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Bibliometric Analysis of Bearing Fault Detection using Artificial Intelligence

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Abstract:
The new industrial revolution called Industry 4.0 is proliferating at its peak. The time is no longer away when the human race is going to witness a huge paradigm shift. Intelligent machines empowered by Artificial Intelligence (AI)will take over the presence of human workers in the industrial manufacturing sector with the target of achieving 100% automation. With the emergence of cut-throat price competition in the product market, it has become equally important to manufacture goods at minimal costs and with the highest quality. Predicting the decrease in machinery efficiency at an earlier stage to accomplish this objective helps to reduce the failure of the system earlier and at a lower cost. As most of these machineries constitute of bearings, early fault detection in bearings has always been a major goal for the manufacturing industry. Recently researchers have explored the power of AI for fault diagnostics in bearings and it has shown promising results. Therefore, in this paper, the authors present an extensive bibliometric study of the research carried out for fault detection in bearings using Artificial Intelligence. The study focuses on 4314 extracted literature from Scopus database in the form of scientific documents such as journals, articles, book chapters over a period of 2010-2020. This paper will give an in-depth view of the research trends in the domain of bearing fault detection.

Keywords: *Bearings, Fault detection, Remaining Useful Life, Artificial Intelligence, Bibliometric Survey, Vibrations, Anomalies*

1. Introduction:

A rolling-element bearing is an instrument that places rolling components between cases called races, such as rolling balls. With less abrasion and more solid grip, the rolling or spinning motion of these races allows the spinning components to rotate smoothly. Figure 1 shows a typical rolling element bearing. The outer race is the larger race that goes into the bore, and the inner race that rides in the shaft is the smaller race.

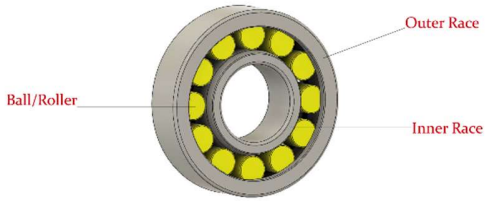

Figure 1: Roller-bearing structure

Unplanned downtimes due to machine failures are a major cause of concern to industrial processes for many years resulting in economic loss and decreased productivity. The faults can either be of electrical nature such as stator and rotor winding faults [1] or of mechanical nature such as bearing faults, gearbox faults, misalignments, etc [2][3]. Bearings form an integral part of industrial machinery that are used widely in mass production across industrial applications. These machineries operate in elevated ambient conditions for a long period of time. This leads to anomalies or faults occurring in bearing machinery due to various factors such as improper usage, inadequate lubrication, inappropriate load, etc. The faults induced to bearing malfunctioning do not cause the immediate breakdown of the machine but they occur over a duration of time ultimately leading to machine failure. Some of the common causes of bearing failure are depicted in Figure 2.

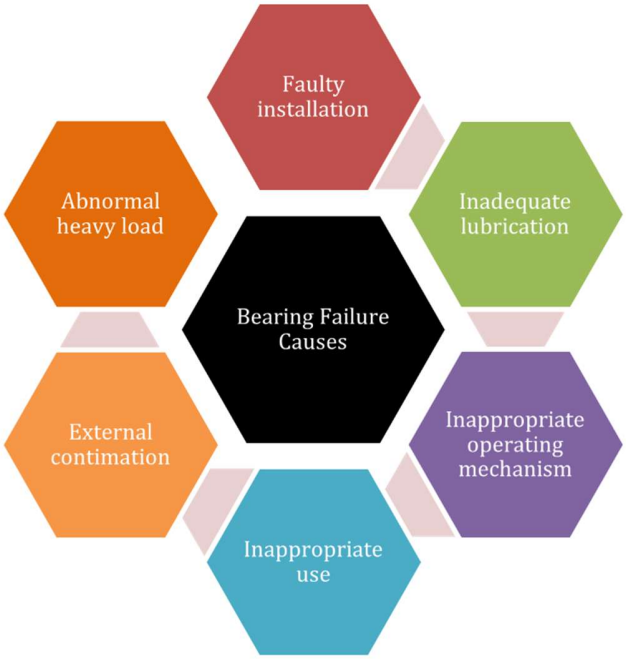

Figure 2: Some causes of Bearing Failure

Some of the surveys conducted by the IEEE Industry Application Society (IEEE-IAS)[4-6] and the Japan Electrical Manufacturers' Association (JEMA)[7] to verify the causes of induction machine failures estimate that bearing fault is the most common cause of such failures, amounting to 30 percent to 40 percent of all machine failures. Table 1 presents some of the challenging facts wrt to bearing machinery [7]:

Table 1: Facts about bearing machinery

Percentage of roller-bearings used in rotating machinery	90%
Percentage of roller-bearings reaching their optimum L10 life	10%
Percentage of bearing failures due to poor lubrication	43%

This leads to a dire need of developing a proactive system that will be able to detect anomalies in bearings ahead of time and also predict its remaining useful life. This will be extremely beneficial to the industry personnel to carry out predictive maintenance of the machinery. As depicted in Figure 3, bearing anomaly detection has been a popular domain of research in industrial setup since 1980.

