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APPLICATION OF THE WAVE EQUATION IN ACOUSTIC AND VIBRATION ENGINEERING: A GLOBAL BIBLIOMETRIC REVIEW

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Abstract:

The wave equation serves as a fundamental mathematical framework in acoustic and vibration engineering, supporting analyses of wave propagation, sound transmission, vibration control, and structural dynamics. Despite its importance, global research on this topic has not been systematically mapped through bibliometric analysis, leaving limited insight into its knowledge structure, emerging themes, and collaboration patterns. This study presents a comprehensive bibliometric review of research on the application of the wave equation in acoustic and vibration engineering. Data were extracted from the Scopus database using the keywords "wave," "acoustic," and "equation," resulting in 883 publications. The Scopus Analyzer was used to examine publication trends, leading countries, institutions, and journals, while OpenRefine ensured data accuracy. VOSviewer further visualized co-authorship networks, keyword co-occurrence, and thematic clusters. Findings reveal a steady increase in publications over the past decade, largely driven by technologically advanced countries with strong international collaborations. Major research themes include computational modeling of wave propagation, acoustic material design, vibration mitigation, and digital simulation integration. Overall, this study provides a quantitative and visual overview of global research activity, offering valuable insights for researchers, practitioners, and policymakers to identify gaps, strengthen collaborations, and guide future research directions.

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Keywords:

Wave Equation, Acoustic Engineering, Vibration Control, Bibliometric Analysis, Research Trends, VOSviewer

Introduction

The wave equation is a fundamental type of partial differential equation, which plays a vital role in the study and application of acoustics and vibration engineering. Originating from d'Alembert's solution to the vibrating string problem, the wave equation has since been discovered to have extensive applications in various engineering domains, including structural engineering, geophysics and medical imaging (Armstead & Karls, 2006), (Bartolo, 2021), (Oliveira, 2021). This equation describes how waves propagate through different media, making it indispensable for modeling sound propagation, vibration analysis and other wave-related phenomena (Gao, 2017; Godin, 2011; G. Liu et al., 2016). Moreover, the versatility and robustness of the wave equation make it a powerful tool for engineers and researchers aiming to solve complex problems in acoustics and vibrations.

The wave equation's application in acoustic engineering is well-documented, particularly in the modeling of sound propagation and scattering. For example, the acoustic wave equation is crucial for analyzing sound propagation in heterogeneous media. It enables the simulation of wave behavior and the study of scattering effects in such environments (Godin, 2011; Schaeken et al., 2022). This capability is crucial for applications such as medical ultrasound and geophysical subsurface imaging, where accurate wave propagation models are necessary for effective imaging and analysis (Bartolo, 2021; Schaeken et al., 2022). Furthermore, the wave equation is used in the development of numerical methods like the Correction Procedure via Reconstruction (CPR), which enhances the accuracy and efficiency of solving acoustic problems (G. Liu et al., 2016).

In vibration engineering, the wave equation is equally significant. It is used to model the vibrations of structures such as beams, strings and plates, providing insights into their dynamic behavior under various conditions (Honegger et al., 2024; Oliveira, 2021). For example, the Euler-Bernoulli beam theory, which is based on the wave equation, is widely used to analyze bending vibrations in beams (Honegger et al., 2024). Note that the wave equation is applied in the study of friction-induced vibrations and acoustic emissions, which are critical for understanding and mitigating noise and wear in mechanical systems (Olejnik & Desta, 2025). These applications highlighted the wave equation's role in diagnosing and optimizing the performance of vibrating structures.

Other than that, the integration of the wave equation with advanced computational techniques has further expanded its applications. Methods such as the Finite Difference Time Domain (FDTD) and the staggered-grid approach have been developed to solve the wave equation numerically, allowing for the simulation of complex wave phenomena in various engineering contexts (Chappell et al., 2014; Schaeken et al., 2022). These techniques enable the detailed analysis of wave interactions with different materials and structures, facilitating the design and optimization of engineering systems. For example, the use of wave equations in the analysis of subsonic flows and their interaction with vibrating structures has led to improved noise reduction strategies in aeronautical engineering (Hussain et al., 2024).

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Furthermore, recent advancements in metamaterials have also leveraged the wave equation to achieve superior control over acoustic and elastic waves. Metamaterials, with their unique structural characteristics, can manipulate wave propagation in ways that traditional materials cannot (Ma, 2025). This has led to significant breakthroughs in sound absorption, noise reduction and vibration isolation with applications spanning from aerospace to consumer electronics (Ma, 2025). The wave equation provides the theoretical foundation for designing these metamaterials, enabling engineers to predict and tailor their wave-manipulating properties effectively.

