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

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Foreword

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

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.

Introduction

Design improvements commonly required for rotating machines such as turbines, generators, compressors and pumps include increases in speed and decreases in size. Foil bearings in turbomachinery operate by generating a self-acting air (or gas) film between surfaces in relative motion. A gap between a rotating shaft or runner and a foil surface compresses a gaseous lubricant to an elevated pressure, separating the relatively moving surfaces and providing a load-carrying capacity. The use of the surrounding air (or gas) as the bearing lubricant eliminates the need for an auxiliary lubrication system to deliver conventional oil lubricants. This permits drastic reductions in the weight, complexity and maintenance costs of foil bearing-supported turbomachines, in comparison to their rolling bearing-supported counterparts. It also permits higher shaft speeds by removing the $n \times d_m$ speed limits (where d_m is the mean diameter of bearing and n is the rotation rate) on rolling bearings.

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

1 Scope

This document specifies the method for comparing performance evaluation results for a foil thrust bearing that supports load with aerodynamic force generated by the rotation of a driving shaft and lubricates using air, not lubricating oil. The test procedure explained in this document measures and evaluates the static load capacity, bearing torque, friction coefficient and lifetime of the foil thrust bearing and compares the test results to those for different test conditions. The measured static load capacity can be varied depending on the capabilities of the test device used.

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
thrust runner
runner
circular disc connected to the rotating shaft and facing the surface of the top foil

Note 1 to entry: The surfaces of the thrust runner should be machined smoothly enough to form the air film between the runner and the top foil.

3.2
take-off
stage aimed to secure the distance between the *thrust runner* (3.1) and the top foil by developing an aerodynamic pressure between them

3.3
clearance
shortest distance between the *thrust runner* (3.1) and the top foil

3.4
bearing torque
torque value developed by rotational friction between the *thrust runner* (3.1) and the top foil

Note 1 to entry: The measurement of the bearing torque is as described in 7.3.

3.5
load
load capacity
weight that can be delivered by a bearing under steady-state conditions

3.6
initial load
load (3.5) exerted on the rotating system in the beginning

Note 1 to entry: It should be lower than the static load capacity and the load at which the lifetime of the bearing is determined, as explained in 7.4 and 9.2.

3.7
reference load
load (3.5) expected to be supported by a bearing

Note 1 to entry: The calculation of the reference load is given in 7.2.

3.8
static load capacity
maximum *load* (3.5) value of a bearing in static state

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

3.9
friction coefficient
flow resistance caused by rotational friction between the *thrust runner* (3.1) and the top foil

Note 1 to entry: The measurement of the friction coefficient is described in Clause 8.

3.10
lifetime of bearing
total number of start–stop test cycles of the foil thrust bearing at which the coating layer disappears

Note 1 to entry: The measurement of the lifetime of bearing follows Clause 9.

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	Units
A	Area	Square millimetre
F	Force, load	Newton
H	Height	Millimetre
h	Humidity	Percentage
L	Lifetime	Number of start-stop cycles
M	Torque	Newton-millimetre
R_a	Surface roughness	Millimetre
r	Distance, radius	Millimetre
T	Temperature	Degrees Celsius
t	Thickness	Millimetre

4.2 Basic characters — Greek alphabet

Table 2 — Symbol — Basic characters — Greek alphabet

Symbol	Description	Unit
μ[a]	Friction coefficient	Non-dimensional
ω	Rotational speed	r/min

[a] The symbol f is also commonly used and accepted.

4.3 Additional signs — Subscripts

Table 3 — Symbol — Additional signs — Subscripts

Subscription	Description
a	Air (surrounding), average, applied
b	Bump foil, bearing
f	Top foil, friction
fs	Top foil surface
i	Inner
inc	Increment
max	Maximum
n	Net
o	Outer
r	Radial, radius, runner, reference
R	Relative
to	Take-off
s	Steady-state, static
u	Upper
ua	Unit area
w	Working

5 Purpose of test

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

6 Test conditions

6.1 General

The static load capacity of a foil thrust bearing should be tested, 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 determined by measuring the bearing torque and the rotational speed of the shaft. The take-off speed, which is the speed at which the runner floats on the top foil without making contact, should be determined. The bearing performance should be measured and compared at a rotational speed that is higher than the take-off speed.

