
**Foil bearings — Guidelines for testing
of the performance of foil journal
bearings — Testing of load capacity,
friction coefficient and lifetime**

*Paliers-feuilles — Lignes directrices pour les essais de performance
des paliers radiaux à feuilles non lubrifiés — Essais de la capacité de
charge, du coefficient de friction et de la durée de vie*



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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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Introduction

Foil bearing is a special type of plain bearing; at the time of publication of this International Standard, no International Standards on foil bearings exist. This International Standard is an attempt to elaborate a test method for the basic performance of a foil bearing.

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Foil bearings — Guidelines for testing of the performance of foil journal bearings — Testing of load capacity, friction coefficient and lifetime

1 Scope

This International Standard describes a method of comparing the performance test results of foil journal bearings, which are lubricated by air (gas) and supported by hydrodynamic force generated by the rotation of the rotating shaft. The test procedure proposed in this International Standard aims to predict and evaluate the static load capacity, friction coefficient and lifetime of the foil journal bearing, and compare the results with those occurring under different test conditions, i.e. dimensions of a foil bearing, rotational speed of a shaft, pressure and humidity of surroundings and so on. The magnitude of the static load capacity can change according to the test setting, as the test conditions can be changed.

The test method described in this International Standard has the following application coverage:

- a) the criterion of the static load capacity is the steady-state, i.e. it is applied in a limited operating condition with a uniform magnitude, load direction and rotational speed;
- b) the evaluation procedure can be applied only if the foil journal bearing is under a uniform rotating inertia at an arbitrary rotational speed;
- c) the dynamic load with a time-variant magnitude and direction is not taken into consideration;
- d) for the purposes of this International Standard (these guidelines), the configuration of a typical foil journal bearing is presented in Annex A.

2 Symbols

For the purposes of this document, the following symbols apply.

2.1 Basic characters — Roman alphabet

Table 1 — Symbol — Basic characters — Roman alphabet

Symbol	Description	Unit
C	Clearance, coefficient	Micrometres, Non-dimensional
D	Diameter	Millimetres
d	Diameter	Millimetres
e	Eccentricity	Micrometres
F	Force	Newton
H	Height	Millimetres
h	Humidity	Percentage
L	Length, lifetime	Number of revolutions
p	Pressure	Newton per square millimetre
Ra	Surface roughness	Micrometres
r	Distance	Millimetres
T	Temperature, torque	Degrees Celsius, Newton- metres
t	Thickness	Millimetres
F_W	Mass, load	Newton

2.2 Basic characters — Greek alphabet

Table 2 — Symbol — Basic characters — Greek alphabet

Symbol	Description	Unit
ε	Eccentricity ratio	Non-dimensional
μ	Friction coefficient	Non-dimensional
ω	Rotational speed	Revolutions per minute

2.3 Additional signs — Subscripts

Table 3 — Symbol — Additional signs — Subscripts

Subscript	Description
a	Air (surrounding), average, applied
ah	Air in bearing housing
b	Bump foil, bearing
f	Top foil, friction
fs	Top foil surface
h	Housing
max	Maximum
n	Net
r	Radial, radius
R	Relative
to	Take-off
s	Steady-state, static

2.4 Additional signs — Superscript (shown on X)

Table 4 — Symbol — Additional signs — Superscript

Superscript	Description (shown on X)
$\bar{X}$	Non-dimensional value

3 Purpose of test

The primary purpose of the test is to measure and evaluate the static load capacity, friction coefficients and lifetime of the foil journal bearing. These are the primary performance metrics of the foil journal bearing as a mechanical element with a specific dimension. These are closely related to the performance of the mechanical systems to which the bearings are applied.

4 Test conditions

4.1 General

In order to compare the static load capacity, the test should be performed after the ambient pressure, temperature and humidity of the environment in which the bearing operates have reached a state of equilibrium. The bearing performance is obtained by measuring the bearing torque and the rotational speed of the shaft. In this case, the take-off speed, at which the shaft floats on the top foil without contact, may be observed. Bearing performance should be measured and compared at a rotational speed which is higher than the take-off speed.

