

Review

Bibliometric Analysis of Heat Generation in Eddy Current Brakes

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Abstract: The eddy current brake (ECB) is a braking technology that continues to be developed. The use of the ECB has excellent potential to be applied to vehicles. Various studies have proposed the design, characteristics, and advantages of each. However, further analysis is needed to assess the performance of the ECB and what factors affect the performance. However, no studies have been found that discuss eddy current brakes using bibliometric analysis. Bibliometric analysis is a method used for mapping and knowledge of existing gaps in a particular topic. This article aims to provide a complete discussion with bibliometric statistical methods that have never been presented before in the field of eddy current brakes, especially the phenomenon of heat generation. In addition, the prediction of research gaps in this field can be identified as the initial results of further research. The analysis was carried out using VOSviewer and Biblioshiny integrated through the RStudio tool. The data are obtained through the Scopus database, which is then exported in CSV form. Obtaining the data depends on the keywords used. In this case, the obtained document is filtered with the features provided by Scopus. From the analysis conducted, it was found that the topic related to heat in eddy current brakes is still a recent discussion. Discussions on the heat increase in the ECB are still limited and require mapping and analysis of what parts still need development. The phenomenon of heat generation is one novelty that allows it to be researched. One example from the scientific data obtained is that there are 207 documents in the form of articles and conference papers with a total of 533 authors.

Keywords: bibliometric analysis; bibliometric; eddy current; eddy current brake; heat; ECB



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1. Introduction

The development of eddy current effects is improving, one of which is the eddy current brake (ECB) [1,2]. ECB is an electric braking system that uses the eddy current principle. This principle uses the generation of primary magnetic induction formed in conductor materials. In general, magnetic materials that have high permeability can produce high magnetic flux [3–6]. In other words, the eddy current phenomenon can be more effectively generated with an electric current in materials with low electrical resistance. Several researchers have proposed several ECB devices by claiming their respective advantages [6–9]. Some other studies propose ECB characteristics by generating different phenomena. It supports the development of eddy current braking systems to be better and more effective [3,10–12]. Increasing the magnetic field can improve the ECB performance. In general, inductance involves a magnetic field from one side. However, recent research has shown that using

magnetic fields from both sides will increase the density of the resulting magnetic field. Previous studies have been carried out using changes to the air gap [13]. Changes in the gap will affect the resulting braking performance. The research is more directed to changes in the density of the magnetic field generated by the air gap but does not pay attention to the influence of the magnetic field used. Other studies have shown that changes in the position of the magnetic field will also affect the resulting braking performance [14]. These changes indicate that a change in the position of the shoe pole will result in a change in braking performance by the ECB. A review journal before 2017 analyzed the ECB system in general and discussed designing ECB systems for various uses, and another review discussed applying NdFeB permanent magnets in various system applications, one of which is the ECB. Waloyo [15] conducted a study on the development of the ECB design. Several discussions put forward by the authors, including journals, discuss the effect of using rotor materials (aluminum, Cu, or ferromagnetic metals) on braking torque [16], including the following: giving the groove on the surface of the rotor [17,18]; adding permanent magnets to the stator to increase the magnetic field's magnitude [19]; adding a back iron structure to increase the magnetic conductivity [20], or a ferrous metal construction coated with a non-ferrous metal [21]; adding a Halbach permanent magnet configuration on permanent magnet ECB [22–24]. Tian [5] has conducted a fairly in-depth analysis of the use of liquid fluid as an ECB coolant, but the study was carried out by providing a liquid cooler on the radial stator of the ECB. The application of this method is very limited to the radial ECB. Meanwhile, studies on other ECBs are still an open field of research because their use is still limited to application methods and improving performance by changing their properties. It is also shown by bibliometric analysis data on technological developments in the field of eddy current brakes. At the beginning of its use, the use of ECB was better known as electric braking. Electric braking is based on a magnetic source from an electric current flowing in the coil. Electric braking has been applied as braking on land vehicles. Applications of electric braking can be carried out in other fields by adjusting the voltage and current used. Then the term “eddy current brake” was introduced to identify an electric braking system that utilizes the eddy current principle. In the early days of development, the research was only intended to determine the braking system's performance using numerical analysis. The research was carried out on a rotating disc. Besides braking, the same working principle is used for the clutch connecting the power source and load. Numerical analysis is widely used as a mathematical approach to determine braking performance. The mathematical formulation obtained is compared with the real test results and continues to be developed by adding various boundary conditions. Research opportunities in the eddy current brake discussion are needed to support ECB development. However, the opportunity for a void in this field is still not widely mapped and published. It is interesting to discuss, given that the potential of eddy current brakes is quite good in recent technological developments focusing on electric vehicles [25–27]. This research gap is certainly needed by several researchers who conduct their research in the electrical field, particularly ECB. The research gap, in this case, can be identified in several ways, such as bibliometric analysis. This paper proposes a bibliometric analysis for the discussion of ECB. With bibliometric analysis, not only can research gaps be identified but so can research trends in the field of ECB, as well as ECB players around the world and ECB-related articles that have been published [28–30].

Bibliometric analysis was carried out using two mutually supporting applications, VOSviewer and Biblioshiny, integrated through RStudio. Both of these applications are open access applications. The bibliometric analysis was based on using keywords in the Scopus database [31–33]. With the selection of keywords used in general and then leading to specific ones, 207 articles were obtained. The articles obtained were 56 conference papers and 151 articles. The use of keywords applied to the Scopus website was related to “eddy current brake.” Then, the search based on the keywords that was performed was limited based on the type of article. The year of publication in this search was not limited, considering the total number of articles obtained is only 207 documents. The selection of keywords in this paper was made because there is still little discussion of heat generation

in the discussion of ECB. It is also one of the findings that represents a research opportunity for ECB studies.

In detail, this paper conducts a co-authorship study of authors and documents. In addition, collaboration or good relations between authors and between countries are also studied. The sustainability of ECB-related research is identified through the trend and evolution of themes in this field. Thus, the research gap in ECB studies can be estimated in the future. To provide information to readers or players in the ECB field, the use of keywords or words often used in this discussion is also mapped. It is expected to help find articles as references to be used. This discussion contributes greatly to the continuation of research related to the ECB in general and the generation of heat in the ECB field in particular. There has been much research related to ECB, but no report shows a bibliometric analysis for eddy current brake studies that specifically discusses the heat-generation part. In addition, in industrial practice, especially on ECB technology which is still under development, this mapping can contribute to literature studies and collaboration opportunities seen from this analysis.

Therefore, taking into account the analysis presented above, this review aims to establish an analytical model of heat generation occurring in the ECB by considering a compact and easy-to-apply design, an approach that has not been covered in the literature so far. This review covers this new way of presenting this cutting-edge analysis; the analyzed papers have been compiled through bibliometric analyses carried out using the VOSviewer software and the Biblioshiny integrated through the RStudio tool, through which a citation network is built that allows us to establish relationships or correlations between items. A discussion of the model is presented, with the aim of establishing its usefulness and the applications in which the forecast model can be used.

