Project Deliverable

Grant Agreement number	308952
Project acronym	OMSoP
Project title	Optimised Microturbine Solar Power system
Funding Scheme	FP7-ENERGY.2012.2.5.1:RESEARCH, DEVELOPMENT AND TESTING OF SOLAR DISH SYSTEMS
Work Package	WP4 – Project Management and dissemination
Deliverable number - title	D1.3.3 Bearing System Selection
Lead Beneficiary	University of Seville (USE)
Dissemination level	PU
Delivery month	March 2014 (Month 14)
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OMSoP project overview

The OMSOP project pre-design phase comprehend the selection of the sustention system of the compressor-turbine coupling and the electric generator, whether these are mounted in a single shaft or in various shafts.

The reference commercial product for the first design is a 3kW micro gas turbine produced by the OMSOP partner Compower. Also, a turbocharger prototype is now under construction by City University of London. The bearing system used by Compower and the bearing systems under study for the prototypes will be described in this report.

At the same time, an overview of the different technologies and materials employed to manufacture the bearings will be presented. Then the technical requirements for the OMSOP system under study will be described and a possible general choice for the bearing system will be proposed.

OMSOP project: bearings system requirements

The requirements set out for the bearings during this pre-design phase are not final but, and on the contrary, will vary depending on the final design of the micro gas turbine and PCU.

The general boundary conditions received from the partners are:

- Shaft speed: in the order of 150000 rpm as indicative value
- Axial (51 N as indicated by City University) and radial loads
- Need for high reliability and lifetime
- Need for low manufacturing and operation costs
- Durability in high temperature environments

The capacity to operate at low shaft speed is also important due to the very likely variable speed operation of the turbine. Also the dynamics of the micro turbine suggest that fast start-up will be a strong requirement. This is reflected in the needing for a high fatigue life of the components.

Typologies of bearings systems

There are many types of bearings which can be selected for a particular application. It is thus a good practice to examine all the possibilities with respect to the specifications of the project prior to a specific design adopting one of them. In this regard, the selection of a particular bearing design must anticipate the system needs as it will be costly and time consuming to change this decision at a later stage.

The bearing system should be cheap, reliable, small, light and efficient in order to reduce capital and O&M costs. At the same time, the choice has to be compatible with the specific load and operation expected from the operating envelope of the system.

The bearings can be are classified in:

- Magnetic bearings.
- Dry rubbing bearings.
- Impregnated bearings.
- Conformal fluid film bearings.
- Rolling-element bearings.

Each one of these typologies have certain operational constrains which eventually discard some of the options. Nevertheless, an initial assessment of the optimal operational range allows to discard some of them due to certain restrictions or, simply, poor performance expected. Hence, a look-up at all the available technologies is initially presented to have an global vision of the design problem before the selection of the most suitable system.

Magnetic bearings. [1]

The active magnetic bearings ensure minimum mechanical losses by relying on magnetic fields to support the shaft. Thus, there is no contact between bearing and rotor, enabling the operation with no lubrication nor mechanical wear. Additionally, the rotodynamics of the shaft can actively be controlled through the bearing.

One of the main application areas is turbomachinery. This kind of bearing is used in small turbo-molecular pumps, blowers for CO_2 lasers, compressors and expanders, large turbo-generators, etc.

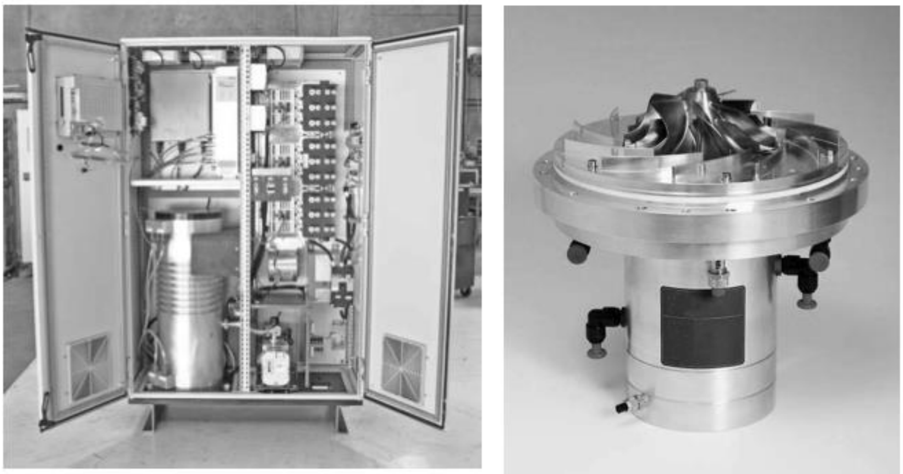

Figure 1: Magnetic bearings in a micro compressor.

The magnetic bearing is a mechatronic device. The main components are:

- a sensor that measures rotor displacement from a reference position,
- a microprocessor that derives the signal,
- a power amplifier that converts the signal into control current
- an actuating magnet that generate magnetic forces with the current circulation.

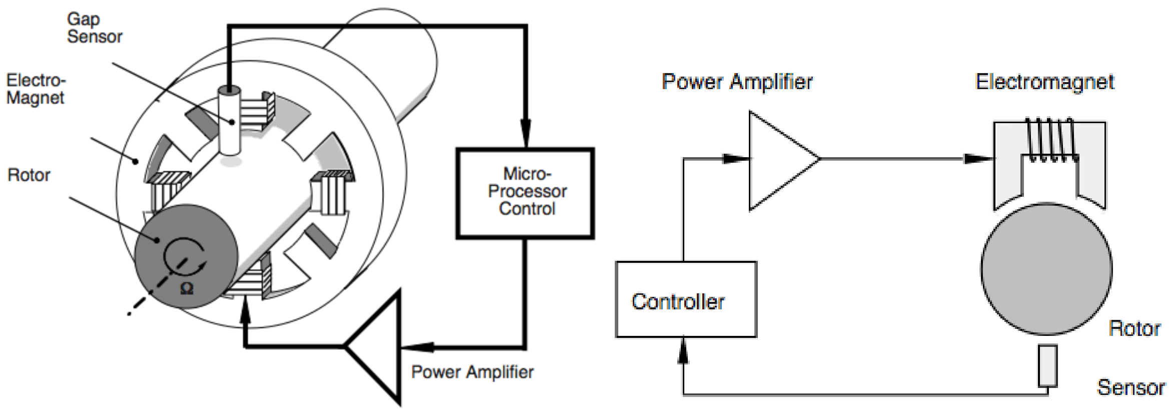

Figure 2: General arrangement of a magnetic bearing.

The control law of the feedback is responsible for the stability of the hovering state and the stiffness and damping of the suspension. Stiffness and damping can be varied widely between physical limits of the bearing, these being be easily adjusted to the technical requirements.

The most widely used magnetic bearings are the active electromagnetic bearings that work with the reluctance force of the magnetic field generated. The main properties of this technology are:

- Free contact, absence of lubrication and contaminating wear.
- The gap between rotor and casing is ≈0.1mm.
- The rotor is allowed to rotate at high speeds. The circumferential speed in the bearing can be as high as 350 m/s and large shaft diameters are possible. This allows for stiffer shaft that are less sensitive to vibrations.
- Low bearing losses. At high operating speeds the losses are 1/5 - 1/20 lower than those of ball and journal bearings, resulting in lower operating costs.
- The specific load capacity of the bearing, with respect to the cross-sectional area, is 20 – 40 N/cm^2, depending on the type of ferromagnetic material and the design of the bearing magnet. The maximum bearing load is proportional to the bearing size.
- The dynamics of the free contact hovering depend on the implemented control law even if the microprocessor makes the design versatile. Thus, it is possible to adapt the stiffness and damping, within the physical limits, to the bearing duty and to the actual rotor state and speed.
- It is possible to use retainer bearings. These are additional ball or journal bearings, usually not in contact, which in case of malfunction or overload operate only for a short time.
- The unbalance compensation and the force-free rotation are control features where the vibrations due to residual unbalance are measured and identified.
- The precision depends on the quality of the measurement signal loop. If there is an inductive sensor, the precision is 1/100 - 1/1000 mm.
- Diagnostics of the operation are readily performed.
- Low maintenance costs and high lifetime.
- The cost structure (breakdown) depends highly on the control software. In a series production, this cost can be strongly reduced.