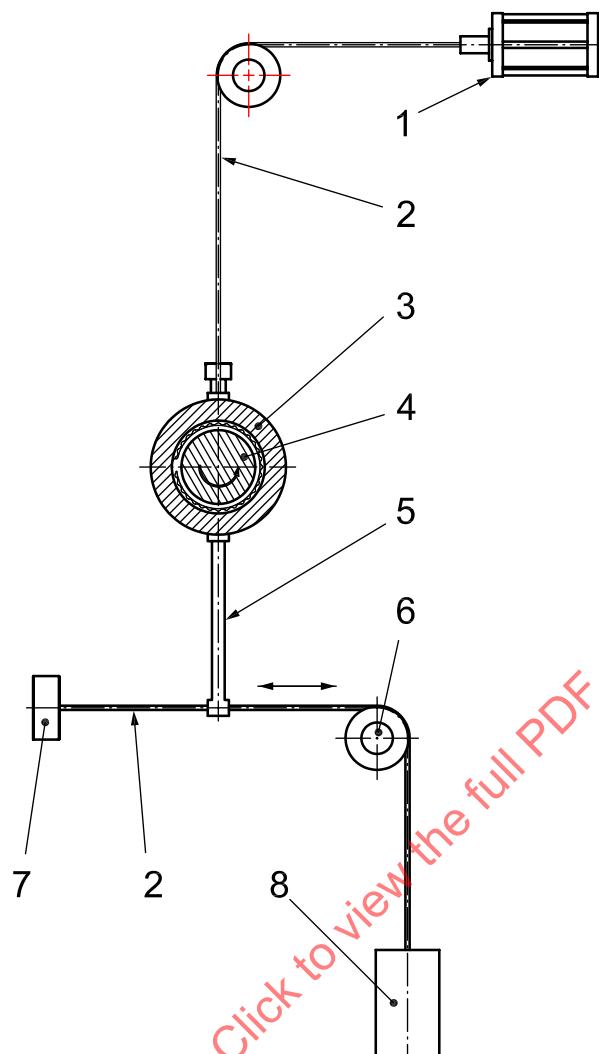
4.2 Design of test facility

The bearing test facility should be designed to control the relative position of the bearing in relation to the shaft. The bearing housing may be connected to a separate supporter, such as a spring or springs. Otherwise, a vibration-proof facility may be applied in order to prevent perturbation, which can have a severe effect on the test results. Also, excessive friction can have a severe effect on the test results due to misalignment of the bearing.

4.3 Installation of sensors

The equipment to measure the bearing torque and static load capacity of the foil journal bearings may be installed as shown in Figure 1. Using the measurement system clarified in Figure 1, the bearing torque and applied load may be measured and calculated as explained in 4.4.

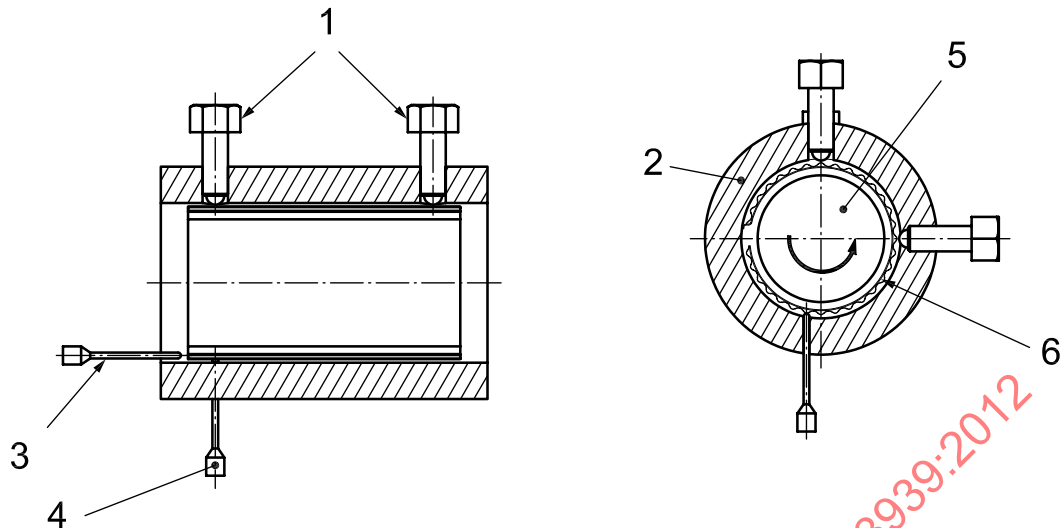
As shown in Figure 2, the displacement sensors are installed at right angles to each other at both ends of the bearing housing. The displacement of the shaft centre may be observed by measuring and comparing the values arrived at. The rotational speed of the shaft may be obtained by applying a fast Fourier transform (FFT) algorithm to the measured displacement data or by the use of a rotational speed meter. A thermocouple is installed inside the bearing housing to measure the temperatures of surrounding air (gas). To measure the surface temperature of a top foil, the thermocouple should be welded to the top foil surface.