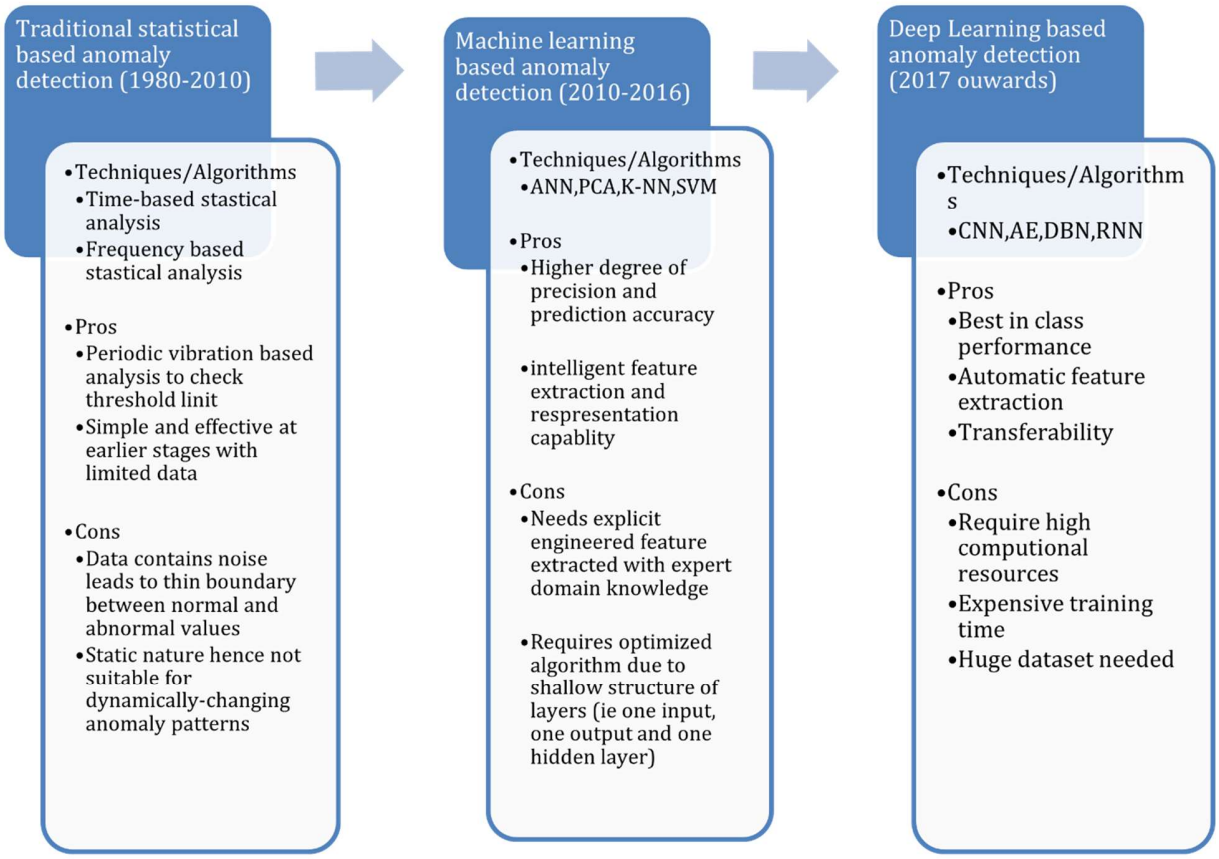

Figure 3: Progress in the approaches used for Anomaly Detection

Traditionally statistical-based techniques were used in fault diagnosis but the desired accuracy was not achieved due to the usage of static fault detection thresholds which were not updated considering the dynamicity in the operating environment of the machinery setup. From the year 2010 onwards, Artificial Intelligence revolutionized the way by which fault detection and predictive maintenance could enable machinery personnel foresee faults in bearing machinery and take preventive measures.

Therefore, the authors of this research report present a systematic review of the various research carried out in the domain of predictive maintenance in bearings using Artificial Intelligence. An extensive bibliometric survey is carried out to evaluate the performance, scope, and impact of research for fault detection in bearings using the techniques of machine learning and deep learning. The term bibliometric stands for “biblio” which means “books” or “literature” and “metrics” which means “measurement” or “quantity”. The authors have

carried out the survey using the recommended Scopus databases bases on articles, citation analysis, geographical locations, etc. This study will help to further assist the research in finding research gaps and provide research directions in this domain.

The objectives of this bibliometric survey are as follows:

1. To analyze the trends in the research publications on this topic based over last 10 years
2. To identify the trends in the publications based on geographical locations of the world
3. To identify the publication trends across university and research organizations affiliations and their contributing authors
4. To analyze the citation count of the publications
5. To identify the type of language used in the publications.

2. Preliminary collection of data

There are different techniques to access research articles, book chapters, and publications. Some articles are charged a "gold-access" fee to be able to read them while some of the publications can be accessed without a publication fee and thereby known as "open access". These publications can be accessed by registering on the journal's website or via the institution's library portals or also via research databases. The authors of this paper have accessed the research publications referred to in this paper from renowned research databases such as Scopus, Mendeley, Science Direct, Google Scholar, etc. A period of 10 years from 2010-2020 is considered as part of this study.

2.1 Analysis of Keywords:

The authors have used the Scopus database for analyzing the prominent keywords- mainly using "bearing" as the primary keyword as it is our primary scope of research in this topic. The secondary keywords include the major goal of our research i. Fault detection in combination with other goals such as "Remaining Useful Life" and "Condition Monitoring". The results due to keywords of "Autoencoders" and "LSTM" are also explored as they are the popular Artificial Intelligence techniques used for fault detection in bearings.

