



Omega Dot

Research and Engineering Solutions

Literature Review on Recent Air Foil Bearings Designs

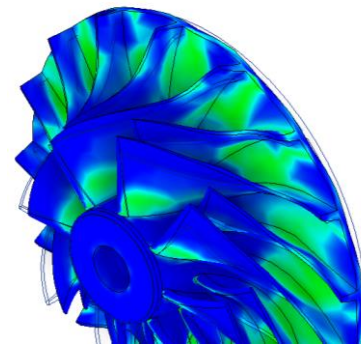
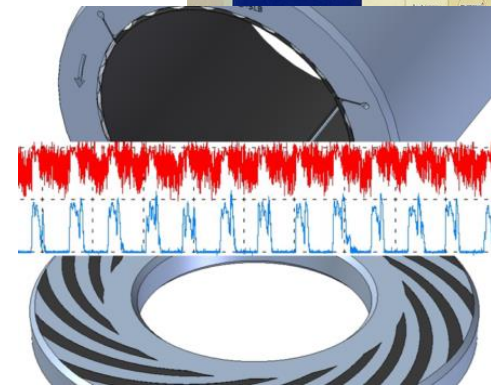
for 3rd Gas Bearing Workshop in Dusseldorf

March 2019

What/Who are we?



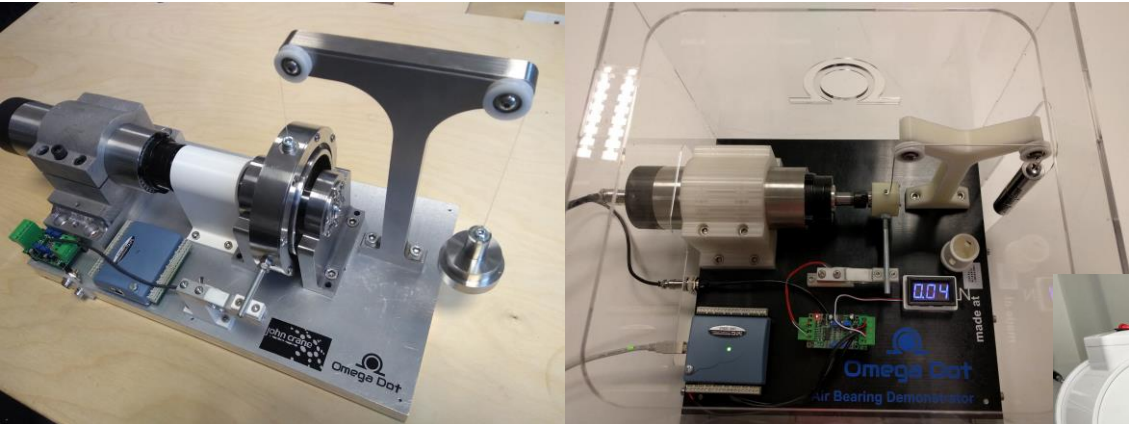
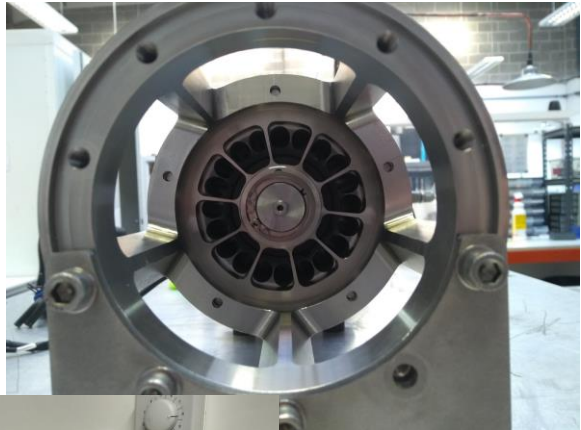
- We are an R&D orientated engineering company offering both **consultancy and product development** services.
- We have more than 10 years of experience in the field of **turbomachinery and bearings**, for the oil & gas, power generation and automotive industry.
- We have access to workshop facilities and partners who can **provide high precision manufacturing** services.
- We have designed, manufactured and test air foil bearings for applications ranging from micro gas turbines to turbo compressors and turbo motors/alternators. We also acted as the chief designer for some of our client's product development.



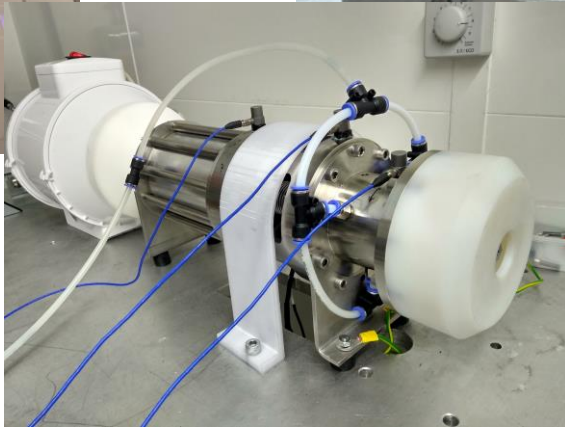
Air Bearings Validation Prototyping and High Speed Testing



High Speed Motor Drive
with air cooling



Low Speed Lift-Off Validation



High Speed Rotordynamic
Stability Testing

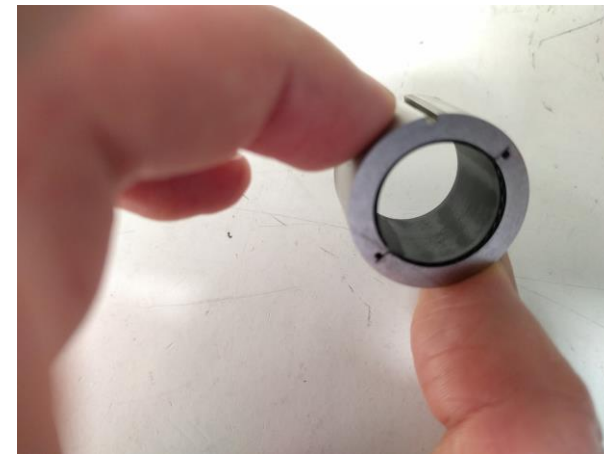
Air Bearings

The future of High Speed Machines



VS

- Oil free machinery.
- Lower friction and running costs.
- Low noise and vibration.
- Maintenance free.
- Zero wear.
- Self acting, no lubrication.
- Compliant features, adaptable.



Air Foil Bearings Applications

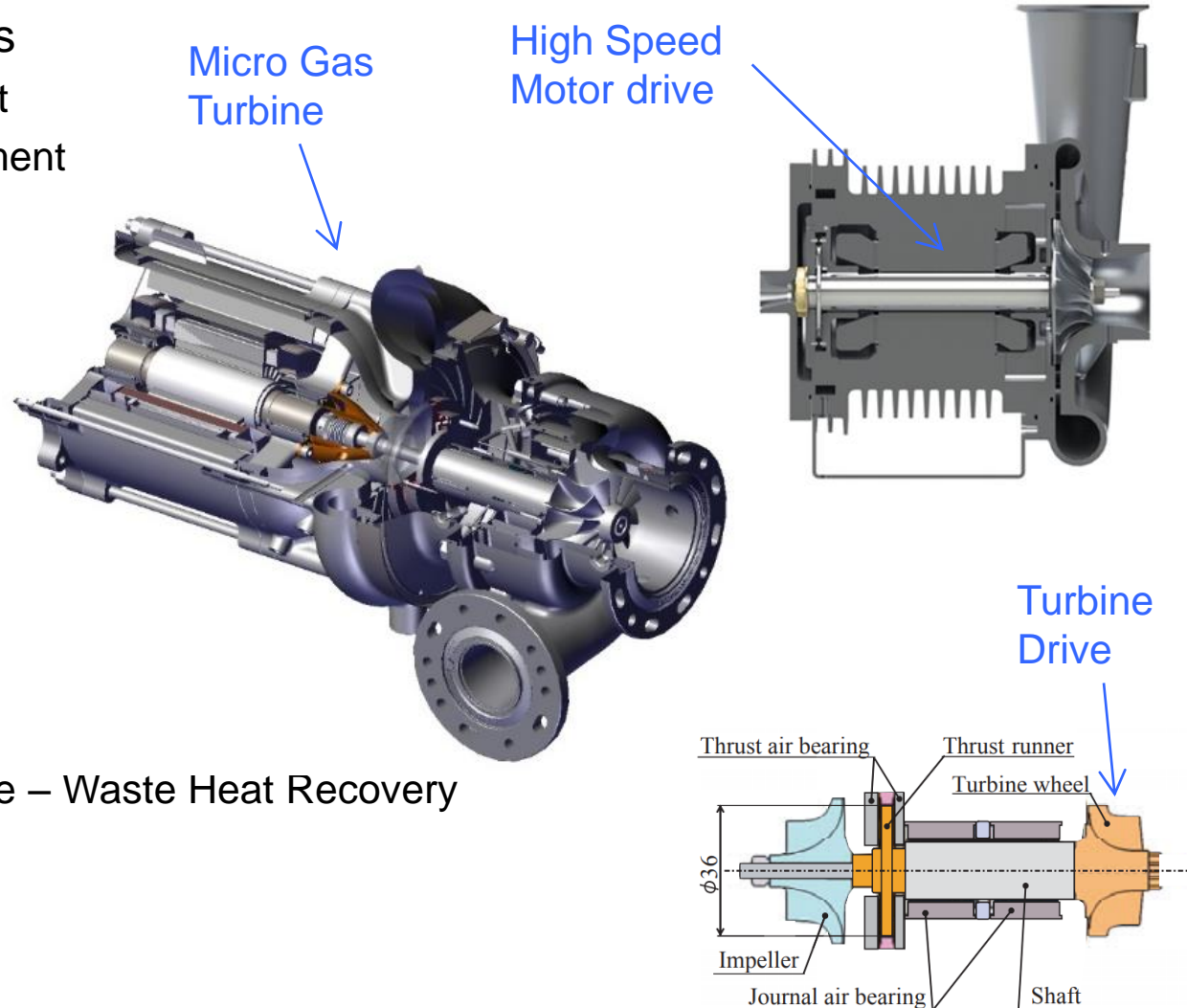


- Turbo Compressors/blowers
 - Waste water treatment
 - Fuel Cell air management

- Turbo alternators
 - Power Generation
 - Micro gas turbine

- Air Cycle Machines
 - Air craft cabin air

- Turbines Drives
 - Organic Rankine Cycle – Waste Heat Recovery
 - Turbochargers

