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# DEVELOPMENT OF THE FOIL BEARING TECHNOLOGY

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## Abstract

Development of the bearing technology with deformable elements of the bearing sleeve utilization are presented in the paper. Foil or a set of foils with the viscoelastic properties comprise the deformable element. Foil bearing technology is utilized mostly in the high-speed turbo machines, such as the energetic microturbines. This results the bearing operating regime: high rotational speed, high temperature, work in the friction conditions during machine start-up and rundown. Three foil bearing generations, which differ in the structure and properties with regard to load capacity, stiffness and undesirable variation damping, were distinguished in such bearing development. Technical solutions of the foil journal and thrust bearings were shown.

## ROZWÓJ TECHNOLOGII ŁOŻYSKOWANIA FOLIOWEGO

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Słowa kluczowe: łożysko foliowe, łożyskowanie maszyn szybkoobrotowych.

## Abstrakt

W artykule przedstawiono rozwój technologii łożyskowania z wykorzystaniem odkształcalnych elementów panwi łożyska. Element odkształcalny stanowi folia lub zespół folii o właściwościach lepko-sprężystych. Technologia łożysk foliowych jest wykorzystywana głównie w szybkoobrotowych maszynach wirnikowych, jak mikroturbiny energetyczne. Wynikają z tego warunki pracy łożyska: duża prędkość obrotowa, wysoka temperatura, praca w warunkach tarcia podczas rozruchu i wybiegu maszyny. W rozwoju tego typu łożyskowania wyróżniono trzy generacje łożysk foliowych, które różnią się konstrukcją i właściwościami pod względem nośności, sztywności oraz zdolności tłumienia niepożądanych drgań. Przedstawiono rozwiązania techniczne łożysk foliowych poprzecznych i wzdłużnych.

## Introduction

In view of the requirements set by rapid technological advancement, technical equipment undergoes constant minimization, while ensuring the right operating parameters, in particular the power output. As regards turbomachines, this requirement implies increased rotational speed. This generates a number of problems. One of the most important considerations is the choice of bearing capable of operating at high speeds. In recent years, foil bearings, a sub-category of journal bearings (Fig. 1), began to receive widespread

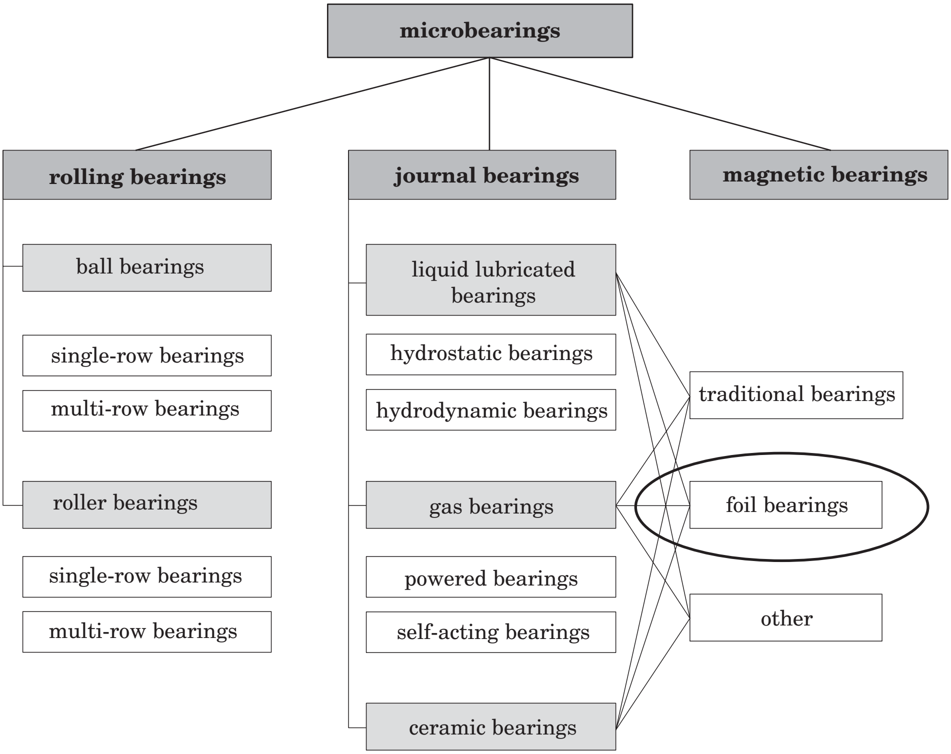


Fig. 1. Microbearing classification in view of bearing structure and operating principle. Position of foil bearings in the classification of microbearings

Source: Żywica (2007).

coverage in scientific publications. The foil bearing concept first appeared in the mid 20th century, yet the required manufacturing technology was developed much later.