Table 2: List of Primary and Secondary keywords

Primary keyword	**"Bearing"**
Secondary keyword using (AND)	" Fault Detection"

Secondary keywords using (OR)	"Remaining useful Life" "Autoencoder" "LSTM" "Condition monitoring" "Artificial Intelligence

Thus the query used to search the documents in Scopus is : ("Bearing" AND "Fault Detection" OR "Remaining useful Life" OR "Autoencoder" OR "LSTM" OR "Condition monitoring" OR "Artificial Intelligence")

Excluded Keyword

"Induction Motors" "Wavelet Transforms" "Learning Systems" "Spectrum Analysis" "Wind Turbines" "Gears" "Entropy" "Envelope Analysis" "Wind Power" "Data Acquisition" "Reliability" "Engines" "Plasma Diagnostics" "Sparse Representation" "Envelope Spectra" "Rotors" "Stator Currents"

2.2 Initial search results

The search query executed on the Scopus database returned the authors a result of 4314 publications in this domain as on 31st August 2020 over the last 10 years comprising of published and yet-to-be published articles. Table 3 depicts the different types of publications in bearing fault diagnosis using AI. Most of the publications in this domain are of journal article category amounting to 58% followed by conference paper category amounting to 36%. Rest of the categories contributed negligibly.

Table 3: Count of publications in bearing fault detection

Type of Publication	Number of Publications	Percentage
Article	2526	58.58%
Conference Paper	1566	36.31%
Conference Review	100	2.31%
Book Chapter	73	1.69%
Review	26	0.60%
Book	9	0.20%
Note	3	0.06%
Short Survey	3	0.06%
Data Paper	1	0.023%
Editorial	1	0.023%

Erratum	1	0.023%
Letter	1	0.023%
Undefined	2	0.046%
	Total	**100%**

Data access information source: http://www.scopus.com (accessed on 31st August 2020)

As depicted in Table 4, the authors further analyse the trend in the language of publications in this domain. The most number of publications are published in English language followed by Chinese language.

Table 4: Language of publications used in bearing fault detection

Sr. No.	Language of publication	Count of publications
1	English	3802
2	Chinese	499
3	Spanish	6
4	German	5
5	Japanese	5
6	Russian	3
7	Polish	2
8	Italian	1
9	Korean	1
10	Turkish	1
11	Ukrainian	1
	Total	**4326**

Data access information source: http://www.scopus.com (accessed on 31st August 2020)

2.3 Exploratory data analysis

The authors also analysed the count of publications related fault detection in bearings over the ten years ranging from 2010-2021. The increasing trend of yearly publications justify

that the fault detection in bearings shows a promising scope of research in coming years. Figure 4 shows the bar-graph depiction of the yearly publishing trends.

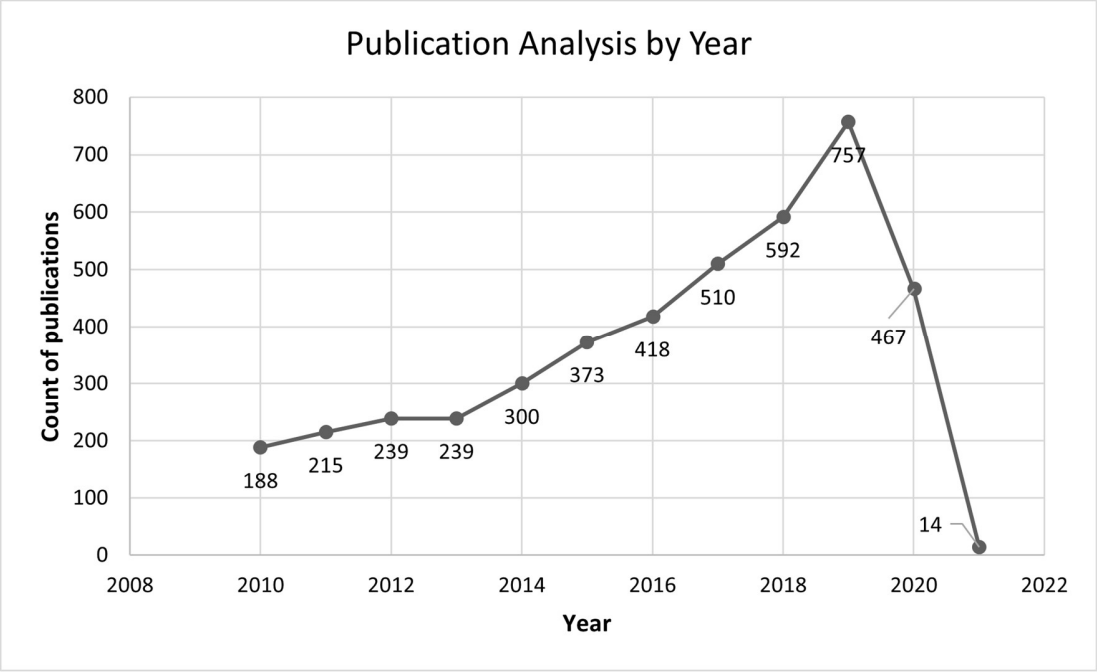

Figure 4: Yearly publishing trends in bearing fault detection (as on 31st August 2020)

3.0 Bibliometric Survey

The bibliometric survey of the bearing fault detection using AI is carried out in form of tabular/graphical analysis of research on basis of geographic locations, contributing authors and their affiliations, funding sponsors, language of publications, keywords and citation analysis, subject area and source titles.

3.1 Analysis by geographic location:

Figure 5 shows the research contribution in this domain on basis of geographic locations. Figure 6 further depicts a bar graph representing top ten countries contributing to research in bearing fault detection. China has the most number of publications at 2302 followed by the United States which have 313 publications. India is third rank with 283 publications in this domain as on 31st August 2020. The graphs are drawn using Microsoft Excel spreadsheet.