2. Materials and Methods

This study uses publication records in the Scopus database to obtain related documents. The document search process in bibliometric analysis using VOSviewer and Biblioshiny highly depends on selecting keywords entered in the Scopus website. Documents displayed by Scopus are then exported in CSV file format. However, the file format used cannot only be used with CSV [19,20]. It depends on the bibliometric analysis application that will be used. In this case, VOSviewer and Biblioshiny are recommended to use CSV. The CSV file is then used for processing with the VOSviewer and Biblioshiny applications. The VOSviewer application is used for document mapping, document citation, collaboration, and author notes. Biblioshiny is used to analyze topic trends, theme evolution, and thematic dendrogram and bring up data in the form of values obtained in the Scopus database and mapping similar to VOSviewer [21].

The keywords used in this analysis are as follows: "TITLE-ABS-KEY (eddy AND current) AND (brake) AND (heat) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp"))." Although documents obtained by selecting these keywords are not limited by the year of publication, it is known based on the Scopus database that 1956 was the first year that related research was published [22,23]. The searches provided initial results in key information, which was then used as material for the discussion of bibliometric analysis, as shown in Table 1.

Table 1 shows several categories of information obtained, including main information, document type, document content, author, and author collaboration. A total of 207 documents recorded by the Scopus database used 145 sources of various types (books, journals, etc.). All documents recorded from 1956 to 2022 are known to have 533 authors with a collaboration index of 2.72.

Table 1. Main information about data and documents.

Description	Results
Main information about data	
Timespan	1956:2022
Sources (Journals, Books, etc)	145
Documents	207
Average years from publication	7.57
Average citations per documents	10.09
Average citations per year per doc	1.448
References	4190
Document types	
article	151
conference paper	56
Document contents	
Keywords Plus (ID)	1716
Author's Keywords (DE)	531
Authors	
Authors	533
Author Appearances	742
Authors of single-authored documents	17
Authors of multi-authored documents	516
Authors collaboration	
Single-authored documents	17
Documents per Author	0.388
Authors per Document	2.57
Co-Authors per Documents	3.58
Collaboration Index	2.72

3. Results

This section describes the popularity analysis of the ECB using bibliometrics and publications that are claimed to be the most accurate and precise. This method was obtained from the bibliometric analysis process using software for analysis.

3.1. Mapping of Scientific Documents

3.1.1. Annual Scientific Production

The growth of research related to heat generation in the field of ECB can be known through bibliometric analysis. In this case, the annual scientific production is shown in Figure 1. Based on Figure 1, the publication of articles recorded in the Scopus database was vacant from 1957 to 1973 and from 1988 to 1995. At the same time, most articles were published in 2019, with as many as 24 documents. The document production is comparable to the results of the analysis of the production of the best authors in related fields, as shown in Figure 2. Figure 2 shows the 20 most frequent authors of all existing authors, as shown in Table 1. The year 2019 was recorded as the highest document production every year. Li and Ye produced the publication on the ECB discussion for heat generation. The results in Figure 2 below are related to the next discussion, namely the most relevant authors and the most frequently cited authors [1].

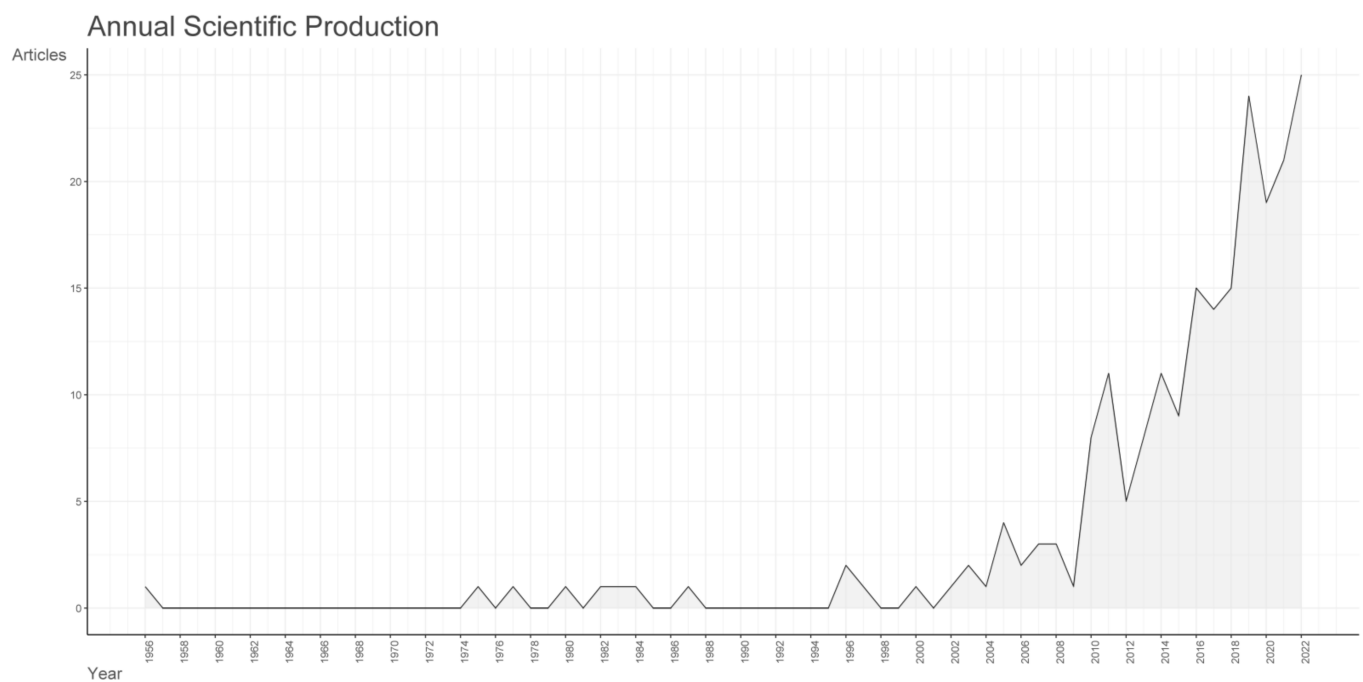


Figure 1. Annual scientific production of eddy current brake for heat generation.