6.2 Design of test apparatus

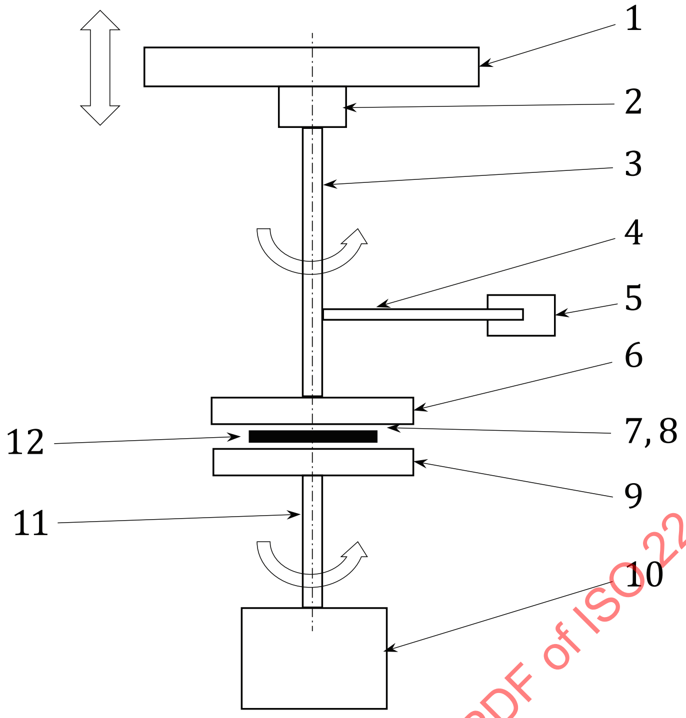
The bearing test apparatus should be designed to control the relative position of the bearing in relation to the runner. Excessive friction due to misalignment of the bearing can have a severe effect on the test results. It shall be avoided not only by maintaining a constant distance between the runner and the top foil, but also by preventing any disturbance that can affect the test results. A schematic illustration of the test apparatus is shown in Figure 1. The test load is applied by moving the loading plate to press against the runner, using a mechanical and/or pneumatic system.

6.3 Installation of sensors

The equipment used to measure the bearing torque and static load capacity of the foil thrust bearings is installed as shown in Figure 1. Using the measurement system shown in Figure 1, the bearing torque and applied load are measured and calculated as explained in 7.3. The rotational speed of the shaft is determined using a rotational speed meter. A thermocouple is installed inside the bearing to measure the temperature of the surrounding air (gas). A thermocouple should be welded to the top foil surface to measure the surface temperature of the top foil (see Figure A.1 and Figure A.2).

6.4 Test specimens

The bump foil, top foil and bearing plate should be designed and fabricated using materials appropriate for the intended use.



Key

1	loading plate
2,5	load cells
3	loading shaft
4	torque rod
6	mounting disk for bearing specimen
7	thermocouple for measuring air temperature
8	thermocouple for measuring top foil surface temperature
9	runner
10	driver
11	driving shaft
12	test bearing specimen

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

7 Test methods

7.1 Principle

The take-off speed and the parameter values necessary to estimate the load-carrying capacity of the foil thrust bearing should be evaluated after sufficient preheating has taken place. The values of the parameters associated with the testing and estimation shall be presented in the test report (see Annex B).

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

The driving shaft is rotated using a driver and the foil thrust bearing begins to operate. Once the driving shaft begins rotating, the bearing specimen is moved close to the runner by moving the loading plate toward the driver. For practical purposes, the threshold (or recommended) value of a thrust pressure of a foil thrust bearing is 0,5 bar, which is the same as 0,05 N/mm^2. The reference load, F_r, is calculated as the product of the recommended value of a thrust pressure and the area of the top foil surface, A_{fs}, as shown in Formula (1):

