Ceramic Spiral Groove Bearings in Oil-Free Compressors

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SYNOPSYS Hydrodynamic spiral groove bearings using process fluid or gas as the lubricant offer the possibility to build real oil-free compressors for refrigeration, air conditioning or general use. This paper explains why ceramic spiral groove bearings are an ideal choice, and describes the properties of the ceramics required. Examples are given that demonstrate how ceramic spiral groove bearings can be installed in centrifugal or scroll compressors, and which calculations are needed to optimise their design.

1 INTRODUCTION

Oil-free compressors are becoming increasingly acceptable and necessary in not only refrigeration and heat pump applications, but also for many general purpose industrial applications. The advantages for oil-free compressors in refrigeration and heat pump applications have been demonstrated for many years; they are primarily improved efficiency due to the lack of oil contamination of the refrigerant, and reduced possibility of leaks due to a hermetic construction (1,2). For other industrial applications the need for oil-free compressors arises either from a need to have absolute surety of oil-free air (for example food preparation (3), or for installation reasons (for example when compressing flammable gases where the oil is considered an added risk (4)).

In all oil-free compressors the problem of what bearing system to use is critical to the success of the entire machine. An inappropriate choice will lead to machine failures and resulting loss of management confidence and support. In this regard we can see the positive effect of the introduction of active magnetic bearings into oil-free compressors on the use of gas lubricated spiral groove seals (5,6). The technology of gas lubricated spiral groove bearings had been around for decades (7), but it was the success of active magnetic bearings that gave industry the impetus to use them as the critical sealing function (8).

Now that spiral groove gas bearings have been accepted as part of normal industrial machinery one can ask where else would their use be advantageous? This paper discusses how spiral groove bearings could provide solutions to existing problems or enable new solutions to gas compression in really oil-free compressors. One can envisage the spiral groove bearings using the process fluid in the gas or liquid phase thus avoiding the need to use oil. What advantages could this give:

- Totally hermetic compressors = no leaks to the environment.
- Low maintenance = no oil changes.
- Long life and low friction = low running costs.
- Physically smaller machines = lower capital cost.

2 SPIRAL GROOVE BEARINGS

Spiral groove bearings are one of the class of bearings referred to these days as *self acting*, previously termed hydrodynamic or aerodynamic depending on the physical form of the lubricant (gas or liquid). As with other self-acting bearings there is no need to provide pressurised lubricant to support the load, the bearings generate their own. Spiral groove bearings were first proposed in 1949 (9) for journal bearings where the pattern of the grooves forms a herringbone. Since then, grooves have been designed on flat-thrust bearings, hemispherical and conical geometries (10). Figure 1 shows these 4 basic types.

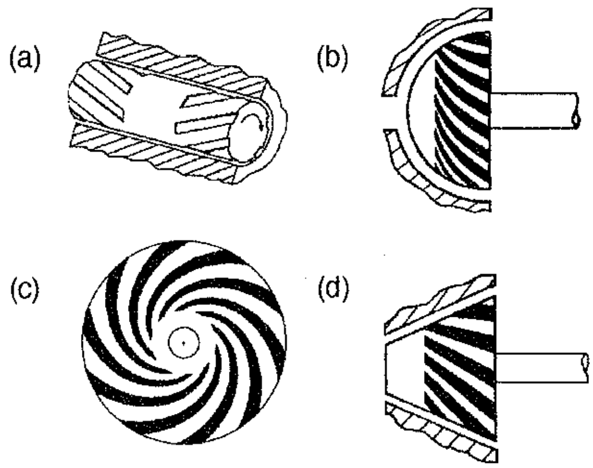

Figure (1) Spiral Groove Geometries (a) Journal, (b) Hemispherical, (c) Flatthrust, (d) Conical.

The form of the grooves on flat-thrust bearings is logarithmic in the sense that the angle to the velocity vector is constant. This is the cause of some confusion as the impression exists that the herringbone journal bearing and the logarithmic spiral flat-thrust bearing have different mechanisms of operation. There is a difference in that the journal bearing geometry will function without the grooves (in a manner), while the flat-thrust geometry will not; but this does not detract from the principle that they both function due to the pressures resulting from the grooves in one surface moving past a mating ungrooved surface.