A summary of the most essential design criteria of active magnetic bearings and their limitations is presented below.

1. The load capacity depends on the arrangement and geometry of the electromagnets, magnetic properties of the material, power electronics and control laws. The requirements of carrying a load (static and dynamic) have to be taken into account when selecting the bearing characteristic that permit optimal operation within the technical limits. The load capacity is limited by the saturation flux in the ferromagnetic material. In other words, the sustentation force generated depends on the magnetic force which depends again on the maximum current; this is a design limitation for the application. For high static loads, the limitation comes about to ensure the adequate dissipation of the heat generated by the coil current and for saturation of the flux density. Therefore, a high design temperature and a proper saturation flux have to be taken as design criteria.

Of special importance is the specific load capacity, which compares the carrying force of different bearing size. In Si-alloyed transformers sheet this parameter achieves 37 N/cm^2 whereas in Cobalt-alloyed units it can increase to $65N/cm^2$.

2. Key components in this type of bearings are the controller and actuator. The controller is a digital signal processor or a field programmable gate away. It controls the dynamic behaviour of the rotor motion. The magnetic actuator has an output voltage power amplifier limited at a certain voltage and a maximum frequency bandwidth.
3. The rotational speed is limited to 5 kHz for problems such as eddy currents in the ferromagnetic material, hysteresis losses, and air drag losses. The circumferential speed is a measure of the centrifugal load that causes the tangential and radial stresses. It has a supercritical threshold which has to be exceeded by the rotor to reach its operational speed.
4. Even if operating temperatures of up to 800°C and 600°C at 50,000 rpm have been demonstrated, materials play a critical role in these applications. Thus, the long-term exposure to high temperature needs further research, as the actually available materials do not yet allow a sufficient lifetime at temperatures above 400◦C. Problems arise from structural changes of the material, micro migration of alloys, and creep. In addition, heat dissipation of the internally generated losses under heavy bearing loads will need special attention.
5. There is no mechanical friction, so the losses are produced in the stationary parts, in the rotor and in the control system. The copper losses of the windings are located in the stator whereas the rotor incurs iron losses for hysteresis (losses proportional to the frequency of re-magnetization), eddy currents and air drag losses.

   The heat source produced by the losses in the windings of the stator and in the amplifier has to be dissipated to not affect the maximum achievable load capacity. The iron losses depend on the rotor speed, the material used for the bearing journal, the distribution of flux density over the circumference of the journal. The breaking torque caused by the iron losses consist of the constant component of hysteresis losses and a component of eddy current losses in direct proportion to rotor speed. The hysteresis losses arise if at re-magnetization the B-H curve travels along a hysteresis loop. The area of the re-magnetization loop depends on the material of the magnet and amplitude of flux density variation. The eddy current losses arise when the flux density within the iron core changes. These losses can be reduced dividing the iron core into insulated, laminated sheets or using sintered cores. The air drag losses can be high at high rotational speeds. Very small air gaps increase the air drag.
6. The precision performance of the active magnetic bearings systems is directly affected by the quality of the sensor signals.
7. The smart machine concept is applicable if there is high level of precision, ability for self-diagnosis, auto calibration, calculation of residual lifetime and auto correction of measurement errors.

The main limitations in AMB are on the state of actual design and materials and on the following basic physical relations.

- Maximum load capacity depends on design.
- Specific load capacity depends on the available ferromagnetic material and its saturation properties: 32-60 N/cm^2.
- Frequency and amplitude of the disturbances acting on the rotor can be controlled through an adequate power amplifier design.
- Maximum shaft speed for commercial applications is 6 kHz, even though the technology has been demonstrated for 300 kHz.

- Circumferential speeds, causing centrifugal loads, are limited by materials to up to 250 - 300 m/s.
- The size of the bearing depends on design and manufacturability.
- High temperature bearings usually exhibit shorter lifetimes.
- Losses at high speeds are low.

Looking at the technical requirements set in the project, this type of bearings would be a possible choice. Nevertheless, even if possible, the high complexity and the corresponding high engineering and production cost call for a different type of bearing to be looked for.

Dry rubbing bearings. [3]

In dry rubbing bearings, the two surfaces rub together in rolling or sliding motion, or both, and are lubricated by boundary lubrication. In boundary lubrication solids are not separated by the lubricant, fluid film effects are negligible and there is considerable asperity contact. The contact lubrication mechanism is governed by the physical and chemical properties of thin surfaces films of molecular proportions.

The frictional characteristic is determined by the properties of the solids and the lubricant film at the common interfaces, the friction coefficient being independent from fluid viscosity. In the boundary lubrication regime, the degree of asperity interaction between surfaces and the subsequent wear rate increase as the load increases.

For the cited characteristics, boundary lubrication is used for heavy loads at low running speeds, where fluid film lubrication is difficult to attain. This type of bearing technology is then not considered a potential candidate for OMSoP, inasmuch as the requirements for this project are just the opposite: high speed and relatively low loads.

Impregnated bearings. [3]

A porous material (usually metal) impregnated with a lubricant is the basis for this type of bearing. The porous material is usually made by sintering a compressed metal powder, where the pores serve as reservoirs for the lubricant. Then, the lubricant absorbed gives a self-lubricating effect to the bearing.

The load-carrying and frictional characteristic depends on the properties of the solid matrix and the lubricant in conjunction with the opposing solid. The lubricant can be a liquid or grease and, in both cases, the lubricant mechanism is that of partial lubrication. This partial lubrication is a mixed mechanism between boundary lubrication and fluid film effects. Interaction takes place between one or more molecular layers of boundary and fluid film effects. This lubrication action develops in the bulk of the space between the solids. The average film thickness is less than 1μm and greater than 0.01 μm.

The application of this type of bearing is restricted to low sliding speeds but they can carry high mean pressures. For this reason, as with dry rubbing bearing, this technology is not further taken into account in the study.

Conformal fluid film bearings. [3]

In conformal fluid film bearings the opposing surfaces are completely separated by a lubricant film which can be in liquid or gas phase.

The load-carrying capacity derived from the pressure within the lubricant film may be generated by: the motion of the machine elements (self-acting or hydrodynamic bearings), external pressurization (hydrostatic bearings), by hydrodynamic squeeze motion or a combination of these actions. The laws of viscous flow govern the frictional characteristics of the bearings. The properties of the material (fatigue life, low friction properties) have also to be considered at low speeds.

The methods used to feed lubricant into conformal fluid film bearings vary considerably. A brief discussion of this follows.

At low speeds and modest loads a simple ring-oiler that draws oil up to the bearing from a reservoir by means of viscous lifting might be sufficient. The oil can be supplied under pressure to ensure adequate filling of the clearance space.

Hydrostatic bearings require elaborate lubricant supply systems where the lubricant enters the bearing at a high pressure (order of MPa). The hydrostatic bearings are useful at high loads and low speeds or when film stiffness perpendicular to surface motion is important.

In the hydrodynamic lubrication, the dynamic viscosity of the fluid dictates the behaviour of the assembly. The bearings adopting this technology are characterized by conformal surfaces. The positive pressure that sustains the load in those bearings is produced because the bearing surfaces converge and the relative motion and the viscosity of the fluid separate the surfaces. A load applied in the normal direction can so be supported. The pressure developed (around 5 MPa) is not generally large enough to produce elastic deformation of the surfaces. The minimum film thickness is a function of normal component of the load applied, velocity of the lower surface, lubricant viscosity and geometry. In particular the proportionality between the minimum film thickness and velocity and load is of the type $h_{min} \propto \sqrt{\frac{v}{N}}$.