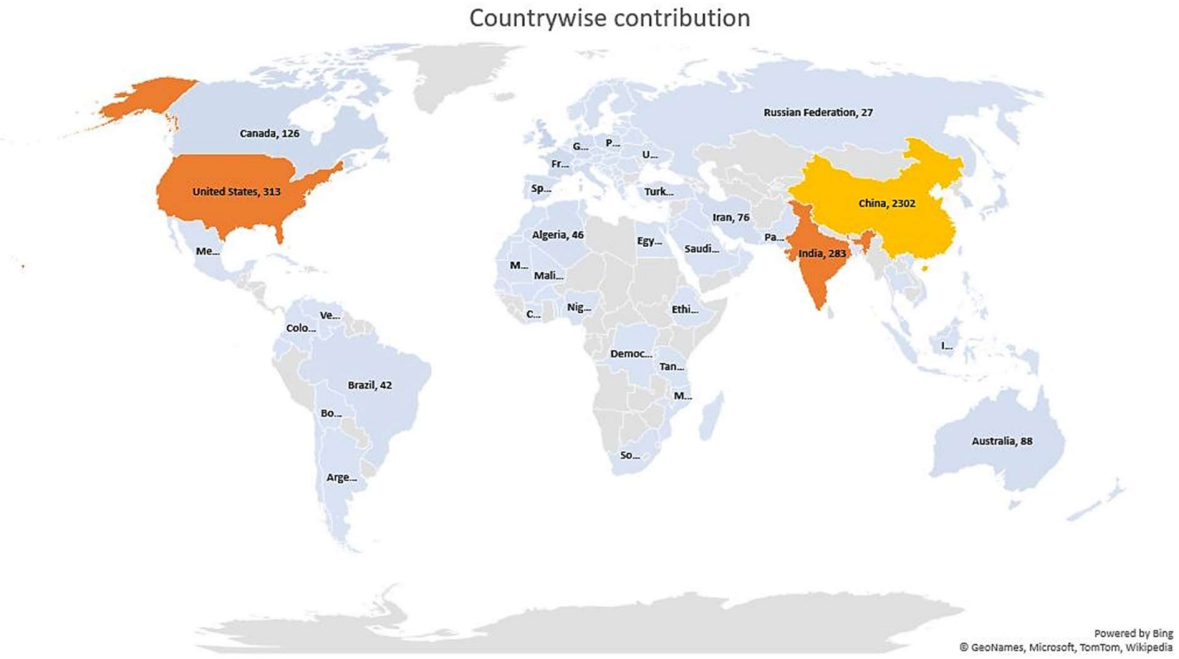

Figure 5: Geographic location-wise contribution in bearing fault detection

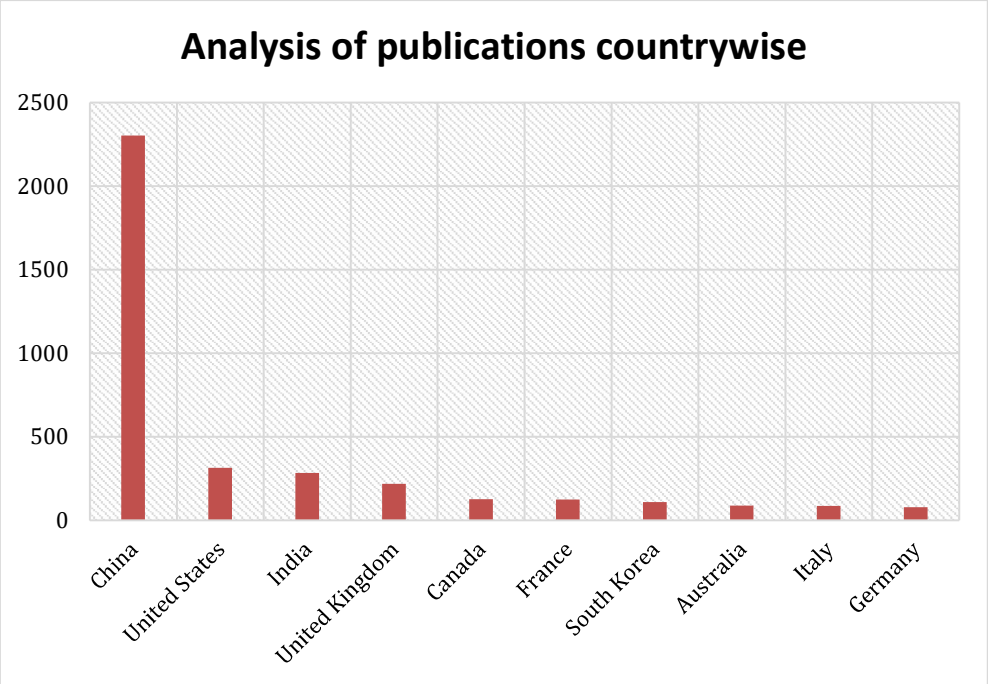

Figure 6: Top ten countries publishing papers on bearing fault detection
Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.2 Analysis based on keywords:

Table 5 shows the ten topmost keywords for bearing fault detection as per Scopus database alongwith the publication count. Keywords are a crucial measure to understand the goal and scope of research. Keywords help researchers tag their publications accurately and the right blend of keywords hep to find the appropriate list of publications for a particular research topic. From the table it can be inferred that Fault detection and diagnosis is the most followed objectives of research in bearings. Also, it can be observed that vibrations of bearing machinery is an important criteria considered by many researchers for fault detection. Further neural networks are gaining popularity for bearing fault diagnostics. Figure 7 depicts a network visualization of all keywords in bearing fault detection research. The bigger bubbles highlight the most popularly used keywords.