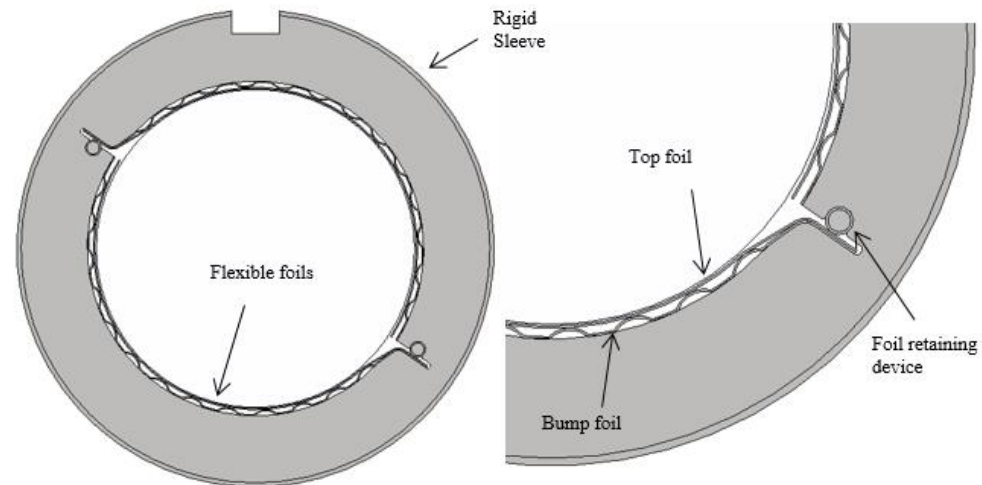
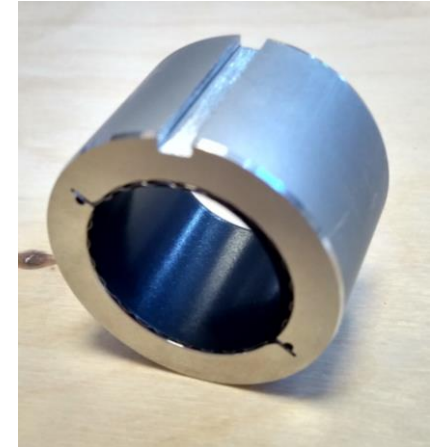


Air Foil Bearings Special Features



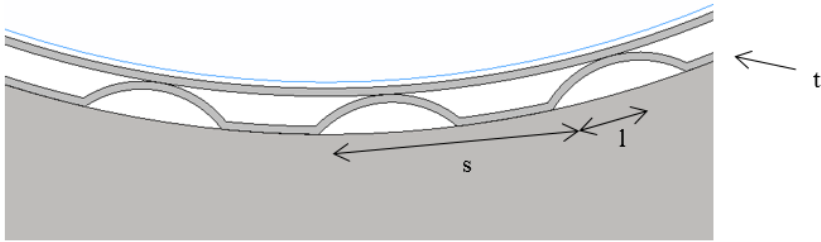
- Air bearings can run to extremely high speeds of up to 200 m/s.
- Extremely **low frictional losses**, less than half than those of the conventional oil bearings.
- Compliant foils allows the bearing to accommodate for **shaft thermal growth**. Allowing the bearing to operate in temperatures above 700 C.
- Bump foils provide important damping features to suppress shaft instabilities.

$$\Lambda = \frac{6\mu\omega}{p_a} \left(\frac{R}{C}\right)^2$$



Bump Foils

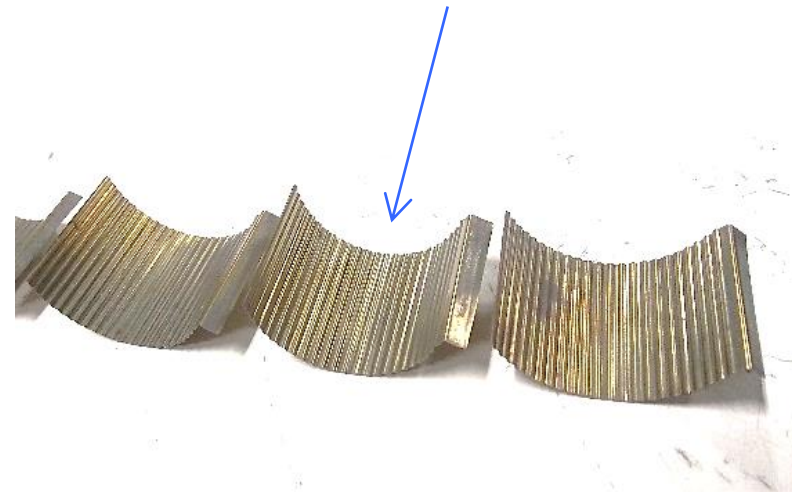
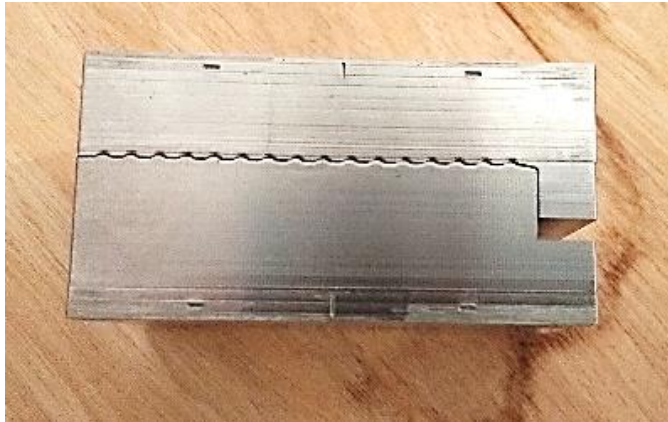
Tooling and Geometry



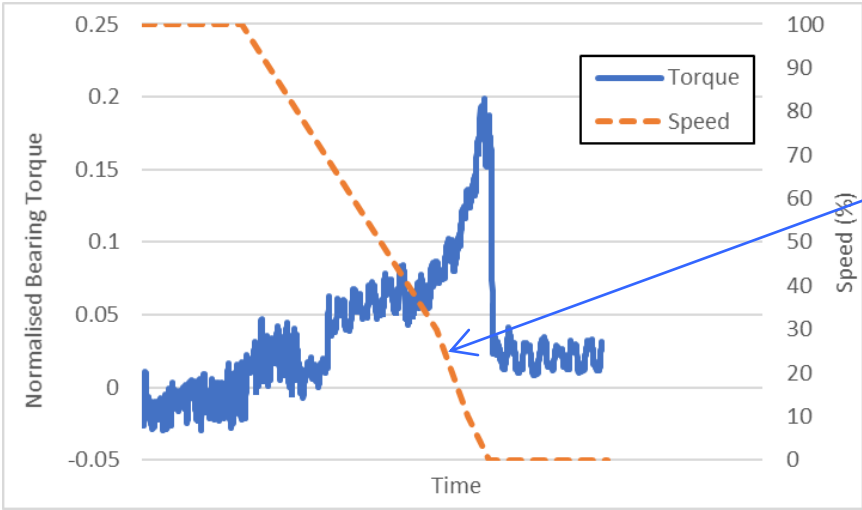
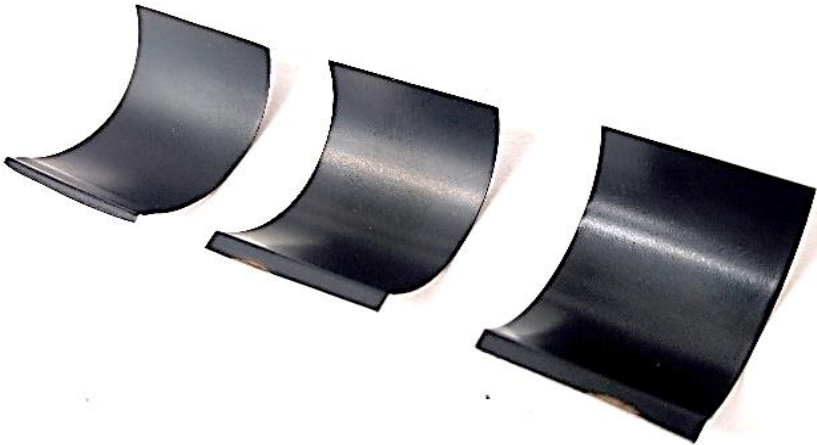
$$K_b = \frac{2s}{E} \left(\frac{l}{t} \right)^3 (1 - \nu^2)$$

