World Applied Sciences Journal 27 (7): 893-897, 2013
ISSN 1818-4952

DOI: 10.5829/idosi.wasj.2013.27.07.13718

The History of the Gas Bearings Theory Development

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Abstract: In recent years the interest towards sleeve bearing with gas lubrication had significantly increased. The reason behind this is changes in the requirements for aircraft and power gas-turbine units. The shaft rotation speed and load capacity were increased and the operating conditions became stricter. At the current stage, the task is to create non-contact gas bearings for high-speed heavy rotors of turbomachines. For creating lift force such bearings can use Bernoulli aerodynamic effect or the supply of the air into the gap between the stator and the rotor under the pressure. It is also possible to combine these two effects. Theory of gas lubrication was majorly developed in the late 19th century in the works of Petrov, Reynolds, Sommerfeld, Chaplygin. The second spurt in growth has occurred in the 60 years of the 20th century and has been linked to the widespread introduction of gas turbines. At the current stage, the main efforts are put into creation of non-contact bearings for aircraft engines. It is also necessary to solve the difficult problems regarding new materials to create high-temperature anti-friction coating. Avoiding the usage of the oil lubrication allows to expect a significant improvement in performance characteristics, simplification and reduction of the construction's cost.

Key words: Gas lubrication · Gas-static bearing · Hybrid gas bearing · The Reynolds equation

INTRODUCTION

Over the last few decades a number of countries actively develop the gas-lubricated bearings. Sufficient experience of creating such devices in small sizes was gained. In present days there are several fields of technology, in which the use of gas-lubricated bearings (Figure 1) is considered appropriate:

- Replacement of ball bearings, used in gas-turbine compressors, oil pipelines pump stations and stand-alone power plants with the gas supports which do not require oil lubrication;
- Cryogenic and turbo-refrigerating units;
- Aviation gas-turbine units.

Promising as well is the usage of non-contact bearings with gas lubrication in turbo- cooling units and gas separation plants (expanders). In these cases it is important that the cooling products and gases will not be polluted with oil lubricant.

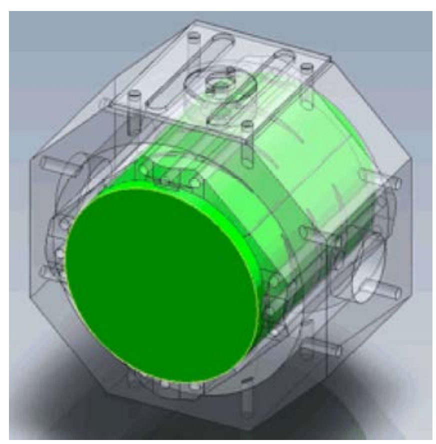

Fig. 1: Gas-static bearing with air supply through a system of flat nozzles

The advantage of using the gas-lubricated bearings instead of ball bearings in aviation and power gas-turbine engines (GTE) lies in increased fire safety, reduction of engine weight, its increased longevity and reduced operation and life cycle costs.

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History: The founder of the gas lubrication gas-dynamic theory is professor N.P.Petrov, who published an article "friction in the machines" in the Journal of the Engineering in 1883 [1]. In the article he adduced a formula for calculating the rotation resistance moment of the cylindrical shaft within the coaxial race, filled with fluid. However, for the first time the behavior of the shaft inside the sleeve bearings with incompressible fluid was fully examined in the second half of the XIX century in the works of Tower and O.Reynolds [2]. In 1886 Reynolds published the article "The hydrodynamic theory of lubrication and its application to the Tower's experiments"[3]. The first patent on a gas bearing was granted in U.S. in 1894. Hydrodynamic theory of lubrication for the smooth cylinder in a coaxial support was completed in the works of A.Sommerfeld, A. Michel, N.E. Zhukovsky and S.A.Chaplygin [2]. The possibility to use the air as a lubricant was tested by Kingsberry [4] and Harrison [5].