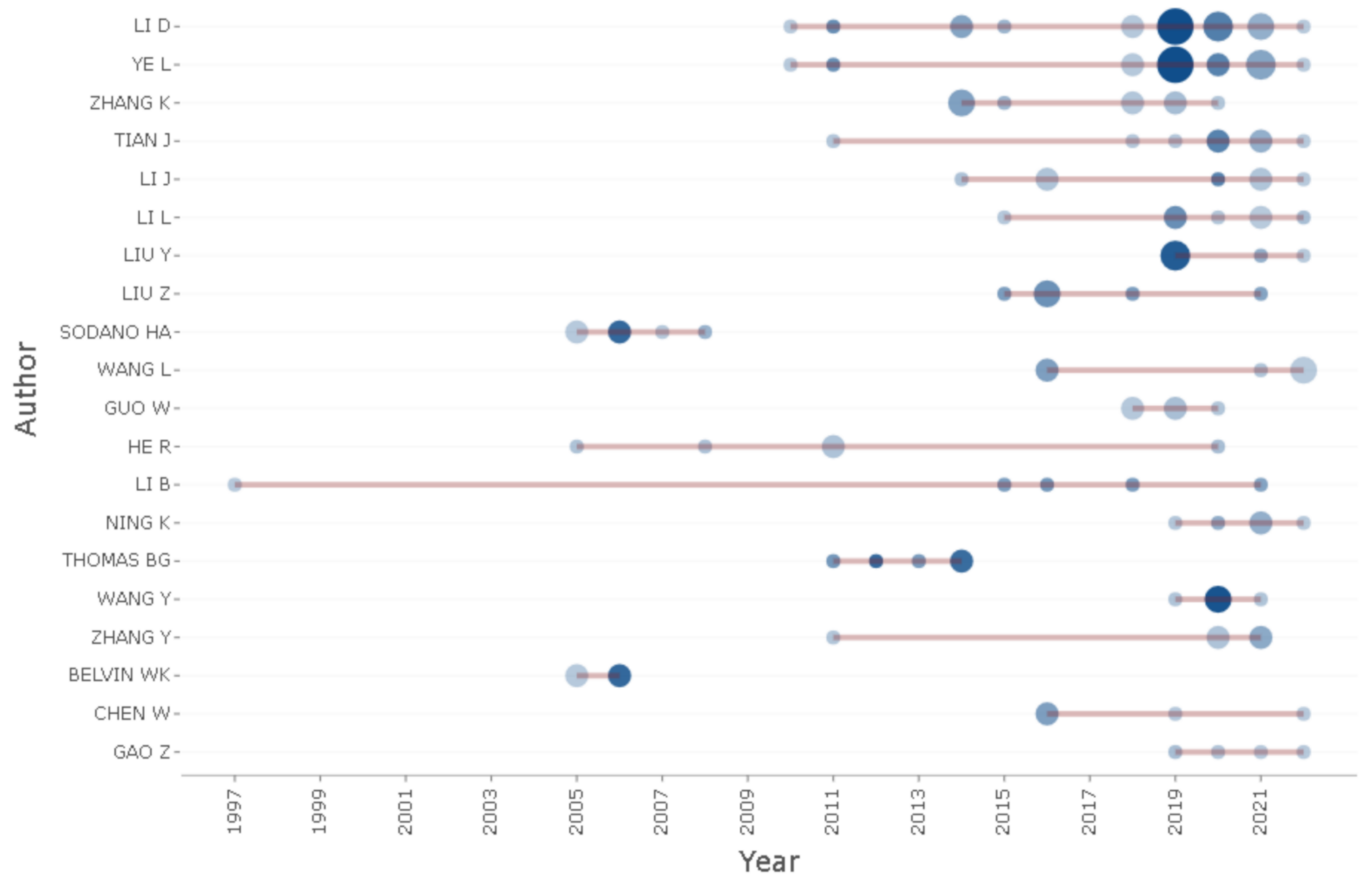


Figure 2. Top-authors' production over time.

3.1.2. Authors Contribution

Many researchers have indeed carried out the discussion of ECB. A search on the Scopus database using the keyword "TITLE-ABS-KEY (eddy AND current)" obtained as

many as 47,155 documents. Meanwhile, if the use of keywords is further narrowed down to the discussion of the braking system with the keywords “TITLE-ABS-KEY (eddy AND current AND brake)”, 704 documents are obtained. It indicates that the discussion of the eddy current braking system is not extensive: only 1.49%. The percentage becomes even smaller if the keywords used are adjusted to this paper, as then the percentage is only 0.43%. With this value, discussions of eddy current brakes that focus on the discussion of heat are still very limited. From the main data information obtained in the bibliometric analysis, it is known that the authors that contributed to this discussion were 533 authors. Of all the authors who contributed, 20 authors were taken as a sample for the most relevant and most contributing authors in this field, as shown in Figures 3 and 4 below.

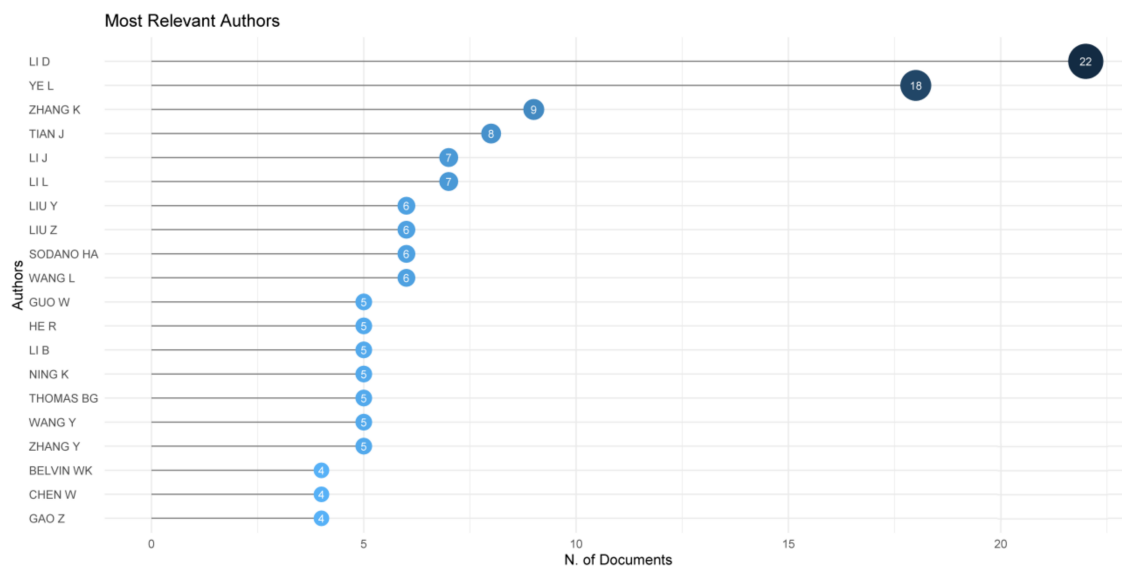


Figure 3. Most relevant authors.

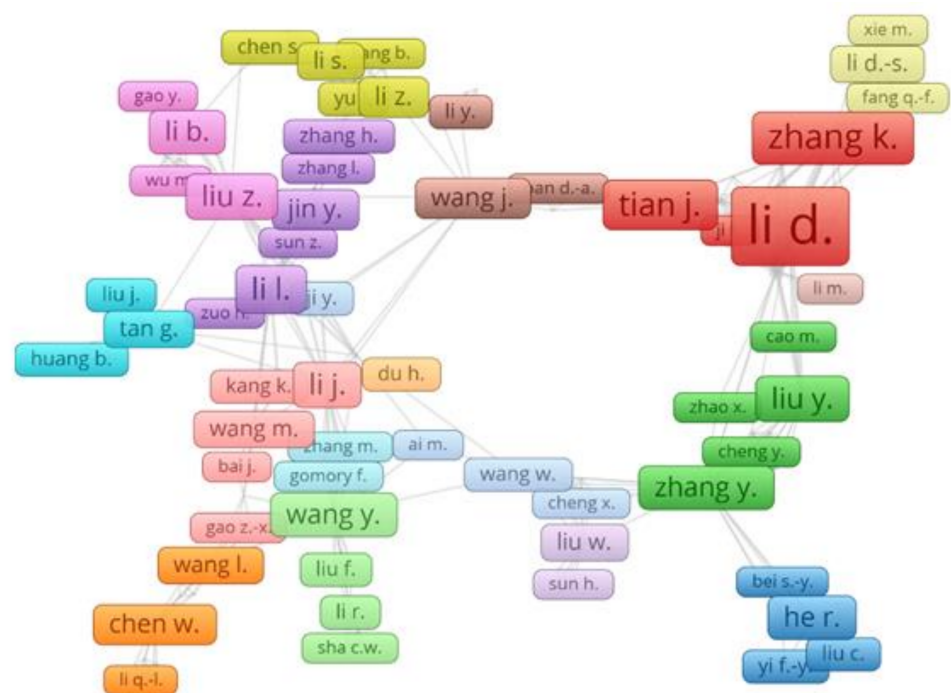


Figure 4. Co-authorship analysis using VOSviewer.