Bump foil geometry affects the bearing stiffness

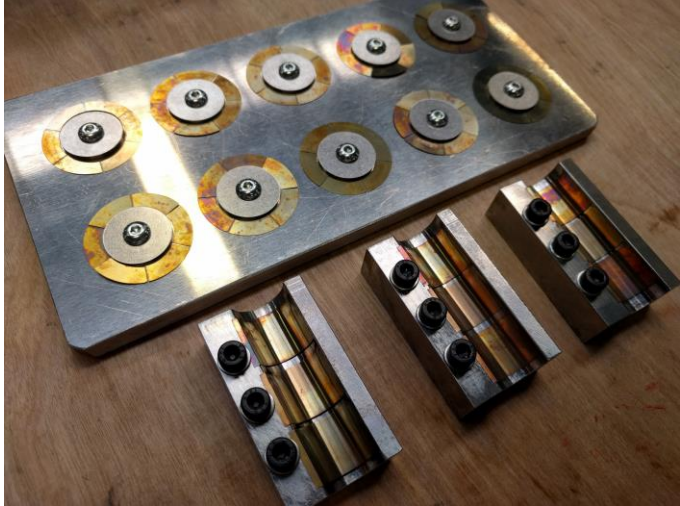
Heat treated bump foils



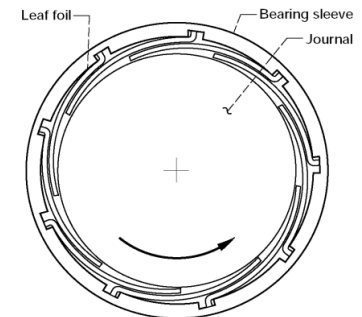
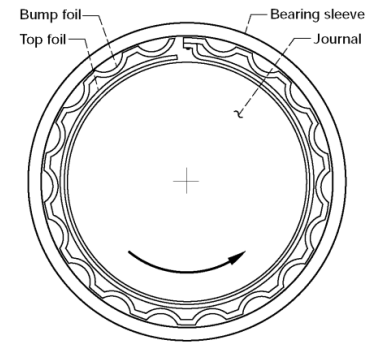
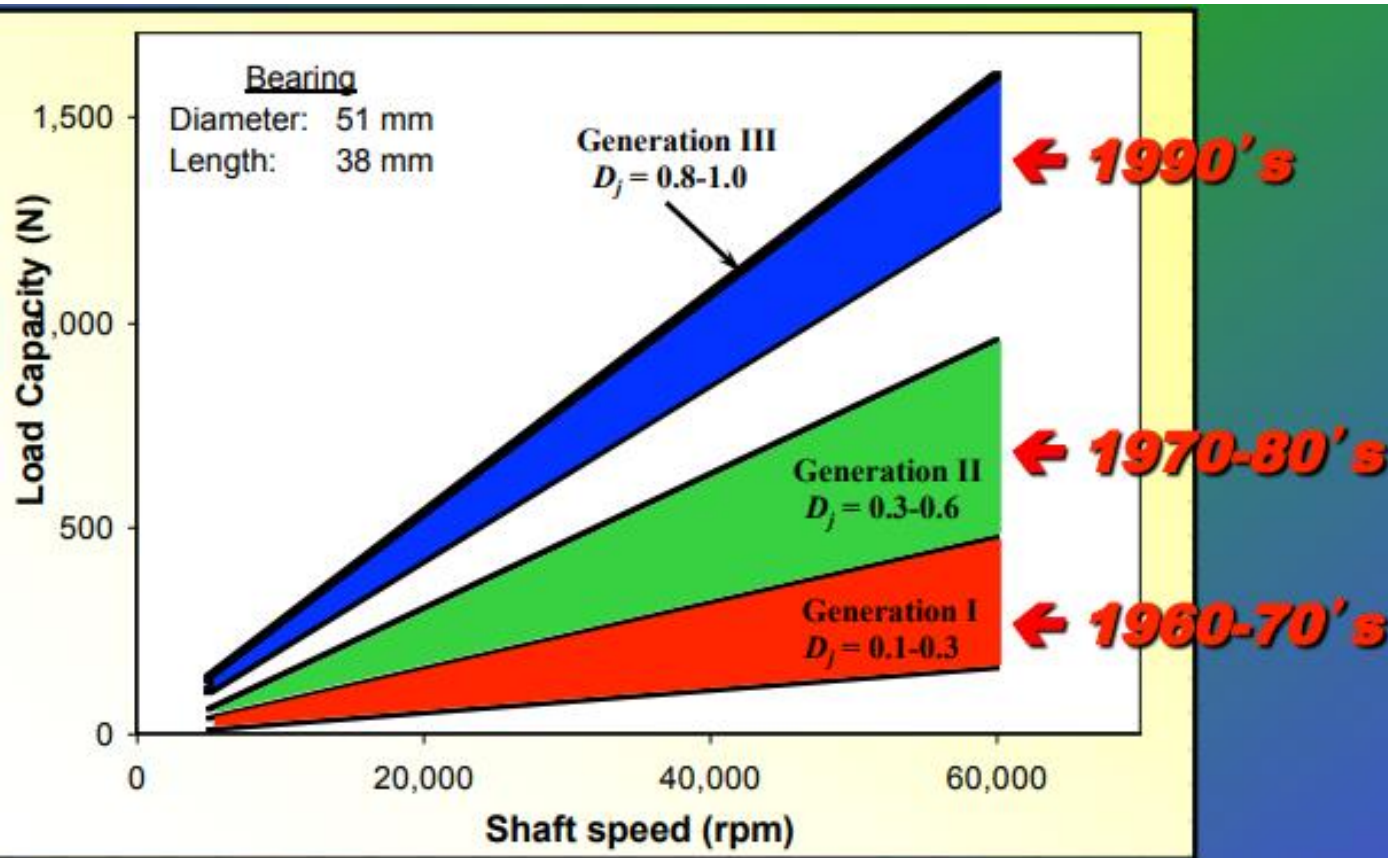
Top Foils Coating and Geometry



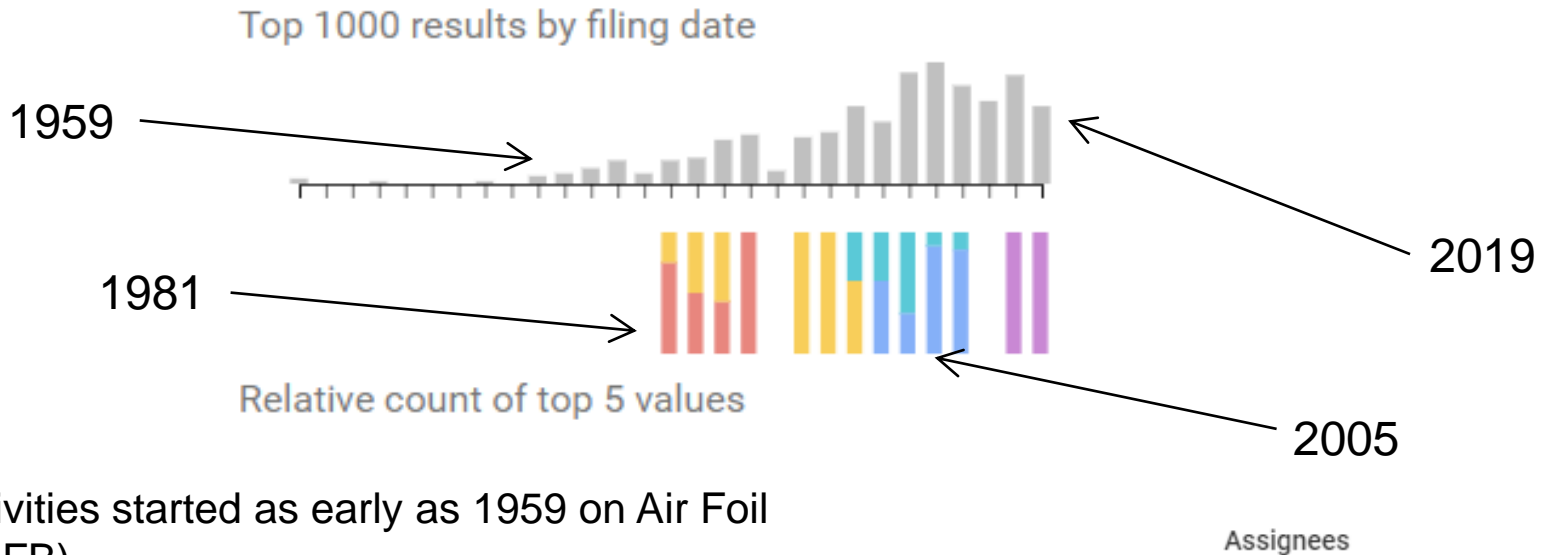
Coatings needed for Start-stop cycles



NASA's Guide to Air Foil Bearings Categories



History of Air Foil Bearings Patents



Patents activities started as early as 1959 on Air Foil Bearings (AFB).

