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Contact

SUBU Denizcilik MYO, Alandere Mahallesi Karadeniz Sahil Yolu Caddesi No:213/1, Sakarya, Türkiye

Tel: +90 264 616 17 02 Web: dergipark.org.tr/tr/pub/joinmet E-mail: joinmet@subu.edu.tr

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Trends and Emerging Themes in Thermal Energy Storage: A Bibliometric Study

Malik Karadag[1], Idris Tan Akçay[2], Asim Sinan Karakurt[3*]

[1] Naval Architecture and Marine Engineering Department, Yildiz Technical University, malik.karadag@std.yildiz.edu.tr
[2] Naval Architecture and Marine Engineering Department, Yildiz Technical University, tan.akcay@std.yildiz.edu.tr
[3] Naval Architecture and Marine Engineering Department, Yildiz Technical University, asinan@yildiz.edu.tr

ABSTRACT

Thermal energy storage (TES) systems play a pivotal role in the efficient integration of renewable energy sources into the global energy landscape. This bibliometric analysis delves into the evolving research landscape of TES systems, focusing on nearly 19000 scientific papers from the Scopus database as the primary source to identify key research trends, influential authors, and leading institutions shaping the field between 2000 and 2023. The analysis reveals a substantial surge in TES research over the past two decades due to factors such as advancing technology and increasing incentives. China has emerged as a global leader in this domain, followed closely by the United States and India. Xi'an Jiaotong University, De Lleida University, and Tsinghua University are the most prolific institutions in this field. The Journal of Energy Storage is the most frequently paper-published, followed by Applied Thermal Engineering and Applied Energy. Key research themes identified include the development, design, and optimization of heat storage systems, TES system integration with renewable energy sources, and the exploration of phase change materials for efficient energy storage. The analysis also highlights the contributions of prominent researchers in the field. Cabeza LF, Li Y, and Wang Y are identified as the most prolific authors, having made significant contributions to the advancement of TES technology. The increasing demand for sustainable and efficient energy solutions has spurred significant interest in TES systems. As the world transitions towards a low-carbon future, TES systems offer a promising solution for storing excess renewable energy and ensuring a reliable and sustainable energy supply.

Keywords: Bibliometric analyses, scopus, thermal energy storage

[3*] Corresponding Author's email: asinan@yildiz.edu.tr

Termal Enerji Depolamada Trendler ve Temalar: Bibliyometrik Bir Çalışma

ÖZ

Termal enerji depolama (TES) sistemleri, yenilenebilir enerji kaynaklarının küresel enerji sistemine verimli bir şekilde entegre edilmesinde önemli bir rol oynamaktadır. Bu bibliyometrik analiz, 2000 ile 2023 yılları arasında TES sistemleri üzerine şekillenen araştırma eğilimlerini, etkili yazarları ve alandaki önde gelen kurumları belirlemek amacıyla Scopus veri tabanındaki yaklaşık 19.000 bilimsel makaleyi incelemektedir. Analiz, son yirmi yılda gelişen teknoloji ve artan teşvikler gibi nedenlerden dolayı TES araştırmalarında önemli bir artış olduğunu ortaya koymaktadır. Bu alanda, Çin küresel bir lider olarak öne çıkarken, onu Amerika Birleşik Devletleri ve Hindistan takip etmektedir. Xi'an Jiaotong Üniversitesi, De Lleida Üniversitesi ve Tsinghua Üniversitesi, bu alandaki en üretken kurumlar olarak öne çıkmaktadır. Journal of Energy Storage, bu konuda en fazla makalenin yayımlandığı dergi olurken, onu Applied Thermal Engineering ve Applied Energy dergileri takip etmektedir. Ana araştırma temaları arasında ısı depolama sistemlerinin geliştirilmesi, tasarımı ve optimizasyonu; TES sistemlerinin yenilenebilir enerji kaynaklarıyla entegrasyonu; ve verimli enerji depolaması için faz değişim malzemelerinin araştırılması yer almaktadır. Analiz ayrıca, alandaki önde gelen araştırmacıların katkılarını da vurgulamaktadır. Cabeza LF, Li Y ve Wang Y, TES teknolojisinin ilerlemesine önemli katkılar sağlayan en üretken yazarlar olarak öne çıkmaktadır. Sürdürülebilir ve verimli enerji çözümlerine olan artan talep, TES sistemlerine olan ilgiyi önemli ölçüde artırmıştır. Dünya düşük karbonlu bir geleceğe doğru ilerlerken, TES sistemleri, fazla yenilenebilir enerjinin depolanması ve güvenilir, sürdürülebilir bir enerji arzının sağlanması için umut verici bir çözüm sunmaktadır.

Anahtar Kelimeler: Bibliyometrik analiz, scopus, termal enerji depolama

1 Introduction

Due to developing technology and increasing needs, we are becoming increasingly dependent on energy today. A large portion of the energy used, although it varies by geography, is obtained from fossil-based energy sources. Due to the decrease in known fossil resources and environmental restrictions, not every energy source can be used everywhere. In addition, energy supply is a major problem in places that are out of the grid or have no access to the grid. One of the solutions offered to such problems is energy storage systems. The operating logic of energy storage systems is to store the production difference in cases where excess energy emerges or when operating at lower loads than efficient working conditions and then use it where or when it is needed. Thus, it is possible to provide reliable and sustainable energy. In this context, energy can be stored as mechanical, chemical, electrical, electrochemical and thermal energy. The energy stored with these methods can be used as electricity or heat when needed (Dincer & Ezan, 2022).

Sensible, latent, and thermochemical systems are the commonly used mainly Thermal energy storage (TES) systems whose selection depends on some variables such as using period, storage period, and economics (Dincer, 2002). Peak load shifting, increased energy economy, integrating renewable energy sources, increased system reliability, and less environmental impact are just a few of the many benefits that TES provides. From an economic perspective, TES systems have a great deal of promise for increasing the effectiveness of thermal energy equipment and facilitating widespread energy substitution (Dincer & Ezan, 2018). The validity of thermodynamic principles, the importance of temperature differences, the relationship between heat and work, cyclic processes, and principles such as conservation of energy form the basis of thermal energy conversion and are important for understanding how systems work. These principles can be applied in many areas from machine design to energy efficiency evaluation. Thermal energy conversion is the process of converting naturally occurring energy flows into usable forms based on temperature differences. This process usually occurs via a heat engine and involves doing work by directing heat flows originating from temperature gradients (Dincer & Rosen, 2021).

There have been many studies in different fields using the bibliometric analysis method. A general literature summary is given below to show both the different areas of use of bibliometric analysis and especially the studies related to energy storage systems. As mentioned above, analyses related to almost every academic field with data can be made with the bibliometric analysis method. For example, using Scopus data, the changes in the subject headings of the articles in the database over the years were examined (Al-Khoury et al., 2022), the studies published in the field of maritime English in a 40-year period were examined (Li et al., 2023), the studies related to both the physical and mental health of seafarers were examined (Masalacı, 2024), the studies related to Workloads in the Maritime Sector were examined (Arslan & Paker, 2023), the studies in the Scopus database related to steam turbines, which have an important place in energy production, were examined (Karakurt et al., 2022), the data of the 100 most cited studies in the field of hydrogen energy worldwide were examined (Bashan & Ust, 2022), the research conducted by researchers in this field in the 30-year period from 1992 to 2022 related to hydrogen energy and storage. There are studies examining the contributions of the authors, institutions and countries worldwide in the field of ocean engineering between 1989 and 2021 (Gunes, 2021). In addition to these, there are studies examining the studies on the intelligent control of TES systems (Tarragona et al., 2020), examining the studies conducted with latent TES between 2000-2019 (Mustapha et al., 2021), examining the studies conducted on sand-based TES systems (Odoi-Yorke et al., 2024), and examining the studies conducted on TES systems proposed for Renewable energy communities (Brunelli et al., 2024). However , what is shared here is a very small part in terms of both scope and quantity. In this study, the studies conducted between 2000-2023 related to TES systems in general will be examined and a projection will be provided regarding the development of the process and its future course.

2 Modeling

Bibliometric analyses are statistical tools that provide information about the course of academic studies prepared on a subject, in a publication or in a publication type (Donthu et al., 2021). In the light of this information, it is possible to access information such as which individuals, institutions and countries stand out, which terms and subject headings are used over the years, and which publications are more effective.

In this study, statistical data belonging to nearly 19000 articles for the "Thermal Energy Storage" subject title in the Scopus database (Scopus, 2024) related to TES systems between the years 2000-2023 were processed using Bibliometrix and MS Excel programs and the results were shared. Since bibliometric analyses are qualitative research tools, no clear mathematical model exists. Instead, the processing steps of data obtained from the database are generally shared, as in the example of Bibliometrix an R tool for science mapping (Aria & Cuccurullo, 2017). Three main steps (data collection, data analysis, and data visualization) in the system are shown in Figure 1.

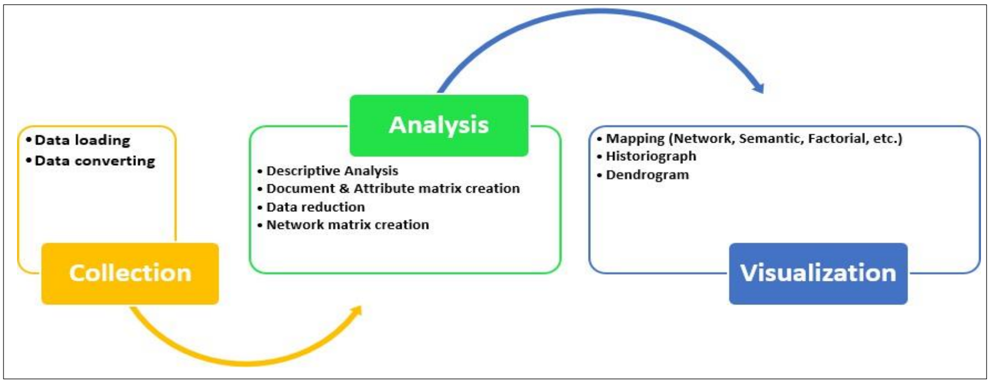

Figure 1: Data processes in the Bibliometrix (Aria & Cuccurullo, 2017)

3 Analysis and Evaluation

According to Scopus data, graphs related to the distribution of studies according to their types, subjects, keywords used in the studies, countries, institutions and journals, and the number of studies and citations were shared. In the biometric analysis, the TES part covers the years 2000-2023, and the number of data obtained without specifying the type of study was determined as 18322. Then, without any restriction in terms of the type of study examined, the number of studies to be investigated was calculated as stated by only restricting the year, and the types of these studies are indicated as percentages in Figure 2. 70% of the studies written are articles, and this number is determined as 12788 in total. The number of conference papers, which constitute 20% of the studies, is determined as 3704.

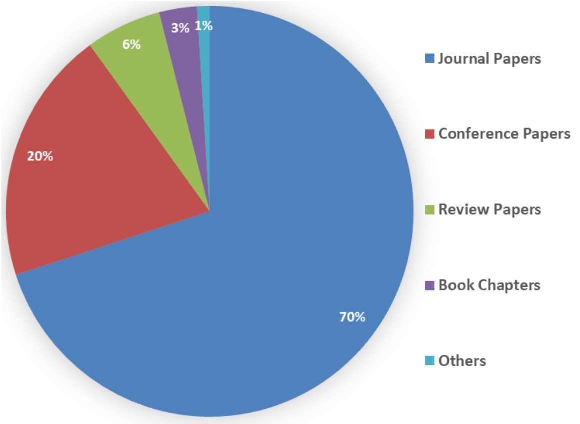

Figure 2: Types of publications on TES systems between 2000-2023.

Figure 3 displays the statistics when the data is assessed in terms of subjects. With almost half of the papers, energy and engineering are the most prevalent fields, suggesting that thermal energy storage technology application is a major area of interest. A sizeable portion (10%) goes to materials science, which highlights the significance of creating new materials for effective thermal energy storage. Together, chemical engineering, chemistry, and physics make up 20%, emphasizing the importance of basic knowledge in improving thermal energy storage systems. 10% comes from the environmental and earth sciences, most likely as a result of research into sustainable energy storage methods and natural materials. The remaining 8% is made up of math, computer science, and other subjects, indicating areas for more multidisciplinary study in thermal energy storage.

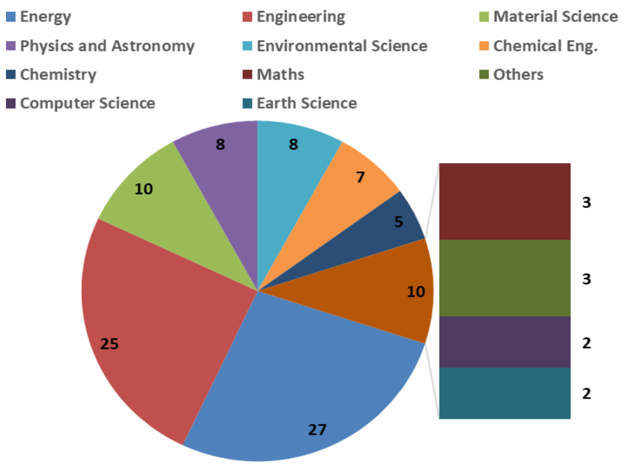

Figure 3: Distribution of studies on TES systems by area between 2000-2023.

Figure 4 shows the citation numbers of the 10 countries with the highest number of citations. As a result of the research on TES, the citations created were created by many countries and China came first with 125834 citations. China took its place at the top of the list with a clear difference compared to the other countries on the list and due to its high population density. China is followed by the United States with 37872 citations. With these values, it can be said that they have a level of citation numbers that can be considered proportional to their population. However, Spain is in third place on the list with a high rate of 29772 articles. In addition to these countries, Turkey is at a very good level in terms of the number of citations compared to its population values; the total number of citations was calculated as 20210 in total for the years 2000-2023 and is in 6th place in the list.

Figure 4 also shows the number of studies written by 10 countries on TES between 2000-2023. The country that has written the most studies on this subject is China with 5075. China is followed by the United States with 2355 studies and India with 1771 studies. Turkey ranks 10th in the ranking with 659 studies.

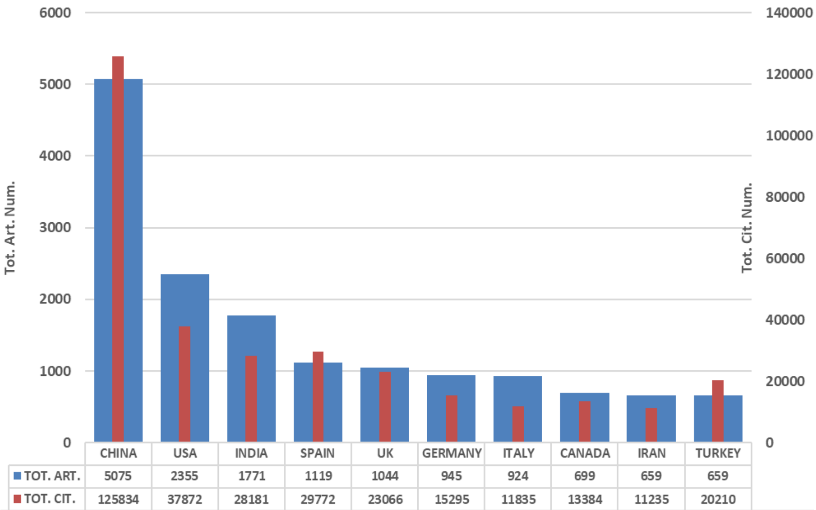

Figure 4: Number of articles and citations written in the field of TES systems by country.

The number of studies written by scientists conducting research on TES systems are given in Figure 5. In this table, the expression indicated by SCP shows the number of studies written by scientists of the country as singular without scientists from other countries, while the expression MCP shows the number of studies written by scientists of the specified country together with scientists from other countries. China ranks first and there are 3742 studies in this ranking. 3069 of these are singular and 673 are multiple studies. Here, the MCP rate, that is, the ratio of studies written multiple to the total studies written on behalf of the country, is calculated as 17.99%.

According to the values understood from here, countries other than China have written a total of 3266 studies and this can be easily understood from the graph. India follows China which consists of 956 studies written singularly and 163 studies written multiple . Here, the MCP rate is calculated as 14.57%. The United States is ranked third with 861 single studies and 170 multiple studies written, the MCP rate was calculated as 16.49%. Turkey ranked 8th in the ranking. With 310 single studies and 103 multiple studies written, it has a 24.94% MCP rate.

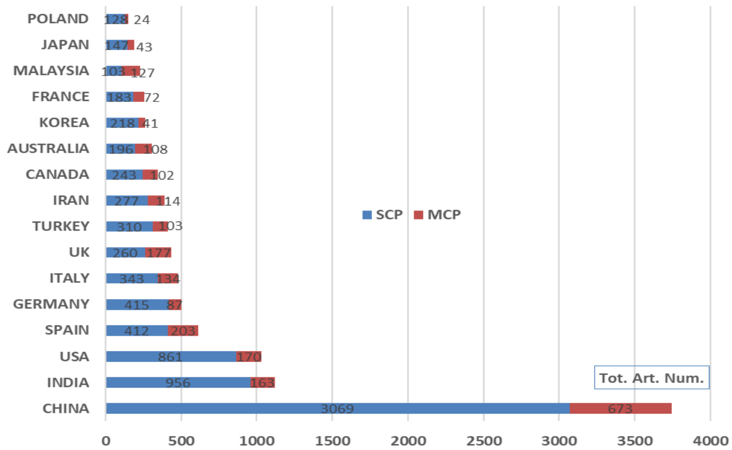

Figure 5: Number of single and multiple articles written by countries on TES systems.

The study numbers of the top 5 countries with the most studies on TES systems are given in Figure 6, depending on the annual increase rate. It can be figured out the exponential characteristics of curves very clearly, especially the last ten years. The general pattern is encouraging for all countries, suggesting that interest in thermal energy storage research is rising internationally. The growing need for effective and sustainable energy solutions is probably what's causing this.

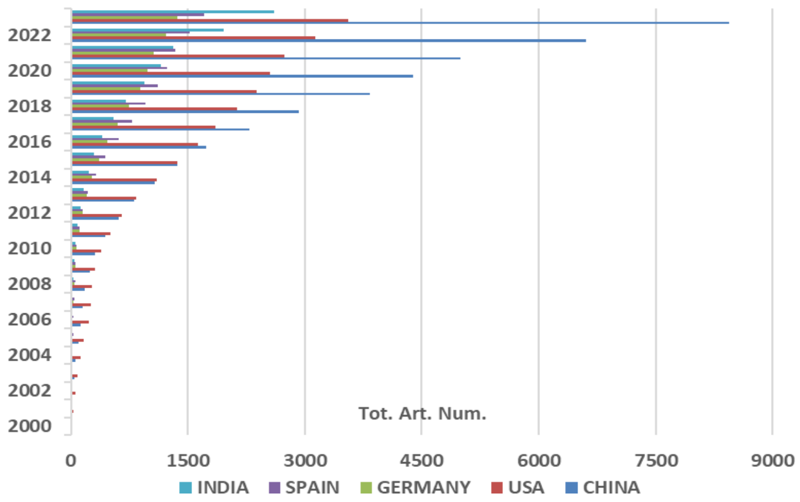

Figure 6: Annual study numbers of the top 5 countries with the most studies on TES systems.

