

At this stage the bearing performance can be compared to the specification developed in section 2-3.

6.1.3 Feedback

The deviations could be quantified from section 4-2 and then the manufacturing and design process could be recalibrated for further analysis.

7 Conclusion

In the current aerostatic bearing manufacturing, one of the key issues that increases the time and complexity of the manufacturing process is the gap generation between bearing surfaces which is responsible for the stiffness of the bearing. This research towards of the failure of the aerostatic bearings and developing a new manufacturing process allows better capability towards bearing gap generation without repeated machining of the bearing surface.

The manufacturing process is more economical with base material as Aluminium coated with hard nickel supported with diamond turning. Which would allow high material removal rate, low manufacturing time, while maintaining the form accuracy of the bearing surface.

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