From 1981 Americans were very interested in AFB.

Peak filing periods for AFB is around 2005, with contributions from Koreans.

Koreans continues to lead in the developments of AFB.

- 삼성테크윈 주식회사
 F16C32/0614 F16C33/1005 F16C32/0603 F16C32/06
- The Garrett Corporation
 F01D5/02 F16C37 F16C37/002 F01D5
- United Technologies Corporation
 F16C17/042 F16C27/06 F16C27/063 F16C17/00
- 한온시스템 주식회사
 F16C2360/44 F04D F04D29 F04D29/00
- 한국과학기술연구원
 F16C17/024 F16C17/02 F05D2240/52 F16C33/14

2016 to 2019 Patents



- Most recent patents filing for AFB showed introduction of Japanese (mainly) and Chinese.

Top 1000 results by filing date



Relative count of top 5 values

Assignees

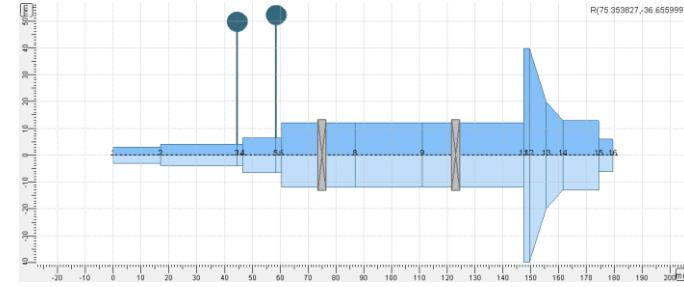
Japanese	→	Ntn株式会社 F16C27/02 F16C27/00 F16C27 F16C17/02
Chinese	→	至翊腾风科技投资集团有限公司 N t n 株式会社 F16C2360/23 F16C2360 F16C2360/00 F16C17/024
Japanese	→	Ntn Corp F16C2360/23 F16C2360 F16C2360/00 F16C17/024 苏州市嘉明机械制造有限公司 H05B2206 H05K2203/101 H05K2203/00 H05B6/36

Main Purpose of Thrust and Radial Bearings



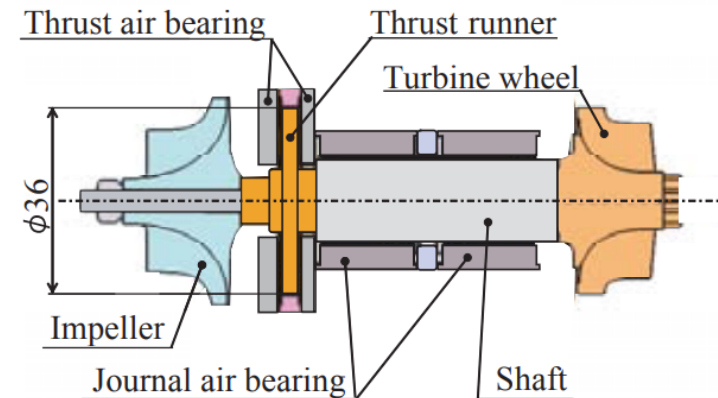
Radial (Journal) bearings

- Used to support shaft weight.
- Support and dampen the shaft vibrations.
- Satisfy Rotordynamics stability of the shaft
- Minimise excursions to prevent Compressor Wheel and Turbine Wheel rub against housing.



Thrust Bearings

- Support large thrust loads, imbalance from Compressor and/or Turbine.



Main Challenges of Thrust and Radial Bearings



Radial (Journal) bearings

- Bump foils yielding or flattening.
- Life of coatings at high temperatures.

Thrust Bearings

- Overloaded Thrust Forces.

Overheated/Overloaded Thrust Bearing

Costs

- Assembly costs
- Costs of parts

Bump foils (underlayer) flattened



Recent Developments

Radial Bearings



● Housing

- Added elastic features in housing (controlled).

● “Bump” foil

- Varied stiffness, circumferential and axial.
- Use of multiple layers of bumps foils, 2, 3.
- Replacing bump foils with aperture foil element, that won't yield.
- Replacing the bump foil with bulk metal mesh or elastic material.
- Replace with a series of PZT actuators.

● Top foils

- Thicker top foils, prevents sagging.
- Use multiple layers.
- Single piece top and bump foil.

Recent Developments

Thrust Bearings



● “Bump” foil

- Varied stiffness, circumferential.
- Replace with dimpled foils.

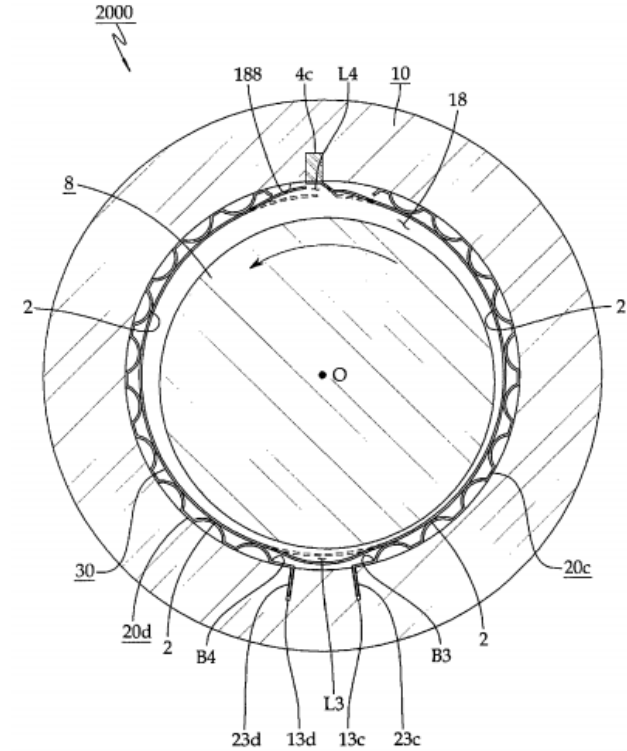
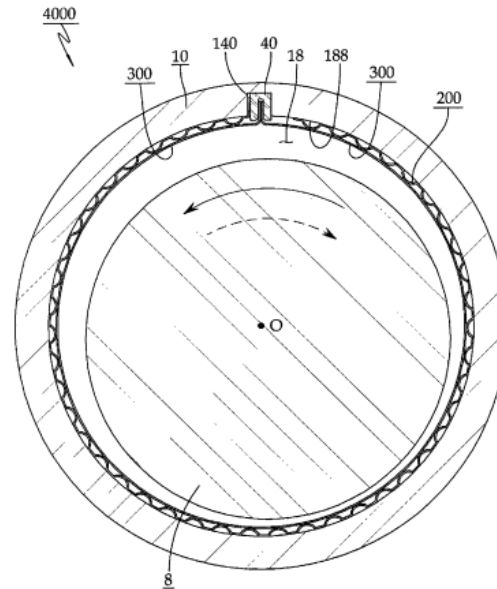
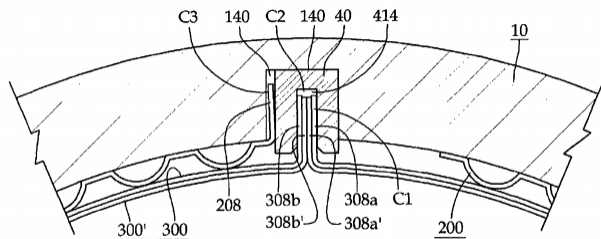
● Top foils

- Additional support for leading edge.
- Teethed trailing edges for more cooling.
- Micro grooves on top foil.

Patent case 1



- 2009
- Chinese Patent
- Double layer top foil
- Reducing Top foil sagging
- Bi-directional



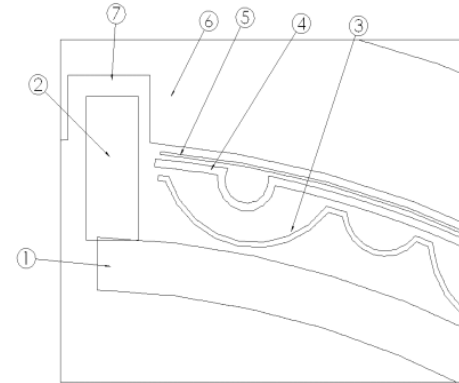
Patent case 2



● 2004

● Korean

- Two layers of pump foils for increased stiffness with displacement.
- Thick top foil to hold the shape better, preventing sagging.