The principles of operation of spiral groove bearings are explained with the help of figure 2. In effect they are viscous pumps that push lubricant towards a restriction thus generating a net pressure rise. The relative motion of the surfaces (grooved, plain or both) causes fluid to flow over the groove-ridge pairs (direction X) thus generating a pressure ripple. This pressure ripple generates flow perpendicular to the direction of motion due to the groove angle ß. The ungrooved portion (plain portion) restricts this flow hence causing a net pressure rise along the groove. To summarise, it is not the pressure ripple in the direction of motion that supports the load, but the resulting pressures perpendicular to the direction of motion. Ignoring secondary effects due to the groove ends, inertia, compressibility and others, the load capacity of spiral groove bearings is independent of the number of grooves.

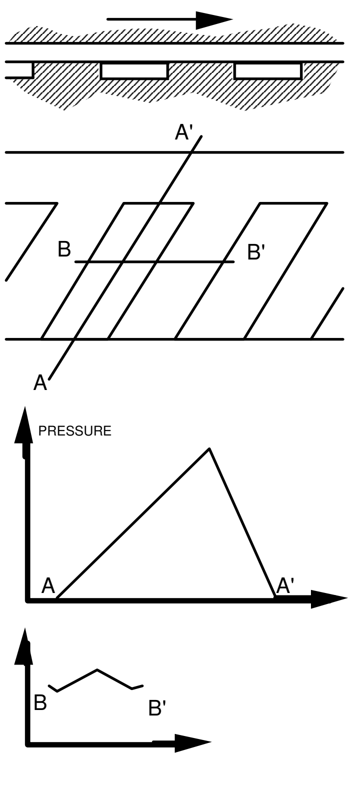

Figure (2) How Spiral Groove Bearings Work.

A great deal of theoretical and experimental work was undertaken in the sixties and seventies for aerospace and to a lesser extent other applications (11, 12 and 13).

2.1 Previous Applications of Spiral Groove Bearings

Although there were many attempts at using spiral groove gas and liquid lubricated spiral groove bearings the first really successful application for spiral groove gas bearings was that of inertial gyroscopes for aeroplane and ship use (14, 15). This was a very successful application with mean time between failures of 80000 hours and 10000 stop/starts claimed. The bearing materials used were boron carbide for both rotating and stationary surfaces with a surface coating to reduce friction (14), and tungsten carbide against steel (15). Speeds were relatively low (surface speeds ≈10 m/s) and precision was the important criterion. The conical bearings described in (15) were later used successfully for optical spinners, where high precision was the criteria.

In the eighties there was a great interest in high speed expanders for cryogenics applications and this led to the use of a variety of self acting gas bearings, including spiral groove types (16, 17). Normal bearing materials tended to be used, that is steel in conjunction with a bronze or carbon mating surface. Speeds were much higher, going up to 400 000 rpm (surface speeds ≈ 400 m/s) and the most important criterion was for low friction.

The last five years has seen the use of self acting spiral groove gas seals (18) in conjunction with magnetic bearings (8). Materials are typically tungsten carbide against carbon based compounds, and speeds medium (surface speeds ≈ 100 m/s). Long life due to the extremely low wear is the important criterion in this case. This application is of even more interest as it demonstrates the use of precision gas bearings (clearances of the order of 2 μm) *in normal industrial environments*, i.e. not especially clean.

Liquid lubricated spiral groove bearing applications (usually oil, but can be practically any) are more limited as their advantages compared to rolling element or plain hydrodynamic bearings are less evident. The most successful application is clearly the motor support bearing for video recorders (19). This was an ideal situation as the static nature of the application meant that there was little tendency for the lubricant to migrate around the machine - the most common problem with oil and grease lubricated bearings. A novel solution to this problem was proposed in the early seventies (20) where a patented recirculating system was used to limit grease loss.

In summary one can see from these applications that spiral groove bearings have demonstrated their ability to support rotors in a wide variety of circumstances.

2.2 Why Spiral Groove Types?

This poses the question as to why would one use spiral groove types in preference to other self-acting bearings, for example tilting pad, Rayleigh step, foil or other. (The use of plain bearings is not discussed as their inherent instability causes problems in many situations.)

The answer to this question is a combination of the following parameters:

Similar performances:

If one compares optimised self-acting gas bearings it becomes apparent that the load, stiffness and to a great extent stability are similar for most of the realistic choices, given the same conditions, i.e. clearances, speeds, surface areas. To be noted that foil and tilting pad bearings usually add an unwanted extra degree of freedom due to support stiffness and damping.

Ease of manufacture:

After machining of the basic geometry the surfaces require only grooving, and the grooves can be formed in a multitude of means: machining, sand blasting, electrochemically, electro-discharge, pressing, moulding, ion-beam etc.

