
Foil bearings — Performance testing of foil journal bearings — Testing of static load capacity, friction coefficient and lifetime

Paliers-feuilles — Essais de performance des paliers radiaux à feuilles non lubrifiés — Essais de la capacité de charge statique, du coefficient de frottement et de la durée de vie

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ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

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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.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 123, *Plain bearings*, Subcommittee SC 7, *Special types of plain bearings*.

This second edition cancels and replaces the first edition (ISO 13939:2012), which has been technically revised. The main changes compared to the previous edition are as follows:

- The content of Scope has been changed to a clearer expression.
- [Table 1](#), [Table 2](#), all figures and all formulae have been reviewed.
- The wording of definitions has been reviewed for consistency with ISO rules.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Foil bearings — Performance testing of foil journal bearings — Testing of static load capacity, friction coefficient and lifetime

1 Scope

This document describes a method for comparing the performance test results of foil journal bearings, which are lubricated by air (gas) and supported by the gas-dynamic force generated via the rotations of the rotating shaft. The test procedure proposed in this document aims to predict and evaluate the static load capacity, friction coefficient and lifetime of foil journal bearings and compare the results of these parameters under different test conditions, i.e. at varying dimensions of foil bearing, rotational speed of a shaft, pressure and humidity of the surroundings. 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 document has the following application coverage.

- a) The criterion for evaluating the static load capacity is the steady-state condition; i.e. the method is applicable under limited operating conditions with 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 time-variant magnitude and direction is not considered.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1 take-off

stage aimed to secure the distance between the rotating shaft and the top foil by developing aerodynamic pressure between them

3.2 clearance

shortest distance between the rotating shaft and the top foil when the axis of the shaft coincides with the axis of the housing

3.3 bearing torque

torque developed by rotational friction between the rotating shaft and the top foil

Note 1 to entry: The measurement of the bearing torque is described in [6.4](#).

3.4

load

load capacity

weight that can be delivered by a bearing under steady-state conditions

3.5

initial load

load (3.4) exerted on the rotating system in the beginning

Note 1 to entry: The initial load should be lower than the static load capacity and the load at which the lifetime of the bearing is determined, as explained in 7.3 and 10.2.

3.6

static load capacity

maximum load (3.4) of a bearing in static state

Note 1 to entry: The measurement of the static load capacity is explained in 7.4.

3.7

friction coefficient

flow resistance caused by rotational friction between the rotating shaft and the top foil

Note 1 to entry: The measurement of the friction coefficient is described in Clause 9.

3.8

lifetime of bearing

total number of start-stop test cycles of the bearing until the first failure is observed

Note 1 to entry: The measurement of the lifetime of bearing is described in Clause 10.

4 Symbols

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

4.1 Basic characters — Roman alphabet

Table 1 — Symbol — Basic characters — Roman alphabet

| Symbol | Description | Unit |
|----------------------|-------------------|------------------------------------|
| <i>C</i> | Clearance | Micrometre |
| <i>d</i> | Diameter | Millimetre |
| <i>e</i> | Eccentricity | Micrometre |
| <i>F</i> | Force | Newton |
| <i>F_w</i> | Weight, load | Newton |
| <i>H</i> | Height | Millimetre |
| <i>h</i> | Humidity | Percentage |
| <i>K</i> | Coefficient | Newton-minute per cubic millimetre |
| <i>L</i> | Length | Millimetre |
| <i>M</i> | Torque | Newton-millimetre |
| <i>N</i> | Lifetime | Number of start-stop cycles |
| <i>p</i> | Pressure | Newton per square millimetre |
| <i>R</i> | Surface roughness | Micrometre |
| <i>r</i> | Distance | Millimetre |

Table 1 (continued)

| Symbol | Description | Unit |
|--------|-------------|----------------|
| T | Temperature | Degree Celsius |

4.2 Basic characters — Greek alphabet

Table 2 — Symbol — Basic characters — Greek alphabet

| Symbol | Description | Unit |
|---------------|----------------------|-----------------------|
| δ | Thickness | Millimetre |
| ε | Eccentricity ratio | Non-dimensional |
| μ | Friction coefficient | Non-dimensional |
| ω | Rotational speed | Revolution per minute |

4.3 Additional signs — Subscripts

Table 3 — Symbol — Additional signs — Subscripts

| Subscript | Description |
|-----------|-------------------------------------|
| a | Air (surrounding), average, applied |
| ah | Air in the 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, shaft |

4.4 Additional signs — Overline (shown on X)

Table 4 — Symbol — Additional signs — Overline

| Overline | Description (shown on X) |
|-----------|--------------------------|
| \bar{X} | Non-dimensional quantity |

5 Purpose of the test

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

The configuration of a typical foil journal bearing is shown in [Annex A](#).