One of the main hypotheses of the hydrodynamic lubricant theory is the assumption of negligible change in the properties of the fluid and the pressure over the whole lubricant layer. A laminar flow occurs in bearing layer of lubrication. The basic equation for determining the pressure of the lubricant in the sleeve bearing was obtained by O.Reynolds from the Navier-Stokes system and equations of continuity based on the hypothesis of the hydrodynamic lubricant theory and the condition of the lubricant sticking to the surfaces of the bearing, taking into account the thinness of the lubricant layer in comparison with the dimensions of the bearing:

$$\frac{\partial}{\partial x}\left(h^3\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial z}\left(h^3\frac{\partial p}{\partial z}\right)=6\mu\left\{(U_0+3U_1)\frac{\partial h}{\partial x}+2V\right\},$$

Where h (x, z) – a function that determines the size of the gap at a given point, P – average pressure in the gap; U_0 and U_1 - velocity of the surfaces that forms the gap; 2V term is used to record movements of one of the gap walls, whereby the value of the function h (x, z) changes.

Theory of gas lubrication was deeply developed in the Soviet Union. There were two major research centers in this field: Experimental Institute of metalworking machines (EIMS) where the work was carried out under the guidance of S.A. Scheinberg [6] and the Department of Mechanics and Mathematics of the Leningrad Polytechnic Institute (LPI), with L.G.Loitsyansky [7] as supervisor. LPI Department was developing the theory of gas suspension gyroscopes, as well as gas-static nodes for accurate device calibration. A chronological overview of the work in this domain is given in the work [7], dedicated to the 100th anniversary of L.G.Loytsyanskiy.

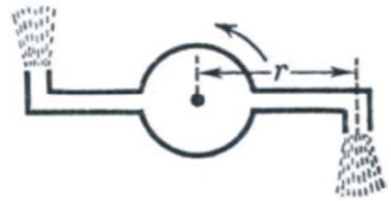

Fig. 2: Reactive turbine based on the principle of segner wheel, where r is the radius of the turbine

Works in EIMS were focused on applications, related to the development of spindle assemblies, gas supports for grinding heads, coordinate tables for metal-cutting machines. As a result, the production of several hundred article types, operating on the principles of gas lubrication was mastered. EIMS developed the pneumatic spindle units based on the principle of segner wheel (Figure 2), which provided the rotation speed of the grinding head up to 200,000 rpm.

Embedded electric drives, both synchronous and the asynchronous were developed. Rotation speed over 300,000 rpm was achieved. Today gas supports are used in GTEs, cryogenic and high-temperature space, land, transport and deep-water plants, nuclear reactors compressors.

The surge of interest in this subject took place in the 60s. In those days the fundamental works by Scheinberg [6] and Constantinescu [8], Rippel [9], Gressem and Powell [10] appeared and summarized all known theoretical and experimental results. At that time as well the first works, where arises the question of application of gas bearings in aircraft gas-turbine engines appears [11].

Air Bearings – Gas-Static and Gas-Dynamic: By the principle of creating a lifting force, the bearings are divided into gas-static (GSB) in which the lifting force is created by an external device with supplying highly pressurized air; gas-dynamic (GDB), where the force is generated by the interaction of the shaft's moving parts with the bearing's thin viscous layer and hybrid (both effects occur). Using radial GSB it is possible to get the shaft to rotate without touching the fixed walls. For this, through the system of specific nozzles and chokes (Fig. 3) the gas from the general collector is supplied to the gap between the shaft and the bearing under the excessive pressure.

The traditional scheme of GDB is pictured on Figure 4. There are the longitudinal slots made in the bearing's housing where the petals, made of spring steel, are fixed (shown in red in Figure 5). The petals form a continuous surface.