Figure 7 visually represents the global landscape of research activity in TES systems. The color intensity of each country reflects the level of research output, with darker shades indicating higher activity. China stands out as a clear leader in TES research. Its dark blue color highlights its significant contribution to the field. This is likely due to China's strong focus on renewable energy integration and its large-scale energy infrastructure projects. The United States shows substantial research activity, particularly in areas like solar thermal energy storage and building-integrated TES systems. Several European countries have active research communities in TES. India and South Korea also exhibit significant research efforts, driven by their growing energy demands and renewable energy initiatives.

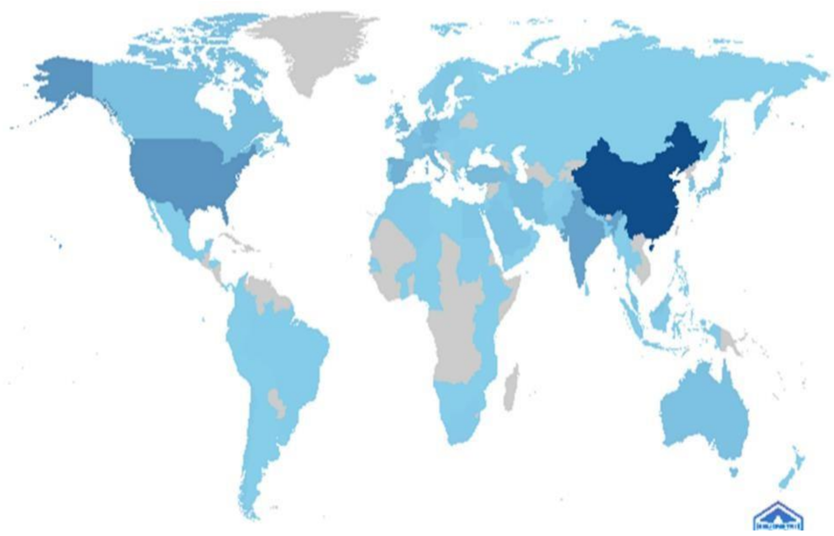

Figure 7: Geographic distribution of research on TES systems.

In the evaluation of TES analysis as an author are shown in Figure 8 as shown. Cabeza LF ranks first with 307 studies. Cabela LF is followed by Li Y with 275 studies in the second place. Wang Y is in the third place with 263 studies. The H index is based on the most cited articles of a scientist and the number of citations received in other publications. According to the table given in the studies written about TES, Cabeza LF has the highest H index of 70. Another person with a high H index on this subject, Sarı A, has an index of 59.

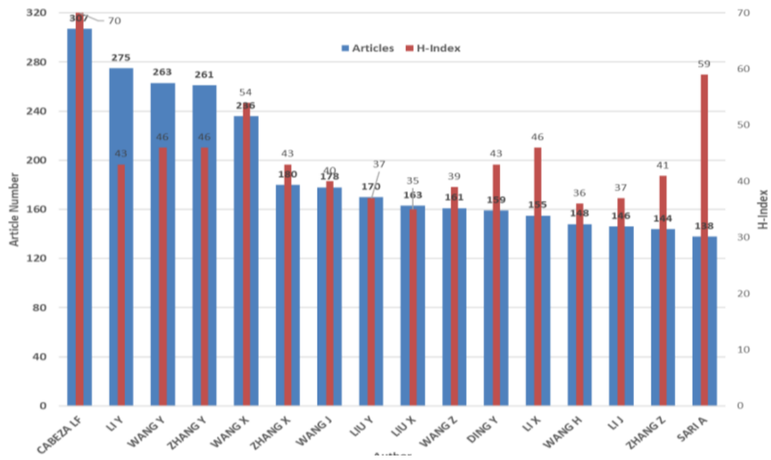

Figure 8: Number of authors' studies on TES systems.

Authors who created studies on TES generally started to create products after 2014. Cabeza LF, who created the most studies, created the most studies in 2016. Cabeza LF created 40 studies in 2016. Li Y, who is second in the number of studies, created an average of 20 studies every year between 2016 and 2020. Li Y, on the other hand, increased the number of articles he wrote after 2020. These values are as shown in Figure 9 .

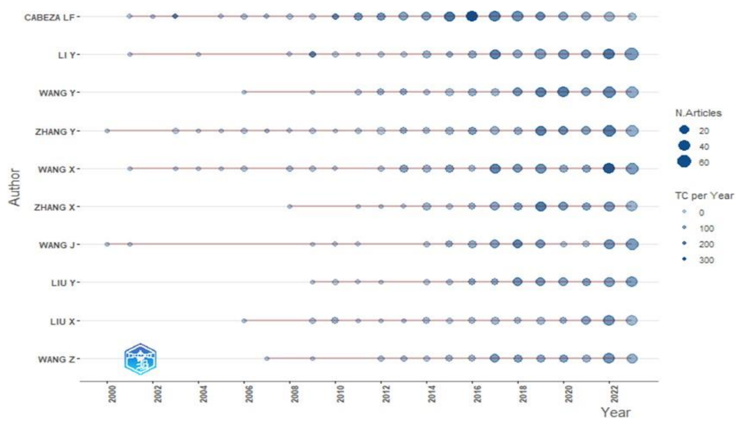

Figure 9: Number of studies conducted by authors on TES systems over the years.

After classifying the citation numbers on a country basis, the classification on an academic basis was also examined. Here, Sharma A. is in the first place with 4432 citations, followed by Zalba B. with 3913 citations. Chen C. is in the third place with 2842 citations. The graph showing the first 10 people on this list is shown in Figure 10.

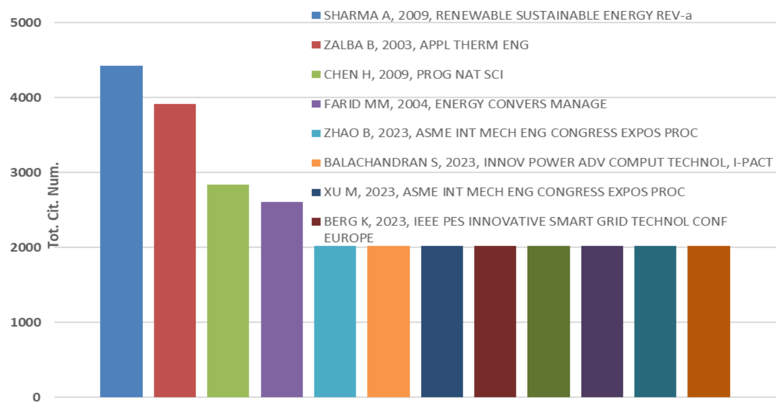

Figure 10: Analysis of the references written on TES systems by authors.

In addition to the extensive research conducted by certain universities on TES, many universities have begun to conduct extensive research on systems that can store energy in the future. Research on TES was first started in 1964, but the first article written on this subject was published by Tsinghua University in 1999. Figure 11 shows the number of studies by year for the top 5 universities that have conducted the most research and have the most studies. The university that conducts the most research is Xi'an Jiaotong University. This university, which has a total of 315 studies, is located in China. Then comes De Lleida University which took the second place on the list with 267 studies. Tsinghua University is in the third place on the list. It managed to write its name on the list of universities that are quite ambitious in this regard with 243 studies written. In Figure 11, the number of articles for a total of 10 universities is compared and given in a graphic form. In Turkey, as mentioned, Karadeniz Technical University is the university that has written the most articles on this subject. The number of studies is 112 and it has taken the 17th place in the world in terms of research conducted on this subject.

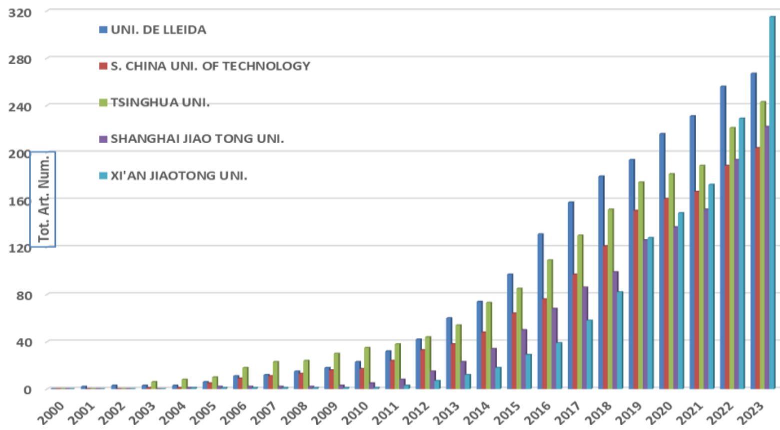

Figure 11: Analysis of universities publishing articles on TES systems by year.

Figure 12 shows the number of studies written on certain topics. In the table given for the TES section, there has been an increase in creating studies on solar energy materials and solar batteries, especially after 2012. 632 studies were written about energy storage, especially in 2022. When we look at the table given, the study creation situation has increased in the topics taken as basis after 2012.

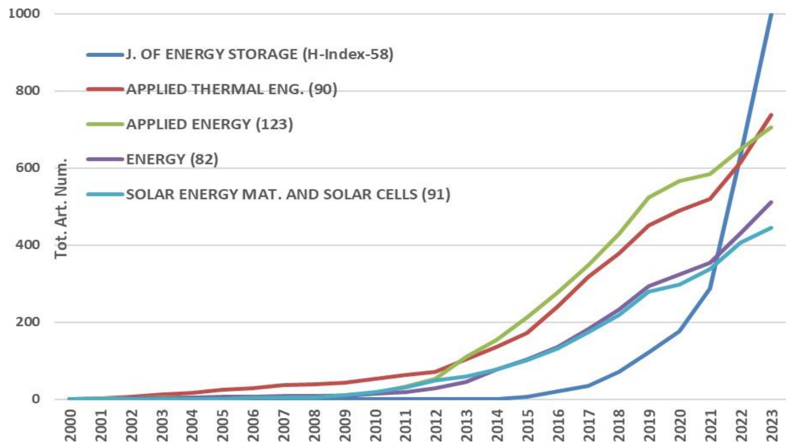

Figure 12: Number of studies on TES systems by specific topics.

Figure 13 shows a map of words used together in articles. Heat storage, thermal energy and phase change materials are the most commonly used word groups together. Since the words used in the research on TES do not differ much in general, this event gave us the need to make a graph and subsequently, these words were included in the literature in this way. The concept of "Heat Storage" took its place at the top of the list and when the change in the frequency of the word used over the years was examined, it was used 13268 times (15%) in 2023 alone and took its place at the top of the list. Following this group of words, the concept of "Thermal Energy", which was written 8607 times (10%), is in second place on the list, followed by the concept of “Phase Change Materials”, which is used 6938 times (8%), in third place. These words are only in the first three places of the list, and are used with increasing numbers every year, without exception.

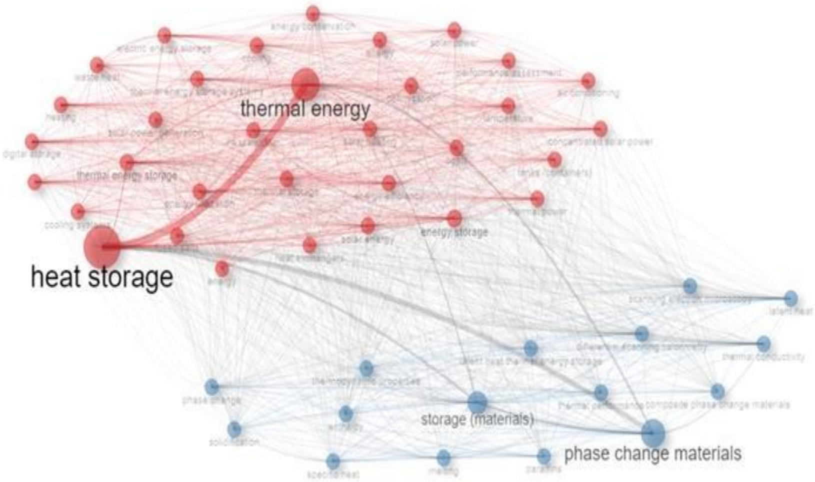

Figure 13: Words used together in the article type written for TES systems.

4 Conclusions

This bibliometric analysis provides a comprehensive overview of the research landscape of Thermal Energy Storage (TES) systems over the past two decades with using almost 19000 studies. The increasing global demand for sustainable and efficient energy solutions has driven significant growth in TES research. The escalating demand for renewable energy sources and efficient energy storage solutions, coupled with advancements in materials science enabling the development of advanced thermal energy storage technologies, has spurred significant growth in research and development activities in this field. Consequently, a notable increase in both the quantity and quality of publications in recent years has been observed. A notable surge in TES research, particularly in thermal energy storage and phase change materials, has been observed. China has emerged as a leading nation in TES research, followed by the United States and India. Xi'an Jiaotong University, De Lleida University, and Tsinghua University are the most popular three centers in terms of the number of publicaitons. The Journal of Energy Storage is the most-published journal, which has been aggressively increasing in the last 5 years, and then Applied Thermal Engineering and Applied Energy journals have come. In order to develop thermal energy storage solutions, engineers, materials scientists, chemists, physicists, environmental scientists, and computer scientists must work together, as evidenced by the wide range of disciplines involved. By understanding the current state-of-the-art and future trends in TES research, researchers and policymakers can make informed decisions to accelerate the deployment of TES technologies and contribute to a more sustainable energy future.

5 Declarations

5.1 Competing Interests

All authors of the manuscript have no conflict of interest to declare.

5.2 Authors’ Contributions

Malik KARADAG: Contributed to the literature summary creation, model design, analysis and interpretation.

Idris Tan AKCAY: Contributed to the literature summary creation, model design, analysis and interpretation.

Asım Sinan KARAKURT: Contributed to the topic proposal, consultancy, literature summary creation, model design, analysis and interpretation.

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Research Article

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Investigation of the Effects of Design Parameters on Tooth Profile Formation and Operating Performance in Cycloidal Reducers

Furkan KORKMAZ[1*], Ahmet KOLİP[2]

[1] Sakarya University of Applied Sciences, Sakarya Vocational School, Electronic and Automation Department, Sakarya, Türkiye, fkorkmaz@subu.edu.tr

[2] Sakarya University of Applied Sciences, Faculty of Technology, Mechanical Engineering Department, Sakarya, Türkiye, akolip@subu.edu.tr

ABSTRACT

Cycloidal reducers have a unique and complex tooth profile design compared to conventional gear systems. Unlike standardized gear profiles, cycloidal reducers provide significant flexibility in design parameters such as module, profile modification coefficient, and eccentricity. However, these parameters interact in a complex manner, affecting both tooth profile formation and the overall performance of the reducer. Inaccuracies in selecting parameters may lead to problems such as excessive contact stress, gear deformation or reduced load transfer efficiency. This study aims to investigate the effects of design parameters on the formation of cycloidal tooth profiles and the operating performance of reducers. By analyzing the relationships and interactions between these parameters, the research provides a deeper understanding that will improve design processes, enhance performance, and contribute to future standardization efforts. The analysis results show that increasing the eccentricity (e) from 1.0 to 1.7 improves transmission efficiency by approximately 0.20% and contact efficiency by up to 8.00%. Conversely, an increase in the reference circle diameter (R_z) leads to a reduction in both transmission and contact efficiencies by approximately 0.2%, highlighting the critical impact of this parameter on performance optimization. In conclusion, eccentricity is identified as the design parameter with the highest impact on efficiency, emphasizing its critical importance in the design process.

Keywords: Cycloidal reducer, design parameters, cycloidal profile, efficiency.

[1*] Corresponding Author's email: fkorkmaz@subu.edu.tr

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Sikloid Redüktörlerde Tasarım Parametrelerinin Diş Profili Oluşumu ve Çalışma Performansı Üzerindeki Etkilerinin İncelenmesi

ÖZET

Sikloid redüktörler, geleneksel dişli sistemlerine kıyasla benzersiz ve karmaşık bir diş profili tasarımına sahiptir. Standartlaştırılmış diş profillerinin aksine, sikloid redüktörler modül, profil modifikasyon katsayısı ve eksantriklik gibi tasarım parametrelerinde önemli bir esneklik sunar. Ancak, bu parametreler karmaşık bir şekilde etkileşime girerek hem diş profili oluşumunu hem de redüktörün genel performansını etkiler. Yanlış parametre seçimi, aşırı temas gerilmesi, dişli deformasyonu veya azalmış yük aktarım verimliliği gibi sorunlara yol açabilir. Bu çalışma, tasarım parametrelerinin sikloid diş profillerinin oluşumu ve redüktörlerin çalışma performansı üzerindeki etkilerini incelemeyi amaçlamaktadır. Bu parametreler arasındaki ilişkiler ve etkileşimler analiz edilerek, tasarım süreçlerini iyileştirecek, performansı artıracak ve gelecekteki standardizasyon çabalarına katkıda bulunacak daha derin bir anlayış sunulmaktadır. Analiz sonuçları, eksantriklik (e) değerinin 1.0'dan 1.7'ye artırılmasının iletim verimliliğini yaklaşık %0.20, temas verimliliğini ise %8.00'e kadar artırdığını göstermektedir. Buna karşın, referans çember çapındaki (R_z) artış, hem iletim hem de temas verimliliğinde yaklaşık %0.2 oranında düşüşe neden olmakta ve bu parametrenin performans optimizasyonundaki kritik etkisini vurgulamaktadır. Sonuç olarak, tasarım parametrelerinden verime en büyük etkisi olan parametrenin eksantriklik değeri olduğu ve tasarım sürecinde kritik bir öneme sahip olduğu belirlenmiştir.

Anahtar Kelimeler: Sikloid redüktör, tasarım parametreleri, sikloid profil, verimlilik.

1 Introduction

Cycloidal reducers have garnered significant attention in the industry due to their unique operating principles and numerous advantages, including high reduction ratios, compact size, and outstanding efficiency. They are extensively used in industries requiring high transmission ratios, such as wind turbines, as well as in compact and precision-demanding applications like robotics and heavy machinery. Unlike traditional gear systems, which rely on standardized profiles defined by basic design parameters such as module and number of teeth, cycloidal reducers exhibit a more flexible and complex design structure. While this flexibility benefits performance optimization, it also introduces challenges in achieving standardization and robust design methodologies.

The performance and durability of cycloidal reducers depend significantly on the design of the cycloidal tooth profile. Critical design parameters such as module, profile modification coefficient, and eccentricity interact in a complex manner, influencing key factors such as contact stress distribution, load transfer efficiency, and overall operational reliability. Improper selection of these parameters can result in critical issues such as gear deformation, excessive wear on contact surfaces, and reduced transmission efficiency. Consequently, a comprehensive understanding of the relationships among these design parameters and their effects on both tooth profile formation and operational performance is crucial.

Previous studies have emphasized the importance of precise design and optimization of cycloidal reducers. For instance, the geometry and dynamic behavior of modified cycloidal reducers with epitrochoidal tooth profiles have been analyzed to improve manufacturability and performance, with specific focus on the influence of the tooth thickness ratio and raceway parameters on efficiency and stiffness (Li et al., 2020). Other studies have investigated the effects of manufacturing deviations and elastic deformations on load distribution in mismatched cycloid-pin gear pairs, offering insights into contact stress and transmission error characteristics (Li et al., 2022). Additionally, research has explored the wear mechanisms of cycloidal drives by examining changes in tooth profiles and operational parameters to enhance durability and reliability (Xu, 2019). Structural parameter studies have also shown significant improvements in transmission efficiency and contact stress distribution through the application of multi-objective optimization techniques (Huang, 2020).