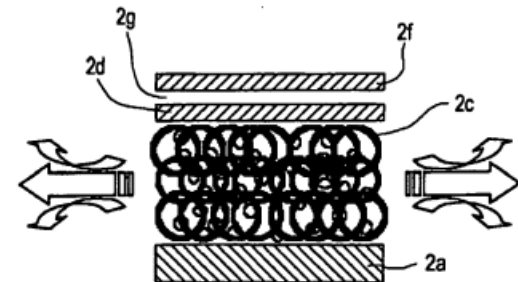
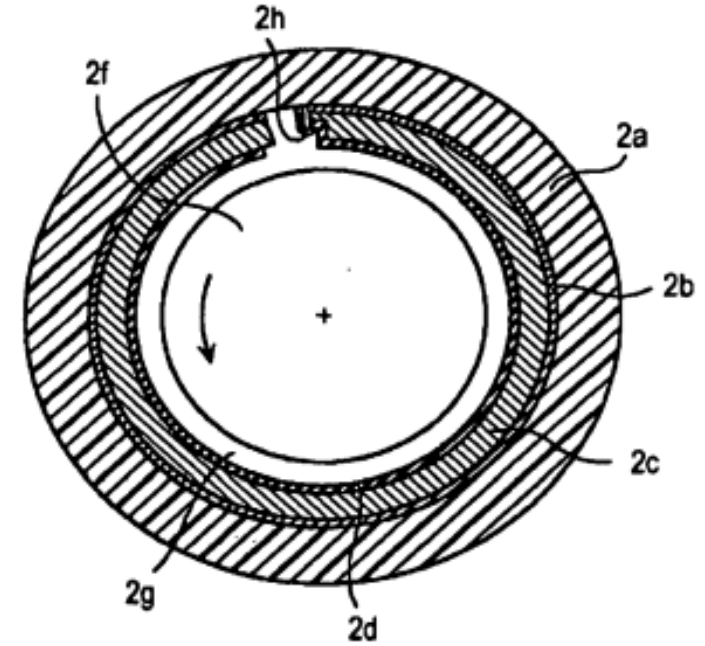
Patent case 3



©2008

©US Patent

©Using a porous metal material as the pump foil. Similar to metal mesh bush.



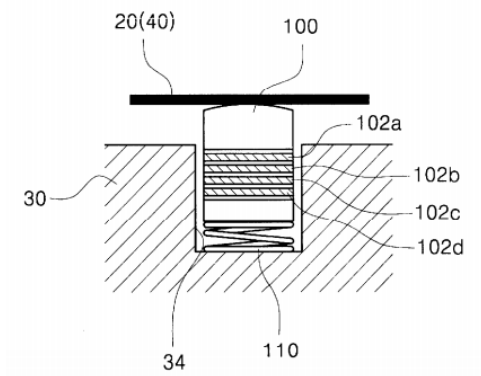
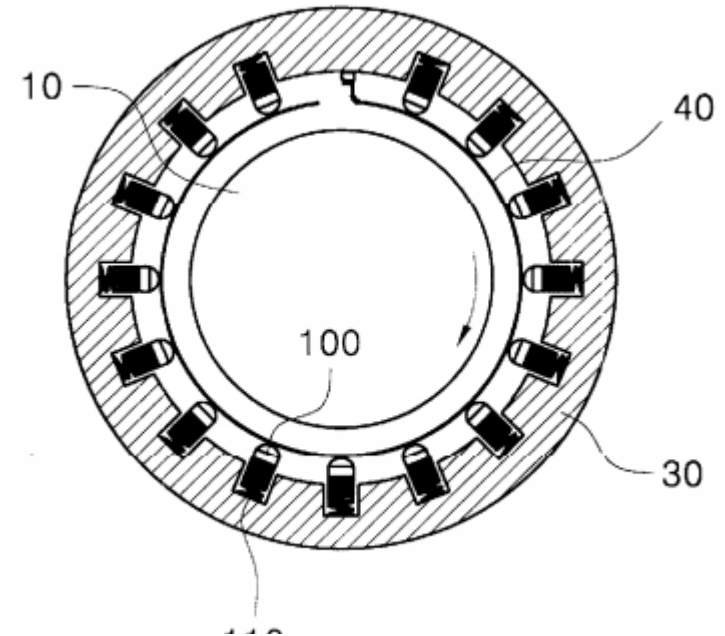
Patent case 4



2001

Korean

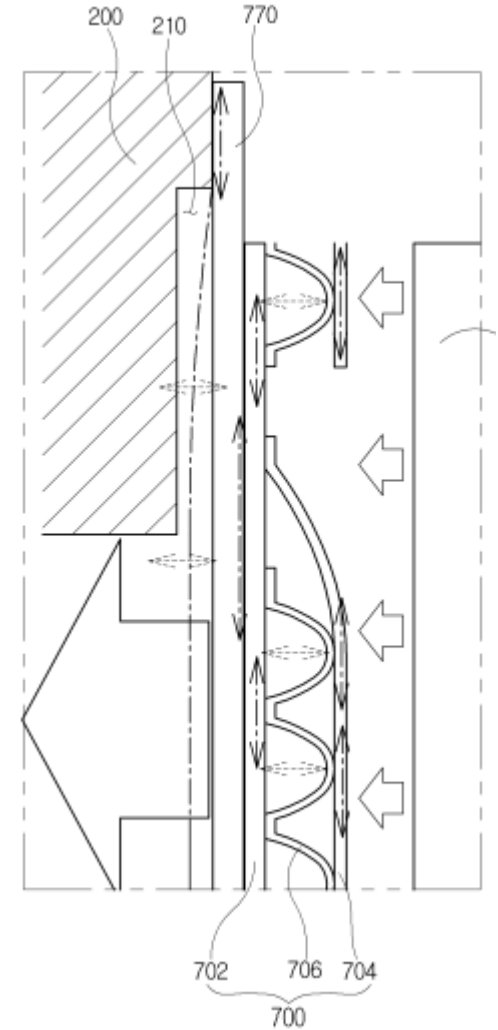
Air foil bearing with PZT actuator



Patent case 5



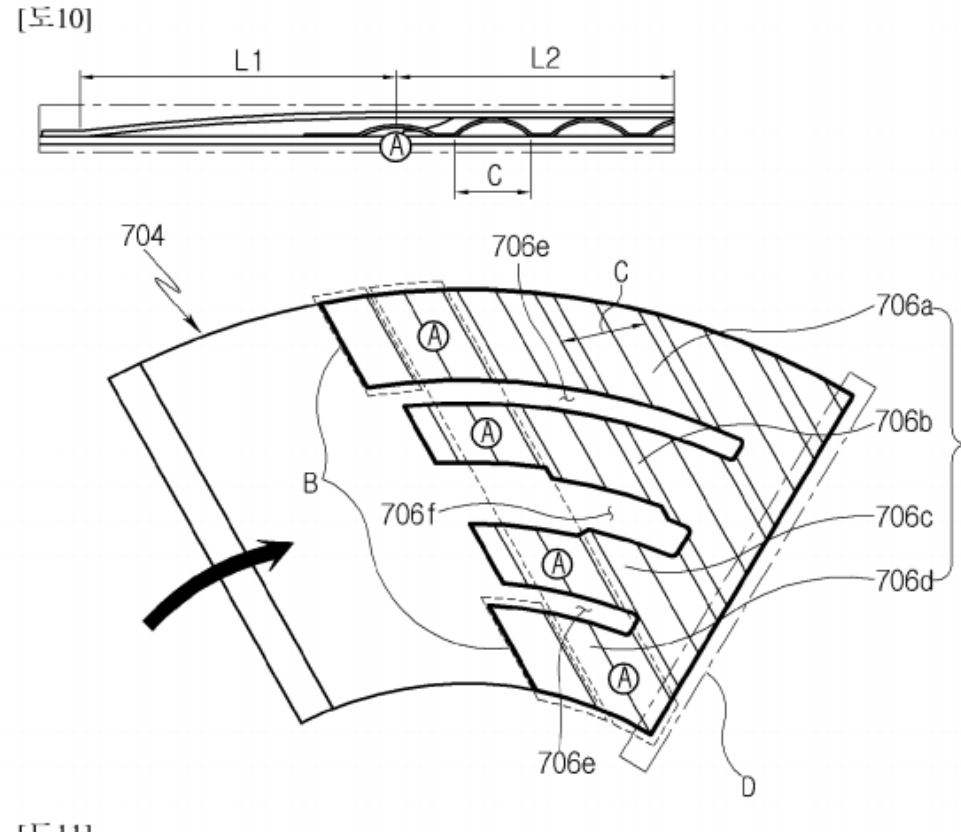
- 2017
- Korean
- Thrust bearing with leading edge support
- Elastic backplate support



Patent case 6



- 2016
- Korean
- Thrust Bearing
- Leading bump is lower
- Less stiffness on leading bumps



Patent case 7



- 2003
- US Patent
- Stacks of formed foils, 5 layers, to create the “bump” foil replacement
- No welding.