In hydrodynamic lubrication the fluid film generally prevents the contact between surfaces. The lubrication of the solid surfaces is hence governed by the bulk physical properties of the lubricant (viscosity), and the frictional characteristics arise purely from the shearing of the viscous lubricant.

The positive pressure profiles that have to be produced in the bearing to sustain normal loads can be obtained with a slider bearing, with a squeeze film bearing and with a externally pressurized bearing (hydrostatic). The slider bearing works as the lubricant film thickness decreases in the sliding direction. The squeeze film bearing works with a squeeze action when the surfaces approach each other. The squeeze mechanism of pressure generation provides a valuable cushioning effect when the bearing surfaces approach each other, hence when the film thickness is diminishing. Finally the hydrostatic lubrication provides a pressure drop across the bearing that supports the load. The load-carrying capacity is independent from bearing motion and lubricant viscosity. There is no surface contact and no wear at start-up and shut-down as there is with slider bearing.

The conformal fluid film bearings are typically divided into liquid or gas lubricated. Nevertheless, other classifications are possible: for their mode of operation into hydrodynamic, squeeze, hydrostatic and hybrid; for the direction of the load they support into journal, combined or thrust; with respect to the nature of the load they support as steady or dynamic and also depending on the many different geometries they can adopt.

Within the scope of this analysis, and due to the application being considered, only the hydrodynamic conformal fluid film bearing will be considered.

There are many additional features that must be looked at when designing one of these bearings. Above them, and besides hydrodynamic considerations, materials are of special importance and so is manufacturing. In order to further assess this aspect, a discussion follows where the different materials are discussed since this has a capital importance not only on costs but also on lifetime and reliability.

On the basis of the characteristics and specifications considered inOMSoP, the different materials of the bearing system for conformal surfaces are categorized as:

- Metallic: Babbitt, bronzes, aluminium, alloys, porous metals and metal overlays.
- Non-metallic: Plastics, rubber, carbon-graphite, wood, ceramics, cemented carbides, metal oxides, and glass.

The principal metallic materials used are:

- Tin and lead-base alloys. Babbitts are tin or lead-base alloys with excellent embeddability and conformability. They have relatively low carrying capacity which can be increased by metallurgically bonding these alloys to stronger backing materials such as steel, cast iron, or bronze. Decreasing the thickness of the Babbitt lining increases fatigue strength as so do the high temperature effect. They exhibit excellent compatibility.
- Copper-lead alloys. On steel-backed bearings two kinds of alloys are used as lining materials. One alloy consist of 60% copper and 40% lead, the other 70% copper and 30% lead. This bearing provides higher load carrying capacity because the alloys are either strip cast or sintered onto the backing strip. They have higher fatigue resistance and operate at higher temperatures. They have poor anti-seizure properties and they are susceptible to corrosion. These two poor characteristics are improved when they are used as tri metal bearings with a lead-tin or lead-indium overlay electrodeposited onto the copper-lead surface.
- Bronzes. Several bronzes alloys are used as bearing material: lead, tin, aluminium bronzes. They have good structural properties and so they can be used as cast bearing without steel backing. Lead bronzes up to 25% lead provide higher load-carrying capacity, fatigue resistance and high temperatures resistance than Babbitt alloys. Tin contents up to 10% improve the strength properties. Higher-lead bronzes are used with soft shaft and lower-lead bronzes are used with hard shaft.

The principal non-metallic materials used are thermosetting materials and thermoplastic materials. In thermosetting materials, the fabrics of non-oriented fibres are set in phenolic or cresylic resins. The limits to using non-metallic materials are maximum capacity load achievable, maximum operating temperature, maximum speed and the PV limit.

- Carbon graphite. This material has excellent self-lubricating properties. It can operate up to 370°C in oxidizing atmospheres and up to 700°C in inert atmospheres. It is highly resistant to chemical attack but their application must be limited to low speeds and low loads due to the lack of lubricant.
- Phenolic. This plastic bearing material is produced in the laminated form. It is made by treating sheets of either paper or fabric with phenolic resin, by stacking the desired number of sheets and by curing with heat and pressure to bond them together and set the resin. Filling materials such as graphite and molybdenum disulphide are added in powdered form to improve lubrication and strength. They have good resistance to seizure, low thermal conductivity, good resistance to chemical attack, good conformability, high degree of embeddability, and good resilience (highly resistant to damage by fatigue and shock loading).
- Nylon. It is a thermoplastic material. Nylon bearings can be melded, or nylon powders can be sintered. Nylon has a good abrasion resistance, low wear rate, good embeddability, good anti seizure properties and low thermal conductivity. The failure usually comes about because of overheating.
- Teflon. It is a thermoplastic material based on the PTFE with low friction coefficient. It has excellent self-lubricating properties so it can be used in dry bearings. It is resistant to chemical attack in a range -260°C +260°C. It has low stiffness, high thermal expansion coefficient, low thermal conductivity and poor wear resistance. This last feature is improved though by adding fibres such as glass, ceramics, metal powder, metal oxides and graphite.

The materials here described can be used to produce different bearings supports:

- Solid bearing. Bearings are machined directly from a single material.

- Lined bearing. Bearing material is bonded to a stronger backing material. The thickness of the linin varies between 0,25mm and 13mm.
- Filled bearing. A stronger bearing material is impregnated with a bearing material that has better lubricating properties.
- Shrink-fit liner bearing. Carbon-graphite or plastic liners are shrunk into a metal backing sleeve by retaining devices such as setscrews, dowels and clamping flanges.

The most promising typology of bearing in the conformal fluid film bearing category is the hydrodynamic fluid film bearing. For this, the working lubricant fluid can be liquid or gaseous and thus both types will be analysed in detail.

Liquid-lubricated hydrodynamic bearings. [5]

The oil-lubricated hydrodynamic bearings most frequently used in micro gas turbine applications are the floating sleeve bearings, as explained by Soares in [4]. The operating principle of these bearings is that the shaft rotates in an eccentric position and with a clearance that creates the load-carrying wedge sustaining the shaft. The minimum oil film thickness has to be from three to five times the roughness of the journal shaft (peak to peak).

Sleeve bearings are designed with a specific oil viscosity in mind, which is selected based on assumptions about the bearing operating temperature ranges, even though things such as oil film thickness, heat generation, and bearing property have to be considered as well. Sleeve bearings can be oil ring or flood lubricated. In oil ring lubrication the ring is rotated by contact on the shaft. The lower portion of the oil ring dips into the oil, and as this portion rotates to the top, the oil runs down the surface of the shaft. Flood lubrication is used where it is not possible to use an oil ring(s) or in cases where additional bearing cooling is required. Although other means of bearing cooling exist, flood lubrication is the most popular. The flood lubrication system must be able to deliver a certain volume of oil at a certain pressure. An orifice within the sleeve bearing housing will throttle the oil to deliver required volumetric flow rate. The oil exits at atmospheric pressure back to the flood lubrication system supply reservoir through the outlet pipe. Sometimes, the bearings can be designed to maintain enough lubrication to handle a coast down if power is lost.

As explained, the oil has to be selected looking at temperatures and heat generation. The total bearing temperature will be a function of the heat generated in the bearing, the heat absorbed by the bearing (caused by external and internal heat sources in proximity of the bearing), and the bearings ability to shed the heat. In sleeve bearing machines, because of the larger bearing clearance, lower (and asymmetric) stiffness characteristic, and a high degree of damping, it is possible to have significant movement in the shaft that would not be detected at the bearing housing.

Although sleeve bearings have speed limits, they are very high. Sleeve bearings are theoretically considered to have an infinite life, and, when properly maintained the life may be extremely long. The only time that a properly maintained sleeve bearing should get any significant wear is at prolonged low speed operation. During low speed operation the oil film will not be at its desired thickness and subsequently, increased bearing wear results. At standstill, the oil film thickness is zero. Such conditions may be encountered during extended startup or coast down periods. If the frequency of such events is often enough, hydrostatic jacking is recommended to minimize bearing wear. Hydrostatic jacking is where the shaft journal is lifted off the bearing by oil pressure from the lower part of the bearing before the shaft begins to turn, thus ensuring adequate film thickness at extremely low speeds (down to zero speed). Hydrostatic jacking requires special sleeve bearings and an oil pressurization system and is normally only available on very large machines.