Figure 3 shows that Li made the most contributions in this area. Li contributed 22 documents, followed by Ye, who contributed 18 documents. The number of documents published by the third author and so on can be said to have a large difference of 13 documents. In addition to the analysis conducted with Biblioshiny, the analysis was also carried out using VOSviewer, which aims to determine the distribution of the authors who contributed, as shown in Figure 4. The results of the analysis conducted with VOSviewer are directly comparable to Biblioshiny. In this case, Li is also the author who contributes the most, as indicated by the largest frame scale among others. Although Li and Ye contributed the most to published records, it does not explain that Li and Ye contributed the most to globally cited document records. This is shown in Figure 5. Figure 4 shows the co-authorship activity in the field, and who performed the research is shown as a map. Figure 4 is based on the ratio of the frame shapes: the bigger the writer, the more contributions.

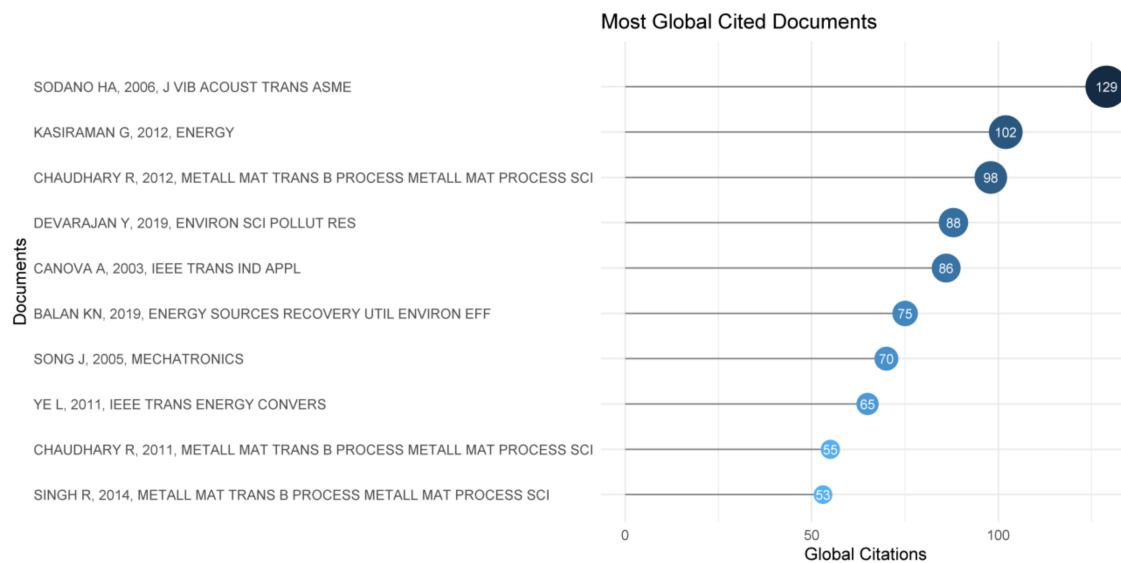


Figure 5. Most global cited documents.

Articles published by Sodano are the most cited globally, with 124 citations. As shown in Figure 3, Sodano only contributed to the publication of 6 articles. As for the top 20 most cited articles, Li is not one of them. One of Ye's articles became the 65th most cited article and occupied the eighth position.

3.2. Document Collaborations

3.2.1. Countries Collaboration

The article's publication is certainly not far from the discussion of research collaborations carried out. For example, in the field of eddy current brakes, there are also several collaborations, both multiple-country collaborations (MCP) and single-country collaborations (SCP) [24–26]. The analysis results based on the collaboration between countries for ECB heat generation were obtained through Biblioshiny, as shown in Figure 6. These results were obtained based on the author's country correspondence records. China has the most correspondence with 5 multiple collaborations and 65 single collaborations. India followed this with 32 collaborations for single collaborations. However, India did not record any collaborations with other countries. Ranking third is the USA with 17 single collaborations and 4 multiple collaborations. Other countries that collaborate with these countries can be seen in Figure 7.

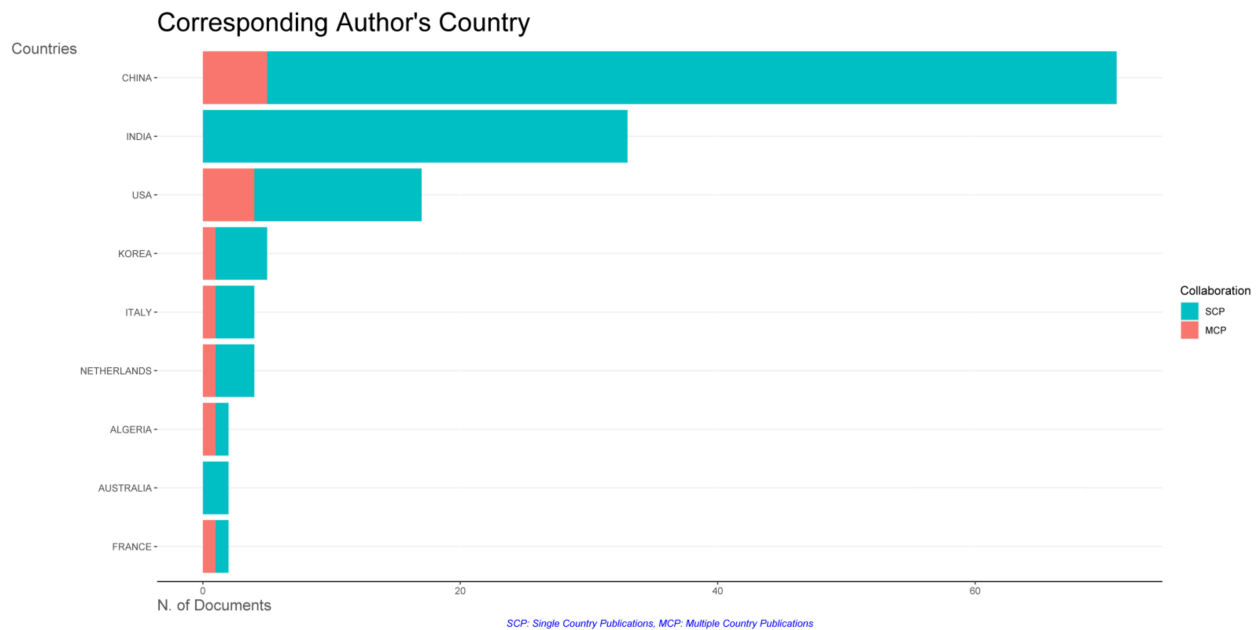


Figure 6. Corresponding author's country.