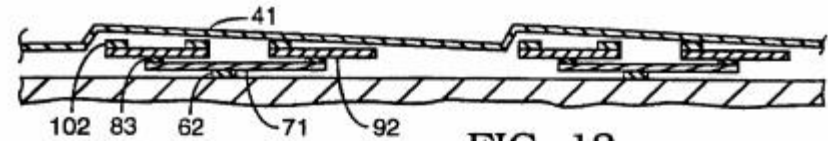


FIG. 12

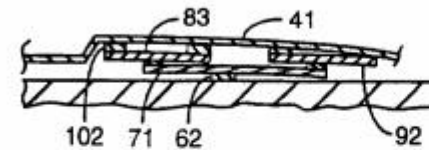


FIG. 13

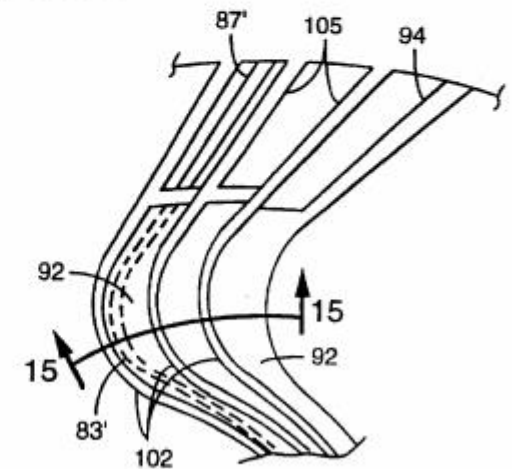
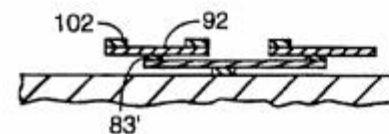


FIG. 14

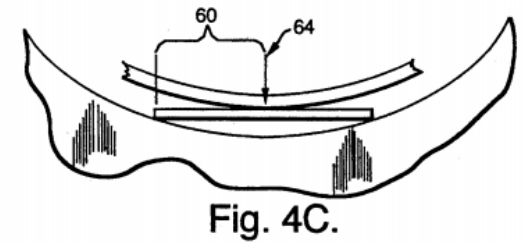
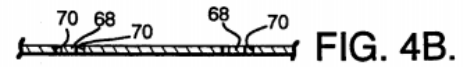
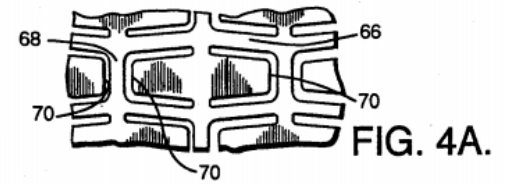
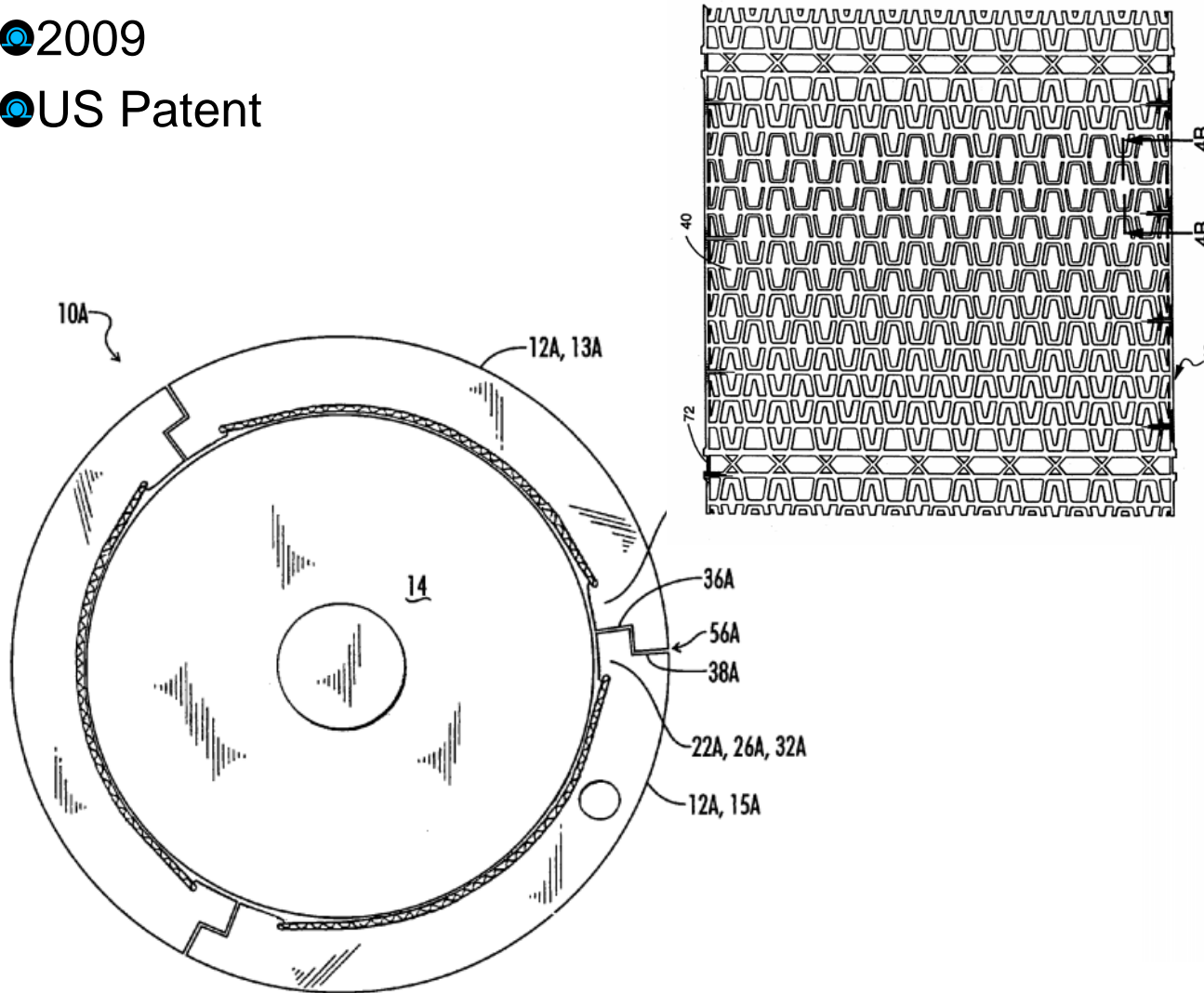


Patent case 8



©2009

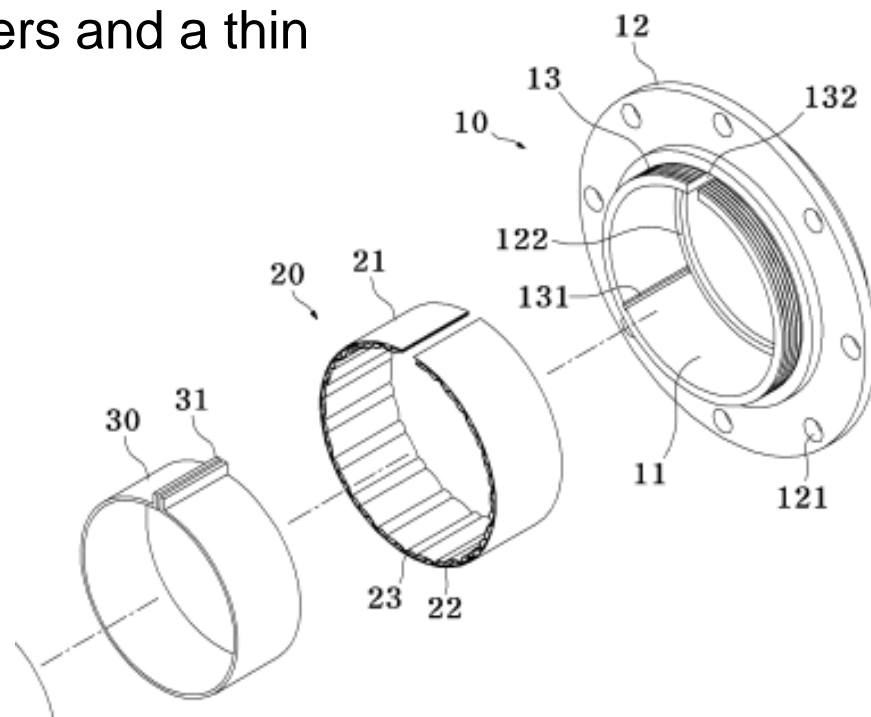
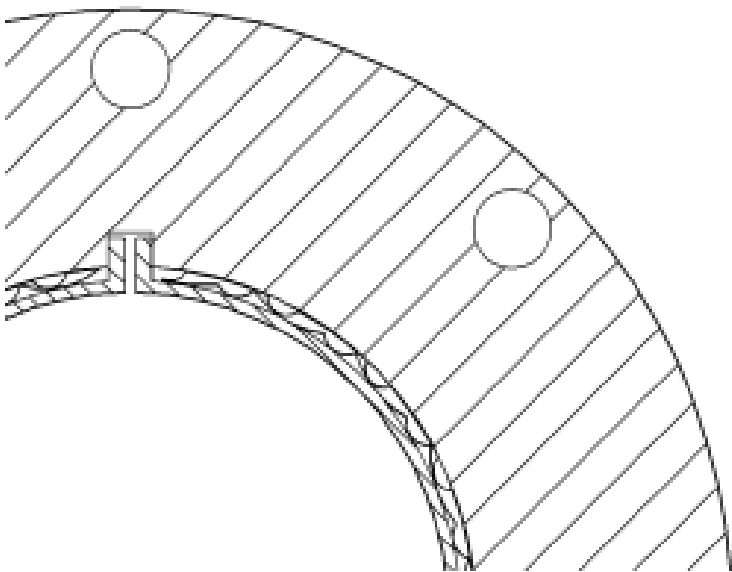
©US Patent