6 Test conditions

6.1 General

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. Bearing performance is obtained by measuring the bearing torque and rotational speed of the shaft. In this case, the take-off speed, at which the shaft floats on the top foil without contact, can be observed. For measuring and comparing the bearing performance, the rotational speed shall be higher than the take-off speed.

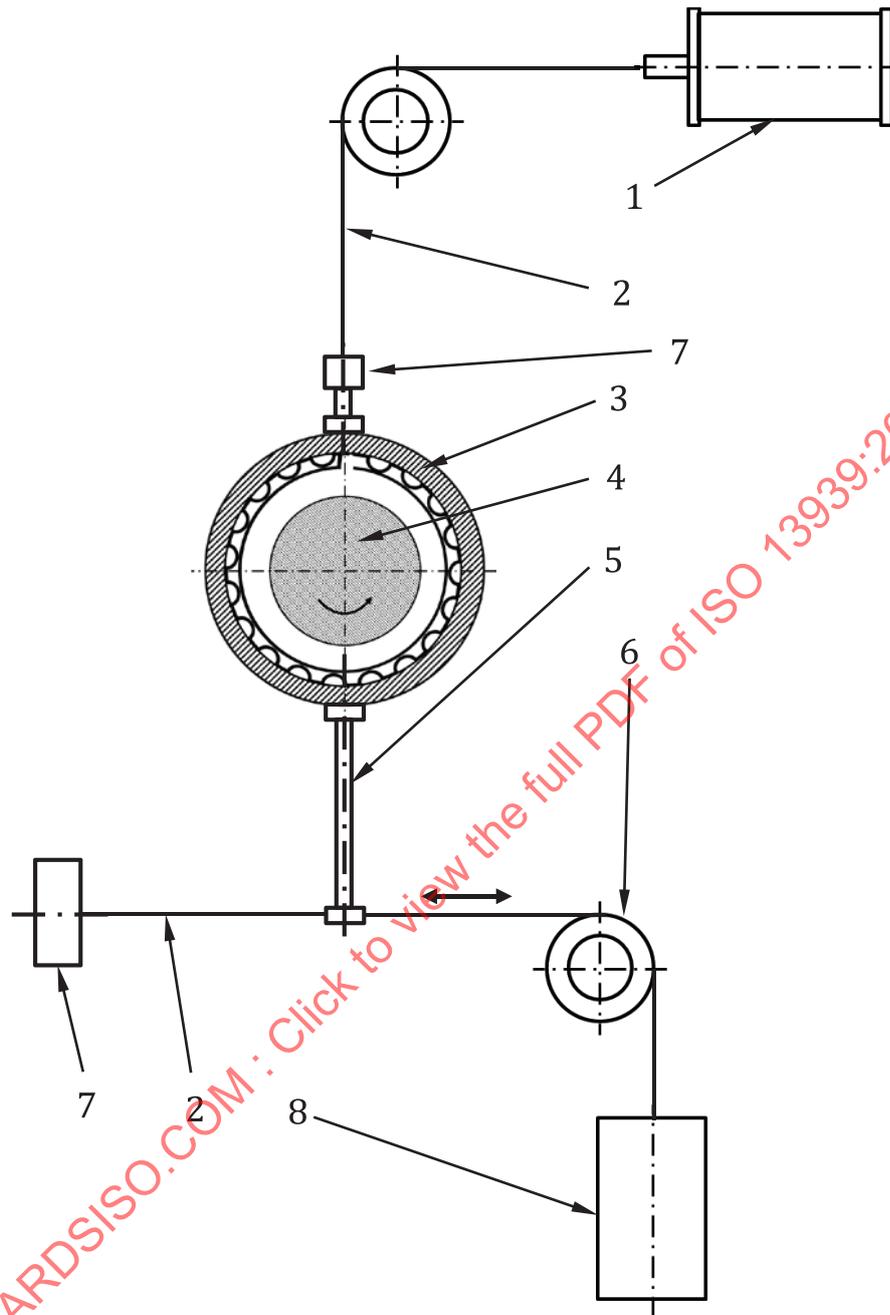
6.2 Design of test facility

The bearing test facility should be designed to control the relative position of the bearing in relation to the shaft. The bearing housing can be connected to a separate supporter, such as a spring or springs. Otherwise, a vibration-proof facility can be applied to prevent perturbation, which can severely affect the test results. Moreover, excessive friction can cause misalignment of the bearing and thus significantly affect the test results.