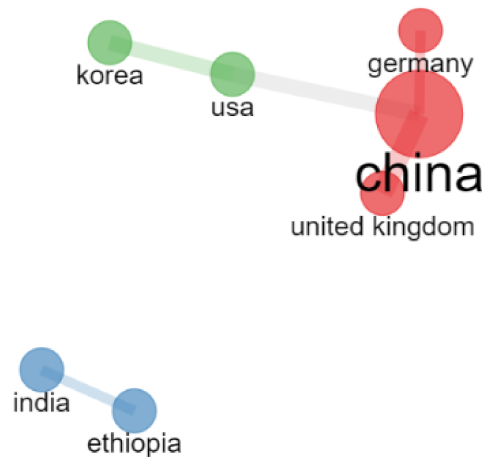


Figure 7. Collaboration networks.

Figure 7 shows some samples of the inter-country collaboration networks that were conducted, but these results are a record of collaboration in general and not just the author's correspondence, as shown in Figure 6. What is different is that India collaborated with Ethiopia, whereas in Figure 6, India did not collaborate with any country because the correspondence determined the result. In addition to the collaboration records between countries, author collaboration is also known in this discussion.

3.2.2. Organization Collaboration

Organizational or affiliate collaboration is carried out using VOSviewer. This is because VOSviewer can display more detailed and organized mapping. The analysis of collaboration between organizations recorded that 317 organizations contributed to this field. Of all the contributing organizations, there are only a few of the most influential organizations with the highest number of links, such as the Birmingham Centre for Railway Research and Education (University of Birmingham), College of Mechanical Engineering (Taiyuan University of Technology), Department of Engineering (University of Aberdeen), School of Mechanical Engineering (Southwest Jiaotong University), and State Key Laboratory of

Traction Power (Southwest Jiaotong University) with a total of 13 links. The collaboration mapping is shown in Figure 8.

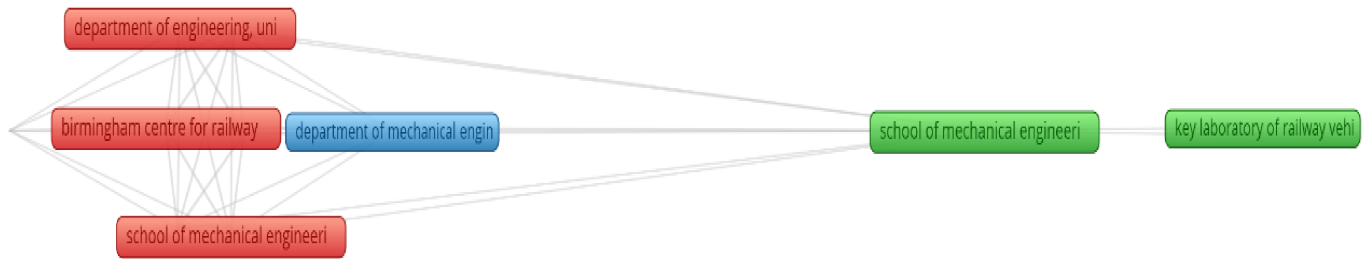


Figure 8. Organization collaboration.

3.3. Keywords Analysis

3.3.1. Author's Keywords

This paper relies heavily on the keywords used by the authors in their articles. Thus, keyword analysis is also needed in this paper. It aims at the suitability of the paper and the ease of searching for articles as references. In addition, the keywords used by the author can also be used as a prediction of possible future discussions or to identify the research gap. The most used keywords in the discussion of eddy current brakes for heat generation are shown in Figure 9. Based on the analysis results, it is shown that the author's most common and relevant keyword is "eddy current brake", used 21 times. It is directly proportional to the theme discussed in this paper, namely eddy current brakes. However, the words "heat" and "heat generated" were not found in the 20 keyword records used by the author. These words should appear if the sampling is expanded. Therefore, the results will be shown in another figure. The second most frequently used relevant word is "diesel engine". These words should have been ranked after the word "eddy current", but they were not. It may be due to the eddy current application performed by the author. Furthermore, as discussed, to bring up the word "heat" or "heat generated", this discussion tries to expand the word usage by using a word tree, as shown in Figure 10.

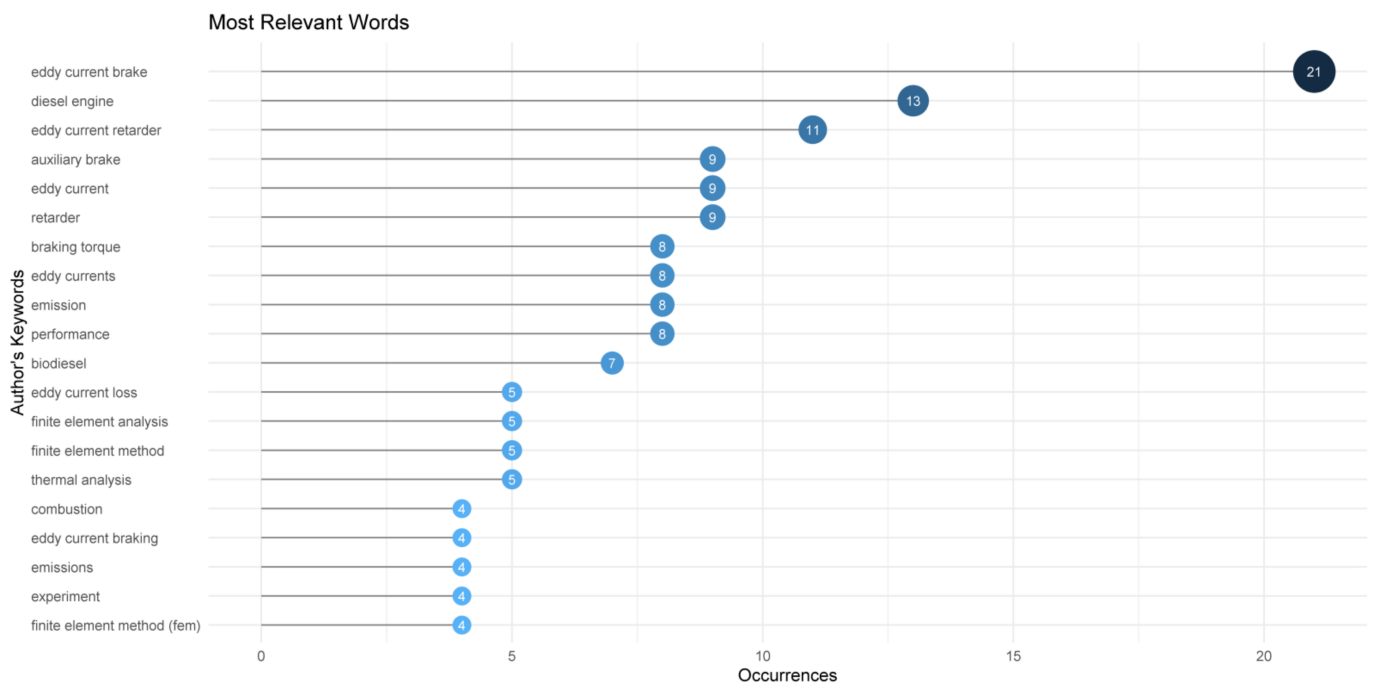


Figure 9. Most relevant words.



Figure 10. Treemap analysis (Field: Author's Keywords).

Figure 10 shows a word treemap with a total of 50 words. Based on the results obtained, the word “heat” does not appear, but the use of words that mean the same as “heat” appears, namely the word “thermal”. As for the different processes, namely with selecting the fields used, the author's keywords are changed to keywords plus in the analysis so that in the word tree of Figure 11, the word “heat transfer” appears.