Patent case 9



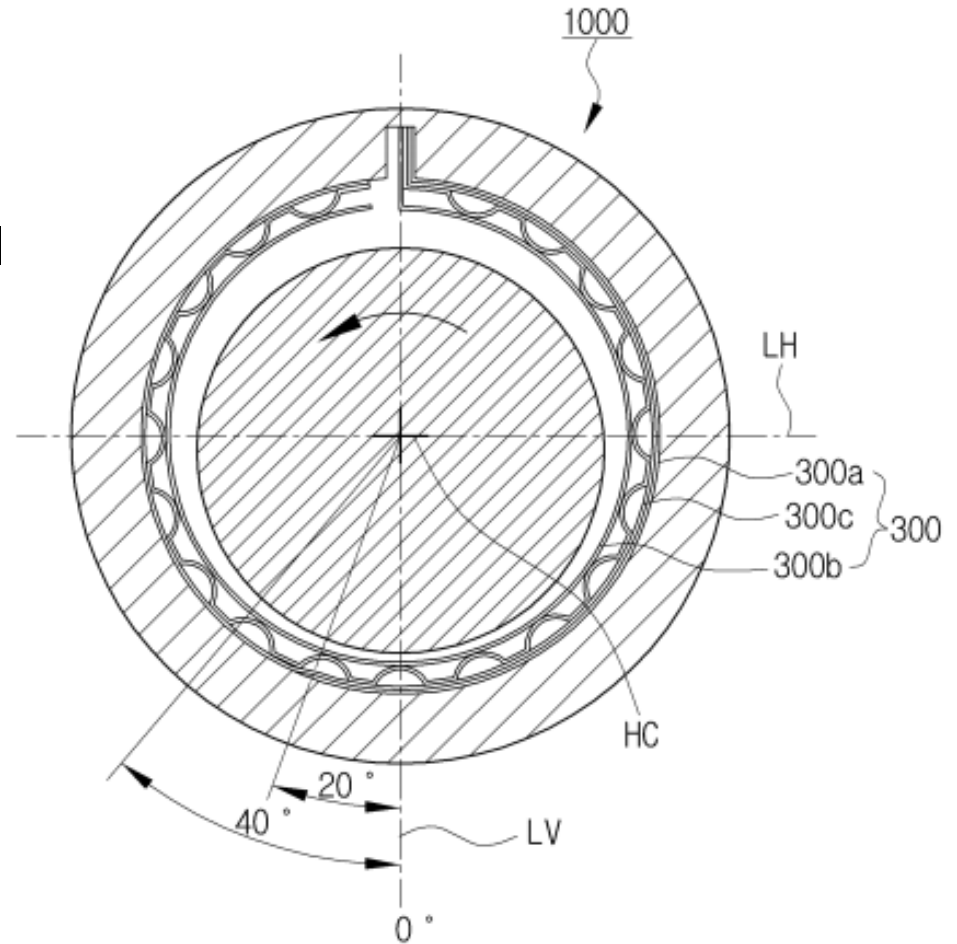
- 2017
- Korean
- Foils mounted directly into the housing, without sleeve.
- Thick top foil
- Bump foil made out of two bumps layers and a thin sleeve.



Patent case 10



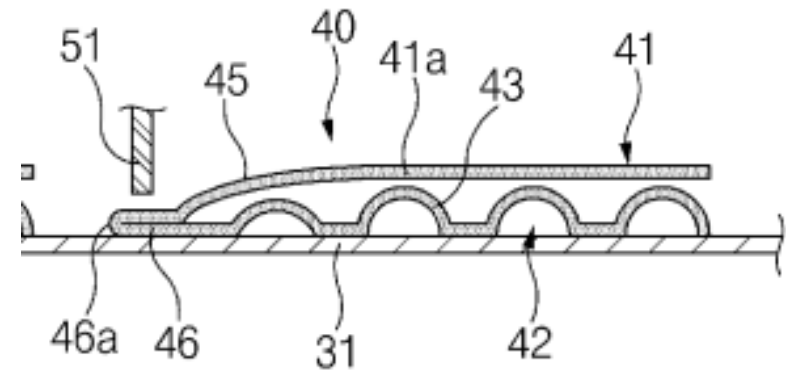
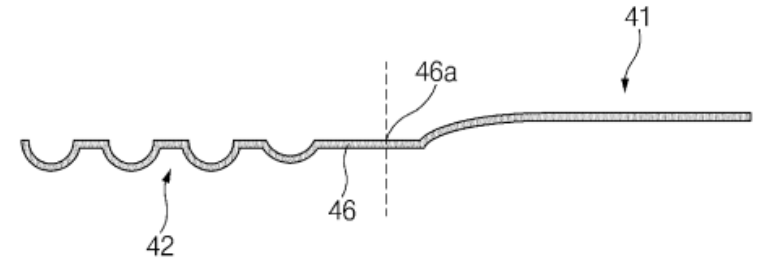
- ©2017
- ©Korean
- ©Pre-load on non-circular bore using extra layer under bump foil



Patent case 11



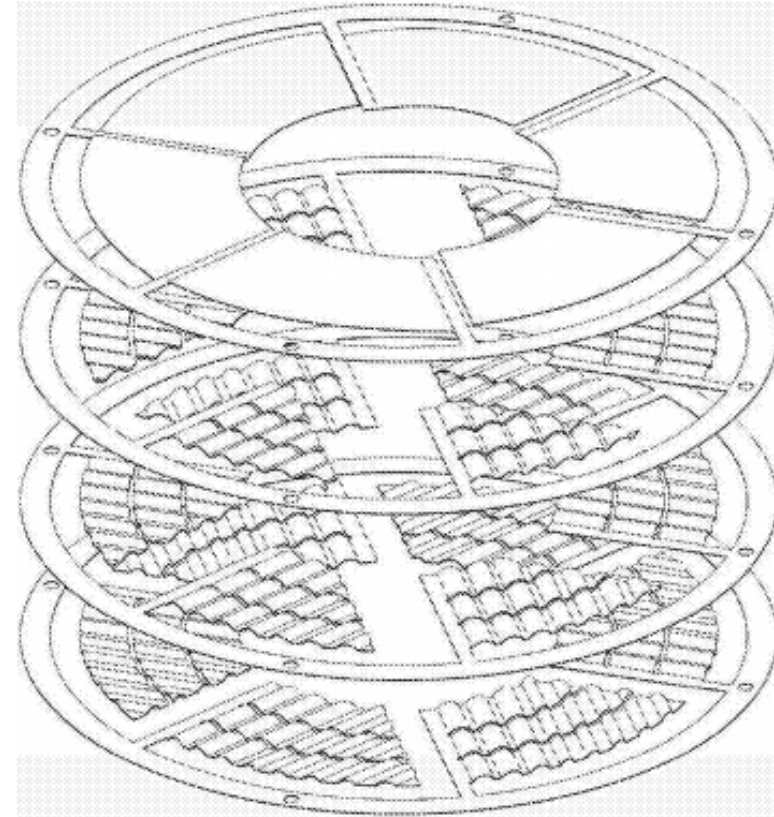
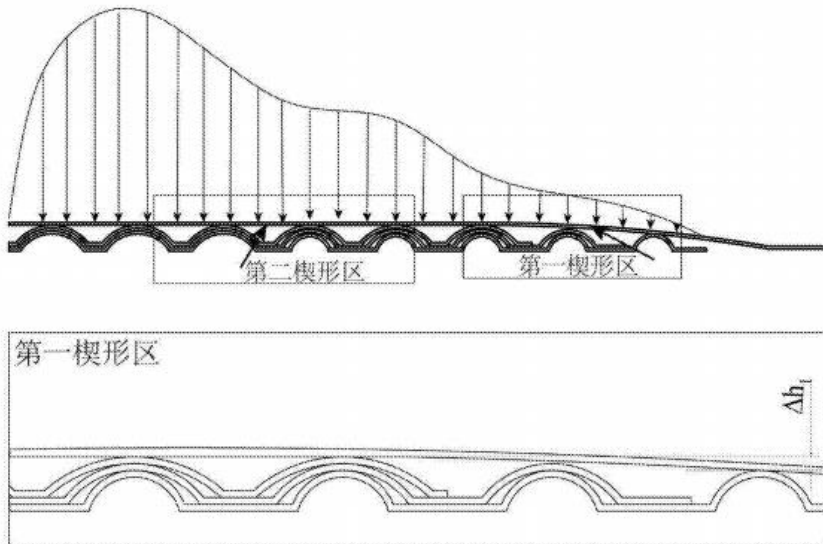
- 2018
- US Patent
- Integrated piece for bump and foil foils