Motor sleeve bearings are not intended for use in applications where there is either side loading or axial loading. In regards to side loading, cylindrical sleeve bearings are only intended to take the weight of the rotor in the nearly vertical direction. As far as axial loading is concerned, there is normally an axial babbitted surface. In most sleeve bearings designed for horizontal application, the axial surface is designed to tolerate only momentary axial loading as could be seen on start up. A sufficient oil film is never developed; therefore, sustained axial loading is not permissible. Some sleeve bearings are designed to take continuous axial load but because of the greatly reduced surface area, the axial load capability is very slight.

The heat generated at the bearing surface is removed through oil being supplied to and flowing through the loaded bearing surface. Three methods are commonly used: self cooled bearings, force-feed lubrication, and water-cooling. In self-cooled bearings the heat in the oil sump is transmitted to the bearing housing, which is cooled by external airflow around the externally finned surfaces. This is always the first choice of cooling methods, but often more heat is generated/absorbed by the bearing than what a self-cooled bearing can reject. If that is the case, one of the other two mechanisms must be employed. In force feed lubrication systems the oil is taken out of the bearing housing. There is a bearing sump, but the key here is that the oil itself is cooled before it returns to the bearing. Water-cooled bearings simply imply that a cooling coil is inserted in the oil sump. Cool water is run through the cooler thus removing heat from the oil.

Sleeve bearings are lubricated with high-grade turbine oil. In this regard, it is crucial to use the proper viscosity oil. If a different viscosity than what the bearings were designed for is used, than several things may occur: inferior rotodynamic performance, change in bearing oil film thickness, or increase in bearing heating.

Sleeve bearings can be replaced without acting on the lower bearing housings and with the driven equipment coupled. This can be a significant feature if rigging requirements make it extremely difficult to remove the motor. When sleeve bearings fail, they tend to be less catastrophic, and generally provide information as to the degrading state of the bearings. When the bearings fail catastrophically, the bearing itself tends to be sacrificial, as the bearing Babbitt is much softer than the shaft steel. Generally it is possible to clean up the shaft with minor regrinding of the bearing journal surface.

The calculated life expectancy of any bearing is based on four assumptions, even though, in general sleeve bearings have an extremely long life.

1. Sufficient lubrication is always available to the bearing.
2. The bearing are mounted without damage.
3. Dimensions of parts related to the bearing are correct.
4. There are no internal defects in the bearing.

Gas-lubricated hydrodynamic bearings. [8]

The use of gas as lubrication fluid can be very useful given their viscosity-temperature relationship. The viscosity of gases increases with temperature and is only moderately affected by changes in temperature and pressure. On the contrary, liquids have a strong inverse variation of their viscosity with temperature and pressure.

These kind of bearings (air foil bearings) do not differ a lot from hydrodynamic oil lubricated bearings except for the fact that the fluid is compressible. Thus, since air is 1000 times less viscous than even the thinnest mineral oils, the viscous resistance is much less. In correspondence, the minimum distance between the bearing surfaces is smaller and hence special precautions must be taken during manufacturing.

Some strengths of gas-lubricated bearings are the extremely low friction or viscous resistance, ample and clean lubricant, not contaminating lubricant, wide range of operating temperatures, film do not break down from cavitation or ventilation.

Some weakness are an specific load-carrying capacity lower than oil-lubricated, fine finish surfaces required, extremely good alignment required, extremely accurate dimensions and clearance requirements, high speed requirement, low load required, poor stability characteristic.

Based on the features, it makes sense that the main field of application is gas machinery in power systems where the cycle gas is used in the bearings, thus eliminating the need for a conventional lubrication system.

After a general introduction to the main pros and cons of the technology, a more ample discussion about its application to turbomachinery is now presented [6]. For the case of foil bearings, the main advantages are:

- High reliability: Foil bearing machines are more reliable because there are fewer parts necessary to support the rotating assembly and there is no lubrication needed to feed the system. When the machine is in operation, the air/gas film between the bearing and the shaft protects the bearing foils from wear. The bearing surface is in contact with the shaft only when the machine starts and stops. During this time, a coating on the foils limits the wear.
- No scheduled maintenance: since there is no oil lubrication system in machines that use foil bearings, there is never a need to check and replace the lubricant. This results in lower operating costs.
- Soft failure: because of the low clearances and tolerances inherent in foil bearing design and assembly, if a bearing failure does occur, the bearing foils restrain the shaft assembly from excessive movement. As a result, the damage is most often confined to the bearings and shaft surfaces. The shaft may be used as is or can be repaired. Damage to the other hardware, if any, is minimal and repairable during overhaul.
- Environmental durability: foil bearings can handle severe environmental conditions such as sand and dust ingestion. Larger particles do not enter into the bearing flow path and smaller particles are continually flushed out of the bearings by the cooling flow. This ability to withstand contamination eliminates the need for filters in the airflow.
- High speed operation: compressor and turbine rotors have better aerodynamic efficiency at higher speeds. Foil bearings allow these machines to operate at the higher speeds without any limitation as with ball bearings. In fact, due to the hydrodynamic action, they have a higher load capacity as the speed increases.
- Low and high temperature capabilities: many oil lubricants cannot operate at very high temperatures without breaking down. At low temperature, oil lubricants can become too viscous to operate effectively. Foil bearings, however, operate efficiently at very high temperatures, as well as at cryogenic temperatures.

The main disadvantages are:

- Low specific load-carrying capacity: this results from the relatively low viscosity and damping of gas films. Thus, for acceptable applications air bearings need larger dimensions and thinner fluid films than liquid-lubricated bearings.
- Fine finish surfaces: thinner films require closer control of manufacturing tolerances surface finishes, thermal and elastic distortions and alignments.
- Poor stability characteristic: the low damping of the gas film makes it necessary to carefully analyse the dynamic characteristic of the mechanical system employing the gas bearing, since if a critical speed or instability is encountered, there may be not enough damping to suppress it or control it. With liquid-lubricated bearings these instabilities might have been suppressed or passed over unnoticed because of the greater damping action that inherently exists with liquids.

The principle of an air or gas bearing is simple. When two surfaces form a wedge, and one surface moves relative to the other surface, pressure is generated between the surfaces due to the hydrodynamic action of the fluid, which carries load. In a journal bearing, the shaft deflects and a wedge is formed due to the eccentricity between the shaft center and the bearing center. Usual problems that do not permit to design a conventional bearing for a big range of loads and temperature are resolved by foil bearings. While stationary, there is a small amount of preload between the shaft and the bearing. As the shaft turns, a hydrodynamic pressure is generated, which pushes the foils away from the shaft and the shaft becomes completely airborne. This phenomenon occurs instantly during start-up at a very low speed. When the shaft is airborne, friction loss due to shaft rotation is very small. As the shaft grows, the foils get pushed further away keeping the film clearance relatively constant. In addition, foils provide coulomb damping due to relative sliding, which is essential for stability of the machine. Various concepts of journal and thrust foil bearings have been tested for airplane engines.