6.3 Installation of sensors

[Figure 1](#) illustrates the installation of the equipment to measure the bearing torque and static load capacity of the foil journal bearings. Using the measurement system shown in [Figure 1](#), the bearing torque and applied load can be measured and calculated as explained in [6.4](#).

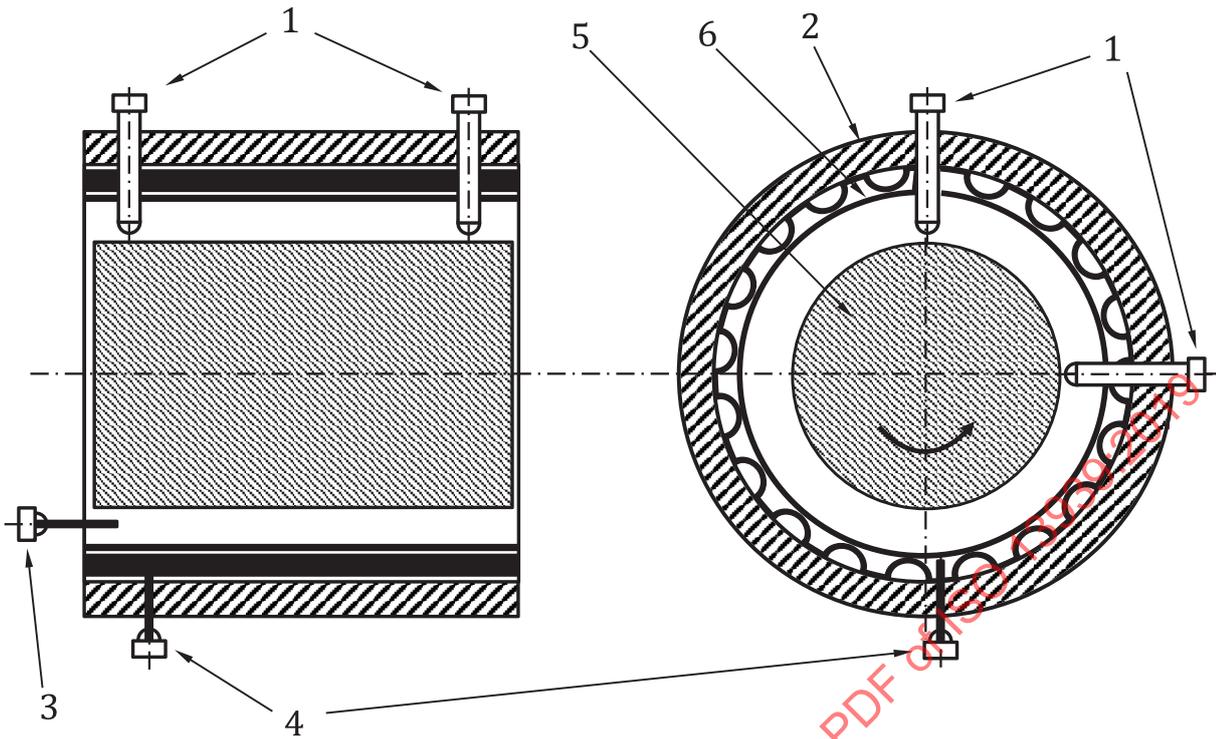
As shown in [Figure 2](#), the displacement sensors are installed at right angles to each other at both ends of the bearing housing. The displacement of the shaft axis is observed by measuring and comparing the obtained values. To measure the rotational speed of the shaft, a fast Fourier transform (FFT) algorithm is applied to the measured displacement data or a rotational speed meter is used. A thermocouple is installed inside the bearing housing to measure the temperature 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 loading apparatus
- 2 cable
- 3 deadweight housing
- 4 shaft
- 5 torque rod
- 6 pulley
- 7 load cell
- 8 counterweight pre-load

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

6.4 Calculation of bearing torque and loads

The friction force, F , can be measured using a load cell linked to the torque rod installed on the outside of the housing. Then, the bearing torque, M , generated by the rotation of the shaft is obtained as the product of the friction force, F , and distance, r , between the two axes of the housing and load cell, as represented by [Formula \(1\)](#):

$$M = F \times r \tag{1}$$

where

- M is the bearing torque, expressed in newton-millimetres (N·mm);
- F is the friction force, expressed in newtons (N);
- r is the distance between the housing axis and the sensor-linked location of the torque rod, expressed in millimetres (mm).