Despite these advances, a comprehensive analysis of the interplay between design parameters and their impact on both tooth profile formation and operational performance of cycloidal reducers remains limited. Existing studies often focus on specific aspects, such as wear mechanisms or load distribution, without integrating these findings into a holistic framework. This gap underscores the need for more systematic research.

In the context of cycloidal reducers, parameters such as module, profile modification coefficient, and eccentricity should be studied not only individually but also in terms of their interactions. For example, eccentricity directly influences the gear contact ratio, altering the dynamic load distribution, while the module determines gear dimensions, thereby affecting load-carrying capacity and contact stiffness (Tsai et al., 2017). Furthermore, profile modification enables the optimization of critical performance factors such as surface wear and vibration (Li et al., 2018).

Studies on cycloidal reducer profiles have particularly focused on minimizing backlash, a critical criterion in precision reducers. To this end, various mathematical models have been developed to address potential errors arising from modification values and manufacturing methods. Alipiev (1988) provided a mathematical model explaining the effects of module and modification values on cycloidal disk geometry and analyzed the relationships among these parameters in detail. Uzun (2019) extended Alipiev's model, analyzing the impact of the Profile Correction Factor on load distribution, determining that its effects on force distribution were non-linear, with an optimal distribution observed at a value of 0.8.

The inability to standardize parameters such as module, modification values, modification coefficient, and profile correction factor in cycloidal disk profile generation allows for design flexibility but complicates profile determination. Mathematical models leveraging transformations in Cartesian coordinate systems have facilitated the definition of these parameters. These models consider factors such as pin radius, the radius of the reference circle where pins are located, the number of pins, and eccentricity. Modification operations are generally conducted by altering either the pin radius or the radius of the reference circle (Li et al., 2020; Lin et al., 2014; Ren et al., 2017; Xu et al., 2019; Yan & Lai, 2002).

Given the critical sensitivity of design parameters, optimization algorithms have been employed to address these challenges. For instance, Korkmaz et al. (2024) optimized profile parameters within specified boundary conditions, while Que et al. (2023) aimed to enhance efficiency through optimization processes, enabling informed decision-making regarding design parameters (Korkmaz et al., 2024; Que et al., 2023). Hu et al. (2020) proposed a method termed "elastic error compensation," designed to reduce sensitivity to potential gaps in the system, reporting significant improvements in contact performance through profile modifications.

This study aims to investigate the effects of critical design parameters on the tooth profile formation and operating performance of cycloidal reducers. By analyzing the complex interactions among these parameters, the research seeks to provide valuable insights for optimizing design processes and improving performance. Additionally, the findings are expected to contribute to efforts to standardize cycloidal reducer designs, ensuring their applicability and reliability across diverse engineering applications.

2 Design Parameters in Cycloid Reducers

There are two different methods used for the design of cycloidal reducers. The first method involves the profile design based on the module and profile modification coefficient. The second method focuses on the disk profile derived by tracing the contact points between the disk and the pins. To examine the effects of design parameters on the profile, it is necessary to evaluate these two methods separately. In the evaluation of the methods, the commonly accepted configuration in studies has been adopted, where the number of lobes in the disk (z_1) is 39, and the pin count (z_2) is 40.

Figure 1 shows the conceptual cycloid disk design that will form the basis of the study (Korkmaz, 2024). The distribution of pins around the disk is also defined.

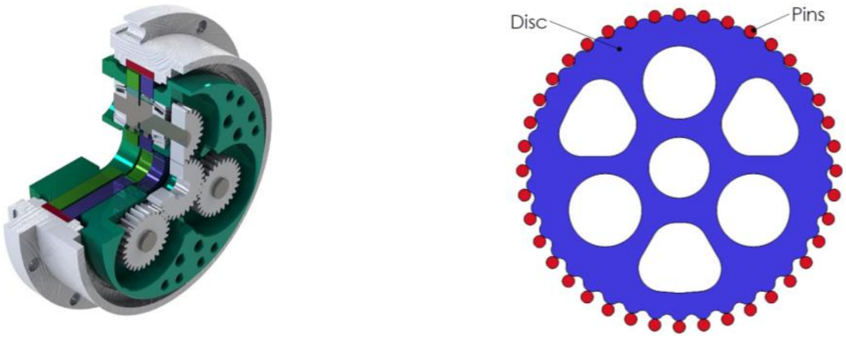


Figure 1: Design of the cycloidal reducer disc and pins

2.1 Parameters of Profile Equations Based on Module and Modification Coefficient

In this method, the cycloidal profile is determined by interrelated parameters: module (m), modification coefficient (x), and profile smoothing factor (r_c^*). The method is based on modeling the cycloidal profile formed by the rolling motion of a circle with a radius of (radius of r_c) on a reference circle without slipping (Alipiev, 1988). The value of is calculated as shown in Equation (1) by multiplying the radius correction coefficient (r_c*) of the profile-generating circle with the module value (Korkmaz, 2024):

$$r_c = r_c^* \times m \tag{1}$$

The r_c^* value is taken as 1 in the definitions found in the literature (Alipiev, 1988a).

Another design parameter, the eccentricity (e) is equal to half of the module value (Alipiev, 1998a).

$$e = m/2 \tag{2}$$

The dimensions of the cycloidal gear and the form of the cycloidal profile are determined based on the parameters provided in Equation (3):

$$\begin{cases} x = \frac{m}{2}\left[(z_1+1)\sin(t) - (1-x)\sin((z_1+1)t) + \frac{2r_c^*[(1-x)\sin((z_1+1)t) - \sin(t)]}{\sqrt{1-2(1-x)\cos(z_1 t)+(1-x)^2}}\right] \\ y = \frac{m}{2}\left[(z_1+1)\cos(t) - (1-x)\cos((z_1+1)t) + \frac{2r_c^*[(1-x)\cos((z_1+1)t) - \cos(t)]}{\sqrt{1-2(1-x)\cos(z_1 t)+(1-x)^2}}\right] \end{cases} \tag{3}$$

2.2 Parameters of Profile Equations Based on the Contact Point Between the Disk and Pins

In this method, the mathematical expression of the path resulting from the relative displacement at the contact point between the pin and the cycloidal profile is utilized. Both the number of parameters and their interrelation are fewer compared to the method based on the modification coefficient. The equation used for this method is provided in Equation (4) (Korkmaz, 2024).

$$R_p(\theta_1) = \begin{bmatrix} r_z \frac{K_1}{\sqrt{1+K_1^2-2K_1\cos\theta_1}} \sin\theta_1 \\ R_z - r_z \frac{(1-K_1\cos\theta_1)}{\sqrt{1+K_1^2-2K_1\cos\theta_1}} \\ 0 \\ 1 \end{bmatrix} \tag{4}$$

Here, R_z represents the radius of the pin reference circle, r_z denotes the pin radius, and K_1 refers to the modification value. The modification value is calculated as shown in Equation (5):

$$K_1 = \frac{e \times z_2}{R_z} \tag{5}$$

As seen in Equations (2) and (3), the parameters in this method are, respectively, eccentricity (e), the radius of the pin reference circle (R_z), and the pin radius (r_z).

2.3 Effects of Parameters on Efficiency

In cycloidal reducers, efficiency calculations are defined based on the contact region between the disk and the pins, and they are directly influenced by design parameters. The transmission efficiency (η_x) defined for cycloidal reducers is provided in Equation (6):

$$\eta_x=1-[(R_z-\Delta R_z)-(r_z-\Delta r_z)]\frac{4\mu}{k1\times z_1\times(R_z-\Delta R_z)\pi} \tag{6}$$

In addition to the given design parameters, ΔR_z is used to account for potential deviations in the reference circle, and Δr_z represents elastic deformations in the pins. These factors are included in the calculations. Furthermore, the coefficient of friction (μ) has also been incorporated, which is assumed to be 0.075 due to the high lubrication level of the system (Gao et al., 2024).

Also, cycloidal reducers have contact efficiency. An increase in gear contact efficiency indicates reduced wear and clearance during engagement and the transmission of motion and power between the cycloidal profile and pins. Therefore, it is highly significant for performance. Contact efficiency is calculated using Equation (8):

$$\eta=\frac{\eta_x}{1+z_1(1-\eta_x)} \tag{7}$$

3 Results and Discussion

The effect of the profile modification coefficient on performance in the method based on the modification coefficient was evaluated by Uzun (Uzun, 2019). The study indicated that a decrease in the profile modification coefficient leads to a reduction in the reaction forces occurring in the disk, which in turn results in a decrease in efficiency. The profile changes resulting from the application of design parameters are illustrated in Figure 2.

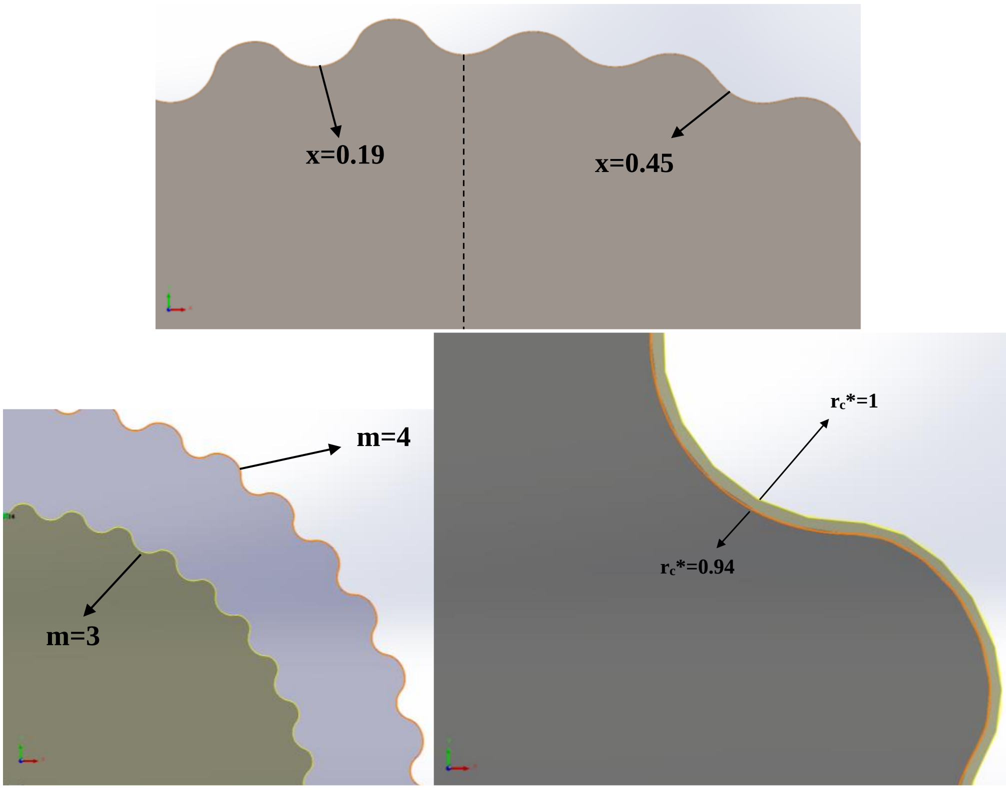
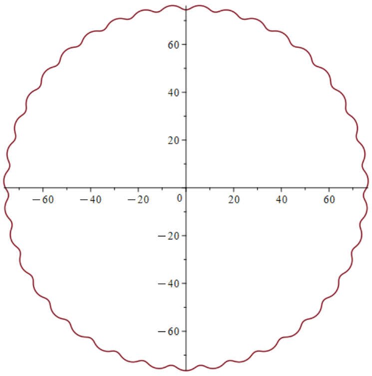


Figure 2: Effects of parameters on profile and disk dimensions in the first method

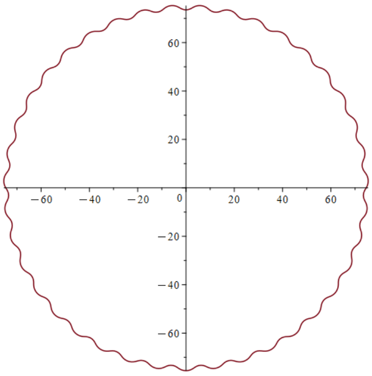
The effects of changes in eccentricity and pin radius on the disk profile in the second method are presented in Table 1. The table shows that variations in eccentricity significantly influence the disk height. On the other hand, changes in pin radius do not cause substantial alterations to the disk profile.

Table 1: Effects of parameters on profile and disk dimensions in the second method



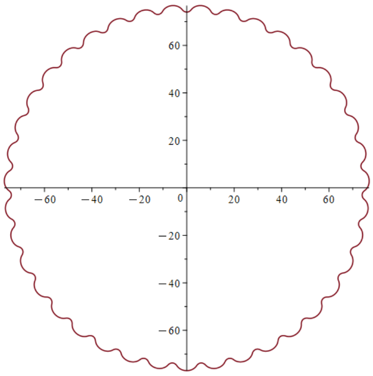
$e = 1; r_z = 2; R_z = 77.5$

A



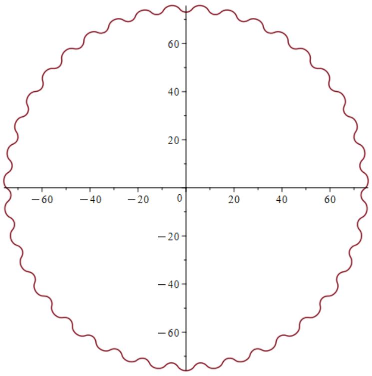
$e = 1; r_z = 3; R_z = 77.5$

B



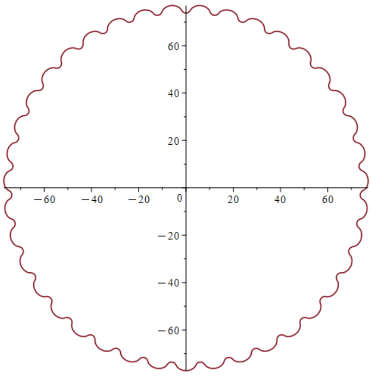
$e = 1.5; r_z = 2; R_z = 77.5$

C



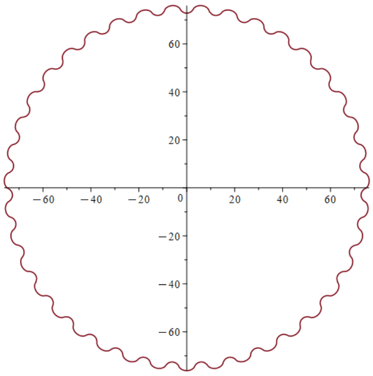
$e = 1.5; r_z = 3; R_z = 77.5$

D



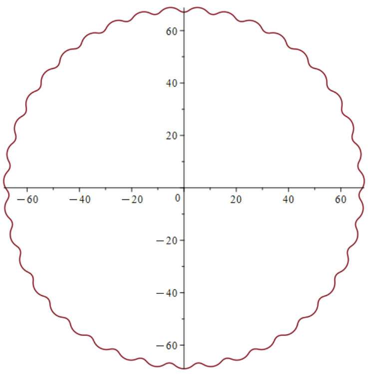
$e = 1.7; r_z = 2; R_z = 77.5$

E



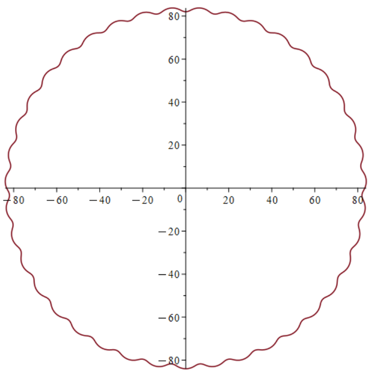
$e = 1.7; r_z = 3; R_z = 77.5$

F



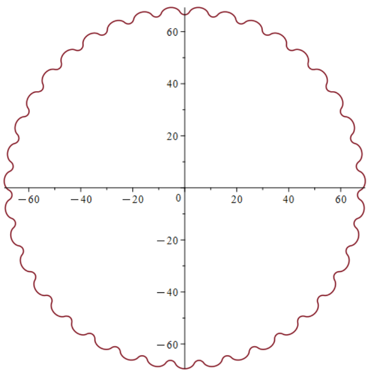
$e = 1; r_z = 2; R_z = 70$

G



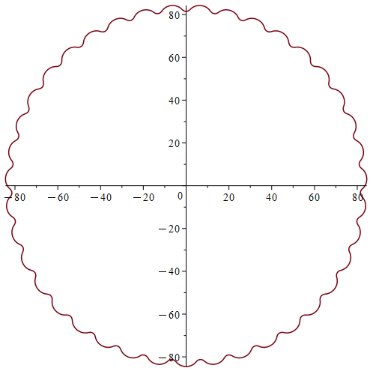
$e = 1; r_z = 2; R_z = 85$

H



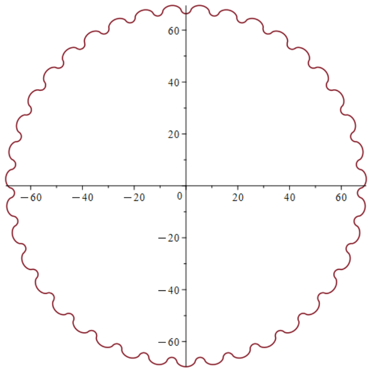
$e = 1.5; r_z = 2; R_z = 70$

I



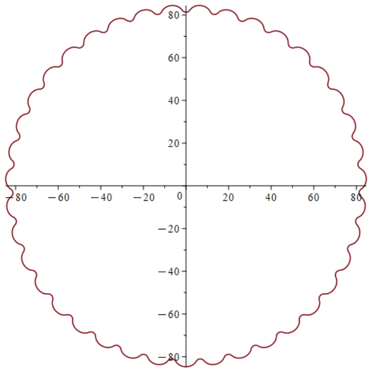
$e = 1.5$; $r_z = 2$; $R_z = 85$

J



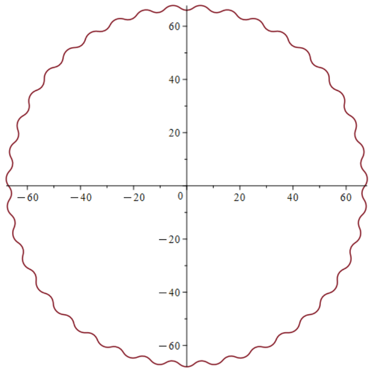
$e = 1.7$; $r_z = 2$; $R_z = 70$

K



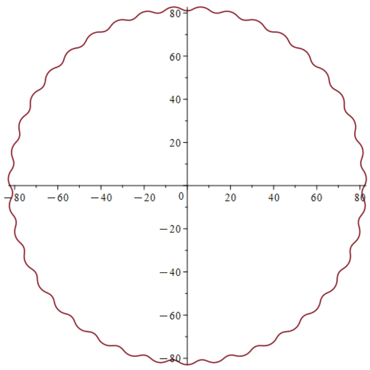
$e = 1.7$; $r_z = 2$; $R_z = 85$

L



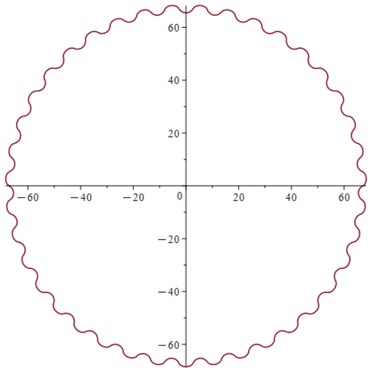
$e = 1$; $r_z = 3$; $R_z = 70$

M



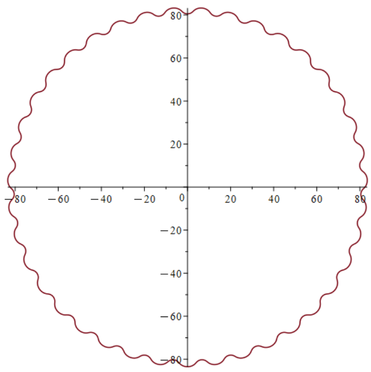
$e = 1$; $r_z = 3$; $R_z = 85$

N



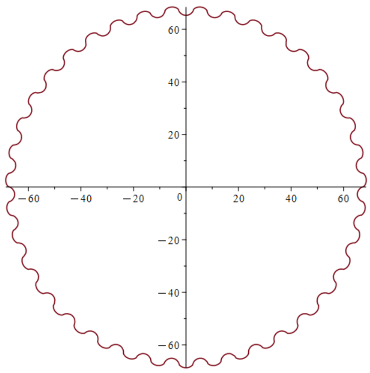
$e = 1.5$; $r_z = 3$; $R_z = 70$

O



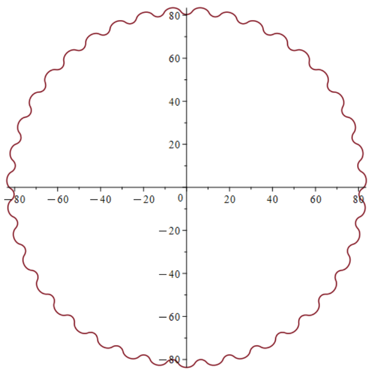
$e = 1.5$; $r_z = 3$; $R_z = 85$

P



$e = 1.7$; $r_z = 3$; $R_z = 70$

R



$e = 1.7$; $r_z = 3$; $R_z = 85$

S

As seen in Figure 3, changes in design parameters such as eccentricity and pin radius have a minimal effect on transmission efficiency. However, while variations in pin radius have a minor impact on contact efficiency, an increase in the eccentricity parameter results in an improvement in efficiency. This indicates that eccentricity is the most critical parameter in cycloidal reducers. Additionally, it is observed that as the reference circle diameter increases, both contact efficiency and transmission efficiency decrease.