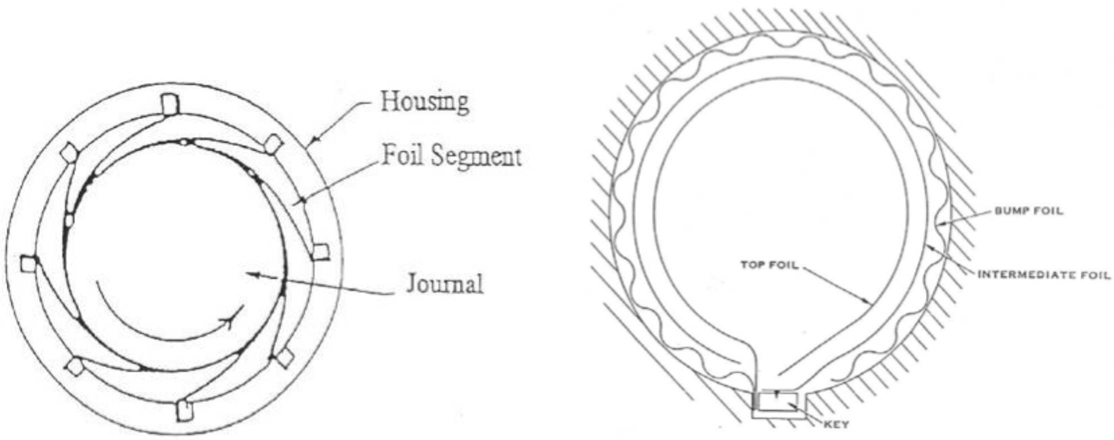

Figure 3: Multipad (left) and reverse Multilayer (right) gas bearings.

AiResearch has pursued the Multipad concept shown in Figure 3. Multiple pads form an iris and provide a preload when the shaft is not running. During starting, the iris expands and a cushion of air is formed between the bearing and the shaft. The top foil is coated with Teflon-S or a polyimide coating to provide lubricity during starts and stops.

Hamilton Standard has pursued reversed Multilayer journal bearing concept for aircraft engines. The single corrugated (bump) foil, which has a bilinear spring characteristic, is restrained in an axial keyway in the outer shell along one edge. The intermediate and top foils are attached to a key along one edge and are wound in opposite directions. The top foil has a thin coating, which provides lubricity during startup and shutdown. As the shaft rotates, a wedge is formed due to the radial displacements of the shaft. Hydrodynamic action draws the working gas into the wedge where it is locally compressed. The corrugated foil acts as a spring that accommodates expansion, excursions and any misalignment. It also provides a flow path for the cooling air to remove parasitic heat from the bearing. In the Reversed Multilayer foil bearing, the adjacent foils move in opposite directions. The net result is that relative movement is additive, which in turn produces high coulomb damping.

Mechanical Technology Inc. (MTI) has pursued Hydresil foil journal bearing. Both the bump foil and the foil are spot welded to the sleeve. Various versions have been patented. The load capacity of the Hydresil is comparable to the Multipad or Reversed Multilayer foil bearing, but it has low damping.

A concept called Reversed Multipad has been patented by R&D Dynamics Corporation. It has the benefits of both Multipad and Reversed Multilayer designs. It has high damping as well as it requires low preload. Lower preload makes the machine start at a lower torque. Due to multipad design, the tolerances are not tight.

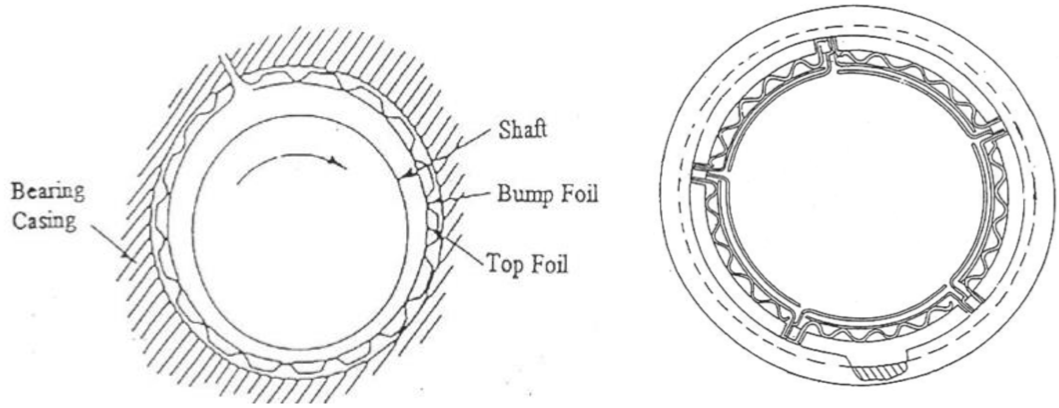

Figure 4: Hydresil (left) and Reverse Multipad (right) gas bearings.

Thrust bearings withstand axial loads in rotating machinery. They work on the same hydrodynamic principle as journal bearings. In a journal bearing the wedge action comes from eccentricity between the center of the rotating shaft and the center of the bearing itself, whereas in a thrust bearing the wedge is built in taking into account any deflection due the axial load.

Further to the previous discussion, DellaCorte – Valco [9] provide the three main technical hurdles to use foil air bearings: unable to withstand high load, lack of lubricants to perform high temperature start/stop, lack of reliable predictive performance methods and design guidelines. The first hurdle does not OMSoP directly due to the low load requirements. The second hurdle is of capital importance both for the start/stop operation and for the high temperatures that are inherent to OMSoP. This hurdle can nonetheless be overcome looking at recent experimental work where high-temperature lubricant coatings have credited over 100,000 starts/stops at temperatures as high as 650°C. This has been achieved with an uncoated nickel-based super alloy foil bearings, lubricated with PS304 plasma sprayed composite.

The third hurdle has not been successfully overcome. Foil bearings are inherently nonlinear and very difficult to model. This modeling difficulty is due to the complex nonlinear structure, hydrodynamic fluid, and thermal interactions between compliant foils and the elastic foundation support structure. Still, the “Rule-of-thumb” method by DellaCorte can be used to calculate the maximum constant load capacity at constant speed and steady-state conditions.

The risk perceived when using this technology is high given the low number of manufacturers with respect to the rolling-element bearings. The fabrication of foil bearings requires a technical knowledge of metallurgy, sheet material forming, and tribology. A recommended approach [10] by DellaCorte and Valco can be used to yield a preliminary design for the foil air bearing system. This four-step approach comprehends a conceptual feasibility approach, a bearing component development and testing, a simulated rotor system testing and a turbomachinery system demonstration.

As presented in [11], and despite these technology gaps, it can be said that the technology is now mature and ready to be commercialized at the large scale.

The most important reference technology, in stationary air-cycle micro gas turbines, for this type of bearings is used by Capstone. This company produces small regenerative micro gas turbines with nominal electrical power of 30kW and 60kW. The air bearings support the unique shaft element that connects the generator with the turbine and the compressor. The speed range is between 45,000 rpm and 96,000 rpm.

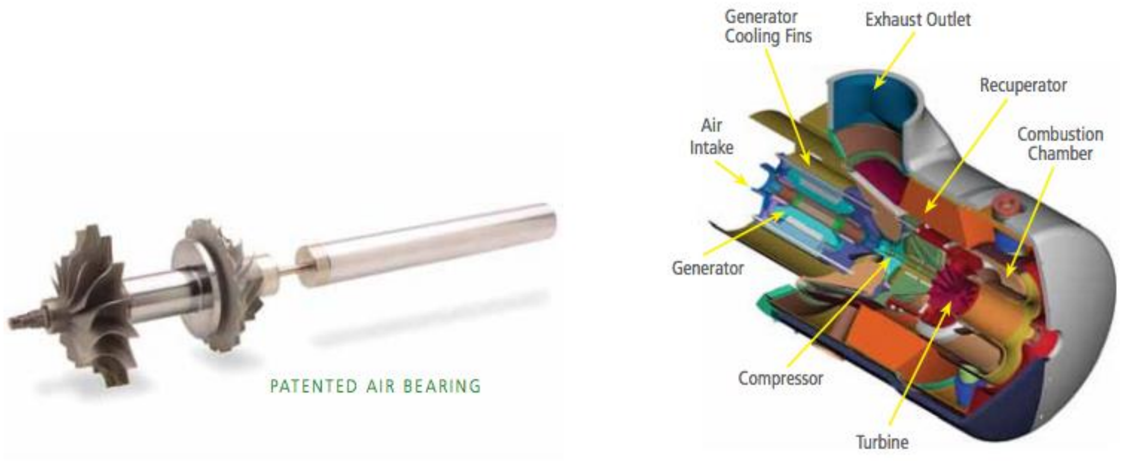

Figure 5: Capstone approach to air bearings.