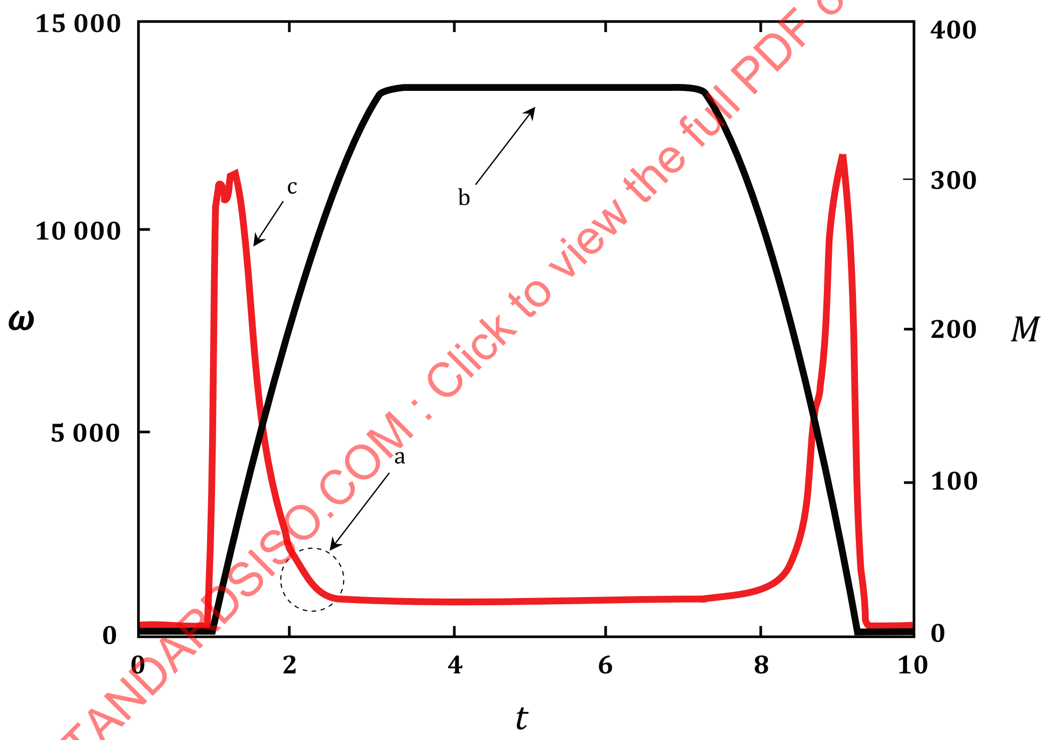
$$F_r = 0{,}05\, A_{fs} \tag{1}$$

where

F_r is the reference load; and

A_{fs} is the area of the top foil surface.

It is appropriate to determine the initial load, F_w, and load increment, F_{inc}, as from 70 % to 90 % and 1 %, respectively, of the reference load, F_r, calculated using Formula (1) above. The bearing torque should be measured as the rotation speed is gradually increased. Figure 2 shows a typical example of variation in bearing torque, which is measured along with the rotational speed of the driving shaft. Typically, as the rotational speed increases, the bearing torque increases suddenly at a certain rotational speed and then decreases to a steady-state level with a fairly constant torque value. As the bearing torque decreases to its steady-state value, the rotational speed is determined as the take-off speed of the foil thrust 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

ω motor speed, expressed in r/min

M torque, expressed in N·m

a Take off.

b The black curve represents the motor speed, ω.

c The red curve represents the torque, M.

Figure 2 — Typical variation of rotational speed versus bearing torque

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

a) Apply the initial load, F_w, on the rotating system and gradually increase the rotational speed of the motor.

b) After the driving shaft reaches the take-off speed, the state should continue for 10 s and then the power to the motor should be shut off to maintain a stopped state for 5 s.

c) The rotational speed, the accumulated number of start-stop cycles, the bearing torque, the temperature inside the bearing and the temperature of the top foil surface should be observed during the stop–start test.

7.3 Calculation of bearing torque and load

The friction force, F, may be measured using a load cell linked to the torque rod installed on the loading shaft shown in Figure 1. The bearing torque, M, generated by the rotation of the driving shaft is calculated as the product of the friction force, F and the distance, r, between the two centres of the loading shaft and load cell, as shown in Formula (2):

$$M = F \times r \tag{2}$$

where

M is the bearing torque;

F is the friction force; and

r is the distance between the axis of the loading shaft and the sensor-linked location of the torque rod.

7.4 Determination of static load capacity

The static load capacity, $F_{w,s}$, is the maximum steady load that can be delivered by a foil thrust bearing under steady-state conditions. The process for determining the static load capacity is as follows.

a) The rotational speed of the shaft is maintained at a given test speed, such as the speed of the actual foil thrust bearing. Measurement shall not take place before thermal equilibrium is reached, as determined from measurements obtained using a thermocouple installed inside the bearing housing. The test speed shall differ from the take-off speed to a degree sufficient to ensure stable running of the bearing system.

b) At the test speed, the initial load, F_w, is applied. In this state, the rotational speed and the bearing torque should be observed for 1 min to estimate whether the air film or bearing ruptures. When a foil thrust bearing has a film of air between the runner and top foil, it rotates smoothly. If the runner and top foil come into contact, unstable vibrations and/or a significant degree of variability in the measured load capacity can occur. In such a situation, step c) below should be skipped and step d) should be performed to avoid sudden adhesion between the runner and top foil, which can occur within just a few seconds.

c) If no failure is generated, the load increment, F_{inc}, should be added to the loading plate to increase the applied load and the bearing should be observed for failure for 1 min.

d) If the bearing fails, the applied load should be removed and the test stopped after the rotation state becomes stable and the 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, $F_{w,a}$. The net load, $F_{w,n}$, exerted on the foil thrust bearing is determined by adding the weight of the upper structure, $F_{w,u}$, to the applied load, $F_{w,a}$, and is recorded in the test report (see Annex B). The upper structure consists of the loading shaft, torque rod and mounting disk.

f) The start–stop test should be repeated at least three times for a given set of conditions and the net load, $F_{w,n}$, should be recorded in the test report (see Annex B) for each test.

g) The minimum value of the net load, $F_{w,n}$, at which the bearing operates successfully is taken to be the static load capacity, $F_{w,s}$, of the foil thrust bearing at the test speed and is noted in the test report (see Annex B).