Table 5: Keyword analysis for bearing fault detection

Sr No.	Keyword	Publication(s) Count
1.	Fault Detection	2442
2.	Failure Analysis	1575
3.	Roller Bearings	1437
4.	Condition Monitoring	1108
5.	Fault Diagnosis	1058
6.	Signal Processing	699
7.	Feature Extraction	588
8.	Vibration Analysis	583
9.	Machinery	435
10.	Neural Networks	359

Data access information source: http://www.scopus.com (accessed on 17th Sept 2020)

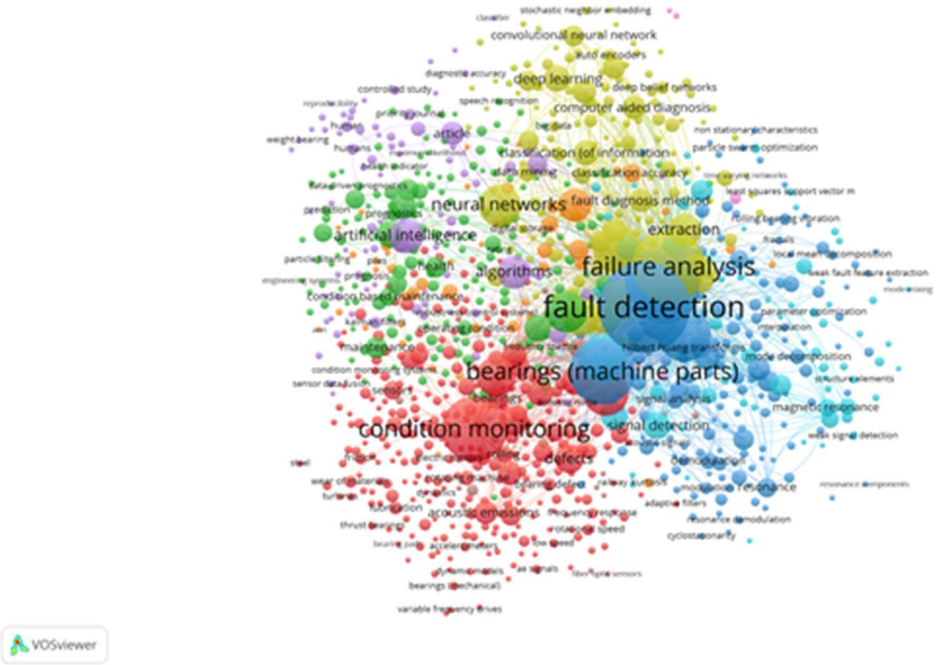

Figure 7: Network cluster of keywords related to bearing fault detection (Source: https://www.vosviewer.com/)

3.3 Analysis based on subject area:

Figure 8 depicts the pie-chart categorization of the subject areas/disciplines retrieved for bearing fault detection. It can be concluded from the diagram that majority of the research contributions in this domain belong to Engineering discipline followed by Computer Science and Physics & Astronomy.

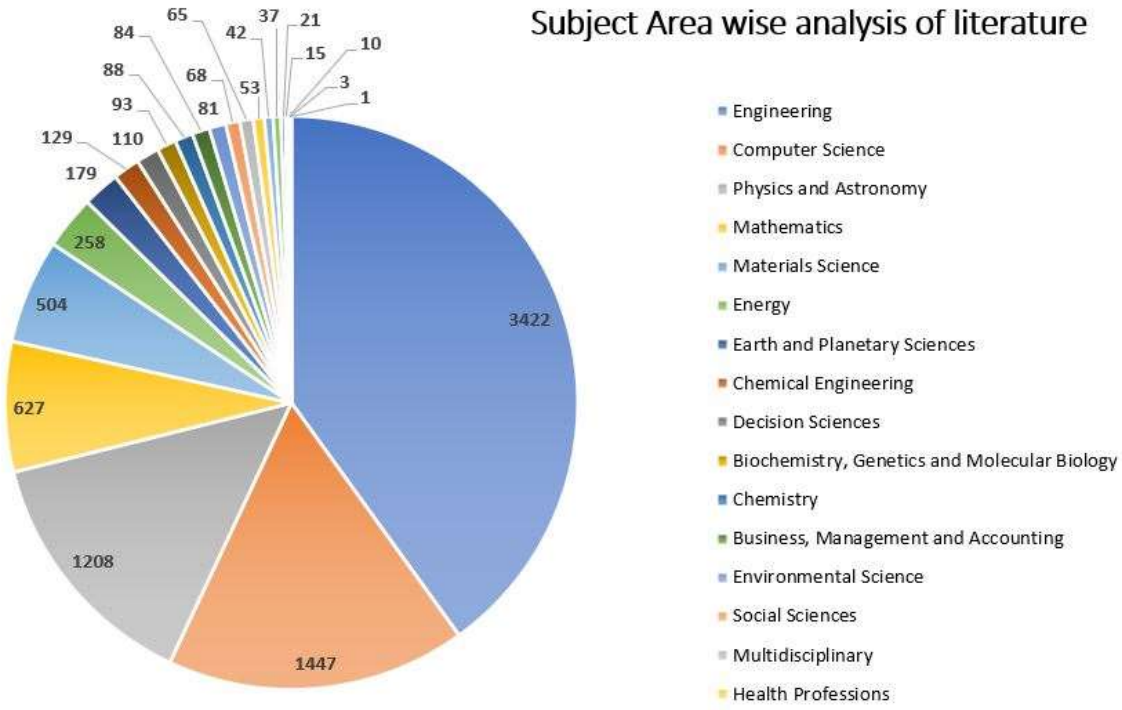

Figure 8: Subject area wise analysis of extracted literature for bearing fault detection Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.4 Analysis of Author contribution

Table 6 shows the top ten contributing authors with their publication counts in this domain of bearing fault detection. Author Gu, Fengshou from University of Huddersfield, United Kingdom is the top contributing author for bearing fault detection and his recent article titled "*Fault feature extraction for rolling element bearing diagnosis based on a multi-stage noise reduction method*" published in 2019 has already received 13 citations as on 31st August 2020[8].