The main characteristics of this technology are that it is oil free, produce less drag, do not wear with time, increase the overall performance and the reliability of the rotating parts, is a clean technology that use the ambient fluid air and do not leak or burn any oil. In order to lift the shaft, this is rotated five times accelerating up to 20,000 rpm. By doing so an air layer will form between the foil and the shaft, which will effectively lift the foils up and away from the shaft. The springs in turn provide counterforce to the foils and air, keeping the shaft centred. There is no friction and no wear because of the absence of any metal-metal contact.

Brayton Energy performed another important proof-of-concept test with this technology during the Brayton power conversion system project [12]. During the project, a solar-fueled turbines system was studied and a foil air bearing system was designed and tested for that application. The main reason to adopt this technology was that this type of bearings could achieve long life and service intervals in the microturbine applications. One of the most important and practical considerations that have to be take into account also in OMSOP is the avoidance of liquid lubricants (as required by oil-lubricated or rolling-element systems). This is due to the need to track the sun and thus the very man different positions adopted by the power conversion unit (where the engine is installed).

Figure 6: Brayton energy air bearing test configuration.

During the test, the engine was operated at 120% shaft-speed (140,000 rpm) with a low-temperature air turbine, configured to have similar weight and inertia of the hot turbine rotor. The test is needed to validate rotor dynamics models and confirm the feasibility of the air bearing design. Addition mechanical analyses were performed yielding the following findings:

- The alternator magnets operate within rated limits.
- A turbine thrust balance analysis provided the necessary loads to properly size the thrust bearing. These loads have been successfully demonstrated on the air bearing test rig.
- Bearing stability was demonstrated over the full dynamic range.
- Within the intended operating range, nominally 95,000 rpm to 120,000 rpm, the vibration levels were below the target levels.
- No structural or fatigue damage was observed after five excursions to 140,000 rpm (20% over-speed).
- A compressor bleed-flow of <1% was found to be adequate to maintain alternator magnet temperatures within acceptable levels.

In conclusion, the airfoil bearings are probably the most appropriate bearing system for the OMSOP microturbine. There are still aspects to be resolved but these cannot be approached from a theoretical standpoint and thus must be postponed to the experimental stage when the final design will be optimized. Also, it must be acknowledged that the cost information for these bearings is not complete due to the lack of producers.

Rolling-element bearings. [3]

In rolling-element bearings the machine elements are separated by elements in predominantly rolling motion. These kind of bearings can be divided into oil or grease lubricated (fluid), ball or roller bearings (mode of operation), thrust, angular contact or radial bearings (direction of load they sustain), steady or dynamic (nature of load), single or double row (geometric form). Replacing the sliding action with a motion that is mainly rolling permits relative motion between machine elements. Some slipping, sliding or spinning might also take place. The relative motion, the load conditions and the lubricant properties determine the frictional characteristics. The lubricant (normally grease) is sometimes sealed into the bearing assembly, or it may be applied in a mist of fine droplets.

The lubrication in this kind of bearing is elasto-hydrodynamic (EHL). In this kind of lubrication, subgroup of hydrodynamic lubrication, the elastic deformation of the lubricated surfaces is also significant. The features of a hydrodynamic slider bearing are also important here: converging film thickness, sliding motion, viscous fluid between the surfaces. This elastic lubrication is associated with non-conformal surfaces. There is a division in this kind of lubrication between hard EHL and soft EHL.

The hard EHL relates to materials with high elastic modulus such as metals. The elastic deformation and the pressure-viscosity effects are equally important. The maximum pressure is usually between 0.5 and 3 GPa. The minimum film thickness usually exceeds 0.1 μm. The elastic deformations in these conditions are several orders of magnitude larger than the minimum film thickness and the lubricant viscosity can vary by more than 10 orders of magnitude within the lubricating conjunction. As in the hydrodynamic lubrication, the film thickness depends on load, velocity, viscosity of the lubricant, geometry and the effective elastic modulus and pressure-viscosity coefficient of the lubricant. The functional dependence of film thickness on load and speed is different than for hydrodynamic bearings. The exponent of the load in the normal direction is seven times larger for HL then for hard EHL, so the film is affected by the load to a lesser extent. The exponent of mean velocity is slightly higher for hard EHL than for HL.

The soft EHL relates to materials of low elastic modulus such as rubber. In soft EHL, the elastic distortion is high even with light loads. The maximum pressure is 1 MPa and this low pressure has a negligible effect on viscosity variation throughout the conjunction. With respect to the

HL, the effective elastic modulus is the only parameter controlling the film thickness. The frictional coefficient is essentially independent from fluid viscosity. These kind of bearing will be taken into account in this analysis for its good compatibility with the requirements set forth by OMSoP.

The same subdivision of metallic and non-metallic materials is used for the bearing of non-conformal surfaces. The bearing system that use non-conformal surfaces contact is that of rolling-element bearings. This bearing operates at high compressive stresses for millions of stress cycles as the balls or rollers rotate through the loaded zone of the bearing. The race and the rolling element must therefore be hard and with high fatigue resistance. The most common materials used, matching these properties, are ferrous alloys and ceramics.

- Ferrous alloys. Several available molybdenum and tungsten alloyed steels have been evaluated for their good capability with higher temperature. These alloys have excellent high-temperature hardness retention. Also, if melted in air, they do not have fatigue resistance for the non-metallic inclusions produced, even if these inclusions can be reduced or eliminated with vacuum techniques (vacuum induction melting, vacuum arc melting).

  Surface-hardened or carburized steels are used in many bearings where, due to shock loads or cycling bending stresses, the fracture toughness of thorough-hardness steels is inadequate. When the oil does not protect from corrosion, a corrosion resistant alloy should be used.

- Ceramics. There are several ceramics materials having been experimented: alumina, silicon carbide, titanium carbide, and silicon nitride. The use of ceramics is advantageous for many reasons. They have high temperature capability because they exhibit elastic behaviour up to 1000°C. They are resistant to corrosion. They have lower density which provides improved capacity at high speeds, where centrifugal effects dominate. Finally, they also have low thermal expansion coefficient with respect to ferrous alloys.

The lubricant and the feeding system are of capital importance to meet the requirements of the bearing system. There are numerous ways to feed oil into the rolling-element bearings, each one of them having advantages and disadvantages.

In addition to choosing the type of bearing to use, the type of lubrication and type of bearing cavity (cleanliness) protection is equally important. Rolling element bearings are typically lubricated by one of three methods: grease lubrication, oil mist lubrication, and oil sump lubrication. Oil sump lubrication is usually employed when the bearings need additional cooling than what can be offered by grease or oil mist lubrication. Typically only vertical motors use this type of lubrication arrangement. A cooling coil is often submersed in the oil for additional cooling. Motors with grease-lubricated bearings have the lowest initial cost (compared to other lubrication methods). They however require highest maintenance. Additionally, this method is the most problematic. Over-lubrication, under-lubrication and lack of cleanliness during re-lubrication are common problems that impact not only cost, but motor reliability as well. As long as the oil mist system is correctly set up and working properly, the bearings are always assured a clean supply of lubricating oil. Although initial cost is higher, in many cases the life cycle cost is lower as the maintenance requirements are much less. In addition reliability is higher.

The OMSOP project partner Compower produces a 3kW micro gas turbine. The thermal motor is connected to the electric generator. As communicated by Compower, the bearing system is composed in this case by two radial ball bearings. These two bearings are placed on each side of the electric generator to support it. The compressor and the turbine are overhung. The lubrication method is an oil spot method that does not require any cooling system and works with compressed air as pulverized grease vector. The design speed for the system generator-compressor-turbine is 150,000 rpm that is supercritical for the shaft, thus managing that the ball bearings work with squeeze film to generate the required positive pressure to sustain the shaft. The so-called oil-spot or oil-air method is used to reduce the temperature at high-speeds.