The net load, $F_{w,n}$, exerted vertically downward on the foil journal bearing, as shown in [Figure 1](#), is obtained by subtracting the weight of the housing, $F_{w,h}$, from the applied load, $F_{w,a}$, where $F_{w,a}$ is measured by the load cell installed between the housing and loading apparatus.

6.5 Test specimens

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

7 Test methods

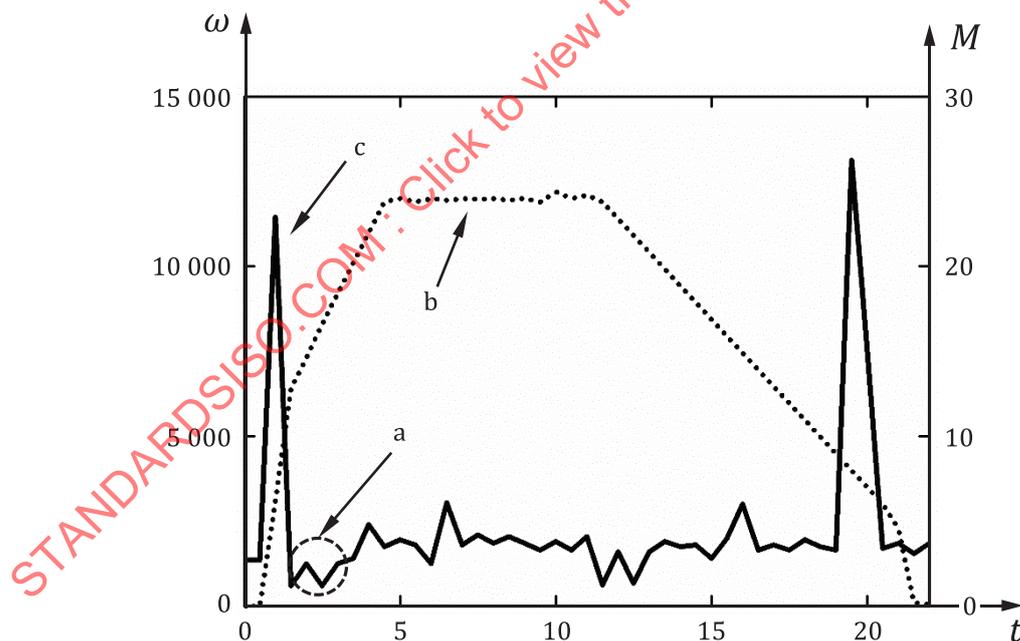
7.1 Principle

To operate and test the foil journal bearing, the take-off speed is measured and the load-carrying capacity is evaluated after sufficient pre-heating. The test report presents the variables required for test and estimation (see [Annex B](#)).

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

The foil journal bearing starts operating when the shaft is rotated using a driver. The bearing torque should be measured when the shaft begins its rotation as the speed of rotation gradually increases.

[Figure 3](#) shows a typical example of variation in the bearing torque measured using the rotational speed of the shaft from the start-stop test. As the rotational speed increases, the bearing torque suddenly increases at a certain rotational speed and then decreases to maintain the steady-state condition with a relatively constant torque value. When 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 increases again and then decreases.



Key

- t time, expressed in seconds (s)
- ω motor speed, expressed in revolutions per minute (min^{-1})
- M torque, expressed in newton-millimetres ($\text{N}\cdot\text{mm}$)
- a Take-off.
- b The dotted line represents the motor speed, ω .
- c The solid line represents the torque, M .

Figure 3 — Rotational speed versus bearing torque

A single start-stop test cycle comprises the following processes.

- a) First, the load for the start-stop test should be determined and applied. For 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 can be calculated as a rule of thumb as follows. Then, the applied load, $F_{w,a}$, can be evaluated by the test process in [7.3](#).

$$F_w = K \times (L \times d_s) \times (d_s \times \omega) \quad (2)$$

where

K is the coefficient of foil bearing load capacity, equal to 1,4 (N·min·mm⁻³);

L is the axial length of the top foil, expressed in millimetres (mm);

d_s is the shaft diameter, expressed in millimetres (mm);

ω is the shaft rotational speed, expressed in revolutions per minute (min⁻¹).