Key

- 1 applied load
- 2 cable
- 3 deadweight housing
- 4 shaft
- 5 torque rod
- 6 pulley
- 7 load cell
- 8 counterweight preload

Figure 1 — Measurement system for the bearing torque and applied load



Key

- 1 displacement sensor
- 2 deadweight housing
- 3 thermocouple for measuring air temperature
- 4 thermocouple for measuring top foil surface temperature
- 5 shaft
- 6 top foil

Figure 2 — Installation of sensors

4.4 Calculation of bearing torque and loads

The friction force, F , may be measured using a load cell linked to the torque rod installed on the outside of the housing. Then, the bearing torque, T , generated by the rotation of the shaft is obtained as the product of the friction force, F , and the distance, r , between the two centres of the housing and load cell, as given by Formula (1):

$$T = F \times r \quad (1)$$

where

T is the bearing torque;

F is the friction force;

r is the distance between the housing centre and the sensor-linked location of the torque rod.

The net load, $F_{w,n}$, exerted on the foil journal bearing, as shown in Figure 1, is obtained by subtracting the applied load, $F_{w,a}$, measured from the load cell installed between the housing and the loading apparatus to the mass of the housing, $F_{w,h}$. Where the load is applied in the lower direction, the net load, $F_{w,n}$, is obtained by adding the mass of the housing, $F_{w,h}$, to the applied load, $F_{w,a}$.

4.5 Test specimens

The housing, bump foil, top foil and shaft comprising the foil journal bearing may be designed and fabricated according to the purpose of use.

5 Test methods

5.1 Principle

To operate and test the foil journal bearing, the take-off speed is measured and the load-carrying capacity is evaluated after sufficient preheating has taken place. The variables necessary for test and estimation are presented in the test report (see Annex B).

5.2 Start-stop test cycle and evaluation of the take-off speed

Using an electric motor or a turbine operated by a high-pressure air supply system, rotate the shaft and then the foil journal bearing starts to operate. Once the shaft begins its rotation, the bearing torque should be measured as the speed of rotation is gradually increased.

Figure 3 shows a typical example of variation in bearing torque, which is measured with the rotational speed of the shaft from the start-stop test. As the rotational speed increases, the bearing torque increases suddenly at a certain rotational speed and then decreases to maintain the steady-state condition with a relatively constant torque value. As the bearing torque decreases to meet its steady value, the rotational speed is determined as the take-off speed of the foil journal bearing and should be recorded in the test report (see Annex B). As the rotational speed decreases to zero, the bearing torque suddenly rises again and then decreases.