A variety of turbomachines are presently on offer, including microturbines with the output of 25-250 kW. Microturbines deliver many advantages, in particular in distributed small-scale power plants. A small number of rotating and moving elements, compact structure, small size and weight facilitate assembly and maintenance. Most microturbine rotors operate at rotational speeds higher than 40 000 rpm with frequent operational interruptions. The temperature inside microturbines usually reaches several hundred degrees Centigrade. For this reason, rotor support bearings in microturbines have to meet stringent requirements as regards:

- allowable rotational speed,
- load capacity,
- allowable operating temperature,
- life and reliability,
- bearing precision and stiffness,
- vibration damping and silent running.

In view of the above requirements, foil bearings are a highly recommended solution and the associated manufacturing technology is becoming more available with time. The operating principles of a foil bearing and a traditional journal bearing are compared in Figure 2, where the structure of a traditional

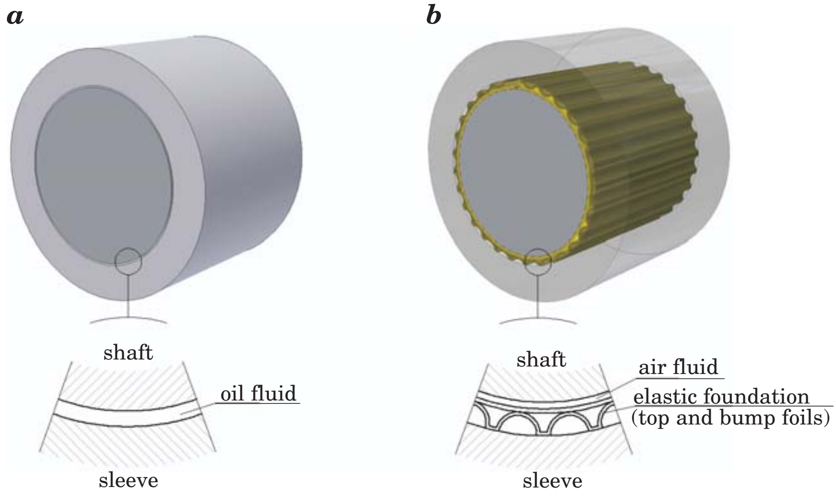


Fig. 2. Comparison of the operating principles of a liquid-lubricated journal bearing and a gas foil bearing

Source: Own work.

bearing is shown on the left, and that of a foil bearing – on the right. The bearing's subsequent layers in the radial direction are presented at the bottom. Despite structural similarities, the main differences are clearly manifested. In a traditional bearing, liquid is the only carrier medium, and the co-acting surfaces are made of alloys resistant to pressure and friction in overloaded bearings. During normal operation, gas is the lubricating medium in foil bearings. During start-up, rundown and overloading of the rotor, the resulting forces are distributed by a set of foil elements whose chemical composition, shape and thickness is determined by the bearing structure (DELLACORTE 2003).

Foil bearings are classified into several generations, of which three will be discussed in subsequent parts of this article. The first foil bearing concept dates back to 1953. Since then, various structural solutions based on the original concept have been developed.

In recent decades, many foil bearing structures were developed together with advancements in the relevant technology, mainly in the area of materials science. In view of the required operating parameters and the geometry that determines operating parameters, foil bearings have been classified into three generations.

## First generation foil bearings

First generation foil bearings are bearings whose load-carrying structure comprises only viscoelastic foil or a foil set whose properties are fixed in all directions. Such bearings are fit for use only in very small devices that are subject to small load, such as fans. Owing to their limited load capacity, they are not suited for turbocompressors or microturbines.