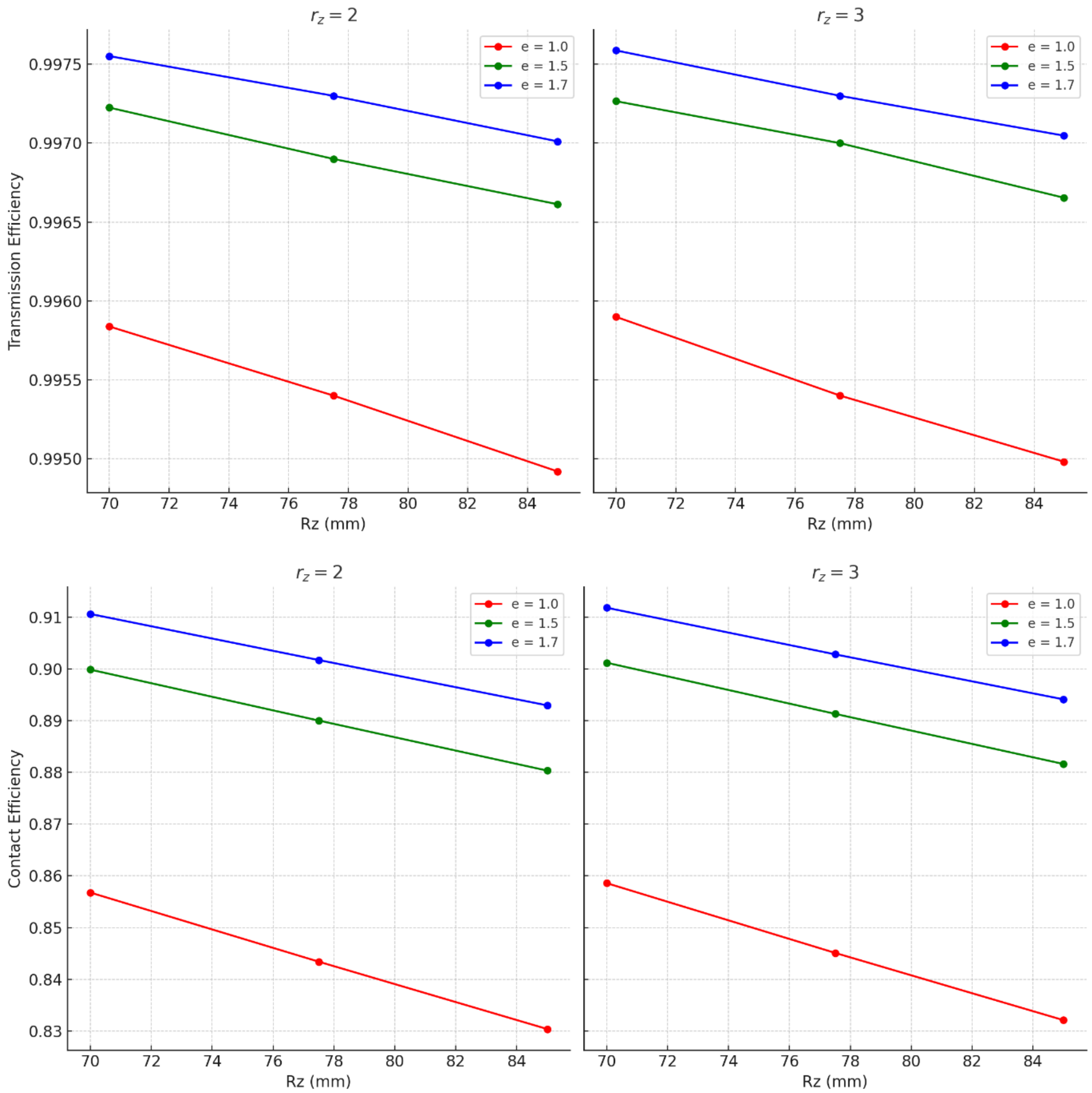


Figure 3: Comparison of transmission and contact efficiency

The results indicate that changes in pin radius (r_z=2 mm and r_z=3 mm) have a negligible effect on transmission efficiency. In contrast, eccentricity (e) plays a more prominent role. For fixed pin radius values, an increase in eccentricity from e=1.0 to e=1.7 leads to a slight improvement in transmission efficiency across all reference circle diameters (R_z). However, as R_z increases, a marginal decline in transmission efficiency is observed, irrespective of the values of e and r_z.

Contact efficiency shows a similar dependence on the design parameters. Higher eccentricity values consistently enhance contact efficiency, with e=1.7 yielding significantly better results compared to e=1.0. This improvement reflects better engagement and interaction between the cycloidal profile and pins. Conversely, an increase in R_z results in a reduction in contact efficiency, likely due to increased clearances or misalignment, which adversely impact power and motion transmission.

Among the analyzed parameters, eccentricity emerges as the most influential in determining both transmission and contact efficiency. Higher eccentricity values not only improve efficiency but also contribute to smoother engagement, reducing wear and enhancing durability. In comparison, variations in pin radius have a minor impact, highlighting the secondary role of r_z in optimizing performance.

In conclusion, while both R_z and r_z influence efficiency, eccentricity stands out as the critical parameter for improving the performance of cycloidal reducers. These findings underscore the importance of optimizing e and carefully selecting R_z to balance efficiency and reliability in cycloidal reducer designs.

4 Conclusion

This study investigated the effects of critical design parameters on tooth profile formation and operational performance of cycloidal reducers. The findings revealed that parameters such as eccentricity, pin radius, and modification coefficient have varying degrees of impact on both profile geometry and operational efficiency. Among these, eccentricity emerged as the most influential parameter that significantly affects both contact and transmission efficiency.

The analysis showed that although changes in pin radius have minimal impact on efficiency, eccentricity plays a critical role in optimizing performance. Additionally, the study showed that although beneficial for smoother transitions in profiles, increasing modification coefficients can lead to increased wear and decreased efficiency due to higher reaction forces. These insights highlight the importance of careful parameter selection to balance durability and performance.

The results of this research contribute to a deeper understanding of the interaction between design parameters in cycloidal reducers, paving the way for improved optimization strategies. Future work should focus on integrating these findings into standard design frameworks and exploring advanced optimization algorithms to further enhance the reliability and applicability of cycloidal reducers in various engineering applications.

5 Declarations

5.1 Competing Interests

There is no conflict of interest in this study.

5.2 Authors' Contributions

Furkan Korkmaz: Contributions have been made in conducting the literature review for the article, formulating ideas or hypotheses for the study, planning the materials and methods necessary to reach the conclusions, organizing the data, and performing comparisons with the developed models.

Ahmet Kolip: Contributions have been made in developing ideas or hypotheses for the article, planning the materials and methods to achieve the results, logically explaining and presenting the findings, and revising the manuscript before submission not only for grammar and spelling but also for intellectual content.

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Connection Cities To The Sea And Looking To The Future From Ports: Rotterdam, Almeria, and Karasu

Süleyman Nurullah Adahi ŞAHİN[1*], Abdulkadir ÖZDEN[2]

[1] Sakarya University of Applied Sciences, Civil Engineering, Technology Faculty, adahisahin@subu.edu.tr

[2] Sakarya University of Applied Sciences, Civil Engineering, Technology Faculty, aozden@subu.edu.tr

ABSTRACT

In this study, it is embarked on an insightful exploration of how maritime infrastructure acts as a critical nexus between urban centers and the global maritime trade network, focusing on the exemplary cases of Rotterdam, Almeria, and Karasu ports. The analysis begins with the Port of Rotterdam, renowned for its advanced technological integration and status as Europe's largest port, serving as a pivotal hub in international trade. The article dissects Rotterdam's strategies in sustainability, digitalization, and infrastructure development that have bolstered its efficiency and global connectivity, positioning it as a model for future port development. The examination then shifts to Almeria, a port with a distinct context and operational scale, emphasizing its role in regional development, tourism, and agricultural export. Despite its smaller size compared to Rotterdam, Almeria demonstrates how ports can leverage unique geographic and economic strengths to enhance their contribution to local and regional economies. Building on the insights gleaned from Rotterdam and Almeria, the article proposes a set of strategic recommendations for Karasu Port. Recognizing Karasu's potential as a burgeoning maritime node on the Black Sea, the recommendations focus on enhancing its operational efficiency, sustainability, and digital infrastructure. The goal is to align Karasu's development with the successful practices observed in Rotterdam and Almeria, ensuring it becomes a critical link in the maritime trade network while fostering economic growth for the city of Karasu and its hinterland. In conclusion, the article emphasizes the importance of ports like Rotterdam, Almeria, and Karasu in connecting cities to the sea and their pivotal roles in shaping the future of global trade and urban development. Through the lens of these three ports, we explore the transformative impact of maritime infrastructure on economic growth, sustainability, and digital innovation.

Keywords: Maritime infrastructure, sustainability, digitalization, global trade, port development

[1*] Corresponding Author's email: adahisahin@subu.edu.tr

Şehirlerin Denizle Bağlantisi Ve Limanlardan Geleceğe Bakış: Rotterdam, Almeria ve Karasu

ÖZ

Bu çalışmada, Rotterdam, Almeria ve Karasu limanları örneklerine odaklanarak, denizcilik altyapısının kent merkezleri ile küresel deniz ticareti ağı arasında nasıl kritik bir bağ işlevi olduğu vurgulanmıştır. Analiz, gelişmiş teknolojik entegrasyonu ve Avrupa'nın en büyük limanı olma statüsüyle tanınan ve uluslararası ticarette önemli bir merkez olarak hizmet veren Rotterdam Limanını ilk olarak ele almaktadır. Rotterdam'ın sürdürülebilirlik, dijitalleşme ve altyapı geliştirme stratejilerini inceleyerek verimliliğini ve küresel bağlanabilirliğini artırmış ve onu gelecekteki liman gelişimi için bir model olarak konumlandırmıştır. Çalışma daha sonra, bölgesel kalkınma, turizm ve tarımsal ihracattaki rolü vurgulanarak, farklı bir bağlam ve operasyonel ölçeğe sahip bir liman olan Almeria'ya geçmektedir. Rotterdam'a kıyasla daha küçük olmasına rağmen Almeria, limanların yerel ve bölgesel ekonomilere katkılarını artırmak için benzersiz coğrafi ve ekonomik güçlerden nasıl yararlanabileceğini göstermektedir. Rotterdam ve Almeria'dan elde edilen bilgiler ışığında, bu çalışma Karasu Limanı için bir dizi stratejik öneride bulunmayı hedeflemiştir. Karasu'nun Karadeniz'de gelişmekte olan bir denizcilik düğümü olma potansiyelini göz önünde bulunduran öneriler, limanın operasyonel verimliliğini, sürdürülebilirliğini ve dijital altyapısını geliştirmeye odaklanmıştır. Amaç, Karasu'nun gelişimini Rotterdam ve Almeria'da gözlemlenen başarılı uygulamalarla uyumlu hale getirmek, Karasu şehri ve hinterlandı için ekonomik büyümeyi teşvik ederken deniz ticaret ağında kritik bir bağlantı haline gelmesini sağlamaktır. Sonuç olarak bu çalışmada, Rotterdam, Almeria ve Karasu limanların kentleri denize bağlamadaki önemini ve küresel ticaret ve kentsel gelişimin geleceğini şekillendirmedeki kilit rollerini vurgulamaktadır. Bu üç limanın merceğinden, denizcilik altyapısının ekonomik büyüme, sürdürülebilirlik ve dijital inovasyon üzerindeki dönüştürücü etkisi ortaya koyulmuştur.

Anahtar Kelimeler: Denizcilik altyapısı, sürdürülebilirlik, dijitalleşme, küresel ticaret, liman geliştirme

1 Introduction

Ports have historically served as crucial lifelines connecting cities to global trade networks (Santos et al., 2018). Their strategic locations and advanced infrastructures facilitate the movement of goods, foster economic activity, and play a vital role in shaping urban development. In an era marked by increasing globalization and growing maritime trade, understanding the strategies employed by successful ports becomes essential for ensuring their continued relevance and fostering sustainable growth (Schipper, 2019). This study embarks on an insightful exploration of how maritime infrastructure acts as a critical nexus between urban centres and the global maritime trade network, focusing on the exemplary cases of Rotterdam, Almería, and Karasu ports.

Ports are not merely gateways for international trade; they are dynamic entities that influence the economic, social, and environmental fabric of the cities they serve. The analysis presented in this article is guided by a conceptual framework that emphasizes the multifaceted relationship between ports, cities, and the global maritime trade network (Parola et al., 2017). This framework is anchored on three key pillars: Connectivity and Infrastructure, Specialization and Innovation, and Sustainability and Community Integration.

This study embarks on an insightful exploration of how maritime infrastructure acts as a critical nexus between urban centres and the global maritime trade network, focusing on the exemplary cases of Rotterdam, Almeria, and Karasu ports. By examining these ports, the study aims to identify key strategies that drive their success and propose actionable recommendations for the development of Karasu Port.

The study is structured as follows: First, it provides a comprehensive background on the importance of maritime infrastructure in global trade and urban development. Next, it delves into the specific cases of Rotterdam and Almeria, highlighting their unique strategies and success stories. The methodology section outlines the mixed-method comparative case study approach used to gather. The results section presents the findings from Rotterdam and Almeria, followed by tailored recommendations for Karasu Port. Finally, the conclusion summarizes the key insights and offers suggestions for policymakers and future research.

By setting this framework, the study not only contributes to the literature on port development but also provides practical implications for enhancing the efficiency and sustainability of maritime infrastructure.

1.1 Connectivity and Infrastructure

The first pillar underscores the critical role of efficient port infrastructure and robust multimodal transportation networks, including road, rail, and inland waterways. These elements are essential in facilitating the seamless movement of goods and connecting ports to regional and global trade routes. Ports serve as essential nodes in the global trade network, supporting economic development not just at the city level but also regionally and globally (Liang & Liu, 2020). This pillar explores how ports like Rotterdam have developed state-of-the-art infrastructure that enhances their connectivity, making them pivotal points in the global supply chain.

1.2 Specialization and Innovation

The second pillar highlights the importance of strategic specialization in attracting diverse businesses and investment. Ports can achieve this by focusing on specific cargo types, developing innovative services like logistics hubs or free trade zones, or leveraging technological advancements to optimize operations. This part explores the impact of digital transformation in port operations, including the adoption of smart technologies, IoT (Internet of Things), and blockchain for improved efficiency, security, and transparency in the logistics chain (Zhuang et al., 2014). For instance, the Port of Almería's focus on specialized agricultural exports has positioned it as a key player in the Mediterranean trade routes, demonstrating the power of niche markets in port success.

1.3 Sustainability and Community Integration

The third pillar emphasizes the growing significance of incorporating sustainable practices into port operations and fostering positive relationships with surrounding communities. This includes implementing eco-friendly initiatives, minimizing environmental impact, and engaging in collaborative projects that contribute to urban development and community well-being. This pillar introduces models of green port initiatives and the importance of incorporating renewable energy, waste management, and emission reduction strategies (Felício et al., 2023). The Port of Karasu, for example, has made significant strides in sustainability by integrating renewable energy sources and establishing programs aimed at reducing emissions, thereby setting a benchmark for other ports aiming to balance economic and environmental objectives.

The conceptual framework for this study is anchored on three key pillars: Connectivity and Infrastructure, Specialization and Innovation, and Sustainability and Community Integration (Parola et al., 2017). This framework guides the analysis of the ports and their impact on urban and economic development. Existing literature on port development underscores the importance of efficient infrastructure and strategic specialization (Zhuang et al., 2014). Studies by Schipper (2019) and Santos et al. (2018) highlight the transformative role of ports in facilitating global trade and promoting sustainable growth. Furthermore, research by Dooms et al. (2013) and Liang & Liu (2020) emphasizes the significance of multimodal connectivity and technological innovation in enhancing port efficiency. By integrating insights from these studies, this research builds on a robust conceptual foundation to examine the success stories of Rotterdam and Almeria, and to propose recommendations for Karasu Port. By examining these three pillars through the lens of the ports of Rotterdam, Almería, and Karasu, this study provides a comprehensive understanding of how successful ports navigate the complexities of modern maritime trade. The findings aim to offer valuable insights for policymakers, port authorities, and stakeholders involved in the maritime industry, contributing to the development of strategies that ensure ports remain vital components of the global trade network while promoting sustainable urban growth.

In conclusion, as ports continue to evolve in response to global trade demands, their role in connecting cities to the world becomes increasingly significant. By focusing on connectivity, specialization, innovation, and sustainability, ports can not only enhance their operational efficiency but also contribute positively to the broader economic and social landscapes they inhabit. This study sheds light on the best practices and innovative strategies that drive port success, offering a roadmap for future developments in the maritime sector.

2 Research Methodology

The research methodology adopted for our exploration into the transformative role of ports in urban and economic development, with a particular focus on Rotterdam, Almeria, and Karasu, is a Mixed-Method Comparative Case Study with Prescriptive Analysis (Perkins, 2014; Fiet, 2007). This approach is meticulously designed to harness the strengths of both qualitative and quantitative research paradigms, offering a rich, multidimensional understanding of how ports like Rotterdam and Almeria have become pivotal in global trade networks, and how their best practices can inform the future development of Karasu Port. At the core of our methodology is the case study analysis, which allows for an in-depth examination of Rotterdam and Almeria ports. These case studies are not randomly chosen; rather, they are selected for their exemplary roles in showcasing the integration of sustainability practices, technological advancements, and their significant contributions to both local and global economies. Through qualitative data—such as operational strategies, sustainability initiatives—we glean insights into the complex dynamics that govern these ports. Complementing this, quantitative data provides a solid backbone of evidence, offering metrics like cargo throughput, efficiency improvements, and economic impacts that help quantify the success and challenges faced by these ports.