This method uses compressed air to transport small, accurately metered quantities of oil as small droplets along the inside of feed lines to an injector nozzle, where it is delivered to the bearing. This minimum quantity lubrication method enables that the bearings operate at very high speeds with relatively low operating temperature. The compressed air serves to cool the bearing and also produces an excess pressure in the bearing housing to prevent contaminants from entering. Because the air is only used to transport the oil and is not mixed with it, the oil is retained within the housing. There is no residual oil to collect. For bearings used in sets, a separate injector should supply each bearing. Most designs include special spacers that incorporate the oil nozzles.

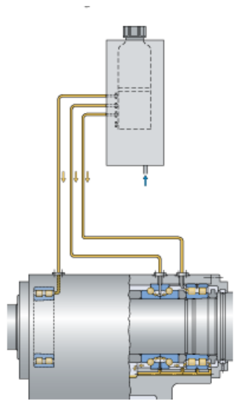

Figure 7: Bearing arrangement resembling the solution adopted in OMSoP.

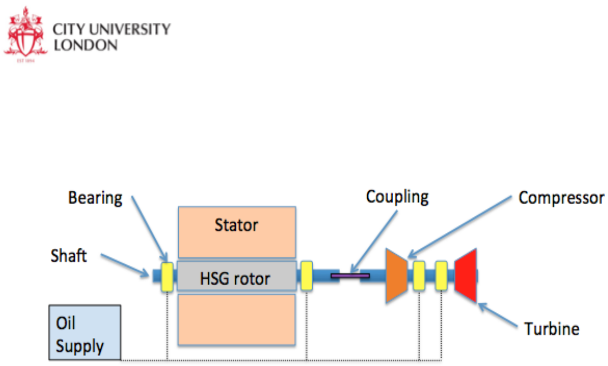

Figure 8: Bearing arrangement developed by City University London for OMSoP.

The bearing system selected for the prototype by the corresponding partners in OMSoP is a ball-bearing system analogous to that of Compower with the difference being that the turbine is not overhung but sustained by ceramics bearings. The bearings that will support the electric generator will probably be angular contact stainless ball bearings. The ceramic bearings, as declared by the manufacturer, can operate safely at speeds up to 150,000 rpm and at high temperature so they are useful for this application. Some characteristics are summarized in the product page provided by the cited partners.

Figure 9: Ball bearing manufactured by MBA. Preselected for OMSoP.

Designation	Main dimensions in [mm] [inch]			Load ratings acc. to DIN ISO		Ball set		Limiting speeds*		Preload		
Basic symbols	d	D	B	C_{0r} [N]	C_r [N]	Z	Dw [mm] [inch]	Oil [min^{-1}]	Grease [min^{-1}]	(L) light [N]	medium [N]	(S) heavy [N]
AC bearings, open, metric												
TYPE 1	**10.00** .3937	**19.00** .7480	**5.00** .1969	507	1556	12	**2.500** .0984	172,000	124,000	8	24	48
TYPE 2	**10.00** .3937	**19.00** .7480	**5.00** .1969	476	1488	12	**2.500** .0984	147,000	106,000	8	24	48
TYPE 3	**10.00** .3937	**22.00** .8661	**6.00** .2362	1050	2824	11	**3.175** .1250	157,000	113,000	15	44	88
			6.00	1407	2700							
TYPE 4	**10.00** .3937	**22.00** .8661	**6.00** .2362	985	2700	11	**3.175** .1250	133,000	96,000	15	44	88
						10						
TYPE 5	**10.00** .3937	**26.00** 1.0236	**8.00** .3150	1916	5137	10	**4.763** .1875	139,000	10,000	26	79	158

* The indicated speed limits are guide values for spring-loaded single bearings with low load; depending on the respective application, higher or lower speed limits may apply in practice.
** For use with oil lubrication, these bearings are also available without shields.
Subject to change due to technical improvement.

Figure 10: Specifications of the preselected ball bearing (I).

Designation	Main dimensions in [mm] [inch]			Load ratings acc. to DIN ISO		Ball set		Limiting speeds*		Preload		
Basic symbols	d	D	B	C_{0r} [N]	C_r [N]	Z	Dw [mm] [inch]	Oil [min^{-1}]	Grease [min^{-1}]	(L) light [N]	medium [N]	(S) heavy [N]
AC bearings, open, metric												
TYPE 1	**10.00** .3937	**19.00** .7480	**5.00** .1969	507	1556	12	**2.500** .0984	172,000	124,000	8	24	48
TYPE 2	**10.00** .3937	**19.00** .7480	**5.00** .1969	476	1488	12	**2.500** .0984	147,000	106,000	8	24	48
TYPE 3	**10.00** .3937	**22.00** .8661	**6.00** .2362	1050	2824	11	**3.175** .1250	157,000	113,000	15	44	88
			6.00	1407	2700							
TYPE 4	**10.00** .3937	**22.00** .8661	**6.00** .2362	985	2700	11	**3.175** .1250	133,000	96,000	15	44	88
						10						
TYPE 5	**10.00** .3937	**26.00** 1.0236	**8.00** .3150	1916	5137	10	**4.763** .1875	139,000	10,000	26	79	158

* The indicated speed limits are guide values for spring-loaded single bearings with low load; depending on the respective application, higher or lower speed limits may apply in practice.
** For use with oil lubrication, these bearings are also available without shields.
Subject to change due to technical improvement.

Figure 11: Specifications of the preselected ball bearing (II).

OMSOP project: pre-design bearings type selection.

The selection of the most appropriate type of bearings for OMSoP started in the previous section already given that some of the available typologies were discarded during the screening process. The candidate typologies remaining are thus the following [4]:

- Oil-lubricated bearings: high-speed metal ball or roller. Floating sleeve. Ceramic surface.
- Air-bearings.

The first category is a well-established technology, requiring an oil pump, oil-filtering system and oil cooler which add to microturbine cost and maintenance.

The second category has been used in the aero industry in embarked auxiliary systems and cabin-cooling systems for many years. They allow the high-speed turbine to be aerodynamically supported on a thin film of air and hence friction is low. No oil, pump or cooling system is required thus reducing the cost with respect to the previous oil bearings. Concerns do nevertheless exist about the reliability of air bearings under numerous and repeated cycling due to metal-on-metal contact during start-up and shutdown. In summary, they offer ease of operation without the cost, maintenance requirements or power drain of an oil supply and filtering system. The only issue is continuous start/stop which might lead to excessive wear.

The characteristics that made rolling element bearings preferred to hydrodynamic ones in the previous section were: low starting and good operating friction, ability to support combined axial and thrust loads, less sensitivity to interruptions in lubrication, no self-excited instabilities, good low-temperature starting and ability to seal the lubricant in the bearing. Within reasonable limits, changes in loads, speed, and operating temperature have very little effects on the satisfactory performance of rolling-element bearings.

On the other hand, the rolling-element characteristics that instead made hydrodynamic a more interesting alternative were: finite fatigue life if subjected to wide fluctuations, large space required in the radial direction, low damping capacity, higher noise level, more strict alignment requirements.

As far as costs are concerned, these depend on the technological level assigned to the complete system and the performance required in terms of reliability and maintenance. As a general rule of thumb, he higher the initial cost, the lower the maintenance cost. This can be appreciated in a correlation for the initial cost depending on the bearing type [7].

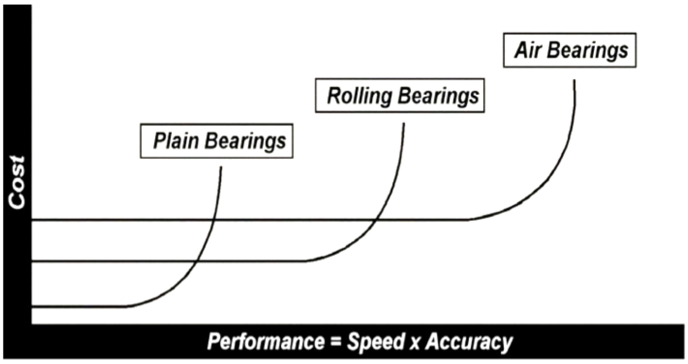

Figure 12: Investment cost vs. bearing type and performance [7].