Fig. 3: Scheme of the gas-static bearings

Fig. 4: A typical gas bearing structure (GDB)

Fig. 5: The suspension of the shaft in a gas-dynamic bearing

Left - by aerodynamic forces, generated on the petals; Right - without the rotation

At the start of the shaft rotation under the influence of Bernoulli's effect the aerodynamic forces arise on the petals (Fig. 5, left). As the speed increases, these forces grow until their values is sufficient to separate the petals from the shaft. Lack of contact between the shaft and the petals allows to achieve very high rotation speed. Furthermore, the elasticity of the petals allows them to "track" the shaft's oscillations. When the shaft is motionless the petals, due to their elasticity, tangles to the surface of the shaft and support it in a hanged state. However, the GDB has the significant drawbacks. At each start and stop the wearing of anti-friction coating, applied to the surface of the petals occurs, so the resource of the bearings is directly dependent on the operation regime and the number of starts and stop.

This problem is particularly relevant for aviation a gas-turbine engines [12], that works in the regime of frequent starts and stops. One of the main problems of using this type of bearings is to ensure reliable operation at high temperatures (>650°C) due to lack of cooling, so the development of heat-resistant anti-friction coatings receives a lot of attention. Studies of high-temperature solid lubricant coatings required for GDB were conducted in NASA [13], commissioned by the U.S. Department of Energy. The PS304 brand coating, considered primary in the U.S. is able to operate at a temperature of 650°C [14]. The technology for producing (applying) solid lubricant coatings includes plasma and detonation methods. Studies in this field were carried out by NASA (Glenn Research Center) [13]. Advances in this area ensured the commercial success of small gas turbines that use GDB [15-16].

A number of works proposes to use the insert in the GDB, one end of which is not fixed and can be moved by the forces of pressure [17, 18]. Due to the fact that the liners unfold around a fixed axis, its surface turns out to be at the attack angle to the incoming flow (Fig. 6). This creates an aerodynamic force. The higher is the speed the greater the force.

These are called hybrid bearings with self-adjusting inserts. At high speeds of shaft rotation they operate like wedge GDB. This bearing, in contrast to the gas-dynamic bearings (GDB) works entirely in non-contact regime, as in the moments of starting and stopping the rotor is upheld by a control system. It is lifted and floats on a layer of compressed air and only then unwinds. At the nominal conditions the load capacity of hybrid GSB is provided by aerodynamic forces, generated by rotating segments, i.e. in the same way as in the GDB, allowing to reduce the air consumption almost to zero. Thus, hybrid bearings combine the best qualities of GSB and GDB.

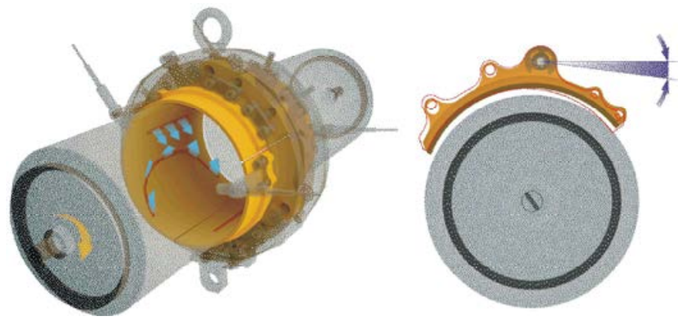

Fig. 6: The structure of the hybrid bearing with turning inserts

CONCLUSION

Basic information about the history of the gas lubrication study is provided. Basic information about the GSB and the GDB is given. The advantages and disadvantages of both of them are shown. The success of the GDB usage totally depends on the availability of suitable high-temperature anti-friction coatings. Hybrid bearings are a reasonable alternative to the GDB, as they operate in completely non-contact regime and do not require expensive coatings. In addition, they are absolutely fireproof and have virtually unlimited life resource when operation in normal regime.

Findings: For GTE, operating in frequent starts and stops regime, the most promising is the use of hybrid air bearings with rotating segments. GDBs are the most cost-effective, but have a low life resource. GSB have an increased consumption of the working gas, which affects the efficiency of the engine. For more than 100 years of gas lubrication theory development the universal approach to the GSB design still haven't been developed.

ACKNOWLEDGEMENTS

This article was prepared as part of the "1000 laboratories" program with the support of Saint-Petersburg National Research University of Information Technologies, Mechanics and Optics.

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