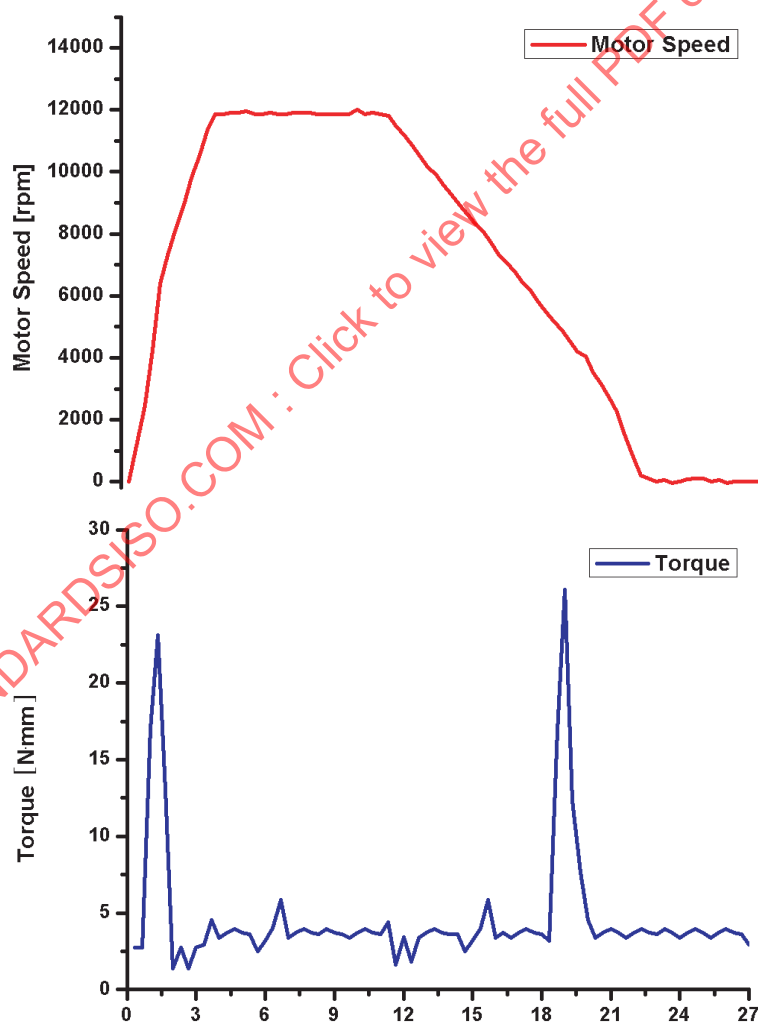


Figure 3 — Rotational speed versus bearing torque

The following processes comprise a single start-stop test cycle.

- a) Firstly, the load for the start-stop test should be determined and applied. Where selecting a load to evaluate the load capacity and lifetime of the bearing, the loading value exerted on the actual rotating system should be applied. Otherwise, the initial applied load, F_w , for a start-stop test may be calculated as follows, as a rule of thumb, then applied load, $F_{w,a}$, may be evaluated by the test process in 5.3.

$$F_w = C \times (L \times d)(d \times \omega) \quad (2)$$

where

- C is the coefficient of foil bearing load capacity, i.e. equal to 2 000;
 - L is the axial length of top foil, in millimetres (mm);
 - d is the shaft diameter, in millimetres (mm);
 - ω is the shaft rotational speed, in thousands of revolutions per minute (r/min).
- b) After the shaft reaches the take-off speed, the state should continue for 15 s, and then the power to the motor should be shut off to maintain a stopped state for 5 s.
 - c) This process is defined as a start-stop test. In the start-stop test, the rotational speed, the accumulated number of shaft rotations, the bearing torque, the temperature inside the housing and the top foil surface are observed.

5.3 Evaluation of static load capacity

The static load capacity, $F_{w,s}$, is the maximum steady load which may be delivered by a foil bearing in a steady-state condition.

The following is the process to determine the static load capacity.

- a) The rotational speed of the shaft is controlled to a given test speed, for example the speed of the actual foil bearing; measurement shall not take place before thermal equilibrium is reached, as measured using a thermocouple installed inside the bearing housing. The test speed should have a margin from the take-off speed to guarantee stable running of the bearing system.
- b) After increasing the rotational speed by about 10 % of the test speed to provide the foil bearing with higher load capacity, apply the initial load, F_w . Then, the rotational speed should return to the test speed. In this state, the rotational speed and the bearing torque should be observed for 5 min to estimate whether the air film or bearing rupture. Whenever a foil bearing has a film of air between the shaft and top foil, it demonstrates smooth rotation without any problems. Where unnecessary contacts develop between the shaft and top foil, it creates unstable vibrations. In this case, be sure to move to process (d) or this can lead to a sudden adhesion in a few seconds.
- c) If no failure is generated, the rotational speed should be increased by about 10 % of the test speed, a load of 1 N should be added and the rotational speed should be decreased to the test speed. Then, the bearing should be observed for failure for 5 min.
- d) If the bearing fails, the applied load should be removed and the test stopped after the rotating state becomes stable and operation is maintained for several minutes at the test speed.
- e) The maximum value at which the bearing operates successfully is taken to be the applied load, $F_{w,a}$. Then, the net load, $F_{w,n}$, exerted on the foil journal bearing is calculated using Formula (1) and is recorded in the test report of Annex B.
- f) The start-stop test should be repeated at least three times for a given test speed, and the net load, $F_{w,n}$, is recorded in the test report (see Annex B) for each test.