As visually noted in Figure 12, rolling bearings are a compromise choice between cost and performance while air bearing is the best product in terms of performance at the expense of a higher initial cost. Oil-lubricated hydrodynamic bearings appear to be not suitable given the poor performance they yield, in particular when the requirements of the system is taken into consideration. This is further aggravated if the complex cooling system for the lubricant oil is also necessary.

A first approach to selecting the particular bearing system can be done by looking at the diagrams from ESDU, Figure 13, typically employed for bearing selection knowing the ranges in which load and speed vary during operation (unfortunately, given that air bearings, this methodology is only partially useful). The particular operating conditions of OMSoP have been plotted in both diagrams, evidencing that it is not load but shaft speed which is constraining the design.

In order to facilitate the selection process, a table is provided in Figure 14 where the advantages and limitations of rolling element and foil air type of journal bearings are summarised. The same table can be derived for thrust bearings. The colouring allows to easily track which pros and cons are associated to each typology.

Conclusions

Based on the thorough analysis presented in this document, it is concluded that foil air bearings constitute the best technology to ensure highest performance with minimum maintenance. Nevertheless, the high initial investment cost and some concerns regarding reliability and operation at high temperature are not finally resolved yet and thus call for specific taks to be developed at a subsequent stage.

On the other hand, it is also recommended that the prototype engine be equipped with standard oil-lubricated ball bearings which is the technology being currently used by the gas turbine manufacturer. This would in turn reduce the risk during this stage of the process, thus allowing for a fast transition towards the erection of the demonstration.

A particular sizing of the different components of the lubrication system has not been approached yet, even if some commercial solutions have been discussed with technology suppliers. In particular, a given set of bearings taken from MBA's product line will be considered during the development of the upgraded turbine.

In summary, short-term and mid-term solutions have been identified in this report and profuse information regarding design and operational aspects has been provided. The next step will take into consideration the particular sizing of the oil-lubricated ball bearings and a pre-design of a set of air-bearings to be implemented in the next generation micro gas turbine.

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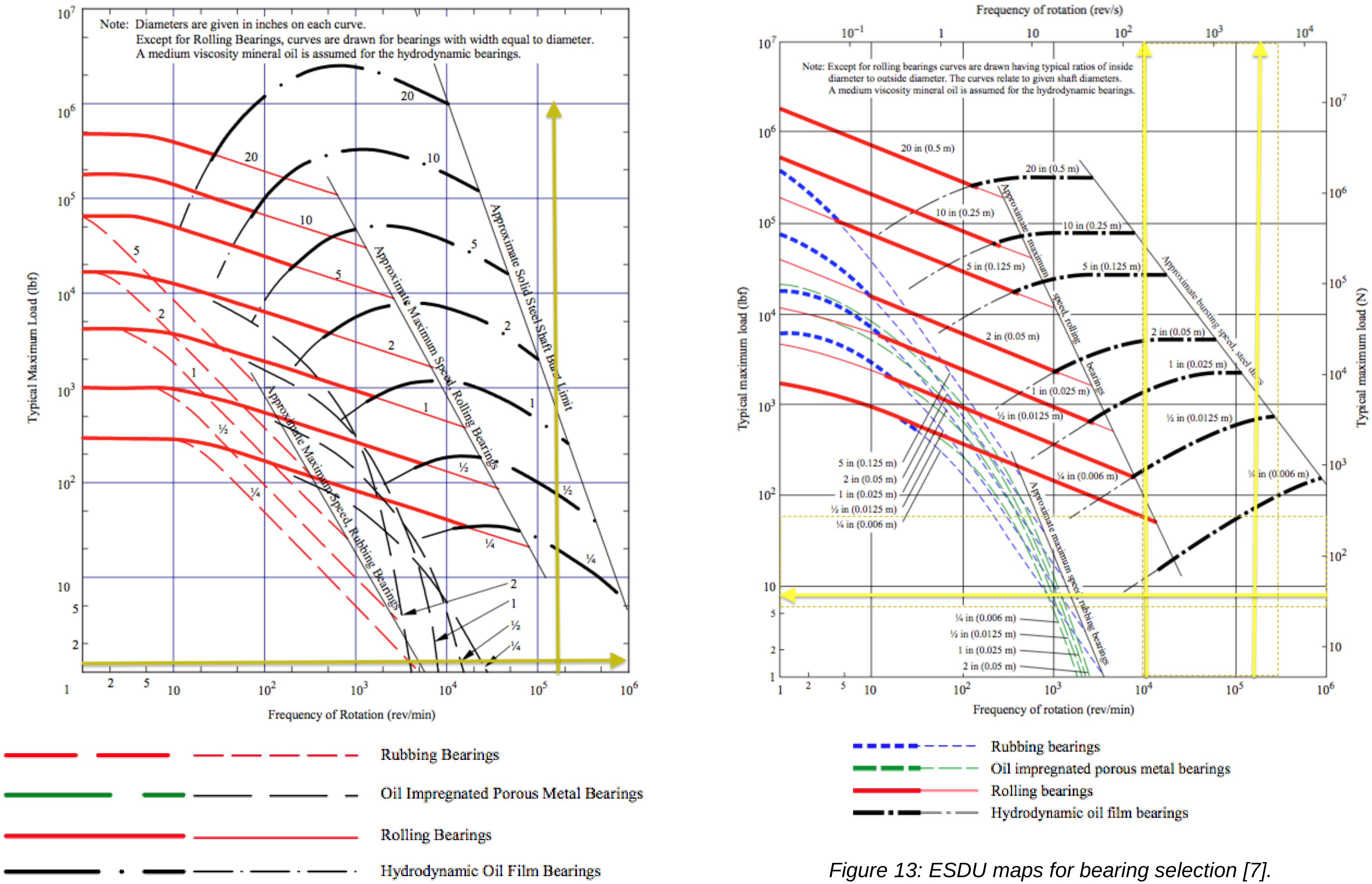

Figure 13: ESDU maps for bearing selection [7].

Journal bearings			
Environmental Conditions	General Comments	Rolling Bearings	Externally Pressurised Gas Bearings
High Temperature	Attentio to differential expansions	Up to 100°C no limitations, from 100°C to 250°C, stabilised bearings and special lubrication procedures probably required	Excellent
Low Temperature	Attention to differential expansions and starting torque necessary	Below minus 30°C special lubricants required, consideration of starting torque necessary	Excellent, thorough drying of gas necessary
External Vibration	Attentio to fretting damage	May impose limitations, consult manufacturer	Excellent
Space Requirements		Bearings of many different proportions, small axial extent	Small radial extent but total space requirement depends on the gas feed system
Dirty or Dusty Conditions		Sealing important	Satisfactory
Vacuum		Lubricant may impose limitations	Not applicable when vacuum has to be maintained
Wet and Humid Conditions	Attention to metallic corrosion	Normally satisfactory, but special attention to sealing perhaps necessary	Satisfactory
Radiation		Lubricant may impose limitations	Excellent
Low Starting Torque		Good	
Low Running Torque			
Accuracy of Radial Location			
Life		Finite but predictable	Theoretically infinite
Combination of Axial and Radial Load Carrying Capacity		Most types capable of dual duty	A thrust face must be provided to carry the axial loads
Silent Running		Usually satisfactory, consult manufacturer	Excellent, except for possible compressor noise
Simplicity of Lubrication		Excellent with self-contained grease or oil lubrication	Pressurised supply of dry clean gas necessary
Availability of Standard Parts		Excellent	Not available
Prevention of Contamination of the Products and Surroundings		Normally satisfactory, but attention to sealing necessary, except where a process liquid can be used as a lubricant	Excellent
Frequent Stop-Starts		Excellent	
Frequent Change of Direction of Rotation			
Running Costs		Very low	Cost of gas supply has to be considered
Desirable characteristic		Good matching with requirement	
Technical requirement		Bad matching with requirement	

Figure 14: Summary of bearing selection process [7].