- b) After the shaft reaches the take-off speed, the state should continue for 15 s. Then, the power to the driver should be shut off to maintain a stopped state for 5 s.
- c) This process is defined as a start-stop test. Here, the rotational speed, accumulated number of shaft rotations, bearing torque, temperature inside the housing and top foil surface are observed.

7.3 Evaluation of static load capacity

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

The process to determine the static load capacity is as follows.

- a) The rotational speed of the shaft is maintained at a given test speed, for example, the speed of the actual foil bearing. Measurements shall be performed only after the 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 higher load capacity to the foil bearing, apply the initial load, F_w . Then, the rotational speed should be equal to the test speed. In this state, the rotational speed and bearing torque should be measured for 5 min to estimate whether the air film or bearing ruptures. A foil bearing with an air film between the shaft and top foil demonstrates smooth rotation without any problems. Moreover, it creates unstable vibration when unnecessary contacts develop between the shaft and top foil. In this case, be sure to move to step d); otherwise, this can lead to a sudden adhesion in a few seconds.
- c) In the case of no failure, the rotational speed should be increased by about 10 % of the test speed, a load of 1 % of the initial load, F_w , should be applied 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 should be stopped after the rotating state becomes stable and the operation is maintained for several minutes at the test speed.
- e) The maximum value at which the bearing successfully operates is considered as the applied load, $F_{w,a}$. Then, the net load, $F_{w,n}$, exerted on the foil journal bearing is calculated by the method given in [6.4](#) and is recorded in the test report (see [Annex B](#)).
- f) The start-stop test should be repeated at least three times for a given test speed. Moreover, the net load, $F_{w,n}$, for each test should be recorded in the test report (see [Annex B](#)).

- g) Among the above-mentioned net loads, $F_{w,n}$, the minimum value at which the bearing successfully operates is considered 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](#)).

7.4 Calculation of non-dimensional static load capacity

The static load capacity of the foil journal bearing is affected by the pressure of ambient air (gas), which is the operating fluid and is related to the bearing projecting area, i.e. the product of the shaft diameter and bearing length.

Accordingly, when the parameters of the operating environments differ, the performance of the foil journal bearing can be compared and estimated by normalising the static load capacity to calculate the load-carrying capacity for each projecting area and thus eliminating the effects of ambient air (gas).

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

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

where

- $\bar{F}_{w,s}$ is the non-dimensional static load capacity;
- $F_{w,s}$ is the static load capacity, expressed in newtons (N);
- p_a is the ambient pressure, expressed in newtons per square millimetres ($\text{N}\cdot\text{mm}^{-2}$);
- L is the axial length of the top foil, expressed in millimetres (mm);
- d_s is the shaft diameter, expressed in millimetres (mm).

7.5 Coefficient of bearing load capacity

The coefficient of bearing load capacity, $K_{w,s}$, can be calculated using [Formula \(4\)](#) and is utilized as a performance metric to estimate the static load capacity. The value is presented in the test report (see [Annex B](#)).

$$K_{w,s} = F_{w,s} / [(L \times d_s) \times (d_s \times \omega)] \quad (4)$$

where

- $F_{w,s}$ is the static load capacity, expressed in newtons (N);
- L is the axial length of the top foil, expressed in millimetres (mm);
- d_s is the shaft diameter, expressed in millimetres (mm);
- ω is the shaft speed, expressed in revolutions per minute (min^{-1}).

8 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 centres of the housing and shaft is defined as eccentricity, e , and the radial direction gap between the shaft and top foil is defined as clearance, C_r , when the axes of the shaft and housing coincide.