Built in stability:

The stability of the bearings is a function of the geometry, not the adjustment of springs or dampers that are frequently found on tilting pad designs.

No moving parts to wear:

The support of tilting pads can be a significant source of problems due to the wear or degradation of the pivot, and foil bearings are suspected to undergo fatigue of the surface and support foils.

Accuracy of rotation:

The bearing clearances are sufficiently small that the clearances of the compressor components can be made smaller than would be the case for example in foil bearing machines.

Cost

The simplicity of design and manufacture compared to the alternatives makes the spiral groove type less expensive for prototype and actual use.

When spiral groove bearings are compared to magnetic bearings one comes to the conclusion that at large sizes the magnetic bearing will probably be the natural choice (high capital cost, difficulty of manufacturing large precise bearing surfaces, more availability of space for auxiliary rolling element bearings and electronics). But for smaller bearings, spiral groove types come into their own (relatively low capital cost, ease of manufacture of precision geometry, small space required). Only a detailed study of the individual application will provide the answer as to the best choice of bearing system, and it is important in these studies to include the possibility of using externally pressurised bearings (either gas or liquid lubricated).

2.3 Gas or Liquid lubricant

Even if one is designing a completely oil-free compressor there still exists the choice of whether to use a gas or liquid lubricant. This usually answers itself in most typical applications as it is preferable to use the higher viscosity liquid phase if possible (higher clearances, less cost to manufacture). In refrigeration and similar applications where the process fluid is frequently a CFC (chlorofluorocarbon) or similar refrigerant, the difference in viscosity between the gas and liquid phases means that one could more easily consider deliberately designing a mixed phase bearing. A typical refrigerant R134a (one of the newer environmentally friendly CFCs) has gas phase viscosity of the order of 12 μPas and the liquid phase viscosity of about 170 μPas (both at 50 deg C).

3 CERAMICS

The applications described earlier were manufactured from classical materials: steels, bronzes, traditional ceramics (tungsten carbide, boron carbide) and carbon based compounds, and it is noticeable that the successful ones used ceramic materials. This was possible due to the relatively low speeds of the components, up to 140 m /s surface speed. At higher speeds the ceramic components were structurally unacceptable due to the high stresses causing failure.

An ideal rotor material would have the following properties:

- Low density to minimise centrifugal growth, stress and weight.
- Good tensile strength (and fracture toughness).
- Low thermal expansion coefficient to reduce thermal distortions.
- High thermal conductivity to dissipate heat.
- High hardness to minimise wear under stop/start conditions.
- Easy machining to high tolerances.

The stationary components do not need certain of these properties but would ideally have the last four.

The newer technical ceramics available only in the last ten years meet many of these requirements. Table 1 lists some of the properties of traditional and these newer technical ceramics.

3.1 Example 1: Centrifugal Air Compressor

The effect of using ceramics on the actual rotor dimensions will be demonstrated by a fictional two stage centrifugal compressor, say 90kw of air at 8 bar outlet pressure running at 120000 rpm, driven by a motor directly integral with the shaft (21). A two stage design with one wheel mounted on each end of the same rotor has the advantage that the axial loads are partially balanced, and if a brushless DC electric motor is used the radial loads are small. For the purposes of this comparison the axial thrust bearing is ignored, naturally in a real design this would not be the case.

Dimensions:
Figure 3 shows the layout of a typical design with compressor wheels of about 70mm diameter for stage 1 and 50mm diameter for stage 2. The wheel masses would be about 170g and 80g respectively, and the motor mass of the order of 250g (all masses not including shaft).

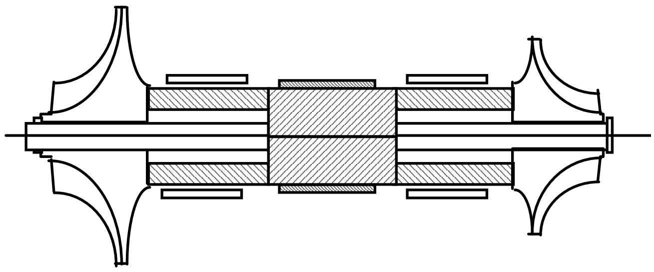

Figure (3) Arrangement for a Hypothetical 90kw Air Compressor.