In its simplest structural form, a foil bearing comprises a foil element which overlays the internal surface of the bearing sleeve (HOU et al. 2004). This solution is illustrated in Figure 3.

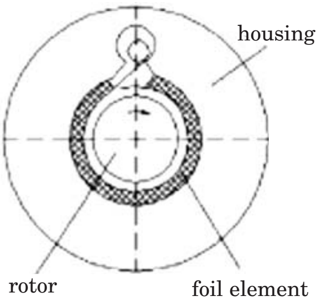


Fig. 3. The structure of a foil bearing with a single viscoelastic foil element
Source: HOU et al. 2004.

The viscoelastic foil overlay is fitted in the bearing sleeve at a single point along the sleeve's circumference. During normal operation, the bearing's functional behavior is similar to that of a traditional gas bearing. During overload, the journal hits the foil surface. Owing to its viscoelastic properties, the foil absorbs the energy displaced in the radial direction. This simple solution does not differ significantly from traditional journal bearings. Various structural improvements have been developed, one of which is shown in Figure 4. One layer of viscoelastic foil has been replaced with a second foil level which is fitted in a similar manner, but the foil element is long enough to wrap the internal diameter of the sleeve several times, creating a foil spiral inside the bearing. The foil is made of beryl bronze (in both cases). Spiral layers are separated with numerous copper wires. The resulting bearing can operate at the speed of around 220 000 rpm. The structure comprising several foil elements is presented on the right side of Figure 4. There are several points for fixing foil elements along the sleeve circumference. The length of foil elements is around 2/3 of the internal circumference of the sleeve, creating two active foil layers which are separated by thin copper wires.

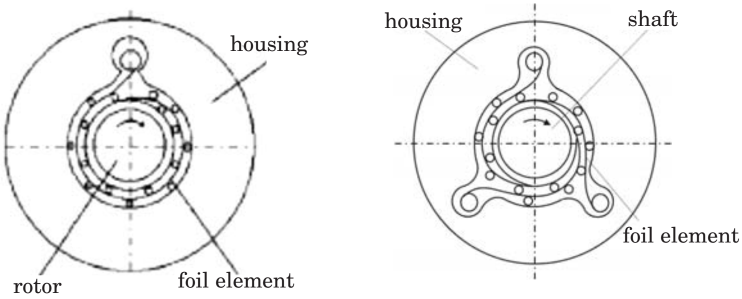


Fig. 4. Foil bearing with spiral foil (Hou et al. 2004) and several spirally-overlaid foil elements
Source: On the basis of Xiong et al. 1997.

The structure of a bearing comprising several foil elements without clearance between particular layers is presented in Figure 5.

During the operation of the bearing shown in Figure 5, the foil element supported by spacing wires is not deflected, and the load is absorbed by the successive foil elements. The length of every foil leaf is designed to overlay half of the length of the successive layer. When load is applied to any part of the foil element, some energy is absorbed by deflecting the element subjected to load, while some energy is distributed to the layer found directly beneath it. Since every terminal part of the element is supported by the most elastic fragment of the element found directly beneath it, the bearing retains its elasticity in the radial direction along the entire circumference of the sleeve.

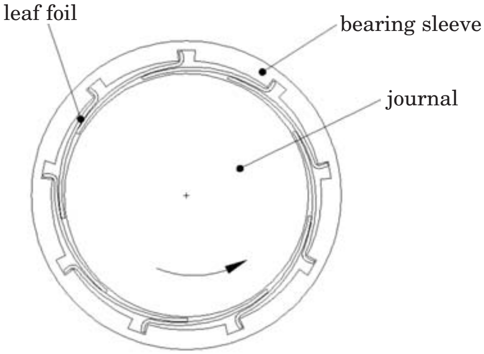


Fig. 5. Structure of a multi-layer foil bearing
Source: Based on DELLACORTE 2003.

The use of first generation foil bearings is limited by, among others, the properties of materials applied in foil production. In addition to delivering a high level of elasticity, foil elements have to be resistant to friction wear at high loads and speeds as well as to extreme temperatures. There are practically no materials that meet all of the above requirements.

Bump foil offers new structural possibilities. The structural model of a foil bearing with an additional foil element is presented in Figure 6.