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

$$C_r = [d_h - d_s - 2(H_b + \delta_f)] / 2 \quad (5)$$

$$\varepsilon = e / C_r$$

where

C_r is the clearance of the foil bearing, expressed in micrometres (μm);

d_h is the inner diameter of the bearing housing, expressed in millimetres (mm);

d_s is the shaft diameter, expressed in millimetres (mm);

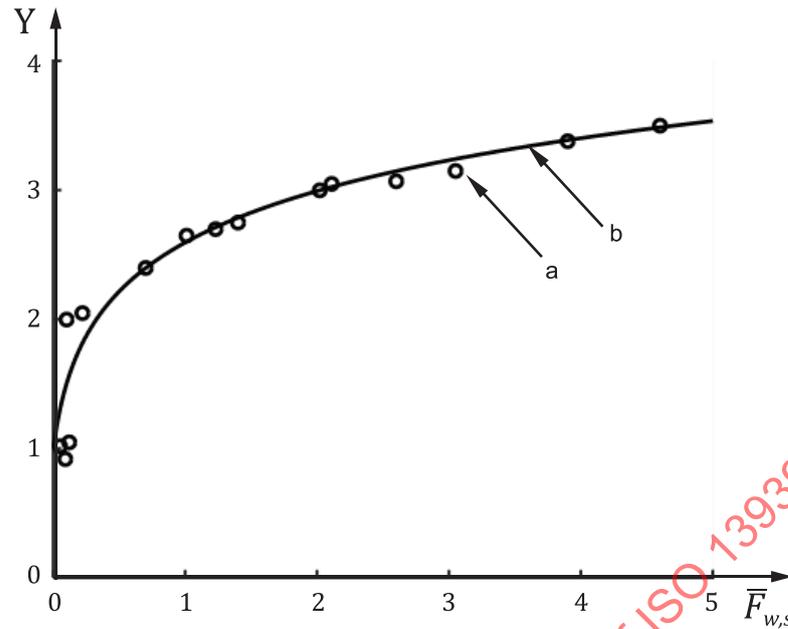
H_b is the height of the bump foil, expressed in millimetres (mm);

δ_f is the thickness of the top foil, expressed in millimetres (mm);

ε is the eccentricity ratio;

e is the eccentricity, expressed in micrometres (μm).

[Figure 4](#) presents the relation between the eccentricity ratio and non-dimensional static load capacity. Clearance is determined during the design and fabrication of the bearing and 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 resultant values of these sensors can be compared to obtain the displacements of the shaft centre. The eccentricity and eccentricity ratio are calculated using these displacements and written in the report (see [Annex B](#)). In this case, the arithmetic mean of the two values measured at both ends is applied.

**Key**

- $\bar{F}_{w,s}$ non-dimensional static load capacity
- Y $1/\varepsilon$
- a Experiments.
- b Curve fit.

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

9 Friction coefficient

Friction force and friction coefficient represent the primary characteristics of the foil journal bearing. These values can be calculated using the measured friction force, F_s , at the steady-state and static load capacity, $F_{w,s}$, from the load estimation system by the pre-stated method in [Formula \(1\)](#) and [7.3](#):

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

where

μ is the friction coefficient;

F_s is the friction force at steady-state, expressed in newtons (N);

$F_{w,s}$ is the static load capacity, expressed in newtons (N).

The friction force generated between the shaft and top foil in the initial operation is the maximum static friction force. The maximum friction coefficient should be calculated using the value of maximum static friction force in [Formula \(6\)](#) and reported in the test report (see [Annex B](#)) because of its significance in determining the lifetime of the shaft and bearing.

10 Durability test and lifetime

10.1 Test procedure

The durability test of the foil bearing can be performed by repeating the start–stop test described in [7.2](#) using static load capacity, $F_{w,s}$, as the applied load.

10.2 Determination of lifetime

The gas-dynamic force generated by the rotation of the shaft is significantly affected by the clearance, C_r , between the top foil and shaft, as explained in [Clause 8](#). That is, when the clearance exceeds the appropriate value owing to the wear of the top foil and/or shaft, performance metrics such as static load capacity can be decreased. Accordingly, the amount of wear should be regulated to ensure that clearance is in the proper range of about 100 μm in a typical foil bearing.

If the top foil is coated with a solid lubricant or other material(s) that significantly affect(s) the bearing performance, the total number of start–stop test cycles of the bearing wherein the coating layer has disappeared is set as the lifetime of the bearing and should be noted in the test report (see [Annex B](#)).

In all other cases, the lifetime is the total number of start–stop test cycles of the bearing 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 every 1 000 cycles of the start–stop test.

11 Test report

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

- a) a reference to this document, i.e. ISO 13939:2019;
- b) the bearing parameters;
- c) the test conditions;
- d) the test methods;
- e) the loading methods;
- f) the test location;
- g) the date;
- h) the operator's name;
- i) the test results.