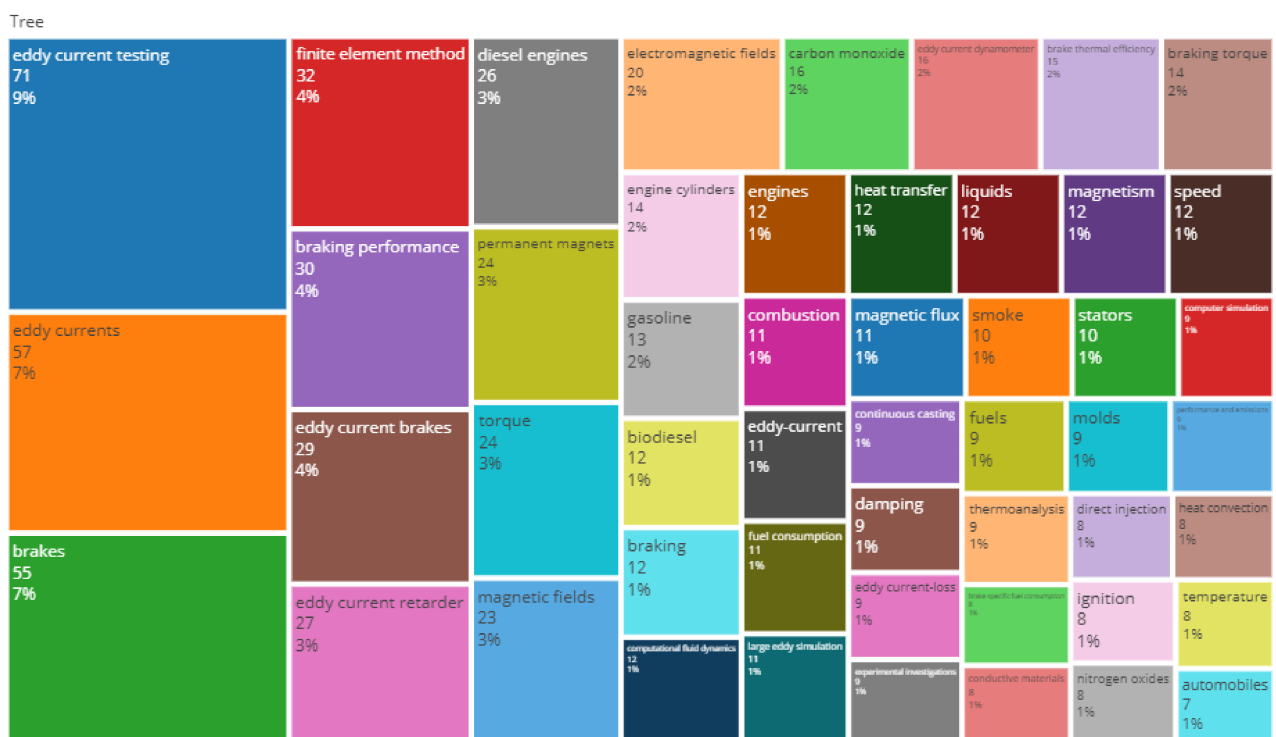


Figure 11. Treemap analysis (Field: Keywords plus).

3.3.2. Trend Topics and Thematics Evolution

Using keywords in the bibliometric analysis also analyzes topic trends in a particular field. For example, Figures 12 and 13 show the topic trend to theme evolution that occurred during the years of data collection or document publication related to the field of eddy current brakes. Figure 12 shows the topic trends of the sampled data over the last 20 years.

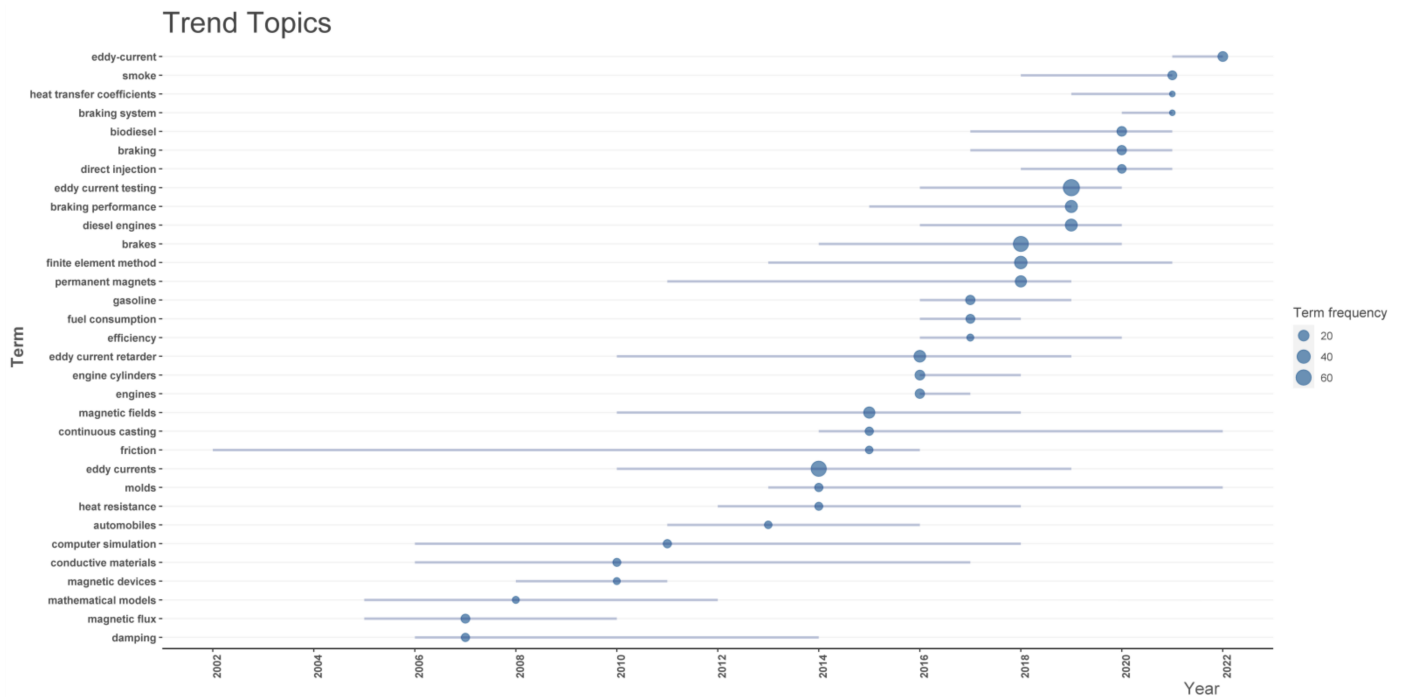


Figure 12. Trending topics for the last 20 years.