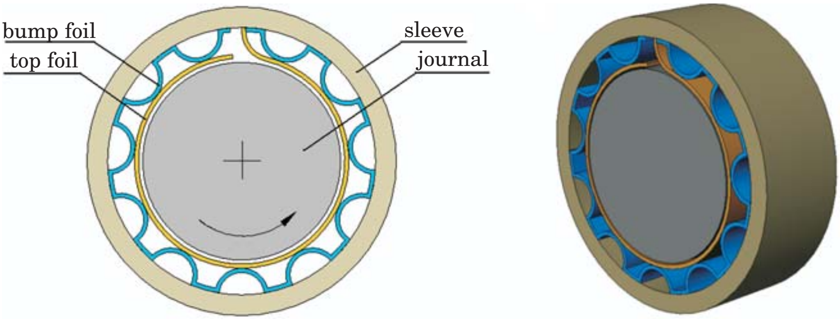


Fig. 6. Bump foil bearing
Source: Own work.

The top foil layer which directly co-acts with the rotating journal remains smooth, and it carries the distributed load to the bump foil layer found underneath. Owing to its shape and material properties, bump foil is subject to local elastic deflections, and it absorbs the energy generated by, for example, overloading. The structure of a bearing where smooth foil has been separated into two separate layers is presented in Figure 7.

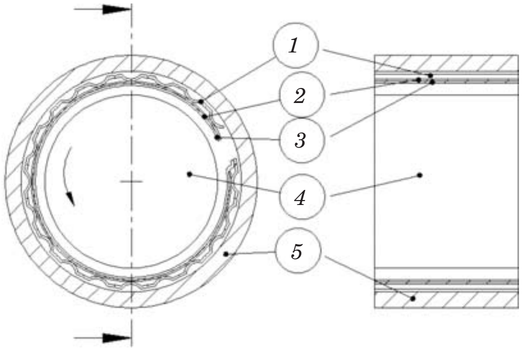


Fig. 7. Structure of a foil bearing with a separate viscoelastic foil layer. *1* – bump foil, *2* – viscoelastic foil, *3* – top foil, *4* – journal, *5* – bearing sleeve
Source: On the basis of LEE et al. 2004.

In the structure shown in Figure 7, top foil is made of tempered molybdenum sulfate. Top foil is wrapped around the bearing sleeve at the angle of 355°. The second layer is made of viscoelastic acrylic polymers resistant to the temperature of 150°C. Prior to assembly, bump foil is formed in the bearing sleeve. A foil leaf identical to the first layer co-acting with the journal is additionally interfaced with the sleeve surface (LEE et al. 2004).

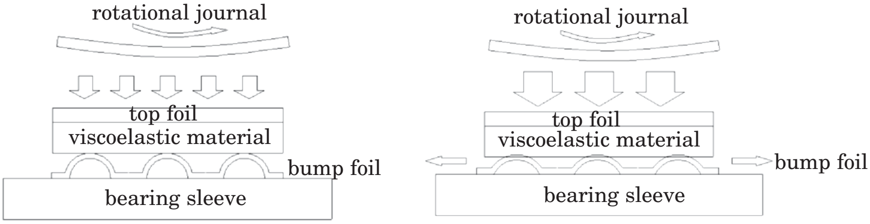


Fig. 8. Operating principle of bump foil bearings
Source: Based on LEE et al. 2004.

The operating principle of bump foil bearings is presented in Figure 8. The bearing operating under normal conditions is shown at the top. The gas or fluid film exerts pressure on the top foil. The top foil is deflected, carrying the load to the viscoelastic layer which absorbs most of the energy. Under higher loads, the excess energy deflects both foil layers, and it exerts pressure on the bumps of adequately shaped foil. The load applied to foil bumps deflects the entire structure of bump foil. In the absence of a separate viscoelastic layer, the top foil takes over its function, and any excess load is carried to the adequately shaped bump foil.

Bump foil delivers a variety of new structural solutions for bearings. A structural diagram of a multi-layer bump foil bearing is presented in Figure 9. Its structure has been modified in such a way that top foil fragments do not overlap and they do not form an elastic layer. The applied foil plays the role of the elastic layer.