The comparative aspect of our methodology comes into play as we juxtapose the findings from Rotterdam and Almeria. This comparison is not merely a side-by-side evaluation but a deep dive into understanding how differing scales, geographic contexts, and strategic focuses influence port operations and their broader implications. By comparing these ports, we identify a spectrum of best practices and challenges that are critical in shaping port development strategies. This comparative analysis is instrumental in distilling actionable insights that are not only relevant but also adaptable to varying contexts, such as that of Karasu Port.

Building upon the comparative case study, our methodology integrates a prescriptive analysis component. This segment of the research is forward-looking and aims at bridging the gap between current states and desired futures. Drawing from the comparative study, we formulate specific, tailored recommendations for Karasu Port. These recommendations are not generic prescriptions but are informed by the nuanced understanding developed through our case studies and comparative analysis. They consider Karasu's unique geographic, economic, and operational context, proposing strategies for infrastructure development, sustainability practices, and digital transformation. The prescriptive analysis is the culmination of our mixed-method approach, synthesizing insights from qualitative and quantitative data to offer a roadmap for Karasu Port's development that is evidence-based, contextually aware, and aligned with global best practices.

The mixed-method nature of our methodology is pivotal (Table 1), allowing for a comprehensive exploration that captures the complexity of port operations and their multifaceted impacts. Qualitative data brings depth to our understanding, highlighting the nuances of port management, and the socio-economic fabric of the surrounding urban and regional environments. Quantitative data, on the other hand, lends rigor and measurability, enabling us to benchmark successes, identify gaps, and project future scenarios with greater confidence. Together, these methods provide a holistic view, ensuring that our analysis is grounded in reality while being attuned to the aspirations and potential of Karasu Port.

Table 1: *Research Methodology*

Stage	Action	Output
Case Study Analysis	In-depth examination of Rotterdam & Almeria ports	Understanding of each port's operations, strategies, and impact on urban & economic development, sustainability, and digitalization
Comparative Analysis	Juxtapose findings from Rotterdam & Almeria	Spectrum of best practices, challenges, and opportunities for port development
Prescriptive Analysis	Formulate tailored recommendations for Karasu Port development	Evidence-based, contextually aware roadmap for Karasu Port's development, focusing on urban & economic development, sustainability, and digitalization

In conclusion, the Mixed-Method Comparative Case Study with Prescriptive Analysis methodology is a comprehensive approach that leverages the strengths of both qualitative and quantitative research to offer deep insights into the operations and strategies of Rotterdam and Almeria ports. It facilitates a nuanced comparison of these ports, drawing lessons that inform prescriptive recommendations for Karasu Port. This methodology not only enriches our understanding of the existing landscape of maritime infrastructure but also charts a course for future developments, ensuring that ports continue to play a crucial role in connecting cities to the sea and driving forward the engines of global trade and urban development. Through this approach, the research aspires to contribute valuable knowledge to the field of maritime infrastructure and urban planning, offering actionable strategies that can adapt to the evolving demands of global trade and sustainability imperatives.

3 Results and Discussion

On this section, the detailed Mixed-Method Comparative Case Study with Prescriptive Analysis presented separately by explaining and giving examples of Port of Rotterdam, Port of Almeria. Afterwards, the possible distinction and the role of Karasu Port has discussed. As Europe's largest port, Rotterdam is renowned for its advanced technological integration and strategic importance in global trade. Official reports from the Port of Rotterdam Authority (Dooms et al., 2013) and research studies (Heijman et al., 2017) highlight the port's success in implementing state-of-the-art infrastructure and sustainable practices. Examples include the use of automated terminals, shore power connections, and extensive multimodal transportation networks.

Although smaller in scale, Almeria is a crucial hub for agricultural exports and tourism in the Mediterranean region. Reports by the Spanish Port Authority (Pérez-Mesa et al., 2019) emphasize Almeria's role in facilitating the export of regional agricultural products and its strategic investments in cruise tourism infrastructure. Concrete examples include the port's specialized facilities for handling perishable goods and the development of tourist-friendly amenities.

These ports were selected based on their distinct operational contexts and their successful strategies, which offer valuable lessons for the development of Karasu Port.

4.1 Rotterdam: A Beacon of Efficiency and Global Connectivity in the Maritime Landscape

The Port of Rotterdam stands as a testament to the transformative power of strategic development and continuous innovation within the global maritime trade network. Renowned for its advanced technological integration and position as Europe's largest port (Figure 1), Rotterdam serves as a pivotal hub, facilitating the seamless flow of goods across continents. Delving deeper into the port's success story reveals a multifaceted interplay of factors that have propelled it to the forefront of global maritime operations.

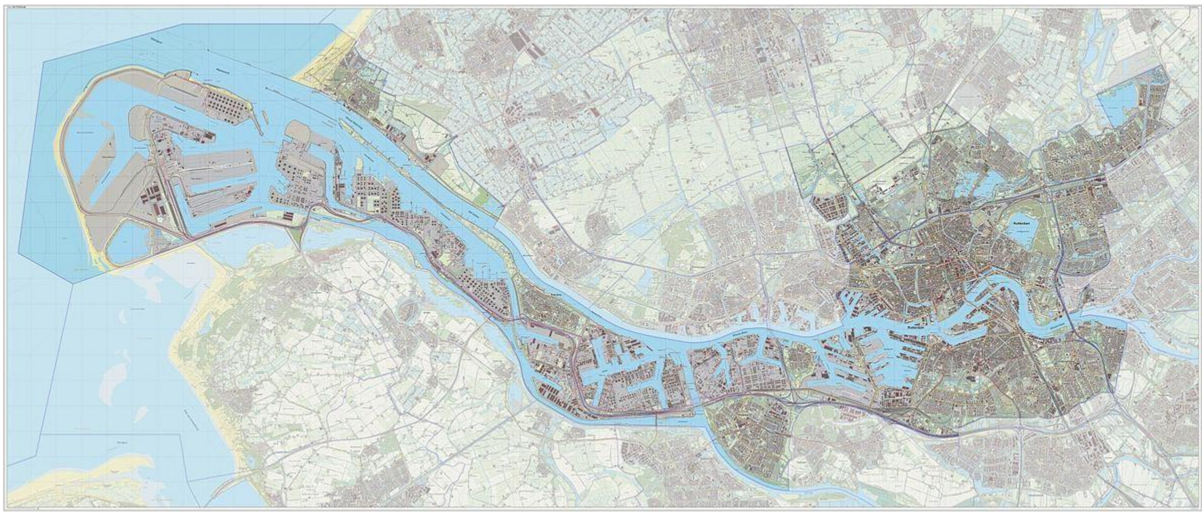

Figure 1: Port of Rotterdam

4.1.1 The Cornerstone of Success: Infrastructure and Connectivity

Rotterdam's pre-eminence is firmly rooted in its robust infrastructure and unparalleled connectivity. World-class port facilities boast an impressive capacity to handle diverse cargo types, from towering container terminals to specialized facilities for bulk cargo handling (Figure 2). This exceptional infrastructure is further complemented by an extensive network of multimodal transportation linkages. Arteries of road, rail, and inland waterways extend outwards from the port, seamlessly connecting it to major European markets and facilitating the efficient movement of goods far beyond the immediate vicinity. Rotterdam's strategic location at the mouth of the Rhine River further amplifies its connectivity, granting direct access to the heart of Europe's industrial and economic powerhouse (Ducruet & Notteboom, 2024). This confluence of factors positions Rotterdam as a central node within the intricate web of global trade, ensuring the swift and efficient movement of goods across vast distances(van Dorsser et. al., 2018).

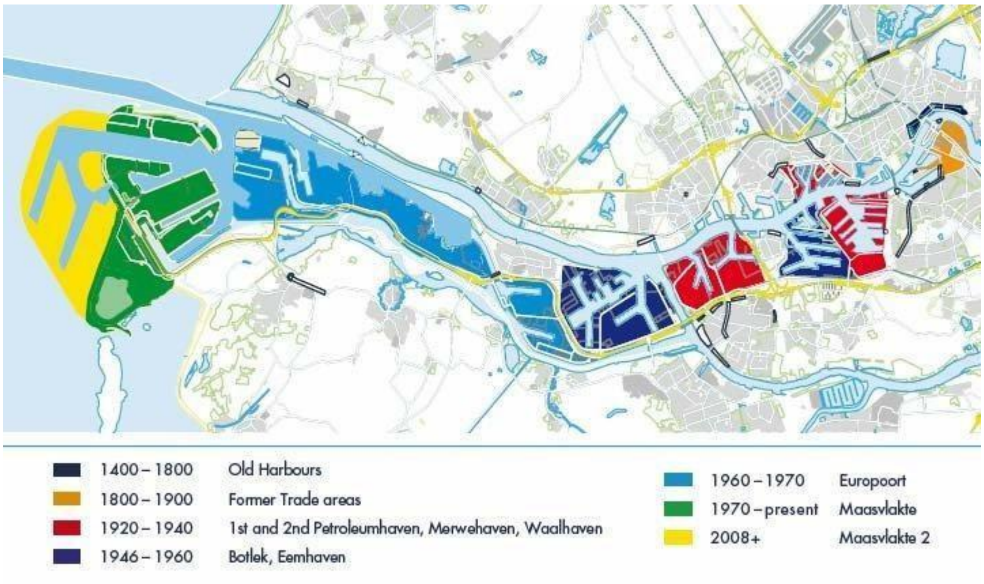

Figure 2: Port of Rotterdam development history

4.1.2 Embracing Innovation and Specialization: A Recipe for Growth

Beyond its impressive infrastructure, Rotterdam's success hinges on its unwavering commitment to innovation and strategic specialization. Recognizing the ever-evolving needs of the global market, the port has adopted a diversified approach, catering to a wide range of cargo types (Figure 3). While remaining a leader in bulk cargo handling, Rotterdam has simultaneously carved out a niche in containerized freight, establishing itself as a crucial gateway for international trade. This strategic diversification allows the port to cater to the diverse demands of a globalized economy, ensuring its continued relevance in the face of shifting market dynamics (Witte et. al., 2018). Furthermore, Rotterdam embraces technological advancements as a cornerstone of its growth strategy. Continuous investments in automation and digitalization have revolutionized port operations, streamlining processes, enhancing efficiency, and optimizing resource utilization. These cutting-edge technologies not only expedite cargo handling but also contribute to cost reductions and improved overall competitiveness (Heijman et. al., 2017).

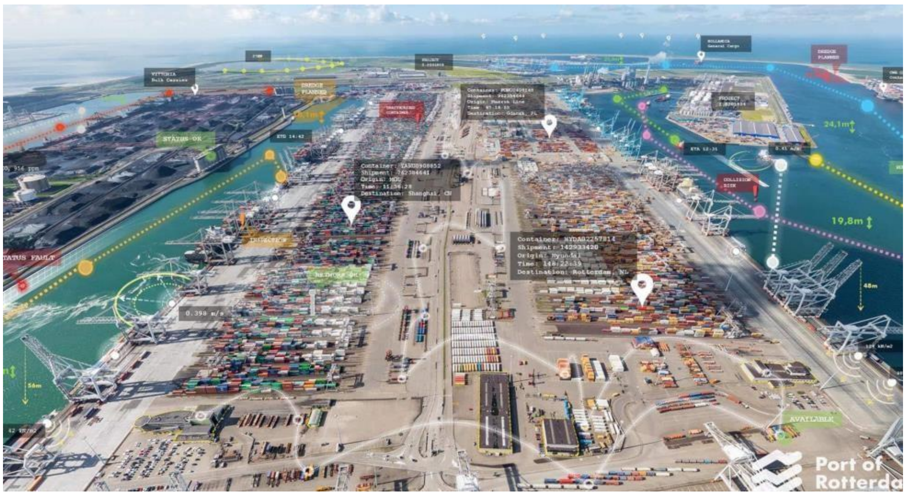

Figure 3: Port of Rotterdam network

4.1.3 Sustainability and Community Integration: Navigating the Future with Responsibility

Rotterdam's leadership extends beyond operational excellence, recognizing the growing imperative of sustainability within the maritime industry. The port has embarked on a commendable journey towards eco-friendly practices, implementing various initiatives to minimize its environmental footprint. Shore power connections for docked vessels significantly reduce air pollution, while investments in renewable energy sources contribute to a cleaner energy mix. These proactive measures demonstrate Rotterdam's commitment to responsible growth, ensuring its long-term viability in an increasingly sustainability-conscious world (Zheng et. al.., 2020).

However, Rotterdam's success transcends mere economic prosperity. The port actively fosters strong ties with the surrounding community, recognizing the importance of mutual benefit and shared value creation. Collaborative projects promote urban development, revitalize waterfront areas, and create opportunities for local businesses. This commitment to community engagement ensures that the port's growth is not only economically productive but also socially responsible, fostering a sense of shared ownership and collective prosperity (Dooms et. al., 2013).

In conclusion, the Port of Rotterdam stands as a shining example of success within the global maritime landscape. Its unwavering commitment to infrastructure development, strategic specialization, technological innovation, and sustainable practices has cemented its position as a pivotal hub for international trade. By recognizing the importance of community engagement and environmental responsibility, Rotterdam has charted a course for sustainable growth, ensuring its continued relevance and leadership in the ever-evolving world of maritime trade. Rotterdam's success story serves as a valuable blueprint for other ports, offering crucial insights into the multifaceted strategies that pave the way for long-term prosperity and responsible integration within the global economic fabric.

4.2 Almeria: A Beacon of Regional Development, Illuminating the Power of Local Strengths

While the colossal scale and global reach of Rotterdam command undeniable attention, the Port of Almeria, nestled on the south-eastern coast of Spain, presents a contrasting yet equally captivating narrative within the tapestry of maritime success stories (Figure 4). Operating on a smaller scale compared to its European counterpart, Almeria demonstrates the remarkable potential of capitalizing on local strengths and fostering deep-rooted connections with the surrounding community to achieve significant regional development and economic prosperity (Alvarez Fanjul et. al., 2018).

Unlike Rotterdam's focus on global dominance, Almeria thrives by embracing its unique identity and strategic location. Situated along the picturesque shores of the Mediterranean Sea, the port enjoys unparalleled access to major trade routes, serving as a vital gateway for both inbound and outbound goods. Furthermore, its proximity to fertile agricultural production areas empowers Almeria to act as a crucial link between local farmers and international markets. This strategic positioning allows the port to play a central role in facilitating the export of agricultural products, fostering economic growth within the region and establishing Almeria as a prominent player in the global agricultural trade landscape(Pérez-Mesa et. al., 2019).

Figure 4: Port of Almeria

Beyond its advantageous geographical location, Almeria's success story is intricately woven with the dynamism of the burgeoning cruise tourism industry. Recognizing the immense potential of this sector, the port has strategically invested in infrastructure and facilities specifically catering to cruise liners. This proactive approach has positioned Almeria as a sought-after destination for international tourists, injecting significant revenue into the local economy and contributing to the creation of employment opportunities within the region. By embracing the burgeoning cruise tourism industry, Almeria not only diversifies its economic portfolio but also fosters cultural exchange and promotes the region's unique heritage to a global audience(López-Bermúdez et. al., 2020).

However, the essence of Almeria's success transcends mere economic benefits. The port recognizes the fundamental importance of fostering strong, collaborative relationships with the local community. This commitment manifests in various initiatives aimed at supporting local businesses, promoting sustainable development, and contributing to infrastructure projects that enhance the overall well-being of the region (Figure 5). By actively engaging with the community and prioritizing shared prosperity, Almeria ensures that its growth is not solely measured in economic terms but also translates into tangible improvements in the lives of its residents. This collaborative approach fosters a sense of ownership and responsibility, ensuring the port's long-term sustainability and continued integration within the social fabric of the region(Molina et. al., 2019).

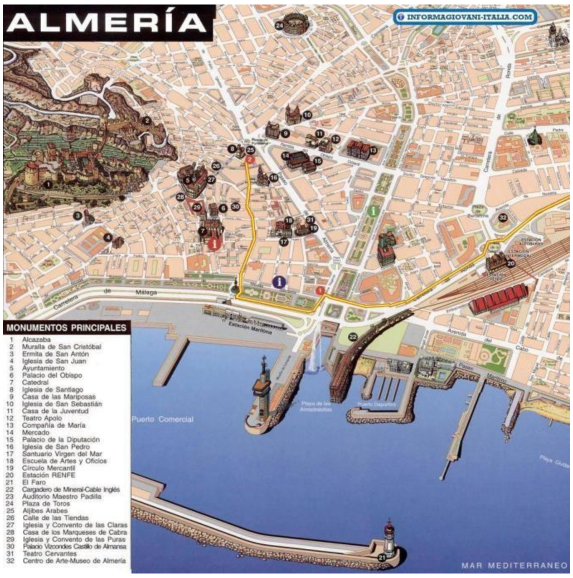

Figure 5: Port of Almeria and the city connections

In conclusion, the Port of Almeria stands as a testament to the transformative power of leveraging local strengths and nurturing community partnerships. By strategically capitalizing on its geographical position, proximity to agricultural production areas, and the burgeoning cruise tourism industry, Almeria has carved out a distinct niche within the global maritime landscape, contributing significantly to regional development and economic prosperity. Furthermore, the port's unwavering commitment to fostering strong ties with the local community underscores the crucial role of collaborative engagement in ensuring sustainable growth and shared success. Almeria's compelling narrative offers valuable insights for ports of all sizes, highlighting the importance of identifying unique strengths, embracing innovative strategies, and prioritizing community well-being as cornerstones for achieving sustainable and impactful development.

4.3 Charting a Course for Success: Recommendations for Karasu Port

Drawing upon the invaluable insights gleaned from the success stories of Rotterdam and Almeria, this study formulates a set of strategic recommendations tailored to empower Karasu Port (Figure 6), a burgeoning maritime node on the Black Sea, to embark on a trajectory of sustainable and impactful growth.

Figure 6: Port of Karasu, Sakarya

4.3.1 Enhancing Operational Efficiency: Building a Solid Foundation

As the cornerstone of any successful port, investing in infrastructure upgrades is paramount for Karasu. Modernizing existing facilities, expanding cargo handling capacity, and incorporating advanced technologies will streamline operations, enhance efficiency, and position the port to cater to the evolving demands of the global maritime trade. Additionally, improving multimodal connections is crucial. Upgrading road, rail, and inland waterway networks will ensure seamless freight movement beyond the immediate port vicinity, facilitating efficient hinterland connections and fostering stronger regional integration. Furthermore, exploring potential for expansion should be considered. Strategically planned expansion projects can accommodate future growth, cater to increasing cargo volumes, and solidify Karasu's position as a key player within the Black Sea region(Ateş & Esen, 2022).

