Research status and developing trends of gas bearing in recent years

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Abstract: As one kind of support elements for rotational machines, gas bearings that use air or gas as lubricant, have many attractive advantages such as low power loss, wide work temperature range, high rotating speed and low maintenance cost. However, gas bearings also have some disadvantages including low carrying load at low speed, wear at start-stop procedure, not easy to predict bearing performance due to the complex bearing structure and so on.

The purpose of this paper is to explore the research status of gas bearing based on the Web of Science datasets and related tools, meanwhile, the developing trends emerged in gas bearing are further studied. The results shows that: 1) the top ten productive countries published 85% papers in the studies of gas bearing; 2) there are eight research clusters emerged in the topics analysis visualization and the top three largest clusters are #1 metal mesh foil bearing, #1 bump-type foil bearing and #2 aerostatic thrust bearing respectively; 3) Comparing to other research topics, foil bearings (metal mesh type and bump type) and aerostatic thrust bearing may be further explored in the future. This study presents intuitive state of research of gas bearings and proposes a fresh perspective for relevant researchers to perform research in the future.

1. Introduction
Due to low power loss, wide work temperature range, high rotating speed, low maintenance cost etc, gas bearings are widely used in high speed rotational machinery such as gas turbines, micro turbines, high temperature blowers, high speed turbo chargers and high speed spindles.

Like other kinds of bearings, foil bearings play a vital role in rotor-bearing system just. The performances of gas bearings (stability, load capacity, for instance) are critical for the bearing-rotor systems. The ability to understand and predict their behaviour is very important for designing bearings and expanding their capabilities and applications. The studies on gas bearings attracted many researchers’ attention and lots of publication appeared during recent years.

The aim of this paper is to figure out the research status of gas bearing and predict the future directions. Firstly, based on Web of Science dataset and related software to identify which countries are studying gas bearings and which countries are the leaders in such studies. Secondly, based on well-designed algorithm, the research topics of gas bearing are demonstrated in clusters and discussed. Thirdly, the key members of clusters are listed on the timeline to seek the current hot topics and predict future development directions.
2. Search Strategy and Analysis Process

Gas bearing is the theme of this paper, which can be divided into several parts. By searching and reading the related articles as well as communicating with experts, three categories for the theme of this paper are obtained. Considering that the special gas bearing can be mainly distinguished as aerodynamic gas bearing and aerostatic gas bearing, the content of search formula can be divided into three parts.

Based on the topic of the research, several issues are mainly tackled: who are studying the foil bearings performance? And who did collaborative work with them? What specialties are they mainly focusing on? What is the future trend on the foil bearings performance? Deep understanding of such issues is important for the development of foil bearings performance. Meanwhile, it will provide valuable reference for related researchers who want to look for search directions and better cooperation partners. Determining the begin year of search period is a critical question to the scope of data retrieval. The max search time span on Web of Science database is from 1950 to 2020. Primary search of foil bearings performance chose the max time span and showed that the first literature about the topic appeared in 1970s. However there are less than 10 publication amounts about foil bearings performance before 2000, moreover, there are only 5 papers studied on foil bearings performance in the first 5 years (2000-2004) of 21st century, and the publication amounts per year has rapidly risen since 2005. Thus, the period of a retrieval of publications related to foil bearings performance was limited to 2005-2020. The source database for topic search is Web of Science Core Collection.

In order to discuss the issues we proposed above, the CiteSpace software is applied to conduct the analysis of cooperation network. At the same time, hot topics and the future of research direction of foil bearings performance can be analyzed through keyword co-currency network analysis. The main analysis process can be divided into the five steps including data extraction from Web of Science, data clean, data import, data analysis and visualization.

3. Results and Discussion

3.1 Publication of the Top Ten Productive Countries

By analyzing the record we collected from Web of Science, it is found that there are more than 30 countries which have published papers related to gas bearing. As shown in Fig.1, the top ten productive countries have totally published 1061 papers in recent two decades, which is 85% of the total publication. Among the top ten prolific countries, China is the only one developing country, which totally published 312 papers. However, the developed countries totally published 713 papers. It shows that a hug gab between develop countries and developing countries in the research of gas bearing may exist. The top two productive countries are China and USA, which published 312 papers and 262 papers respectively. In addition, no other country published papers more than 105 in the field.

Fig.2 demonstrates the annual publication amounts for the top two productive countries. USA is the most prolific country before 2013, and China holds the most prolific place since 2014. It may indicate that scientists in China pay more attention to gas bearing than researchers in other countries in recent years.
3.2 Research topics of gas bearing

Generally, the study of researchers in a specific field focused on some sub-fields or topics. The content of such research topics are very important to relevant scientists and engineers, which will be benefit for their recognition of this field and promote the research in gas bearing. In order to find out the main topics of the research of gas bearing, the software Citespace was adopt well-designed algorithm to analyze the date that extracted from web of Science. The analysis output was showed in Fig. 3.