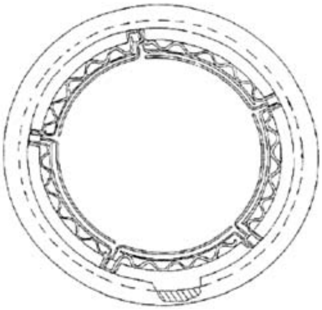
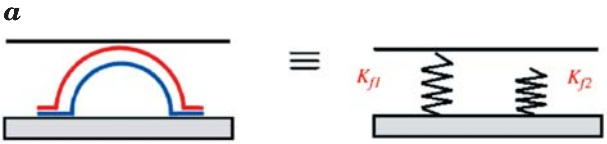
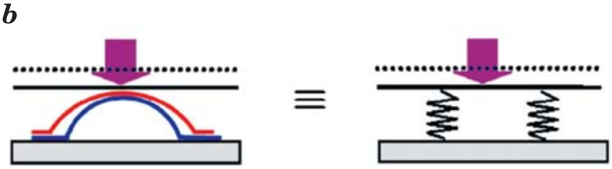


Fig. 9. Multi-layer bump foil bearing

Source: Agrawal 1997.



light load (one active bump)



heavy load (two active bumps)

Fig. 10. The operating principle of a double bump foil layer

Source: Kim, San Andres 2007.

The solution presented in Figures 6 and 7 may be deployed to protect the shaft journal and the supporting bearing against critical load with the use of a double bump foil layer. The first layer is more elastic, while the second layer delivers greater stiffness. The operating diagram of a double bump foil element is presented in Figure 10. The upper foil layer is activated at the initial stage of applying the load. The upper layer is deflected to discharge the load. If a heavier than designed load is applied, the second, stiffer layer is activated.

Similar structural solutions may be applied in foil thrust bearings. The bearing surface is divided into several sections. Each section is covered by a petal. The leading edge is fixed to the bearing surface, and the top foil petal rises gradually above the surface to which it is fixed. Bump foil is placed under the top foil layer. The top foil petal is inclined in the circumferential direction, and lubricating film is produced during rotational movement (DellaCorte 2004).

## Second generation foil bearings

The 1980s witnessed the onset of bearings which are suitable for use in turbocompressors and turbopumps. In second generation bearings, the geometry of the support structure changes in one of the directions. Variability in the axial direction is most frequently noted. It eliminates edge leaks caused by the gas lubricant, thus significantly increasing the bearing's load capacity. Structural models of second generation bearings are presented in Figures 11 and 12.

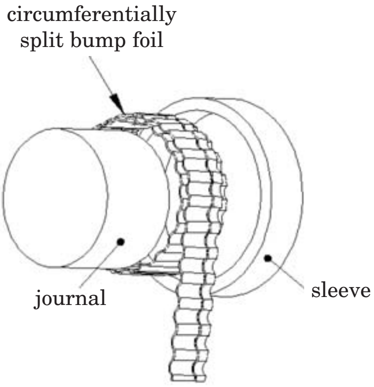


Fig. 11. Structural model with variable pitch of bump foil in the axial direction
Source: On the basis of DellaCorte 2000.

A model with a variable load-carrying structure in the circumferential direction is presented in Figure 12. Bump foil deflections were compacted in places where the upper foil layer was marked by the lowest stiffness.

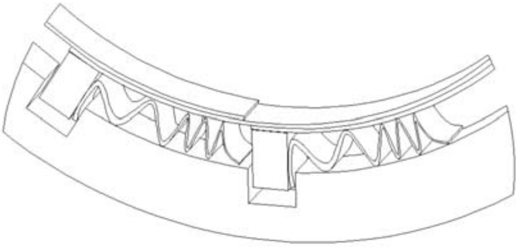


Fig. 12. Structural model with variable-pitch bump foil in the circumferential direction
Source: Own work.

Second generation foil bearings paved the way to the development of more complex structures that combine the physical properties of the available materials with variable bump foil geometry in all directions.

## Third generation foil bearings

In third generation foil bearings, changes in the properties of the load-carrying structure are observed in minimum two directions. Third generation bearings feature several bump foil layers where, subject to load and deflection, the elastic properties of the load-carrying structure vary in the radial direction. Third generation bearings also include any combinations of second generation foil bearings. A structural model of a third generation foil bearing is presented in Figure 13.