Table 6: Author analysis for bearing fault detection

Sr. No.	Author Name	Publication Count
1.	Gu, F.	37
2.	Kim, J.M.	34
3.	Lin, J.	34
4.	He, Q.	30
5.	Lei, Y.	30
6.	Qin, Y.	30
7.	Zhu, Z.	28

8.	Wang, H.	27
9.	Chen, J.	26
10.	Cheng, J.	26

3.5 Analysis based on Affiliations

The top ten universities and organizational affiliations contributing towards the field of bearing fault detection are represented in Figure 9. Xi'an Jiaotong University has the most number of contributing publications in this topic with 173 publications followed by Ministry of Education China at 131 publications as on 31st August 2020.

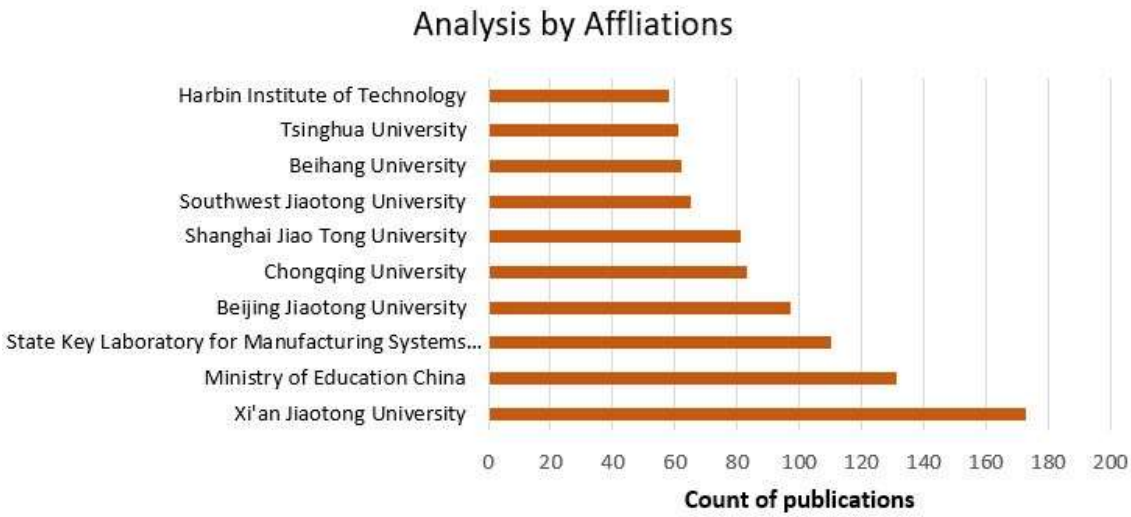

Figure 9: Affiliation statistics for bearing fault detection
Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.6 Analysis based on Source Types

Source types indicates the category where the scholarly articles belonging to the topic of bearing fault detection got published. From Figure 10 it is evident that as per Scopus database, 58.6% publications belong to journal article category followed by 36.3% belonging to conference proceedings category. Hardly 0.6% publications belong to literature review category hence this becomes one of the motivations to write this bibliometric review on bearing fault detection.

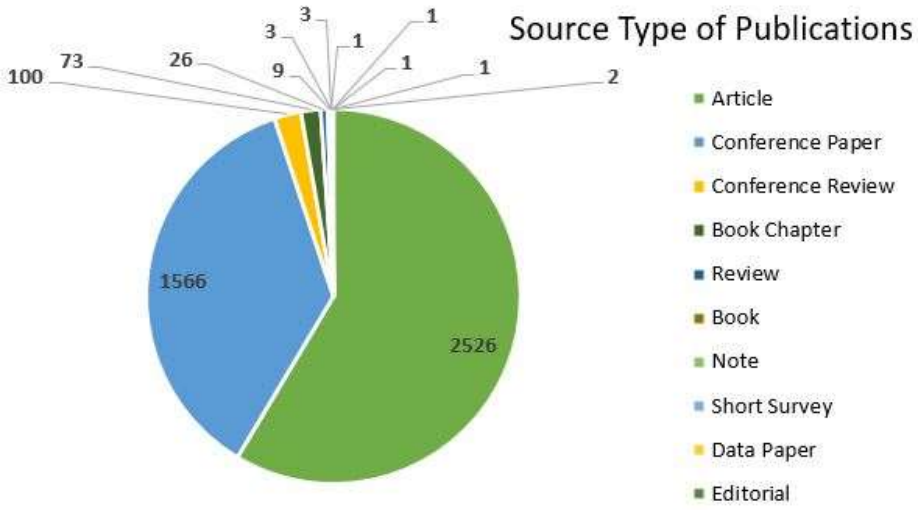

Figure 10: Source types for publications in bearing fault detection
Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.7 Analysis based on Source Titles

An analysis of top ten source titles pertain to bearing fault detection was carried out as shown in Figure 11 as on 31st August 2020. The maximum number of publications were done in the source title of Mechanical Systems And Signal Processing which had 153 publications followed closely by Zhendong Yu Chongji Journal Of Vibration And Shock at 148 publications.