Patent case 12



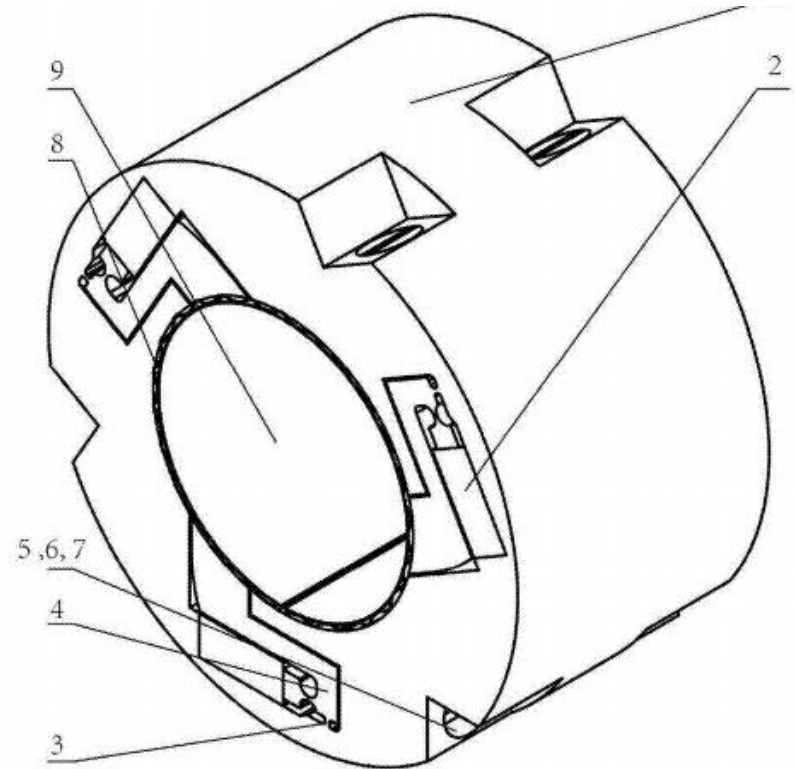
- 2017
- Chinese Patent
- Thrust bearing for high loads.
- Stacked bump foils for increased stiffness from leading lead to trailing edge.



Patent case 13



- 2017
- Lobe shape control using PZT and elastic hinges.
- Active control on the stability.



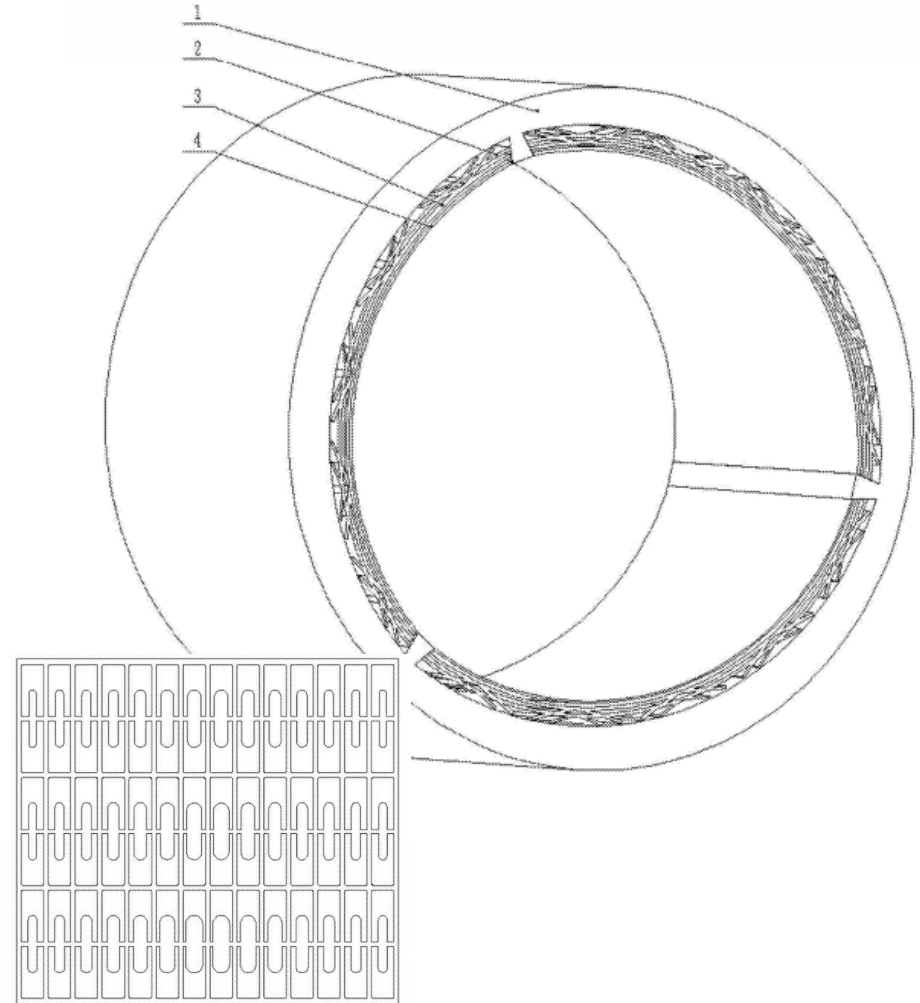
Patent case 14



©2017

©Chinese Patent

©Similar to Capstone.



Patent case 15



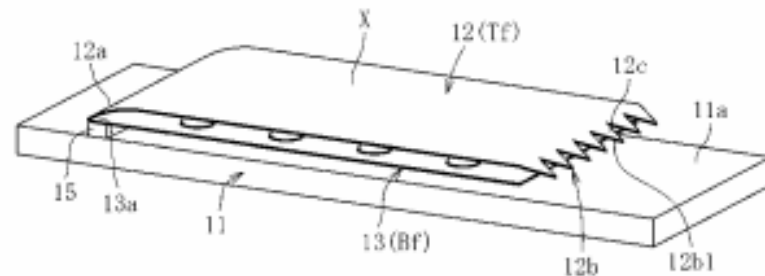
●2018

●Japanese Patent

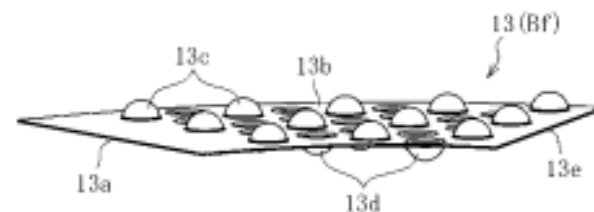
●Two sided dimples for bump foil.

●Teeth edge on trailing edge of top foil

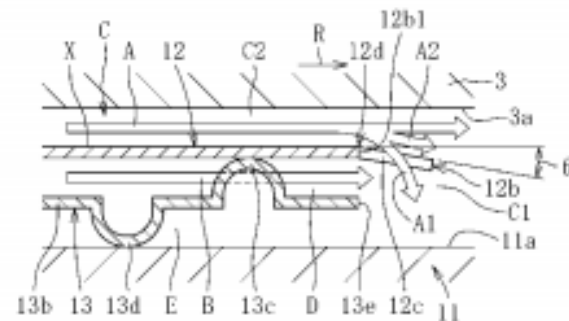
【 図 3 】



【 図 4 】



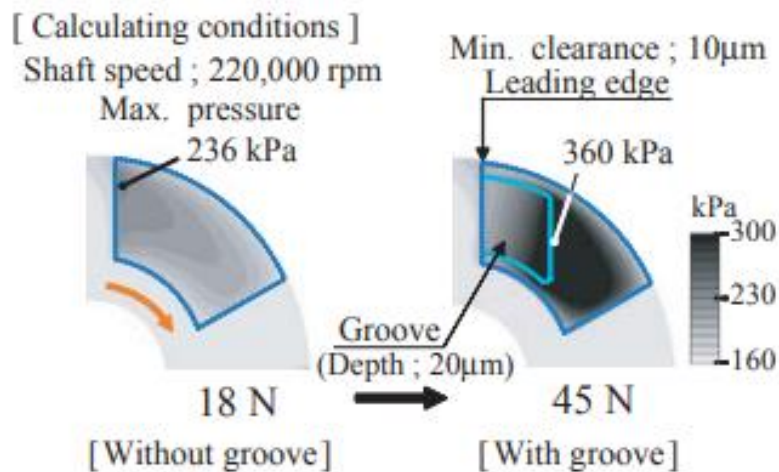
【 図 5 】



Patent case 16

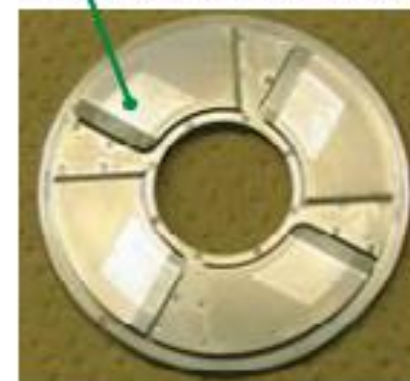


- Toyota Air Bearing For Turbocharger
- Conference Technical Article
- Micro Groove pad for enhanced load capacity



Conventional version
[Without groove]

Groove (Depth ; 20μm)



Trial version
[With groove]

Concluding Remarks



- Air Foil Bearings (AFB) has merged into the market for applications of high speed machinery, such as Air Cycle Machine, turbo blowers and micro gas turbine. Main driver being oil free applications.
- There remains strong interests in AFB developments and patents filing, initially from US, Korean and now Japan and Chinese.
- Many of the patents or innovation are somewhat similar aim and focused on improving reliability of the “bump” foil feature and/or load capacity.
- Cost reduction of AFB has always been a key driver, this is either by reducing the assembly process or number of parts.

Condition Monitoring Sensors



- Predictive maintenance.
- Reduces machine down-time.
- Data analytics for optimisation of machines.
- Improves reliability.