7.5 Evaluation of static load capacity per unit area

The static load capacity per unit of bearing, $F_{w,ua}$, is calculated by dividing the static load capacity by the top foil surface area, according to Formula (3):

$$F_{w,ua} = \frac{F_{w,s}}{\pi\left(r_o^2 - r_i^2\right)} \qquad (3)$$

where

$F_{w,ua}$ is the static load capacity per unit area of the bearing;

$F_{w.s}$ is the static load capacity;

r_i is the inner radius of the foil thrust bearing; and

r_o is the outer radius of the foil thrust bearing.

8 Friction coefficient

The friction force and the friction coefficients are the characteristic values used to represent the primary characteristics of the foil thrust bearing. The friction coefficient is calculated by dividing the measured friction force, F_s, under steady-state conditions by the net thrust load, $F_{w,n}$, determined as described in 7.4, according to Formula (4)

$$\mu = \frac{F_s}{F_{w,n}} \frac{2r}{r_i + r_o} \qquad (4)$$

where

F_s is the friction force under steady-state conditions;

$F_{w,n}$ is the net thrust load;

r is the distance between the axis of the loading shaft and the sensor-linked location of the torque rod;

r_i is the inner radius of the foil thrust bearing; and

r_o is the outer radius of the foil thrust bearing.

The friction force generated between the runner and the top foil during the initial operation is the maximum static friction force. The maximum friction coefficients should be calculated as a function of the maximum static friction force using Formula (4) above and reported in the test report (see Annex B).

9 Durability test and lifetime

9.1 Test procedure

The durability of a foil thrust bearing may be tested by repeating the start–stop test described in 7.2 using the static load capacity, $F_{w,s}$, as the applied load.

9.2 Determination of lifetime

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 start–stop test cycles of the foil thrust bearing at which the coating layer disappears is taken to be the lifetime of the bearing and should be recorded in the test report (see Annex B).

In all other cases, the lifetime is taken to be the total number of start–stop test cycles of the foil thrust bearing before the wear rate of the top foil 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 1 000 cycles of the start–stop test.

10 Test report

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

a) a reference to this document, i.e. ISO 22423:2019;

b) the bearing parameters;

c) the test conditions;

d) the test methods;

e) the loading methods;

f) the test location;

g) the date;

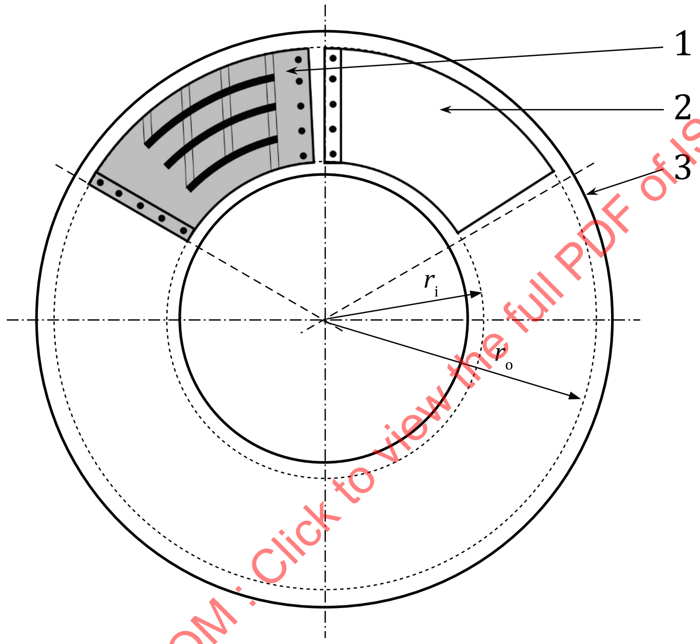
h) the operator's name;

i) the test results.

Annex A
(informative)

Configuration of a typical foil thrust bearing

The configuration of a foil thrust bearing used for testing is shown in Figure A.1. The bearing is composed of a bearing plate, bump foil (which is firmly attached to the bearing plate) and top foil (which is located on top of the bump foil and serves to receive the axial load from the thrust runner). Appropriate clearance between the runner and the top foil should be ensured to generate an air film by aerodynamic force as the shaft rotates.



Key

1 bump foil

2 top foil

3 bearing plate

r_i inner radius of top foil

r_o outer radius of top foil

Figure A.1 — Configuration of a foil thrust bearing