4.3.2 Identifying Strategic Specialization: Charting a Unique Course

To carve out a distinct niche within the competitive maritime landscape, identifying strategic areas of specialization is essential for Karasu. A comprehensive analysis of the region's strengths and potential is crucial in this endeavour. Capitalizing on Karasu's proximity to agricultural production areas, for instance, could position the port as a vital export hub for regional agricultural products. Alternatively, leveraging its strategic location on the Black Sea, Karasu could evolve into a gateway to Central Asia, facilitating trade between the region and international markets. This targeted approach, informed by a deep understanding of regional strengths and potential, will enable Karasu to attract targeted investments, attract specific businesses, and establish itself as a leader in its chosen niche (Kılıç & Akpinar, 2022).

4.3.3 Embracing Sustainability: Navigating the Future Responsibly

In an era of increasing environmental consciousness, embracing sustainability is no longer an option but a necessity for any forward-thinking port. Karasu must prioritize the implementation of eco-friendly practices throughout its operations. Utilizing renewable energy sources, such as solar or wind power, can significantly reduce the port's carbon footprint and contribute to a cleaner environment. Additionally, minimizing waste generation through efficient waste management practices and promoting recycling initiatives are crucial steps towards sustainable port development. By prioritizing environmental responsibility, Karasu not only aligns itself with global sustainability commitments but also demonstrates its commitment to responsible growth and attracts environmentally conscious businesses and investors.

4.3.4 Engaging with the Community: Building Bridges for Shared Prosperity

A successful port thrives not only in isolation but also in collaboration with the surrounding community. Fostering partnerships with local stakeholders such as businesses, government agencies, and community organizations is essential for ensuring mutually beneficial growth. Supporting community development initiatives through infrastructure projects, job creation programs, and educational opportunities allows the port to contribute to the overall well-being of the region. Furthermore, promoting transparency in port operations by actively engaging with the community and addressing concerns builds trust and fosters a sense of shared ownership. By prioritizing community engagement, Karasu ensures that its growth translates into tangible benefits for its residents, fostering a sense of shared prosperity and securing long-term community support (Ülger & Tanrıvermiş, 2023).

Sharing strategic similarities with the established Port of Rotterdam, a global trade leader, and the Port of Almeria, a key player in regional agricultural exports, the Port of Karasu possesses a geographically advantageous location, positioning it as a potential future gateway for trade. This trio of ports share significant development potential, with Karasu uniquely situated to learn from both Rotterdam's cutting-edge technological advancements and Almeria's successful strategy of catering to a specialized market (agricultural exports). Moreover, incorporating practices observed in both Rotterdam and Almeria, such as fostering strong community engagement and prioritizing sustainability initiatives, can be instrumental in shaping a well-defined development trajectory for Karasu, propelling it towards a more prominent role in the global trade landscape.

In conclusion, by implementing these strategic recommendations, Karasu Port has the potential to emulate the success stories of Rotterdam and Almeria, carving its own path towards sustainable and impactful growth. By prioritizing operational efficiency, identifying strategic specialization, embracing sustainability, and engaging with the community, Karasu can establish itself as a vital hub within the Black Sea region, contributing to regional economic development and shaping a brighter future for both the port and its surrounding community.

4 Conclusions

The analysis presented in this study underscores the multifaceted relationship between ports, cities, and the global maritime trade network. By drawing insights from the success stories of Rotterdam and Almeria, and acknowledging the unique context of Karasu Port, this research proposes a set of strategic recommendations for fostering a thriving connection between the port and the city.

The Port of Rotterdam is a major hub for global trade, handling an estimated 14.5 million TEUs (Twenty-foot Equivalent Units) annually. This signifies its prominent role in facilitating international commerce. Furthermore, the port boasts a significant cargo throughput of 469 million tonnes in 2022, highlighting its capacity for large-scale freight movement (Port of Rotterdam Authority, 2022). The Port of Almeria plays a crucial role in regional agricultural exports. While its annual TEU volume is around 0.5 million, significantly lower than Rotterdam, it excels in bulk cargo movement, achieving a throughput of 3 million tonnes in 2022 (Spanish Port Authority, 2022). This suggests the port caters to the specific needs of the surrounding agricultural sector. The Port of Karasu currently handles a relatively modest cargo volume, approximately 0.1 million TEUs annually. This indicates that the port is not yet a major player in global trade. However, its potential for expansion is acknowledged, with strategic investments and development initiatives likely to propel its growth in the future.

- Enhancing Connectivity and Accessibility: Investing in infrastructure development beyond the immediate port vicinity is crucial. Upgrading road networks, expanding public transportation options, and exploring the potential for a dedicated port shuttle service can facilitate seamless movement of people and goods between the city and the port. Additionally, establishing efficient logistics corridors that connect Karasu to regional and national transportation networks will further enhance accessibility and solidify the port's position as a key node within the broader trade landscape.

- Promoting Urban Regeneration and Waterfront Development: Strategic urban planning initiatives can transform the waterfront area into a vibrant hub that fosters economic activity and community engagement. Revitalizing the waterfront with mixed-use development projects, including public spaces, recreational facilities, and commercial establishments, can create a dynamic and attractive destination. Furthermore, integrating the port into the city's urban fabric through pedestrian-friendly walkways, bicycle paths, and green spaces can foster a sense of connection and encourage community interaction with the maritime environment.

- Fostering Collaboration and Knowledge Sharing: Building strong partnerships between port authorities, city officials, businesses, and educational institutions is essential for sustainable development. Collaborative initiatives can promote knowledge sharing, facilitate skills development, and encourage innovation within the maritime sector. Additionally, fostering collaboration with international partners can provide valuable insights and best practices for port-city integration, enabling Karasu to learn from successful examples around the world.

- Investing in Sustainable Practices: Implementing eco-friendly initiatives throughout the port and city is crucial for ensuring long-term sustainability and responsible growth. Promoting green building practices, utilizing renewable energy sources, and implementing efficient waste management systems can significantly reduce the environmental footprint of both the port and the city. Furthermore, collaborative efforts to address environmental challenges, such as air and water pollution, can foster a shared commitment to a sustainable future for both the port and the surrounding community.

The study presented in this study underscores the multifaceted relationship between ports, cities, and the global maritime trade network. By drawing insights from the success stories of Rotterdam and Almeria and acknowledging the unique context of Karasu Port, this research proposes a set of strategic recommendations for fostering a thriving connection between the port and the city. The findings align with the existing literature on port development. Similar to the conclusions drawn by Schipper (2019) and Santos et al. (2018), this study highlights the critical role of infrastructure, specialization, and sustainability in port success. The practical examples from Rotterdam and Almeria provide concrete evidence supporting the theoretical insights offered by Zhuang et al. (2014) and Dooms et al. (2013). For policymakers, the recommendations emphasize the importance of investing in advanced infrastructure, promoting strategic specialization, embracing sustainable practices, and fostering community engagement. These strategies can enhance the operational efficiency of Karasu Port and contribute to regional economic development. Future studies should explore the impact of port development on social and cultural factors, conduct longitudinal analyses to assess the long-term outcomes of implemented strategies, and investigate the applicability of the proposed recommendations in different geographic and economic contexts.

By implementing these recommendations and fostering a collaborative approach, Karasu has the potential to create a thriving connection between the port and the city. This synergy can contribute to regional economic development, create employment opportunities, and enhance the overall quality of life for residents. As Karasu embarks on this journey of transformation, continuous monitoring, evaluation, and adaptation will be essential to ensure the long-term success of these initiatives and the sustainable development of both the port and the city.

4.1 Study Limitations

While providing valuable recommendations for Karasu Port, this study's scope is limited by focusing on specific cases, using existing status-quo, and having a future-oriented perspective. Further research in diverse contexts, considering social and cultural factors, is crucial for a more comprehensive understanding of port-city connections.

4.2 Competing Interests

There is no conflict of interest in this study.

4.3 Authors' Contributions

Süleyman Nurullah Adahi ŞAHİN: Developing ideas or hypotheses for the research and/or article, taking responsibility for the explanation and presentation of the results, taking responsibility for the creation of the entire manuscript or the main part.

Abdulkadir ÖZDEN: Supervising, editing and correction of spelling of manuscript.

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Review Article

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SAKARYA UNIVERSITY OF APPLIED SCIENCES

Review of Phased Array Ultrasonic Testing of Weld Joints

Desi Gustiani[1*], Hüseyin UZUN[2]

[1*] Mechanical Engineering, Faculty of Technology, Sakarya University of Applied Sciences, 22500909002@subu.edu.tr

[2] Metallurgy and Materials Engineering, Faculty of Technology, Sakarya University of Applied Sciences, huzun@subu.edu.tr

ABSTRACT

Welding is a prevalent joining technique used on metals in industrial manufacturing. It is very important to detect welding defects that may occur without damaging the welding constructions. The conventional ultrasonic inspection is the most widely used non-destructive test method for the detection of weld defects. Phased Array Ultrasonic Testing (PAUT) is a significant method within the category of ultrasonic non-destructive testing methods because ultrasonic phased arrays offer significant technical advantages over conventional ultrasonic methods such as improved sensitivity, accurate characterization and faster inspection. The aim of this article is to provide a comprehensive review on analysing defects in welded joints by utilizing PAUT. Different studies in the literature related to the non-destructive testing of weld joints by PAUT have been reviewed. Various examples of how the type, depth, and size of welding defects are detected in a highly effective manner have been provided. As a result, it was concluded that phased array ultrasonic testing is a highly efficient technique compared to conventional ultrasonic methods for detecting welding defects.

Keywords: Phased Array Ultrasonic Testing (PAUT), Ultrasonic Testing (UT), Evaluation of Weld Imperfections or Defects

[1*] Corresponding Author's email: desigustiani2929@gmail.com

Kaynaklı Birleştirmelerde Phased Array Ultrasonik Tekniğinin Kullanımı Hakkında Derleme

ÖZ

Endüstriyel imalatlarda metallerin birleştirilmesi amacıyla en yaygın kullanılan birleştirme tekniği, kaynaktır. Kaynaklı imalatların kaynak bölgelerinde oluşabilecek kaynak kusurlarının, önceden tespit edilmesi en önemli mühendislik süreçlerinden birisidir. Konstrüksiyona zarar vermeden kaynak kusurlarının tespit edilmesi amacıyla en yaygın kullanılan tahribatsız muayene yöntemi ise ultrasonik muayene tekniğidir (UT). Son yıllarda ultrasonik muayene teknikleri arasında hacimsel kaynak kusurlarının tespitinde en yaygın kullanılan tekniklerden birisi de phased array ultrasonik tekniğidir (PAUT). Bu tekniğin geleneksel ultrasonik muayeneye tekniklerine göre tercih edilmesinin başlıca sebepleri şunlardır: Daha ileri seviyede geliştirilmiş kusur tespit hassasiyeti, kusurların daha doğru ve net tespit edilebilmesi, çok daha geniş bir bölgenin daha hızlı bir şekilde muayene taramasının yapılabilmesi. Bu makalenin amacı kaynaklı konstrüksiyonlarda meydana gelebilecek hacimsel kaynak kusurlarının PAUT ile tespiti hakkında kapsamlı bir inceleme yapmaktır. Çeşitli literatür çalışmaları incelenerek, PAUT analizlerinin nasıl yapıldığı ile ilgili bilgi vermektir. Bu tekniğin geleneksel ultrasonik yöntemlere göre kaynak kusur türlerinin tespit edilmesinde, hataların boyutu, şekli ve derinliği ile ilgili bilgilerin elde edilmesinde ne kadar hassas, etkin ve verimli olduğunu göstermektir. Sonuç olarak, kaynak kusurlarının hacimsel tespitinde phased array ultrasonik muayenesinin, geleneksel ultrasonik tekniklere göre çok daha verimli, hızlı ve doğru analiz yapılabilmesi imkânını sağlayan bir teknik olduğu değerlendirilmiştir.

Anahtar Kelimeler: Ultrasonik Muayene (UT), Phased Array Ultrasonik Muayene (PAUT), Kaynak Kusurlarının Değerlendirilmesi

1 Introduction

Non-Destructive Testing (NDT) includes a group of analysis methods that assess the properties of a material, structure, or component without causing any damage to its functionality or serviceability (Nilsson et al., 2023). NDT method is designed to identify the type, quantity, shape, position, and dimensions of defects in the specimen, covering both surface and internal defects (Zhao, 2021). NDT is important in inspection procedures within the industrial sector, as the precision of defect information measured is critical for ensuring the safety of factory operations (Hampson et al., 2022). Currently, industrial applications employ NDT techniques to identify fractures and defects in various materials (Selim et al., 2020). The American Society of Non-destructive Testing describes NDT as “the examination of an object using technology that does not affect the object's future usefulness”, specifically the examination of specimens without damaging the structure (Jodhani et al., 2023).

NDT is an approach that uses physical principles to ascertain the properties of materials, thus helping identify and evaluate potentially dangerous defects or faults (Hu et al., 2012). NDT methods are defined by ISO 9712 as a discipline based on physical principles and engineering. ISO 9712 classifies NDT procedures into multiple tests, which include: acoustic emission testing (AT), eddy current testing (ET), infrared thermographic testing (TT), leak testing (LT), magnetic particle testing (MT), penetrant testing (PT), radiographic testing (RT), computed tomography (CT), strain gauge testing (ST), ultrasonic testing (UT), and visual testing (VT) (Segovia Ramírez et al., 2023). Ultrasonic testing is a commonly used non-destructive technique for analysing weld joint (H. Zhou et al., 2018). Testing evaluates materials, components, or defects in the welded joint without damaging the material (Deepak et al., 2021). Ultrasonic testing is commonly used to inspect welding results and mentions specific standards such as BS EN ISO 17640 and BS EN ISO 19285 (Mohseni et al., 2021). It introduces two distinct types of defects in welded joints: (1) external defects, which are easy to identify and occur on the material's surface, and (2) internal defects, which occur inside the welded joint. It then discusses the importance of pursuing advanced non-destructive testing technologies to effectively identify internal defects in welds, which is indeed an important topic in modern industrial manufacturing (Zeng et al., 2020).

Non-destructive ultrasonic testing uses high-frequency mechanical waves to create images of the internal structure of a component. In the last decade, there has been a significant increase in the utilization of ultrasonic phased arrays in ultrasonic non-destructive testing for the standardized examination of components (Singh et al., 2020). Phased array ultrasonic testing (PAUT) is a modern non-destructive testing (NDT) method that utilizes the Ultrasonic Testing (UT) technique (Mirmahdi, Khamedi, et al., 2023). PAUT has been the preferred method for inspecting thick welded sections in joints, tubes, and pressure vessels since its emergence (Mohseni et al., 2021).

This manuscript aims to serve as a reference for researchers engaged in non-destructive testing processes, particularly Ultrasonic testing. It discusses the types of weld joint defects identified through phased array ultrasonic testing analysis.

2 Importance of non-destructive testing of welded joints

Welding is a commonly used method for production and joining in industrial manufacturing. However, welding is also the joining technique most commonly linked to defects or imperfections. These can include cracks, porosity, lack of fusion, incomplete penetration, and spatter. Such issues may result from careless or inexperienced welders, poor welding conditions, incorrect materials, improper welding procedures, or an unfavorable environment.

Welding defects can cause catastrophic failures under stress, especially in important structures like bridges or airplanes. Welding defects can weaken the welded joints. Therefore, welded joints must be inspected before, during, and after the welding process to ensure the quality and reliability of the welds.

The most important techniques for inspecting weld regions are non-destructive testing (NDT) methods. NDT enables the detection of imperfections in weld regions, ensuring the product's safety before it enters service and preventing catastrophic failures. NDT is an essential quality control measure, helping to maintain high welding standards and reducing the risk of poor welds. Compared to destructive testing, NDT methods are more cost-effective, as they allow for weld assessment without damaging or scrapping the work-piece. This enables timely repairs and prevents defects from spreading.

3 Ultrasonic Testing

Ultrasonic testing (UT) is a type of acoustic inspection that falls under non-destructive testing. It is used to find defects in structures by using different methods and classifying the defects. Since 1975, this technique has been proven effective at detecting defects because it is simple and highly sensitive (Jodhani et al., 2023).

Ultrasonic Testing (UT) uses high-frequency sound waves to check the condition of an object and find defects on its surface, below the surface, or inside. The sound waves used are higher than the range of human hearing. The choice of frequency depends on the material being tested and the type of information needed (Inês Silva et al., 2023). UT works by sending ultrasound waves into the object, and the receiver detects the resulting wave response (Mirmahdi, Afshari, et al., 2023). The high-frequency sound waves are directed towards the specimen region or areas where fractures are expected to structure. The defects in the material can be identified by analysing the changes in the receiver wave response (Kong et al., 2020). The frequency range of the ultrasonic signal is between 1 MHz and 20 MHz, which impacts the sensitivity and resolution of measurements. Increased frequencies enable more precise identification of small defects. However, they also reduce penetration depth due to surface scattering (Selim et al., 2020).

UT is a widely used method for testing industrial components. (Chabot et al., 2020). It is usually carried out using either single-element transducers or ultrasonic arrays, which are transducers that consist of many independently connected elements (Javadi et al., 2020). An ultrasonic array transducer consists of numerous piezoelectric elements stimulated with carefully timed pulses to generate wave beams that sweep across different specimen areas. This causes the wave fronts of the delayed signals to combine and create Huygens' interference patterns (Xu & Zhou, 2014). An array offers the advantage of enhanced image quality due to its ability to manipulate the direction and focus of ultrasound by adjusting the time delay between firing the elements of the array (Singh et al., 2020).

Ultrasonic arrays are increasingly being adopted as a standard technology across various industries due to their ability to implement advanced detection and imaging techniques (Ménard et al., 2020). An ultrasonic array is a transducer with several interconnected parts (Drinkwater & Wilcox, 2006). The phased array beams can be electrically scanned, guided, swept, and focused during the defect identification. Ultrasonic beam steering optimizes the selected beam angle by directing it perpendicular to the displayed defect (Szávai et al., 2016).

4 Phased Array Ultrasonic Testing (PAUT)

Ultrasonic inspection has been used since World War II to check the safety and quality of industrial equipment. In the 1960s, phased array ultrasonic testing (PAUT) was developed, using transducers with multiple emission sources. PAUT is mainly used in the media industry, but in the 1980s, it began being applied to assess industrial equipment (Payão Filho et al., 2022). Phased array ultrasonic testing has become more popular in recent years because it offers better imaging, greater flexibility, and the ability to perform fast and multiple inspections (Sumana & Kumar, 2020). PAUT is an advanced type of non-destructive testing employed to evaluate defects, including weld joints (Jayasudha & Lalithakumari, 2022). PAUT has developed popularity in numerous NDE applications because of its superior array flexibility compared to single-element transducers (Sweeney et al., 2023). Considering the advancement of UT technology, PAUT has taken the role of traditional ultrasonic methods and NDT testing in a wide range of evaluation applications, particularly in assessing post-welding (Huggett et al., 2017).

Ultrasonic phased arrays have effectively detected defects, measured thickness, and analysed welding inspections (Feng & Qian, 2020). The latter offers several advantages when comparing systems that use single-element transducers to those that use ultrasonic arrays (Phased Array Ultrasonic Testing). Firstly, it provides higher and faster inspection flexibility, allowing for scanning complex geometric components. Secondly, it enables synthetic scanning and focusing aperture. Lastly, it allows scanning at various angles and positions while keeping the transducer stationary (Javadi et al., 2020). Another advantage of the Phased array ultrasonic testing technology is its ability to achieve deflection, focussing, and scanning, resulting in improved detection of material defects (Gao et al., 2024). Conventional phased array ultrasonic testing employs multi-element probes and a hardware delay law to concentrate the beam on specific specimen locations (Chabot et al., 2020). PAUT has the characteristics of a compact transducer and high inspection precision due to proper time-delayed pulses of array elements (Li et al., 2019). Phased arrays have many piezoelectric transducers, arranged in a linear or matrix fashion (Duernberger et al., 2022). Figure 1 illustrates the process of weld testing using the phased array ultrasonic testing. The equipment primarily includes a probe array, encoder, and acquisition unit. During the testing process, the probe comprises a sequence of piezoelectric transducers connected to the evaluated structure. These transducers are provided with gel or water. The test can be positioned on or near the base metal component, and the probe must be systematically traversed along the weld. Figure 1 illustrates the X direction, also known as the Scan-direction, which refers to the direction in which the probe moves (Bouzenad et al., 2022).