There are 8 clusters displayed in the figure, which are numbered from #0 to #7, i.e. #0 metal mesh foil bearing, #1 active bump-type foil bearing, #2 aerostatic thrust bearing, #3 head-disk interface, #4 foil journal bearing, #5 hard disk drive, #6 gas rarefaction effect and #7 parallel computing application respectively. The names with yellow colour followed by year mean the milestone papers of such clusters. The nodes in each cluster represent the relevant papers in corresponding topic. The link lines of nodes in different clusters show the relevance of the research content in these papers. Two high impact papers were selected from search record of database for each cluster. For instance, the high impact papers for cluster #0 metal mesh foil bearing are Andres LS (2009) and Feng K (2010) respectively, meanwhile papers published by Salehi M and Carpino M are the key papers for cluster #4 foil journal bearing.

![Fig.3 Overview of clusters for the research of gas bearing](image)

3.3 Developing trends of gas bearing

In addition to find out the main topics of research field, the development of such topics may also attract the attention of scientists and engineers. The publication for each cluster according to year distribution is demonstrated in Fig. 4. The time span is from the year of 1997 to 2020. Each cluster has a corresponding dotted line added with nodes and link lines. Nodes with bigger size represent more impact papers in relevant topics.

It is easy to conclude that most papers for clusters #4 to #7 were published before the year of 2007, and most studies for clusters #0 to #2 were announced after the year of 2007. It may indicate that researchers of gas bearing in recent years pay more attention in clusters #0 to #2. In the next part, the publication of clusters #0 to #2 are discussed in detail so as to further understand the development of such topics.
Fig. 5 reveals that most important papers for metal mesh foil bearing were published in the period of 2006 to 2013. The high impact papers appeared in the period 2008 to 2010 which included the two milestone papers indicated in Fig. 3. The paper (Dellacorte C, 2008) that reviewed first- and second-generation bump-style foil bearings to demonstrate the design, fabrication, and performance of such bearings precluded the subsequent studies in the metal mesh foil bearing as well as the other two papers (Park DJ, 2008; Andres LS 2008)[1, 2]. Andres LS predicted the structural parameters of foil bearing in 2009, at the same time, Kim D discussed the dynamic response of the foil bearing and Dykas B proposed a design tool to fabricate foil thrust bearings for microturbomachinery[3, 4]. In 2010, Feng K announced a complete analytical model of bump-type foil bearings to predict bearing load and film thickness and Andres LS introduced a thermohydrodynamic (THD) model for prediction of gas foil bearing (GFB) performance. Both of them were cited by many other papers in the studies of gas bearing[5, 6].

Two outstanding references from the timeline visualization of cluster #1 appeared in 2014, as shown in Fig 6. Three papers that were published in 2013 mainly discussed the rotordynamic performance of bump-type foil bearing[7, 8]. Bonello P developed efficient algorithms for the simultaneous solution of the state equations to compute the nonlinear dynamic response of a foil-air bearing rotor system in 2014, which has the most citation amount in cluster #1. Meanwhile, numerical and experimetal investigations of bump-type foil bearing were addressed by Larsen JS and Gad AM in 2014[9, 10]. Larsen JS implemented a method to simulate the nonlinear steady-state response of a rotor supported by three pads segmented air foil bearings, which gave theoretical and experimetal contributions for bump-type foil bearing[11].
Cluster #2 is the third largest cluster in the research of gas bearing. Unlike the clusters discussed above, the high impact papers for cluster #2 appeared in two periods, i.e. the first period (2010 and 2011) and the second period (2015 and 2016). Chen YS calculated the stiffness of the designs with various geometric parameters for aerostatic journal bearings, which provide helpful design guidelines for gas-bearing spindles in high-precision machine applications in 2010[12]. One milestone paper that was published in 2011 by Morosi S represented a mechatronic answer to the growing industrial need to high performance turbomachinery[13]. The other milestone paper explored the coupling of the aerostatic and aerodynamic effects within ultra-high speed aerostatic journal bearings[14].

4. Conclusions
This paper aims to study the research status of gas bearing by analyzing the data record that was extracted from the database of Web of Science. First, the publications of productive countries are pointed out and typical countries are further demonstrated. Next, the research topics of gas bearing in recent years are visualized. Meanwhile, the developments of major topics are discussed based on the timeline figures. Some conclusions are obtained as follows:

(1) During the period of 2005-2021, China and USA are the top two productive countries which published 312 papers and 262 papers respectively. Chinese scientists have paid more attention to gas bearings than researchers in any other countries since 2014.

(2) According to the analysis of research topics of gas bearing, it is found that there are eight clusters appeared in the output visualization which represent that the interests of scientists and engineers in gas bearing are mainly divided in such topics. These topics are #0 metal mesh foil bearing, #1 active bump-type foil bearing, #2 aerostatic thrust bearing, #3 head-disk interface, #4 foil journal bearing, #5 hard disk drive, #6 gas rarefaction effect and #7 parallel computing application respectively.

(3) The survey of the key members of clusters from time perspective indicates the developing trend for relevant topics. Comparing to clusters #4 to #7, clusters #0 to #2 are more active in recent years, which means foil bearings (metal mesh type and bump type) and aerostatic thrust bearing will be further explored in the future.
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