Assuming that as design criteria one is looking to:

- maximise load capacity
  stiffness
  stability
  clearance (to reduce manufacturing costs)
  bearing diameter (for maximum bending critical speed)

- minimise power consumption
  compressibility number of bearing (11)

Metal shaft design:
Using a steel rotor would limit the bearing diameter to 24mm with a clearance radially of 10 to 12 µm. A larger diameter would cause excessive centrifugal growth and a smaller diameter a loss of bearing stiffness coupled with more difficult rotordynamic design (to be under the first bending critical speed). A larger clearance would be unstable and a smaller clearance suffer thermal and structural deformations (centrifugal growth of the shaft). It has been shown (17) that thermal instability is a major problem in gas bearing design. The grooves would typically be about 20µm deep for this design to maximise stability.

Ceramic shaft design.
Assuming a SYALON type ceramic would allow a bearing diameter up to 42mm with a radial clearance between 15 and 19 µm. Groove depth would be about 30 µm for this design. To make the rotor easier to assemble, the ceramic bearing components are made hollow, thus the actual bearing diameter is reduced to 34mm to allow for the increase in centrifugal growth that this causes.

Performance comparison:
What would be the theoretical performances of these designs:

Rotating bearing material	Metal	Ceramic
Rotor mass kg	1.40	1.22
Bearing diameter/length mm	24/24	34/30
Cold clearance radially µm	11	15
Final operating clearance µm	9.1	12.2
Radial stiffness MN/m	8.6	13.0
Stability (critical mass) kg	6.4	10.8
Power consumption W	134	388
First bending critical speed rpm	90 000	145 000

Although one might be attracted by the low power consumption of the metal design, its first bending critical speed is in a position that would be unacceptable in operation. One could reduce the diameter of the ceramic bearings to reduce power consumption, but as it represents only 0.388% of the machine power one would normally decide to keep the diameter high so as to keep the bearing stiffness and stability higher.

3.2 Design and manufacture of ceramic components:

It is commonly accepted that the use of ceramics as a structural material (i.e. stressed in tension) requires a different approach due to their brittle nature. Fortunately methods are now becoming available (22) that enable the design of stressed ceramic components taking into account their fracture toughness rather than their tensile failure strength.

An alternative heuristic approach relies on the superior performance of the technical ceramics to support tensile stresses coupled with proof testing. In this method the usual approaches are adopted for designing in metals, for example Finite Element Analysis (FEA) and comparing the maximum tensile stress predicted with the maximum supportable by the ceramic. SYALON will have a typical tensile failure strength of 450 MN/m^2, and if one designs keeping maximum tensile stress less than say 200 MN/m^2 and proof test all the components to this level, one can have a high level of confidence that in operation there will be an acceptable low level of failures.

The method of machining of ceramics can considerably reduce their strength (23) but again one can perform tests to show whether the proposed method is acceptable. For gas bearing manufacture the normal fine grinding to near final size, followed by lapping will ensure a good structural performance, and careful design will normally always ensure that no rough machining is needed.

The operation of putting the grooves into the surface of the ceramic can be achieved in a variety of ways depending on the exact type. Sand-blasting, ion-beaming, electro-discharge (24) or laser machining are some of the easiest. Figure 4 shows the profile of grooves in SYALON made by laser machining and diamond grinding. A study (25) suggests that the errors seen on the bottom of the grooves will cause insignificant reduction in bearing performance.

There are considerably fewer problems in making the stationary components of ceramic as they can usually be designed to be have only compressive stresses, or at least very little tensile stress.

If many stop-starts are required the surface of the ceramic can be coated or sputtered (26) with a low friction material, for example Molybdenum Disulphide (MoS_2).

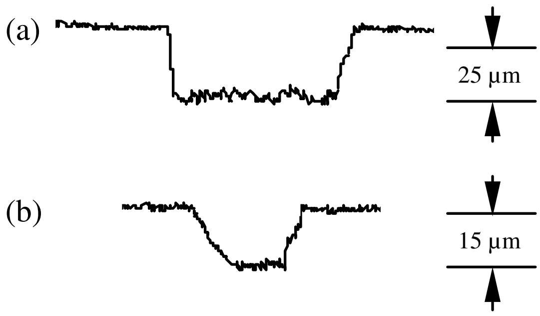

Figure (4) Profiles of Spiral Grooves in Silicon Nitride Ceramic, (a) Laser, (b) Diamond Grinding.

4 ANALYSIS METHODS

The two most important analytic methods for successful incorporation of ceramic spiral groove bearings into a machine are FEA and rotordynamic analysis.