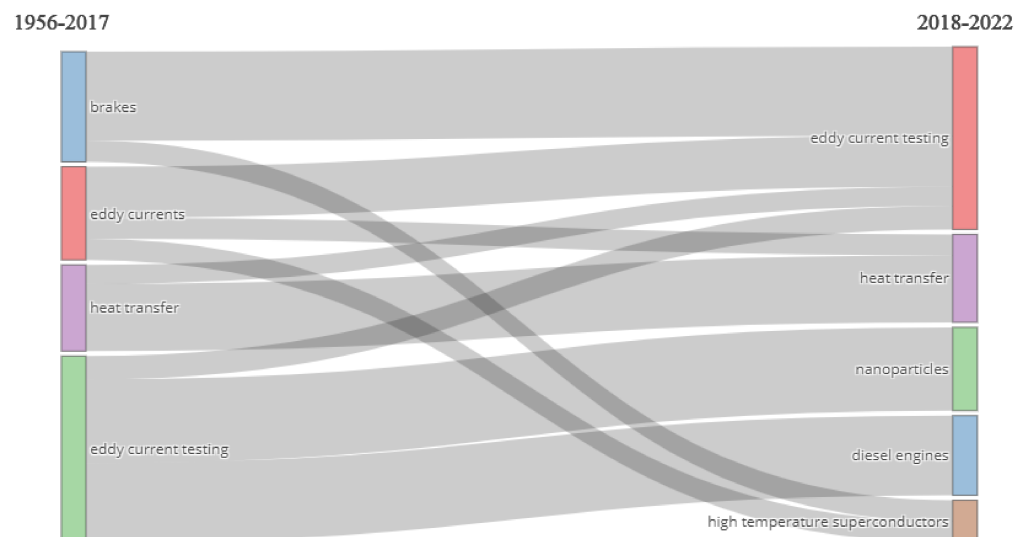


Figure 13. Thematic evolution.

Based on Figure 12, the word often used in the eddy current brake field for heat generation is “friction,” with the most intensity in 2015. The discussion of heat in eddy currents has occurred significantly in the field in the last five years. The use of the word “heat” began to be actively used. It indicates that the discussion of heat generation is starting to become a topic of interest, and there has not been much discussion in previous years. It is also shown in Figure 13.

Figure 13 shows the evolution of themes in the field of eddy current brakes. The analysis is divided into two parts: the last five years (2018–2022) and the previous year from the start of the publication of documents related to eddy current brake heat generation. The discussion of braking began to change to “eddy current testing” and “high-temperature superconductors”. The discussion of “eddy currents” changed to “eddy current testing”, “heat transfer”, and “high-temperature superconductors”. The theme change proves that, in the last five years, there has been a change in the theme, wherein it is more likely that heat in eddy current brakes will be discussed. The transition is taken based on the most frequently used keywords in the topic of eddy currents. These results indicate the development of research from the discussion of eddy currents, which generally becomes more focused for the advanced level of discussion.

4. Discussion

Eddy current brakes are one of the technological developments that have caught the attention of researchers. Various articles have been published showing the advantages and discussing the disadvantages of each. Moreover, nowadays, electric vehicles are one of the most popular topics. With the eddy current brake said to be very suitable in the use of electric vehicles, articles related to the eddy current brake are certainly much sought after, both for the theoretical basis in the form of basic knowledge to research gaps that may exist in the discussion. However, analysis to find out the research gap in a field of discussion is still a rare thing to find. Thus, in this paper, bibliometric analysis is used for one of these purposes. Research gaps are searched by mapping various types of analysis, such as published scientific documents. In this case, annual scientific production and author contributions are mapped based on the existing Scopus database. The known annual production data show an increase in production of even more than 20 documents with a total of 533 contributing authors.

Furthermore, the countries and affiliations contributing to this field can also be known through this analysis. This knowledge of countries and affiliations allows new authors who want to conduct research in the field of eddy current brakes to collaborate between countries and domestically. It is an excellent opportunity to increase the authorship collaboration index. Knowledge of contributions can even be known up to the stage of the author’s name, both the first author and the corresponding author. Another opportunity that can be obtained is the determination of the selection of promoters or advisers in taking advanced studies (doctoral degree). It can be carried out by looking at Figures 3, 5 and 14.

The cluster plot is presented in Figures 14 and 15, which shows clusters in two-dimensional space (Dim1 and Dim2). These parameters can be thought of as primary components (PCs). PCs are independent (orthogonal) to other PCs and are linear combinations of the original variables. The first principal component (PC1), a new variable that accounts for the majority of the variation in the initial digitalization variables, in this case, 72.16%, as seen in Figure 15, corresponds to the horizontal dimension (Dim1) in Figure 15. The second principal component (PC2), which accounts for 9.08% of the overall variance 81.24%, is shown by the vertical axis. This can be seen from the contribution index or the use of keywords used. Mapping can be performed to find the fields that can still be related to the discussion of eddy current brakes. For example, as shown in the conceptual structures map in Figure 15, several topics can be researched, such as braking torque, magnetics, conductive materials, etc.

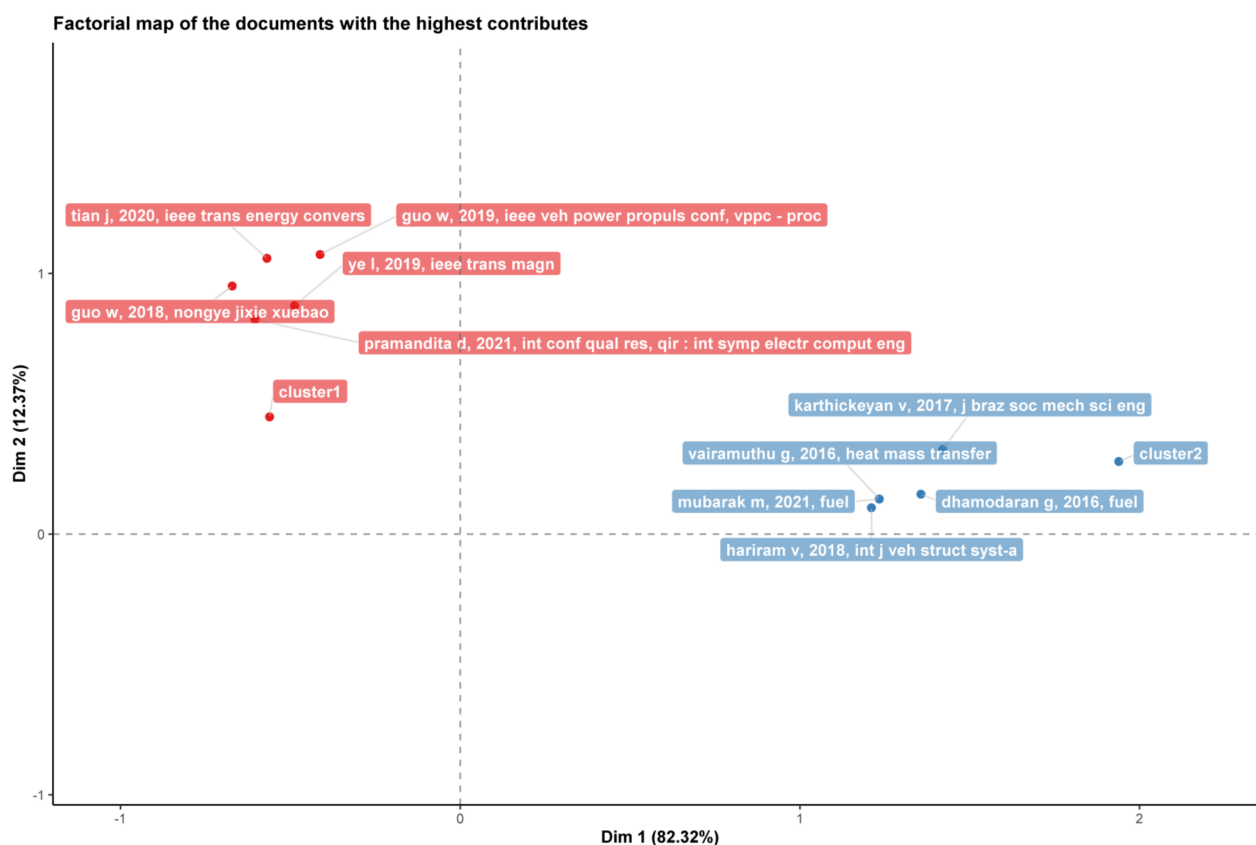


Figure 14. Factorial map of the documents with the highest contributes.