4.1 PAUT Inspection of Weld Imperfections

Bouzenad et al. (2022) conducted a study on PAUT testing and presented a simulation validation. They tested three different situations using ultrasonic testing, including numerical modelling to simulate real defects like holes or artificial voids. In the final case, they performed in-situ testing to examine natural defects. The specimen is a V-butt welded joint connecting two carbon steel pipes, each with a thickness of 7.62 mm and a circumference of 300 mm, as shown in Figure 2. The results show that to best detect defects, scanning should be done on both sides of the weld beam using the 1/PAUT method, with the welding probe positioned at different distances of the welding probe, specifically Y_{Offset}..

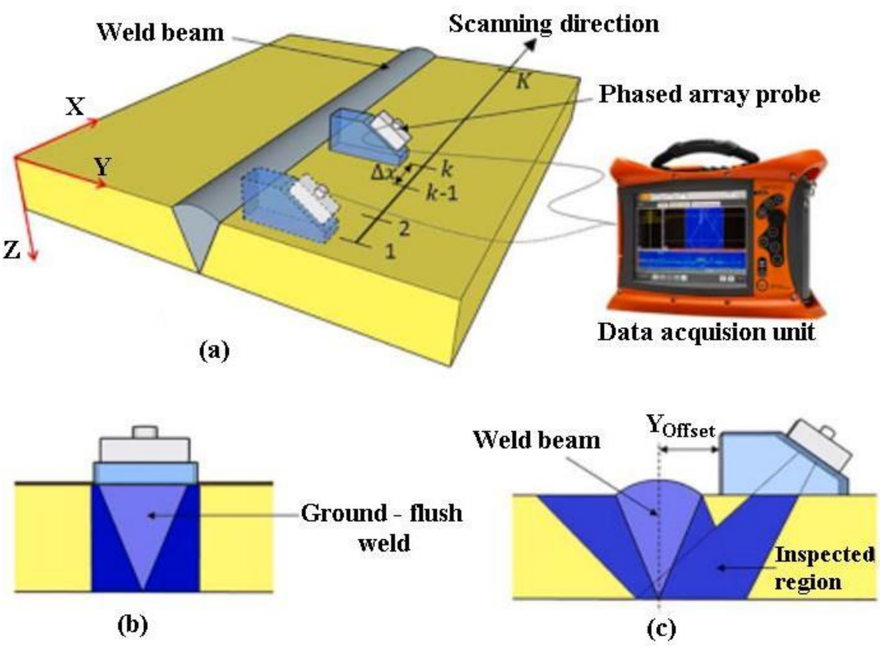


Figure 1: The lateral weld beam experimental setup (a), the B-scan for a ground-flush weld (b), and the S-scan for a regular weld (c) comprise the weld beam PAUT inspection process (Bouzenad et al., 2022)

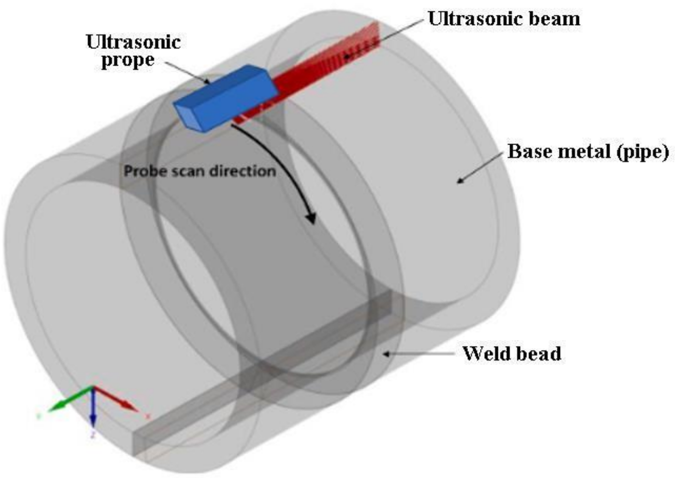


Figure 2: An example of the specimen (pipe) in 3D design (Bouzenad et al., 2022)

Phased array ultrasonic testing (PAUT) has proven to be a powerful tool for assessing the quality of joints. It provides clear images that help differentiate between bonded and de-bonded areas, using different colours and intensities. Upadhyay et al. (2019) studied the PAUT inspection of an explosively welded stainless steel and aluminium joint. They created A-scan, B-scan, and C-scan images from all sections of the plate. The C-scans showed the bonded and de-bonded areas in different colours and intensities. The results confirmed that more than 70% of the SS-Al joint was bonded.

PAUT offers clear advantages over traditional ultrasonic testing (UT) for detecting critical flaws. Ali et al. (2023) studied the challenges of using PAUT to identify defects in friction stir welded Al 6061-O plates. They estimated three defect parameters: (a) defect length, (b) defect height, and (c) defect position using PAUT. The quality of the results depends on several key factors that affect the probability of detection (POD). PAUT has been shown to have a higher probability of detection, but it is important to choose the right probe, scanning method, and defect orientation to get consistent results. The study also found that PAUT can effectively detect lack of fusion (LoF) defects.

Analysing the location and size of defects in weld region is crucial, so welding defects should be defined in three dimensions. The 3D PAUT technique is used for this purpose. Provencal and Laperrière (2022) studied a method that simultaneously identifies weld geometry and defects, while reconstructing both the surface of the welded joint and the defects. Welding defects can include lack of fusion (LoF), slag, incomplete root penetration, root fusion issues, cracks, and porosity. Figure 3 shows the data used in the segmentation model. The initial column displays the S-scan input column, the second column shows the identified weld imperfections, and the final column labels the weld geometry class.

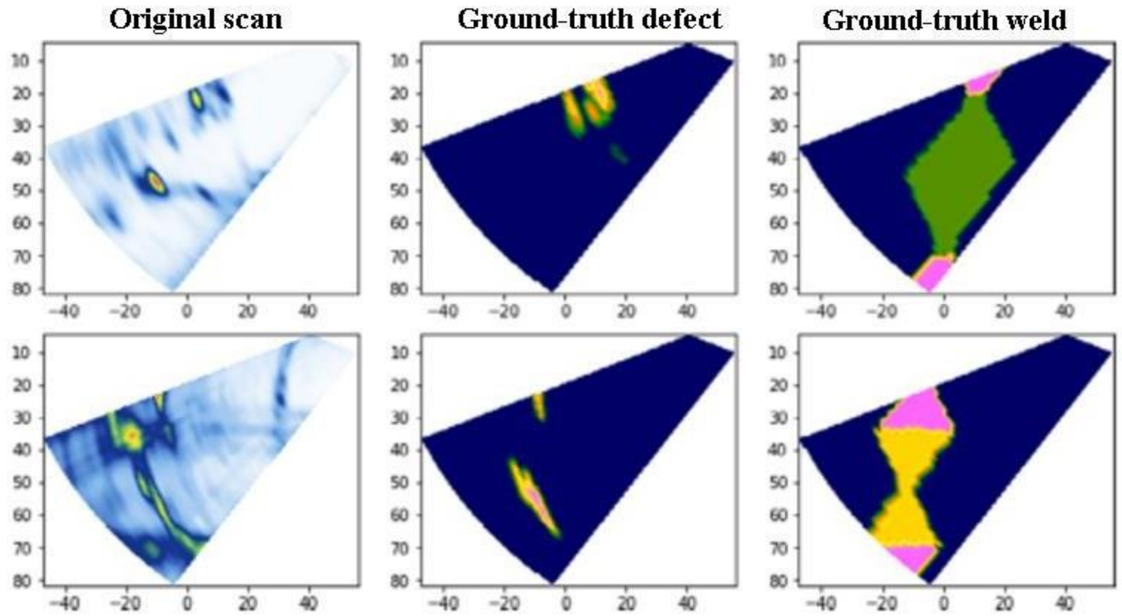


Figure 3: Sample input and ground-truth data. Weld geometry (final column): base material (blue), incomplete reflection (pink), single V (green), double V (yellow) (Provencal & Laperrière, 2022)

One of the major problems in welded joints is lack of penetration, especially at the weld root. PAUT is effective in accurately detecting lack of penetration in the weld region. Mandache et al. (2012) conducted a study to identify penetration defects in butt joint friction stir (FS) welds. Figure 4 shows the results of the PAUT analysis on these joints. The study found that PAUT could detect reflections caused by defects up to about 160 mm, but not beyond 179 mm from the initial welding point. Although there were signs between the cursors at 217 and 235 mm in subsequent results, these indications did not surpass the background noise level in the signal. Therefore, they cannot be attributed to discontinuities in the weld.

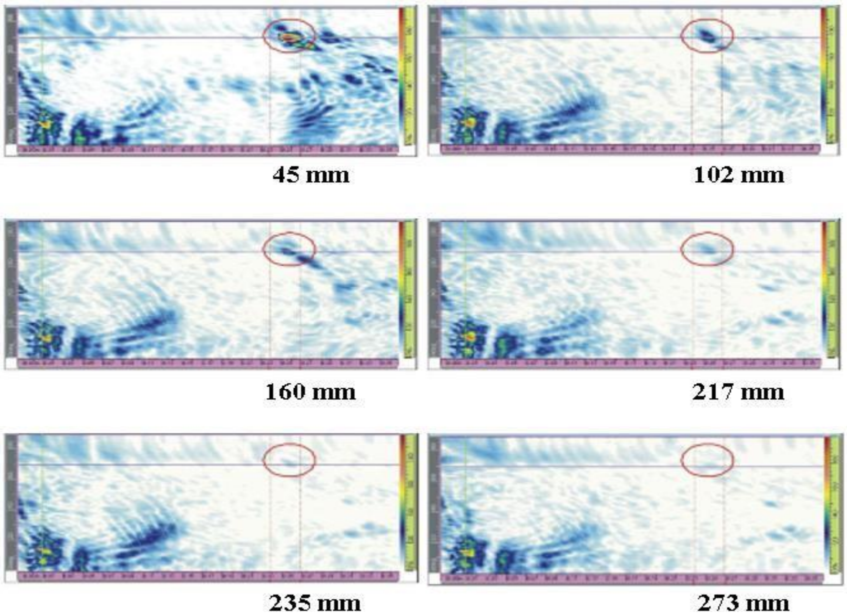
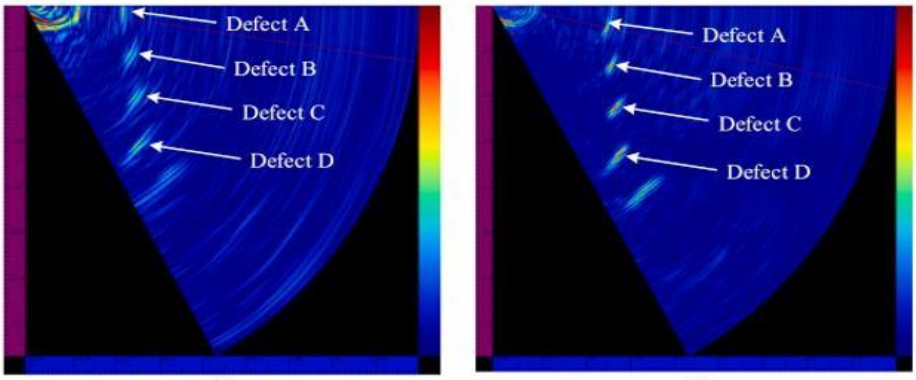


Figure 4: Phased array ultrasonic sectorial scans are varying distances from butt weld start (Mandache et al., 2012)

Numerous studies have been conducted on applying phased arrays in welding joints, specifically in V-groove weld designs. One of these studies is the work titled "Application research on ultrasonic phased array detection algorithm for austenitic stainless steel with V-groove weld" conducted by Li et al. (2024). The analysis uses a central frequency of 10 MHz with 32 array elements with respective element spacing of 0.6 mm and 0.5 mm. Figure 5 shows the phased array detection results, indicating the exact location of the defect. Additionally, the image clarity and correction are significantly improved, as shown in the comparison image before and after applying the focusing law correction.

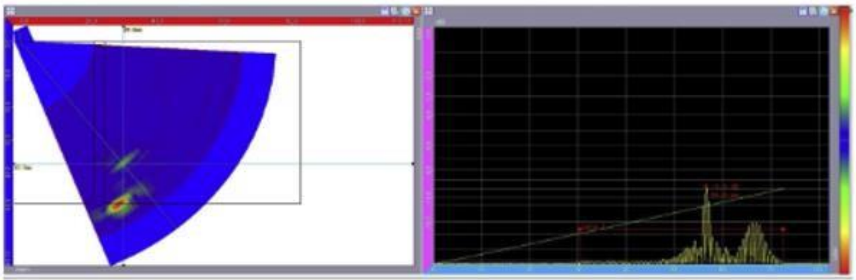
The success of phased array ultrasonic testing for weld defects like vertical cracks, lack of fusion, and lack of penetration depends on whether a dual element matrix probe or a single linear array probe is used. Fu et al. (2019) studied vertical defects in electron beam butt joints using a performance probe. They tested the defects with a 2.5 MHz 64-element dual element matrix probe and a 2.25 MHz 64-element single linear array probe. Figure 6 shows the lack of penetration in the EBW test sample was determined using the PAUT of dual element matrix array probe at 2.5 MHz and single linear array probe at 2.25 MHz. The results show that the outcomes obtained with both types of probes are of acceptable quality.

PAUT also provides very good results in inspecting weld regions on circular surfaces (pipes). Zhou et al. (2018) studied PAUT for detecting and measuring circumferential surface cracks in welded steel pipes. Figure 7 shows the results from standard A-scan data and sectorial scan data obtained using phased array ultrasound on a welded pipe sample.

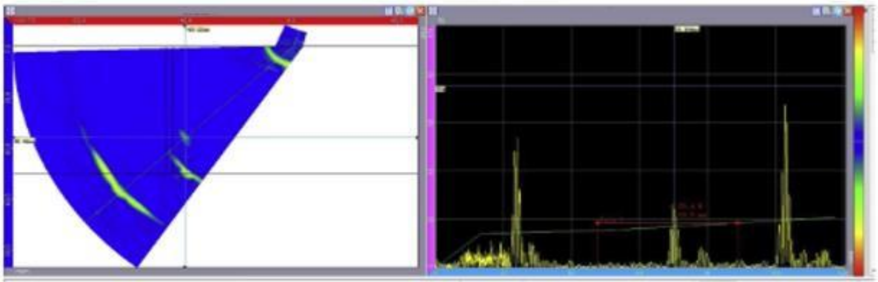


(a) (b)

Figure 5: Sector testing results (a) before and (b) after correction of focusing law (Li et al., 2024)



(a)



(b)

Figure 6: The lack of penetration in the EBW test sample was determined using the PAUT (a) dual element matrix array probe at 2.5 MHz and (b) single linear array probe at 2.25 MHz (Fu et al., 2019)

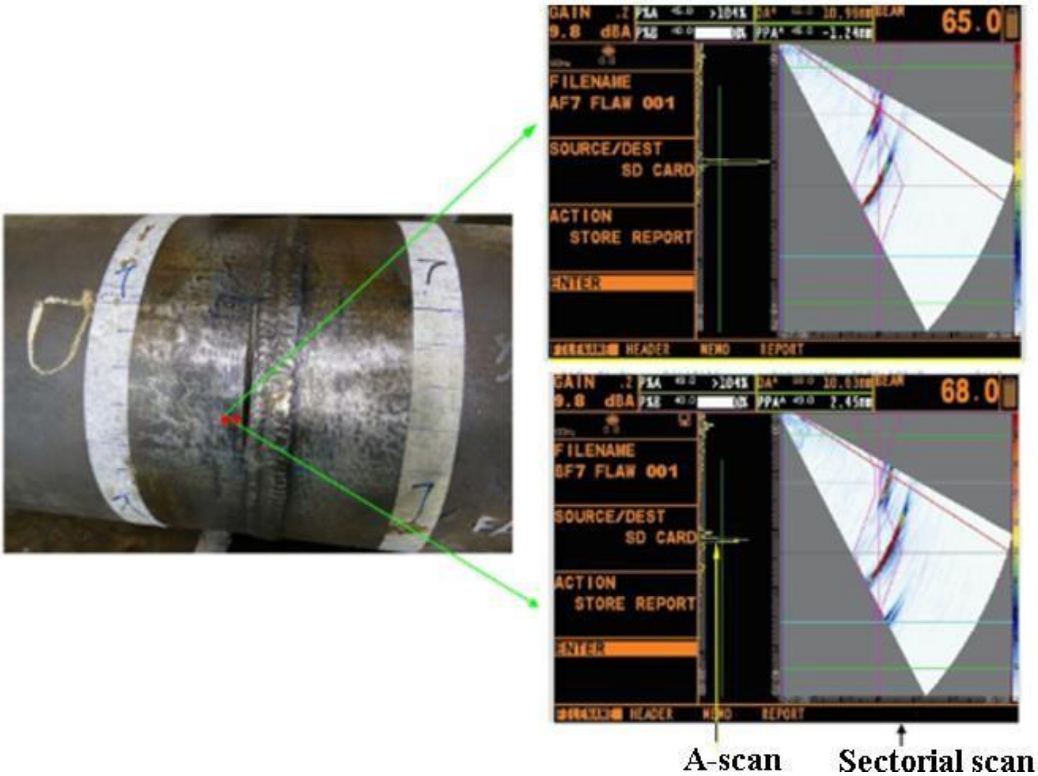


Figure 7: Typical A-scan and sectorial scan measurements taken at various points along the welded pipes (Zhou et al., 2018)

PAUT signals have been improved with the support of artificial intelligence (AI), making it easier to detect small weld defects, such as microcracks. Kim & Lee (2024) studied AI for phased-array ultrasonic testing, using training data sets and neural networks to help differentiate between normal and defect signals. They analysed 20 welded joint samples using OmniPC software to extract A-scan signals. Figure 8 shows a comparison between the S-scan image from the OmniPC program and the S-scan image from the study's method. Although the colours differ, the two results are similar and can be easily compared. Figure 9 shows the B-scan and C-scan results, which share the same X-axis during scanning, with both normal and defective signals shown at the same time.