- g) Among the above-mentioned net loads, $F_{w,n}$, the minimum value at which the bearing operates successfully is taken as the static load capacity, $F_{w,s}$, of the foil journal bearing at the test speed and is noted in the test report (see Annex B).

5.4 Calculation of non-dimensional static load capacity

The static load capacity of the foil journal bearing is affected by the pressure of the ambient air (gas), which is the operating fluid and has a relationship with the bearing projecting area, which is the product of the shaft diameter and the bearing length.

Accordingly, where the parameters of the operating environments differ, the performance of the foil journal bearing may be compared and estimated where the static load capacity is normalized to calculate the load-carrying capacity for each projecting area, to eliminate the effects of the ambient air (gas).

The non-dimensional static load capacity, $\bar{F}_{w,s}$, is calculated using Formula (3) and is recorded in the test report (see Annex B).

$$\bar{F}_{w,s} = F_{w,s} / p_a / (L \times d) \quad (3)$$

where

- $\bar{F}_{w,s}$ is the non-dimensional static load capacity;
- $F_{w,s}$ is the static load capacity, in newtons (N);
- p_a is the ambient pressure, in newtons per square millimetre (N/mm²);
- L is the axial length of top foil, in millimetres (mm);
- d is the shaft diameter, in millimetres (mm).

5.5 Coefficient of bearing load capacity

The coefficient of bearing load capacity may be calculated using Formula (4), and may be utilized as a performance metric to estimate the static load capacity. The value is written in the test report (see Annex B).

$$C = F_{w,s} / (L \times d) / (d \times \omega) \quad (4)$$

where

- $F_{w,s}$ is the static load capacity, in newtons (N);
- L is the axial length of top foil, in millimetres (mm);
- d is the shaft diameter, in millimetres (mm);
- ω is the shaft speed in thousands of revolutions per minute.

6 Clearance and eccentricity ratio

The non-dimensional static load capacity is closely related to the variation of the centre position of the shaft. The difference between the centre of the housing and the centre of the shaft is defined as the eccentricity, e , and the radial direction gap between the shaft and the top foil is defined as the clearance, C_r .

The clearance and eccentricity ratio are calculated using Formula (5):

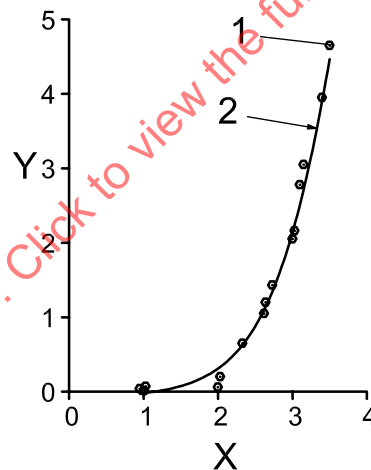
$$C_r = [D - d - 2(H_b + t_f)] / 2 \quad (5)$$

$$\varepsilon = e / C_r$$

where

- C_r is the clearance of foil bearing, in micrometres (μm);
- D is the inner diameter of bearing housing, in millimetres (mm);
- d is the shaft diameter, in millimetres (mm);
- H_b is the height of bump foil, in millimetres (mm);
- t_f is the thickness of top foil, in millimetres (mm);
- ε is the eccentricity ratio;
- e is the eccentricity, in micrometres (μm).

Figure 4 presents the relationship between the eccentricity ratio and the non-dimensional static load capacity. The clearance is the value determined whenever designing and fabricating the bearing, and is noted in the test report (see Annex B). As shown in Figure 2, the displacement sensors are installed at right angles to each other at both ends of the bearing housing, and the displacements of the shaft centre may be observed by measuring and comparing the values. Using these displacements, the eccentricity and the eccentricity ratio are calculated and written in the report (see Annex B). In this case, the arithmetic mean value of two values measured at both ends is applied.



Key

- X eccentricity ratio
- Y non-dimensional static load capacity
- 1 experiment
- 2 curve fit

Figure 4 — Typical relationships between the eccentricity ratio and non-dimensional static load capacity

7 Friction coefficient

The friction force and the friction coefficients are the characteristic values used to represent the primary characteristics of the foil journal bearing. The values may be calculated using measured friction force, F_s , at

the steady-state and static load capacity, $F_{W,s}$, from the load estimation system by the prestated method in Formula (1) and 5.3:

$$\mu = F_s / F_{W,s} \quad (6)$$

where

- μ is the friction coefficient;
- F_s is the friction force at steady-state;
- $F_{W,s}$ is the static load capacity.