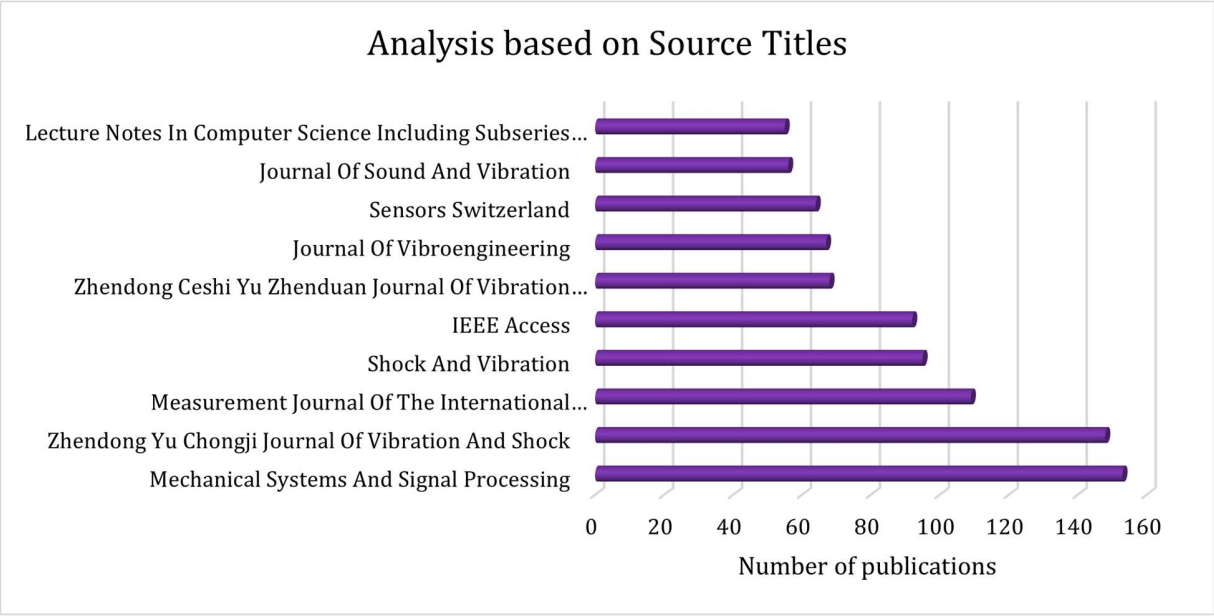

Figure 11: Source titles for publications in bearing fault detection

Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.8 Analysis based on Funding Sponsors

Sponsoring agencies play an extremely important role in the setting up the experimentation for bearing fault detection. Figure 12 depicts the top ten funding sponsors and it can be clearly observed that National Natural Science Foundation of China is the highest funding foundation followed by Fundamental Research Funds for the Central Universities.

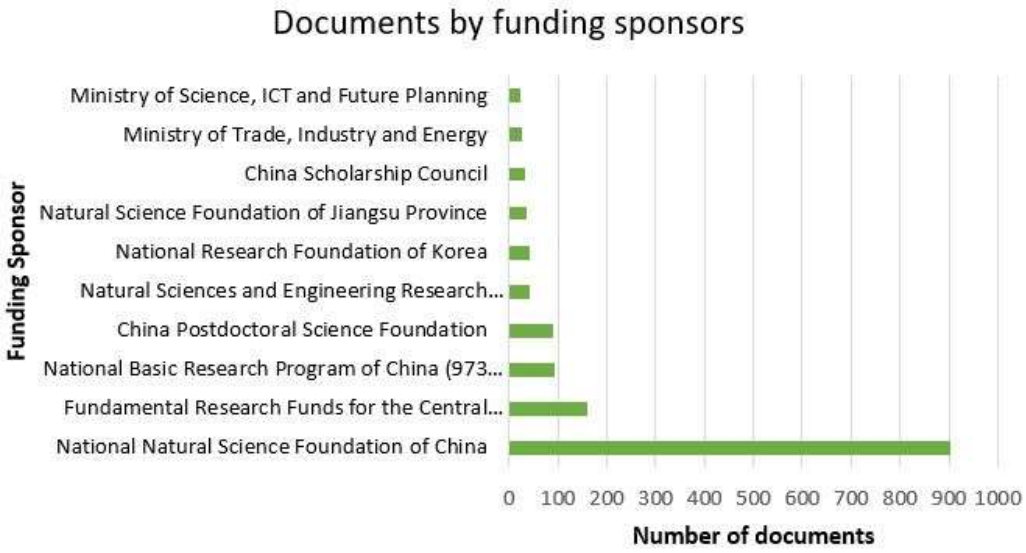

Figure 12: Funding sponsors statistics in bearing fault detection
Data access information source: http://www.scopus.com (accessed on 31st August 2020)

3.9 Citation Analysis:

3.9.1 Analysis of Citations Yearwise

Citation analysis is a technique wherein citation count of individual publications is calculated. The citation analysis strongly justifies the significance of research in this domain. Table 7 shows the total citation count yearwise for bearing fault detection with the total count of citations reaching 38951 as on 12th September 2020 . Bearing fault detection has shown a steady rise in the terms of citations with papers published in the year 2020 already have around 553 citations. Table 8 lists the top ten papers along with their citations received tillas on 12th September 2020 for this research.

Table 7: Analysis of citations for publications related to bearing fault detection
Source: https://www.scopus.com/ (accessed on 17th Sept, 2020)

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Total
Citation Count	2012	3053	2959	3725	2572	5728	6192	4812	4355	2990	553	38951

Table 8: A citation analysis of the top ten publications related to bearing fault detection Source: https://www.scopus.com/ (accessed on 17th Sept, 2020)

Publication Title	<=2016	2017	2018	2019	>=2020	Total
Deep neural networks: A promising tool for fault characteristic mining and intelligent diagnosis of rotating machinery with massive data(2016) [9]	17	81	142	238	196	674
An Intelligent Fault Diagnosis Method Using Unsupervised Feature Learning Towards Mechanical Big Data(2016) [10]	5	48	80	134	158	425
Application of empirical mode decomposition and artificial neural network for automatic bearing fault diagnosis based on vibration signals (2015) [11]	52	56	70	106	80	364
A New Convolutional Neural Network-Based Data-Driven Fault Diagnosis Method (2018) [12]	-	-	16	125	175	316
A review of microarray datasets and applied feature selection methods (2014) [13]	75	55	65	74	45	314
A recurrent neural network based health indicator for remaining useful life prediction of bearings (2017) [14]	-	10	51	101	120	282