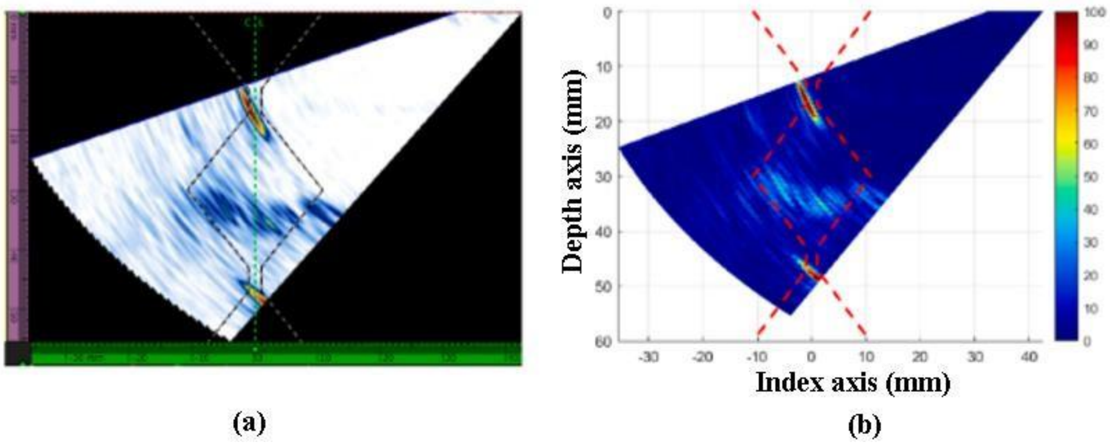


Figure 8: The outcomes of (a) the OmniPC program and (b) the coordinate transformation technique on S-scan images (Kim & Lee, 2024)

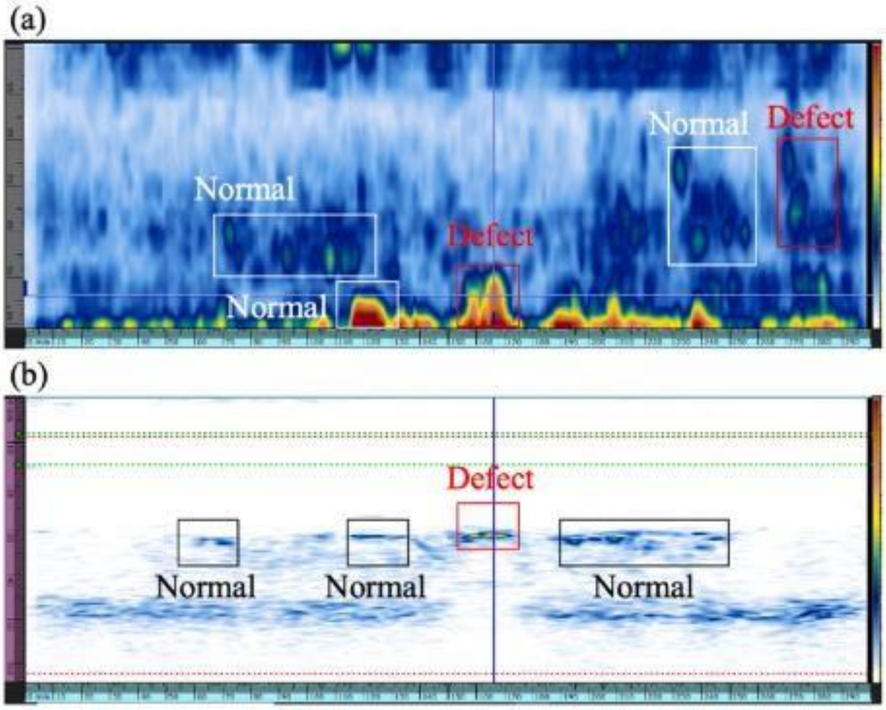


Figure 9: (a) C-scan and (b) B-scan images (Kim & Lee, 2024)

Some researchers have focused on the comparison between the detection capabilities and characterization of flaws in welded joints using phased array ultrasonic testing (PAUT) and radiographic testing (RT). One of these researchers, Harara & Altahan (2018), studied and compared phased array ultrasonic testing (PAUT) and radiographic testing (RT) to examine welded joints on steel plates. In this study, four specimens, each 35 mm thick, were analysed using both PAUT and RT methods to detect any faults in the welded connections. It has been concluded that, when a suitable PAUT procedure is applied, using the PAUT technique instead of RT is much more advantageous, as it is faster and poses no health risks to humans. Figure 10 shows images of welded joints assessed using both radiographic and PAUT methods. The radiograph indicates slag infiltration but no fractures. In contrast, the PAUT image clearly shows three indications and provides detailed information about the type, location, and size of each defect in the welded joint.

Phased array ultrasonic testing (PAUT) is commonly used to detect defects in welds created by different welding methods. In particular, the study by Deepesh et al. (2019) investigated the friction welding of tube-to-tube plates using an external tool (FWTPET) to develop an effective PAUT method for detecting and characterizing defects. This technique introduces a new method for connecting the tube to the tube plate and requires a detailed investigation to identify and characterize any defects in the weld. Figure 11 shows the results of the PAUT analysis, revealing internal defects. It was found that the defect alters the reflection pattern on the edge of the tube.

Figure 12 displays PAUT images showing void and ring tunnel defects. Once an indication is detected, the size and location of the de-bonding defect can be assessed by analysing the A-scan signals. Specifically, the severity and position of the defect can be estimated by examining the defect signal's amplitude and the reduction in the edge amplitude.

Figure 13 shows macrographs of the FWTPET specimen, illustrating de-bonding on the root side, a ring tunnel defect, a cavity, and excessive flash. In the case of ring tunnel defects, there is a noticeable decrease in the edge signal. It can be concluded that digital radiography and phased array ultrasonic testing provide more significant results.

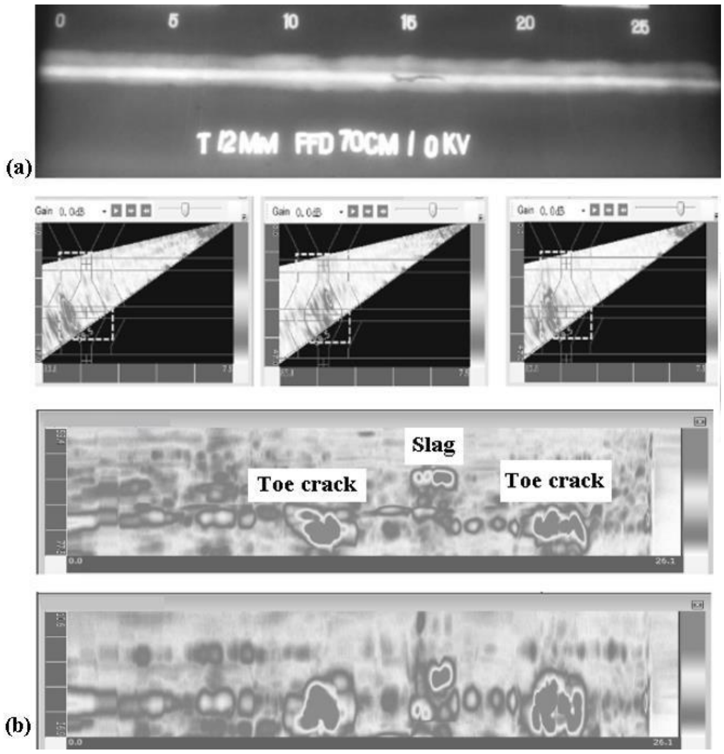


Figure 10: The second welded joint's testing results from (a) RT and (b) PAUT, as well as the indications of faults found by each of the two inspection methods (Harara & Altahan, 2018)

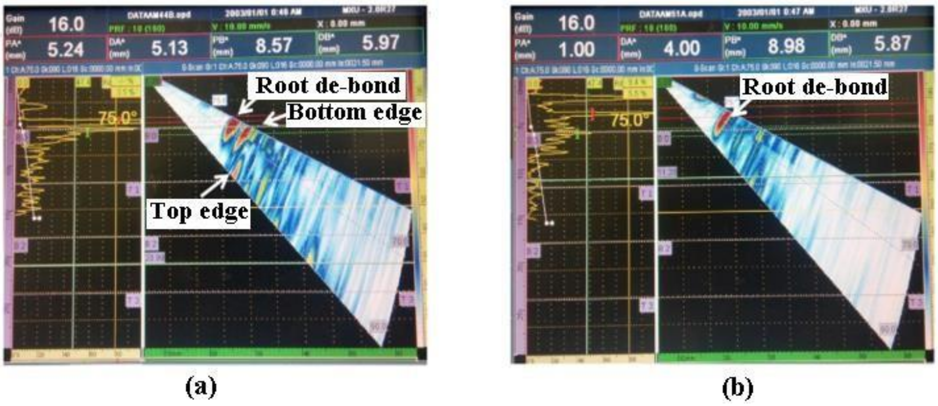


Figure 11: Image from PAUT displaying root de-bonding defects (Deepesh et al., 2019)

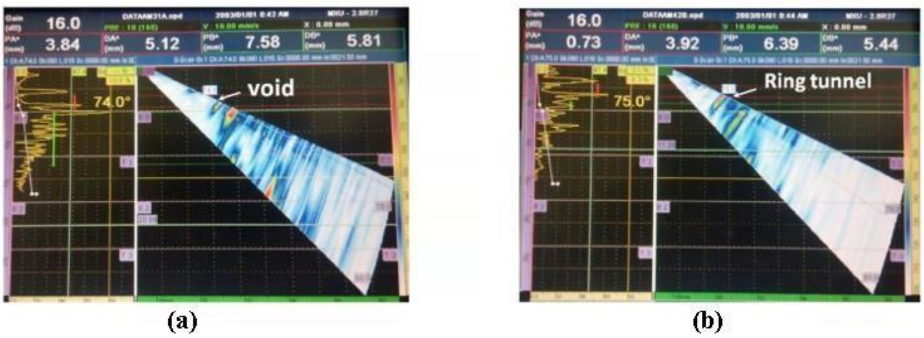


Figure 12: PAUT image showing (a) void (b) ring tunnel (Deepesh et al., 2019)

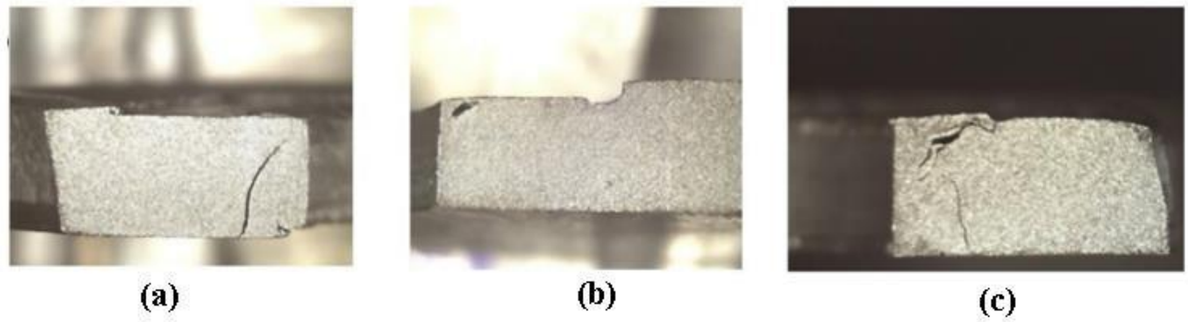


Figure 13: FWTPET specimen macrographs illustrating (a) de-bonding on the root side, (b) a ring tunnel, and (c) a cavity and excessive flash (Deepesh et al., 2019)

PAUT can be used to detect imperfections in welds from various welding techniques. Kumar et al. focused on PAUT analysis to examine defects in welded joints made using the shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) welding methods. In this study, welded samples of SS 316LN and Alloy 800, containing artificial defects such as lack of fusion, were created using metal arc welding. Figures 14 and 15 show the S-scan results of the GTAW and SMAW weld samples from both the SS 316LN side and the Alloy 800 side, respectively. In these diagrams, Defect 1, Defect 2, and Defect 3 are identified for each welding technique, with each having different depth values. The size and depth of the defects depend on the scanning direction and the orientation of the defects. The S-scan method enables precise detection of defects on both sides of the weld.

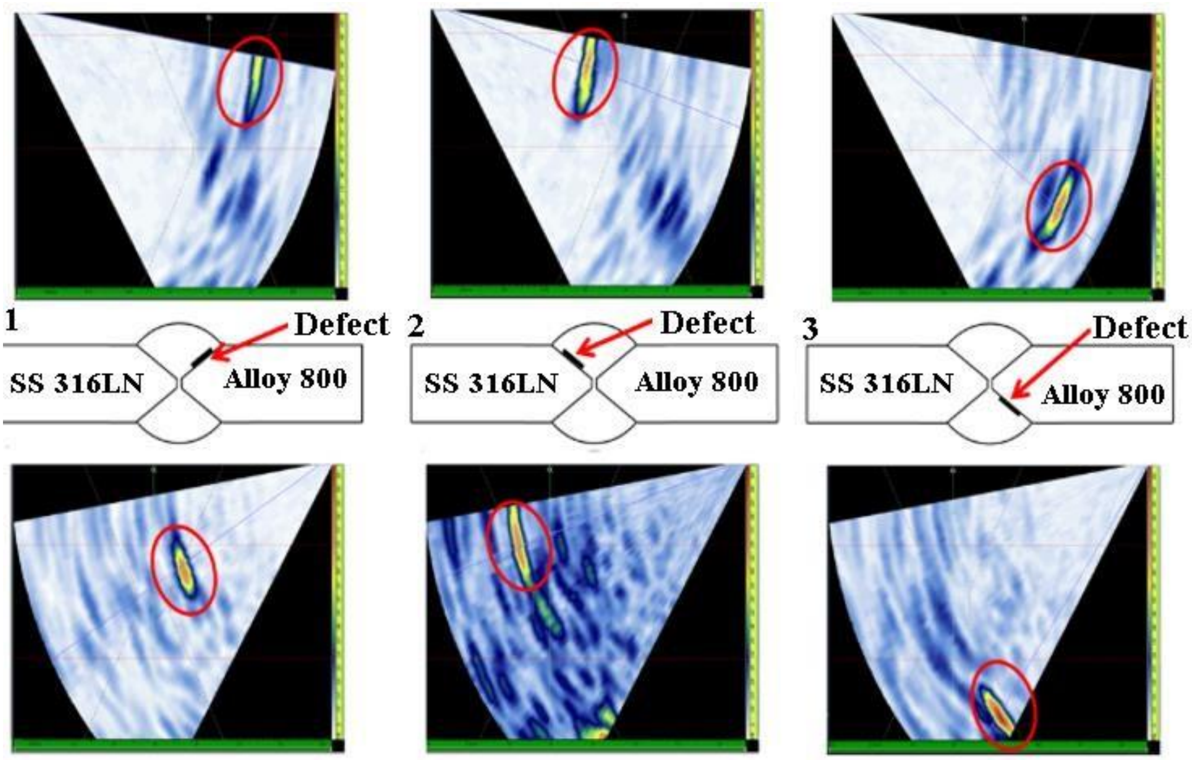


Figure 14: The GTAW weld sample was scanned (S-scan) from the SS 316LN side (top) and the Alloy 800 side (bottom) (Kumar et al, 2022)

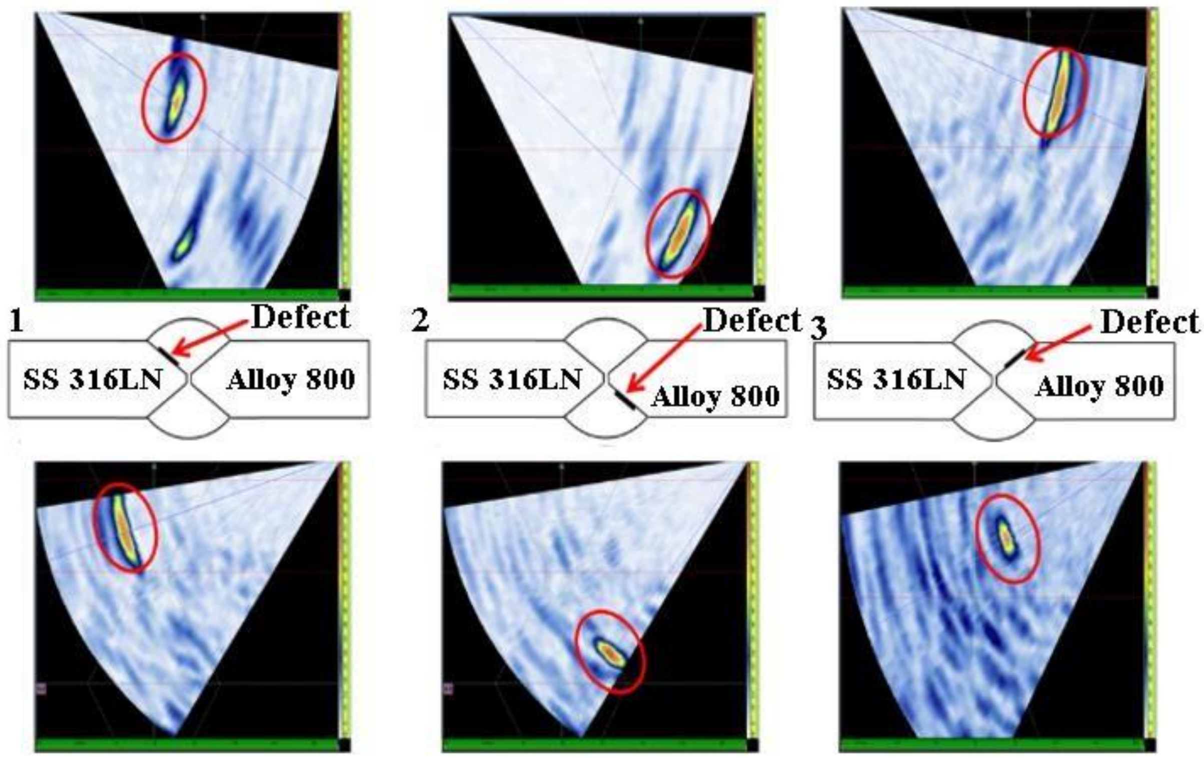


Figure 15: The SMAW weld sample was scanned (S-scan) from the SS 316LN side (top) and the Alloy 800 side (bottom) (Kumar et al, 2022)

5 Conclusions

This study comprehensively reviewed recent progress in non-destructive testing of weld joints using phased array ultrasonic testing (PAUT), which is an efficient method for detecting internal weld defects. It was also concluded that the main advantages of PAUT over conventional ultrasonic testing include improved inspection times and efficiency, increased reliability of measurements, and the ability of phased array probes to capture hundreds of signals simultaneously, which allows for faster flaw identification and weld quality assessments. Based on these observations, the following conclusions were drawn:

(a) The PAUT technique is widely recognized for its ability to detect both bonded and de-bonded areas in different material joints, making it highly effective for examining welded specimens.
(b) To detect and characterize defects in welded joints, the phased array ultrasonic testing (PAUT) procedure must involve simultaneous sectoral scanning of both sides of the weld axis, using an encoder and phased array probes.
(c) The PAUT analysis shows a high probability of detection, but some factors need careful attention. Inconsistent results can arise from parameters such as probe selection, operator skill, scanning method, and defect orientation.
(d) The PAUT technique is effectively used to detect defects in joints made by various welding methods.

6 Declarations

6.1 Study Limitations

Phased Array Ultrasonic Testing (PAUT) is an important method within ultrasonic non-destructive testing, effectively detecting defects, measuring thickness, and analysing welds. This review considers imperfections or defects in welded joints using the PAUT.

6.2 Competing Interests

There is no conflict of interest in this study.

6.3 Authors' Contributions

Desi GUSTIANI: Contributed to the process of developing, arranging, and presenting data for an article. The responsibility for doing a comprehensive literature review as part of the research process and responsible for authoring the full main manuscript.

Hüseyin UZUN: Contributed to the process of identifying concepts, supervising, and reviewing. In addition, responsible for analysing and interpreting the findings of the article.

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