The friction force generated between the shaft and the top foil in the initial operation is the maximum static friction force. The maximum friction coefficients calculated using the maximum static friction force should be calculated using Formula (6) above and reported in the test report (see Annex B) as an important factor to determine the lifetime of the shaft and the bearing.

8 Durability test and lifetime

8.1 Test procedure

The durability test of the foil bearing may be performed by repeating the start-stop test described in 5.2 using static load capacity, $F_{W,s}$, as the applied load.

8.2 Determination of lifetime

The hydrodynamic force generated by the rotation of the shaft is greatly affected by the clearance, C_r , between the top foil and the shaft, as explained in Clause 9. That is, where the clearance exceeds the appropriate value due to wear of the top foil and/or the shaft, performance metrics, such as static load capacity, can be decreased. Accordingly, the amount of wear should be regulated to guarantee that clearance is in the proper range of about 100 μm in a typical type of foil bearing.

If the top foil is coated with a solid lubricant or other material(s) and the coating itself has an important effect on the bearing performance, the total number of revolutions of the shaft where the coating layer has disappeared is set as the lifetime of the bearing, and should be written down in the test report (see Annex B).

In all other cases, the lifetime is the total number of revolutions of the shaft before the wear rate of the top foil or whenever the shaft reaches 20 % of the thickness of the top foil, and should be recorded in the test report (see Annex B).

The wear rate is estimated after each 100 cycles of the start-stop test.

9 Test report

The test report (see Annex B) should contain the following:

- a) the bearing parameters;
- b) the test conditions;
- c) the test methods;
- d) the loading methods;
- e) the test location;

- f) the date;
- g) the operator's name;
- h) the test results.

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Annex A (normative)

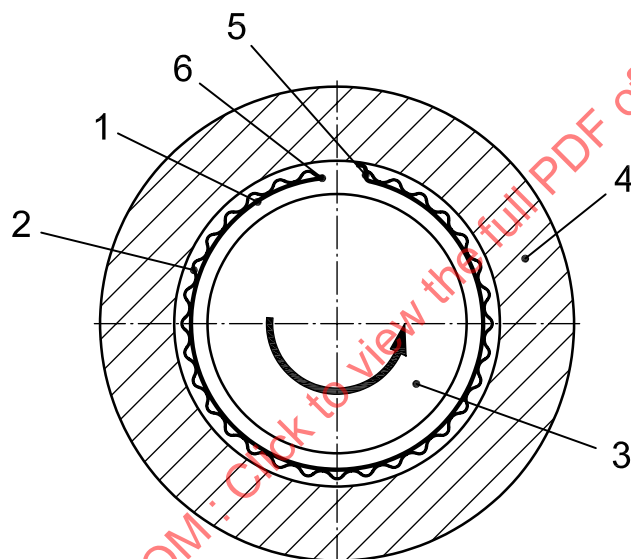
The configuration of a typical foil journal bearing

The foil journal bearing consists of a bearing housing, a bump foil or elastic foundation with a similar function, the top foil set between the above elastic foundation and the shaft, as shown in Figure A.1.

An additional casing outside of the bearing housing may be added according to design conditions.

Secure the clearance between the shaft and the top foil to generate the air film by hydrodynamic force as the shaft rotates.

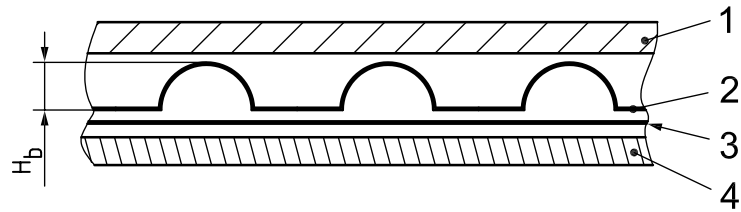
The configuration of the bump foil and top foil is described in Figure A.2.



Key

- 1 top foil
- 2 bump foil
- 3 shaft
- 4 bearing housing
- 5 trailing edge
- 6 leading edge

Figure A.1 — The configuration of a typical foil journal bearing

**Key**

- 1 shaft
- 2 top foil
- 3 bump foil with height of H_b
- 4 bearing housing

Figure A.2 — Configurations of bump foil and top foil