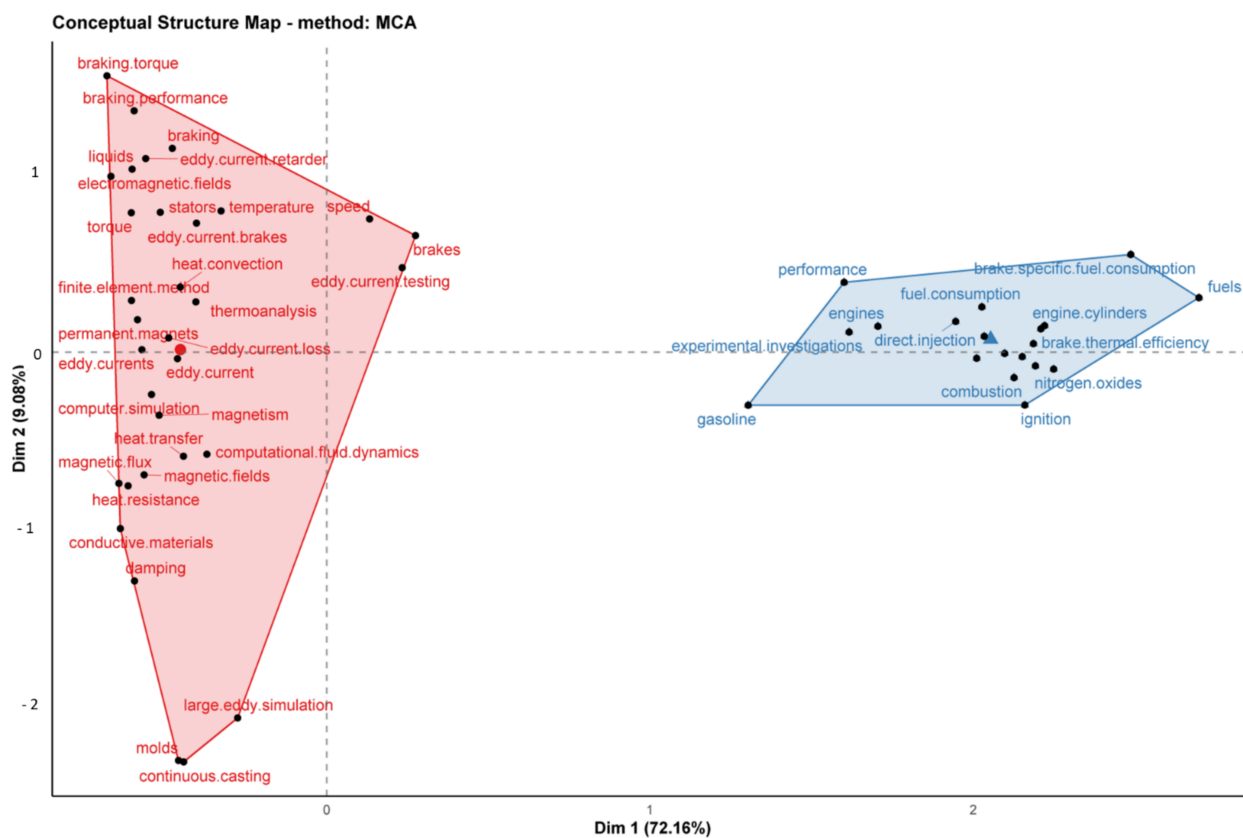


Figure 15. Conceptual structure map.

An exciting part of the discussion was the search for research gaps with bibliometric analysis. Of course, this is only a prediction, but based on the Scopus database, the percentage of words used as keywords by authors is known. In addition to the use of keywords, the evolution of themes that occur can also be displayed in this analysis so that this section can also be used as one of the solid reasons for estimating existing research gaps and possible popular themes in the future. However, there are still shortcomings in this bibliometric analysis, such as the discovery of the same two names with different numbers of documents, the discovery of the same affiliation, and data differences such as collaborations. These shortcomings reduce the percentage of research gap predictions in a field. These shortcomings can be minimized in various ways, such as pre-selection before the analysis. As is known through the data that have been processed, topics related to heat in eddy current brakes are still very little explored. Even topics that specifically discuss the generation and demonstration of heat phenomena in eddy current brakes have never been explored. Making this analysis is very useful in determining the research topics to be carried out. From the results obtained, further heat-generation and heat-release phenomena will be studied more deeply in subsequent research. In addition, other topics have not been discussed. It is an opportunity for readers who have a focus on the development of eddy current brake technology.

5. Conclusions and Further Studies

The purpose of this study is to provide an overview of the research conditions regarding the heat generation that occurs in the ECB. In addition, this study provides a new type of novelty that has not been presented previously, namely statistical analysis using bibliometric methods in the field of eddy current brakes for the phenomenon of heat generation. The analysis process has obtained several exciting results with the help of VOSviewer and Biblioshiny applications integrated by RStudio. The results of the analysis have also answered the questions about this article's problem and purpose. From the analysis that has been conducted, it can be concluded as follows:

1. The overall discussion in the Scopus database related to "eddy current" alone obtained more than 40,000 documents. However, by narrowing the data in accordance with the temporary conjecture as written in this article, only 200 data were obtained. It shows that there are still many opportunities to discuss eddy current brake heat generation. Of course, it is very reasonable, considering that heat is generated in the braking process both with friction and with eddy current brakes.
2. Of all the documents obtained and analyzed, it is shown that the use of the keyword "heat transfer" only appears as much as 1%, while the use of the phrases "heat generation" and "heat generated" is still not found. Accordingly, discussions related to the theme of heat generation are still very good for eddy current brake research. There are other possible discussions for this field, such as discussions of magnetic parts, cooling, and computational fluid dynamics. It is thus expected that the author will next conduct research into the phenomena of heat generation and heat release that occur during the braking process of eddy current brakes.
3. The total number of researchers who have conducted research in the field of eddy current brakes in the discussion of heat generation is 533 authors with a total of 207 documents. These documents are 151 types of articles and 56 types of conferences.
4. Collaboration in this field is quite good with a collaboration index of 2.72. However, in the documents recorded in the Scopus database, the number of publications is still dominated by China for both single and multiple countries.
5. From a total of 531 author's keywords and 1716 plus keywords in this field, the words "heat generation", "heat phenomenon", or "heat" are only 1%.

The author knows that it is an opportunity that can contribute to the results of the bibliometric analysis that has been carried out. The findings of this study indicate that the hot research that has arisen in the ECB is an interesting discussion that is starting to be investigated. It is caused by the many phenomena that need to be overcome due to heat generation, such as changes in performance or decreases in the life of the ECB. In

addition, techno-economy analysis has not yet been discussed, where the age of use and the required investment will be interesting topics to study in the main context. Advances in heat-treatment technology on the ECB are ongoing, and soon, more technologies will be available in the future.

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