Annex A (informative)

Configuration of a typical foil journal bearing

The foil journal bearing comprises a bearing housing, bump foil or elastic foundation with a similar function and top foil set between the above elastic foundation and shaft ([Figure A.1](#)).

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

Secure the clearance between the shaft and top foil to generate the air film using the gas-dynamic force generated via the rotation of the shaft.

[Figure A.2](#) describes the configurations of the bump foil and top foil.

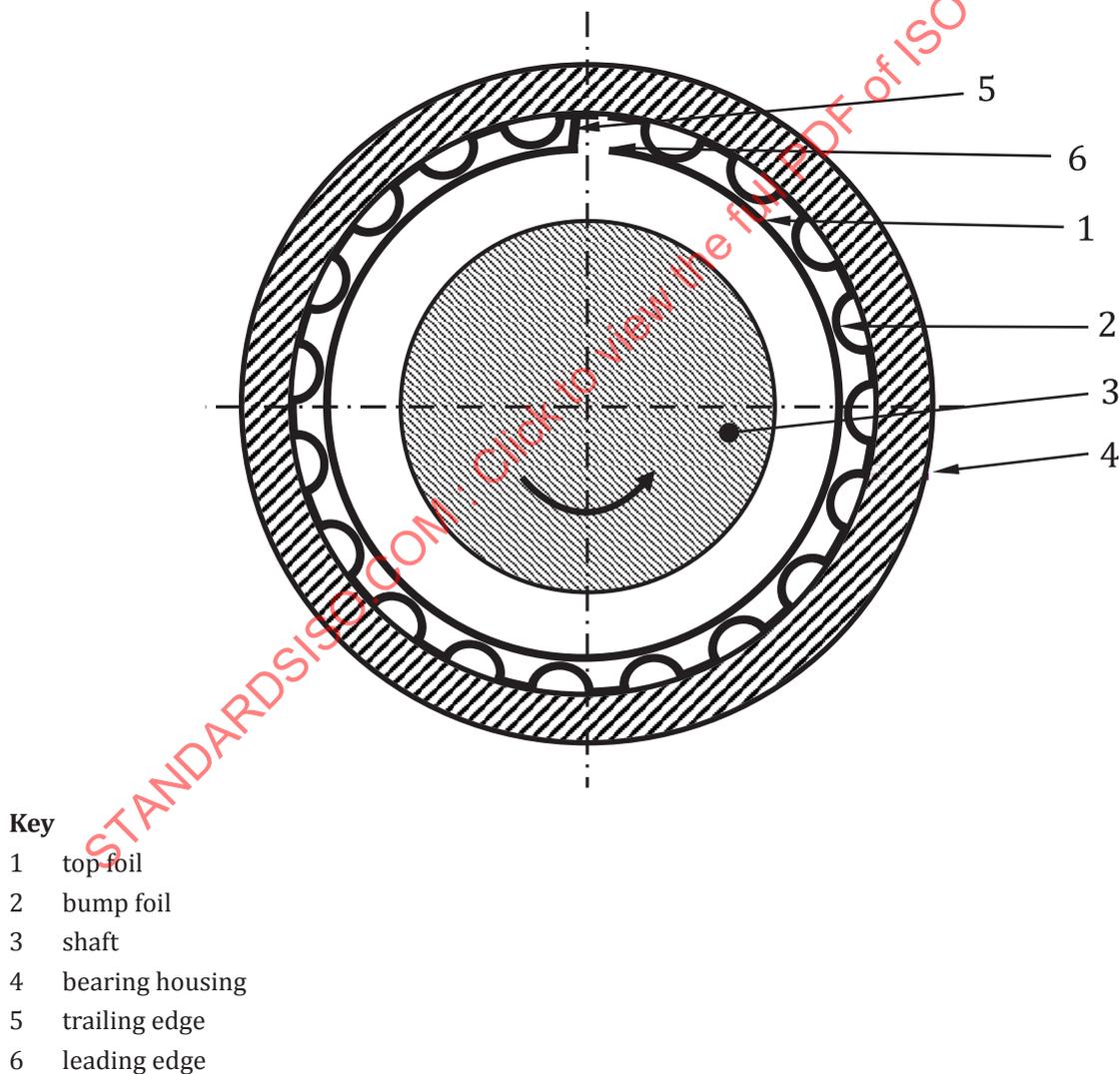


Figure A.1 — Configuration of a typical foil journal bearing