Hierarchical adaptive deep convolution neural network and its application to bearing fault diagnosis(2016)[15]	-	19	47	111	95	272
Advances in electrical machine, power electronic, and drive condition monitoring and fault detection: State of the art (2015)[16]	50	55	71	66	27	269
Construction of hierarchical diagnosis network based on deep learning and its application in the fault pattern recognition of rolling element bearings (2016)[17]	7	30	63	82	73	255
Maximum correlated Kurtosis deconvolution and application on gear tooth chip fault detection (2012)[18]	57	30	35	76	46	244

3.9.2 Analysis of Citations Source Title wise:

Figure 13 shows the analysis of the citations for the top ten source titles in bearing fault detection. The journal of Mechanical Systems and Signal Processing has the maximum number of citations of 154 in this topic followed by the journal of Zhendong Ceshi Yu Zhenduan Journal Of Vibration Measurement And Diagnosis at 149 citations. The analysis gives the researchers an idea of the popular journals for publishing their research on basis of citations.

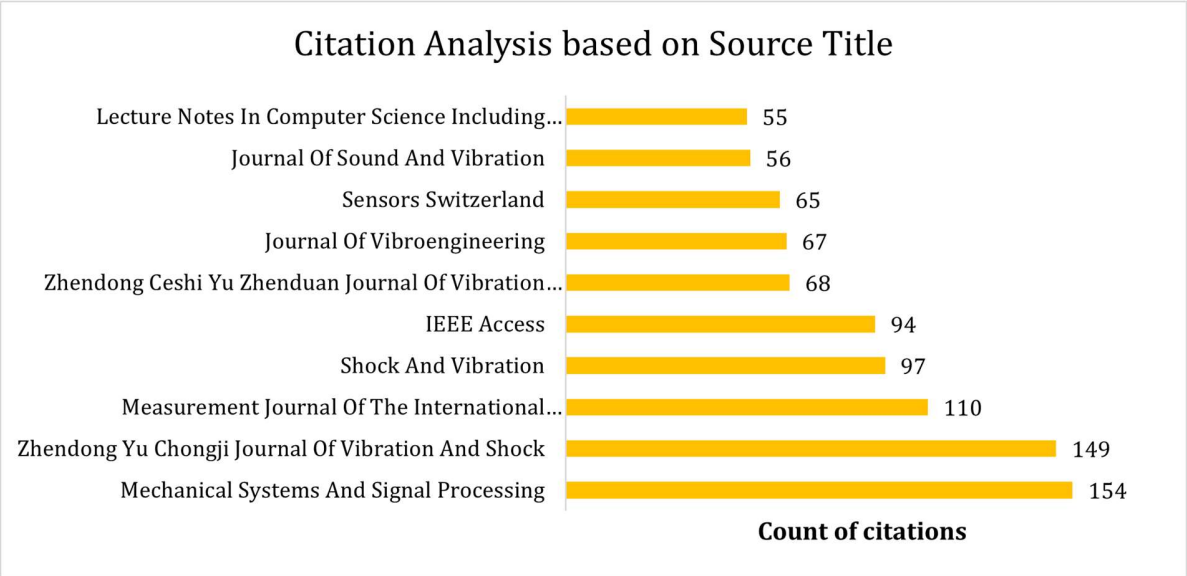

Figure 13: Citation analysis based on Source titles for bearing fault detection (accessed on 17th Sept, 2020)

3.9.2 Keyword Analysis

Table 9 shows the keywords and the respective publication count of the ten topmost used keywords in bearing fault detection. Keywords help researchers tag their publications accurately and the right blend of keywords hep to find the appropriate list of publications for a particular research topic. Figure 10 depicts a network visualization of all keywords in bearing fault detection research. The bigger bubbles highlight the most popularly used keywords.

Table 9: Top ten keywords related to bearing fault detection Source: https://www.scopus.com/ (accessed on 17th Sept 2020)

Keyword	Count
Fault Detection	2442
Failure Analysis	1575
Roller Bearings	1437
Condition Monitoring	1108
Fault Diagnosis	1058
Bearings (machine Parts)	943
Signal Processing	699
Rolling Bearings	617
Feature Extraction	588
Vibration Analysis	583

4.0 Inferences drawn and limitations of this study:

Bearing fault detection has been a popular domain of research since many years but with the advent of Artificial Intelligence, the research in this domain has been majorly revolutionized which can easily be observed from the growth in the count of publications over last ten years. Countries like China are at the forefront for the varied research work in bearing fault detection due to large availability of funding sponsors to carry out experimental study. Surprisingly India is making its mark behind China and the United States with many of the leading publications by Indian authors. Also majority of the publications in this domain are published in form of high-quality journal articles further justifying the quality of research in this area. Due to the nature of the research, maximum number of publications in this topic belong to Engineering domain followed by Computer Science due to advent of AI. The limitations of this study are that only the publications limited to English language are analyzed in this study. Also only publications and citations as per Scopus database are considered in this study. There are many other popular databases such as Web of science and Google Scholar which the authors are planning to consider for their further bibliometric research.

Conclusion:

Bibliometric study helps researchers gain a deeper understanding of the prospective research topics and the research gaps. This bibliometric survey for bearing fault detection helped the authors in identifying the various aspects which could be considered while carrying out their research in this domain. The authors were able to identify the prospective journals alongwith their citation analysis for their further experimental pubications and the keywords which could be used for carrying out further literature survey. Bearing fault detection has a lot of scope for research and deep learning techniques such as autoencoders and LSTM (Long Short-Term Memory) can make worthwhile contributions to this domain by predicting the remaining useful life of the bearing machinery.

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