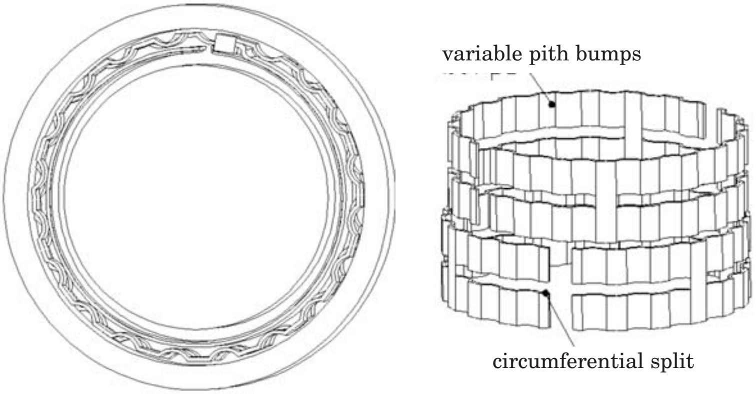


Fig. 13. Structural model using variable pitch bump foil in the circumferential and axial direction
Source: Based on DELLACORTE 2003.

Due to their high load capacity, third generation bearings are used in micro-power plants, microturbines and devices in which first and second generation bearings could not be applied due to heavy load constraints.

The load capacity of different generation bearings can be compared based on the results of research studies investigating specific solutions, as shown in Figure 14.

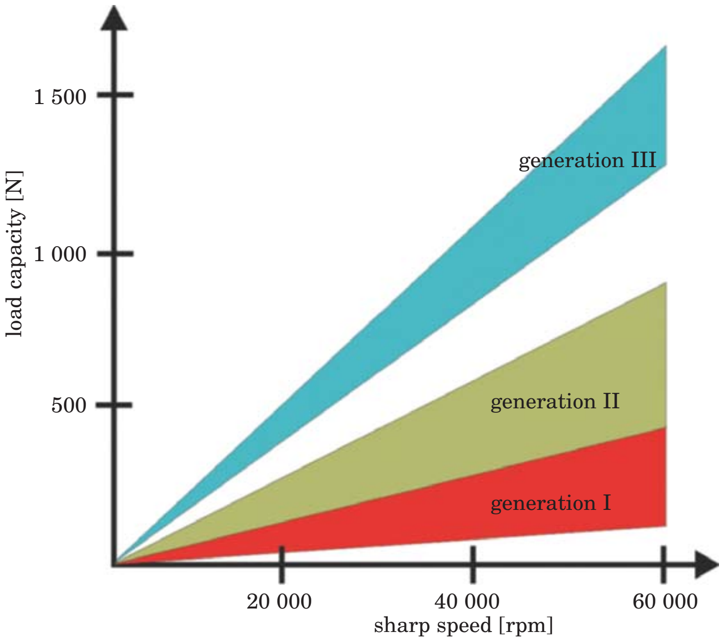


Fig. 14. A comparison of the load capacity of three generations of foil bearings
Source: On the basis of DELLACORTE 2003.

## Conclusions

The presented overview of the structural solutions deployed in bearings in microturbines and other devices of the type illustrates the great variety of technical solutions supporting the operation of contemporary rotor machines. The greatest advantages delivered by traditional rolling bearings are the stiffness of the structural support and low sensitivity to sudden load change. Foil bearings guarantee stable rotor operation at high speed and small loads. Except for overload, start-up and rundown, moving parts do not come into contact with stationary parts. Gas and foil bearings do not require the use of lubricants harmful to the environment. Owing to those properties, state-of-the-art foil bearings deliver rotational speed of 2 million rpm at operating temperatures as high as 800°C. Regardless of the strengths and weakness of different support solutions for microturbines and other technical devices, the knowledge and practice of building and diagnosing microbearings is undergoing rapid expansion world-wide. Research studies are initiated in various areas that range from material technology to modeling support structures in foil bearings. New technologies supporting the production of structural elements, new research methods and testing equipment need to be developed to verify the properties of the processed materials and finished elements.

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