4.1 Finite Element Thermal and Structural Analysis

Previous work (17) has demonstrated the thermal instabilities that arise when the heat generated in the bearing clearance causes deformations that further increase the heating. To avoid this, a thermal FEA followed by a structural FEA should be considered that includes all the motor and other heat sources and sinks. In applications where the power input is high compared to the physical size this is even more important. Figure 5 shows the temperature profiles for the example of the 90kw air compressor cited above, assuming water cooling.

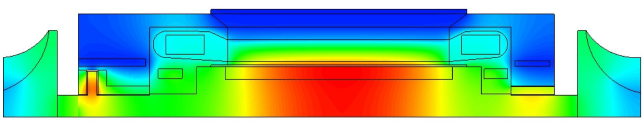

Figure (5) Temperature Distribution Calculated by FEA in the 90kw Air Compressor.

4.2 Rotordynamic Design

Rotordynamic analysis is necessary to ensure that the dynamic behaviour of the rotor in its bearings is acceptable, principally that the displacements of the rotor do not cause contact either within the bearings or elsewhere (e.g. tip clearances).

To accomplish this objective it is necessary to know the bearing characteristics at the speed in question and then to model the rotor together with them. Various programs are available for these purposes, depending on whether the user requires a detailed research tool (27) or a user friendly design tool (28). Figures 6 and 7 show the bearing performance and rotor critical speed map for the example 90kw air compressor produced using the latter of these two software packages. This program is also unique in that it allows the rotor designer to interactively position liquid or gas lubricated spiral groove bearings on the rotor and then perform bearing and rotor analyses. Bearing temperature rise and gas compressibility are also automatically taken into account depending on lubricant type.

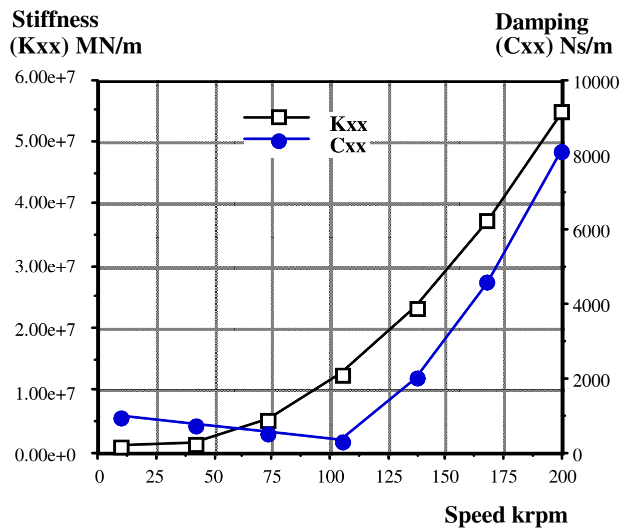

Figure (6) Journal Bearing Performance for the 90kw Air Compressor

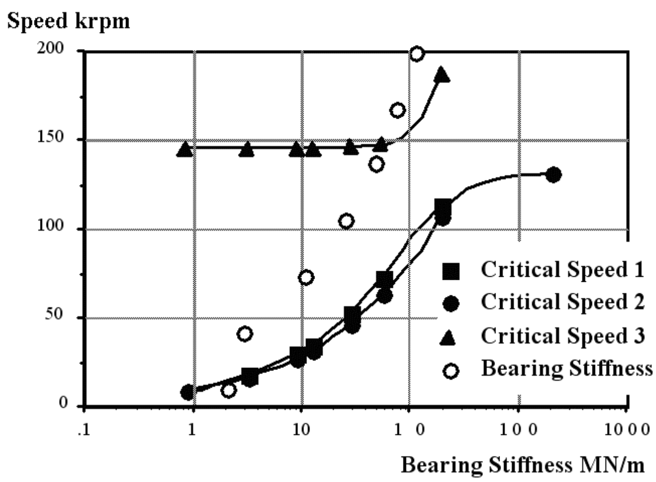

Figure (7) Critical Speed Map for the 90kw Air Compressor.

6 CONCLUSIONS

This paper describes the advantages in using ceramic spiral groove bearings for oil-free compressors: namely the complete elimination of oil. The operation of spiral groove bearings is explained as well as why modern technical ceramics are an ideal material for their construction.

Two examples are given that show how spiral groove bearings using the process fluid can be incorporated into different compressor designs and applications; a centrifugal air compressor and a scroll heat pump compressor.

The use of modern analytic methods is demonstrated showing how they now enable a designer to use ceramic spiral groove bearings in industrial machinery.

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