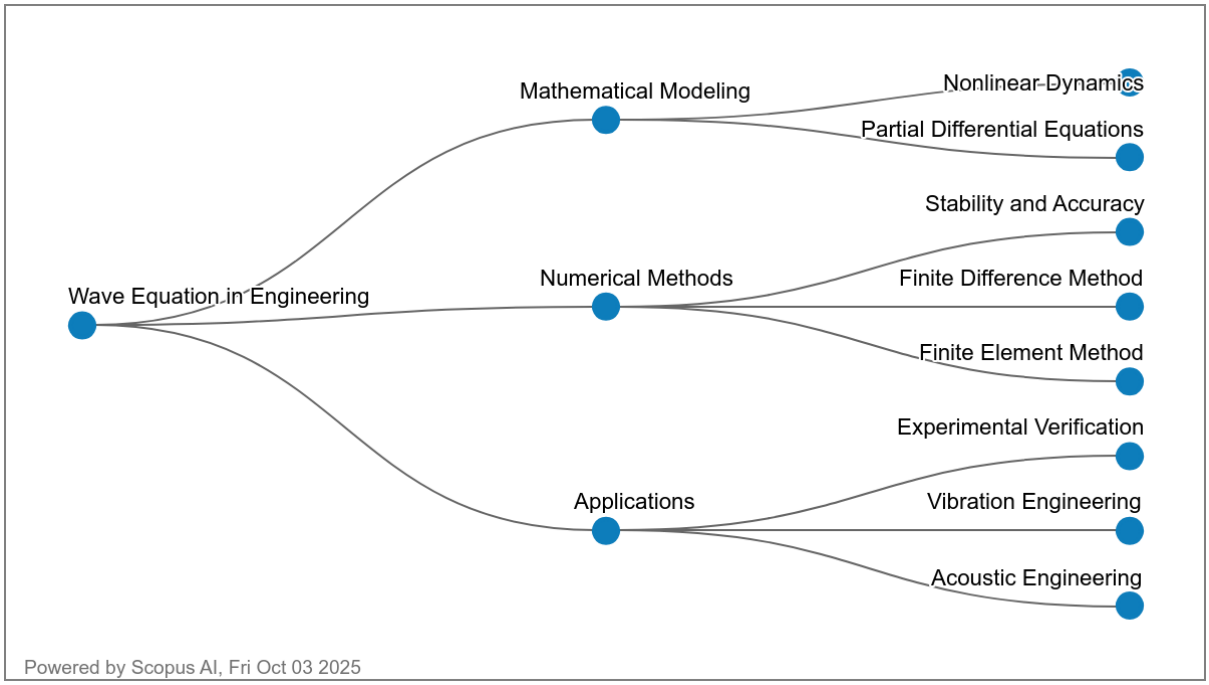

Figure 1: Concept Map of Application of the Wave Equation in Acoustic and Vibration Engineering

Source: (Scopus AI, Fri Oct 03 2025)

Figure 1 presents the concept map illustrating the application of the wave equation in acoustic and vibration engineering. It outlines the fundamental pathways through which the wave equation is applied within these engineering fields. It begins with Mathematical Modeling, which includes nonlinear dynamics and partial differential equations as core theoretical tools. From there, numerical methods such as the finite difference method and the finite element method are applied to solve the wave equation, ensuring stability and accuracy in simulations. These methods are often validated through experimental verification. Finally, the results and models are applied to real-world scenarios, especially in vibration and acoustic engineering. In these fields, understanding wave behavior is essential for effective system design and analysis. This integrated approach highlights how mathematical theory, computational tools and practical engineering converge to leverage the wave equation in solving complex dynamic problems in acoustics and vibrations.

In summary, the wave equation remains a cornerstone of acoustic and vibration engineering, underpinning a wide range of applications from structural analysis to advanced material design. Moreover, its ability to model wave propagation with high accuracy has made it a powerful analytical tool in engineering. When integrated with modern computational methods, it

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continues to drive innovation and remains indispensable to both researchers and practitioners.

Research Question

RQ1: What are the research trends in this field based on the annual distribution of publications?
RQ2: Which are the top 10 most cited articles in this area of study?
RQ3: Which countries are the top 10 contributors based on the number of publications?
RQ4: What are the most frequently used keywords associated with this research field?
RQ5: What are the patterns of international collaboration based on co-authorship among countries?

Methodology

Bibliometrics is a powerful methodology that entails the systematic collection, organization, and analysis of bibliographic data from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). Beyond fundamental metrics such as key journals, publication years and prominent authors, it employs advanced techniques like document co-citation analysis to uncover deeper patterns and intellectual structures within a research domain (Wu & Wu, 2017). Conducting a rigorous literature review requires a carefully structured, iterative approach involving the strategic selection of keywords, comprehensive literature searches and in-depth analytical evaluation. This process ensures the construction of a well-rounded bibliography and the generation of reliable, meaningful insights (Fahimnia et al., 2015). In this context, the present study focused on high-impact publications. Hence, these works are valuable as they highlight the core theoretical frameworks that define and shape the field. In order to ensure data accuracy and coverage, Scopus was used as the primary data source (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). To maintain scholarly rigor, only peer-reviewed journal articles were included, deliberately excluding books and lecture notes to ensure consistency and quality (Gu et al., 2019). Note that the final dataset comprised publications indexed in Elsevier's Scopus from 1951 through September 2025, offering a current and relevant foundation for bibliometric analysis.

Data Search Strategy

To ensure the relevance and quality of the literature analyzed, a structured search strategy was employed using the Scopus database, renowned for its comprehensive coverage of peer-reviewed research. The search was conducted on Oct 03 2025, using the advanced search query shown in Table 1: TITLE ("wave" AND "equation" AND "acoustic") AND (LIMIT-TO (LANGUAGE, "English")). This query was designed to retrieve documents with high topical relevance by requiring all three keywords: *wave*, *equation*, and *acoustic* to appear in the title field. A systematic screening process was followed, based on predefined inclusion and exclusion criteria summarized in Table 2. Note that only English-language publications were included to maintain linguistic consistency and avoid translation limitations. In terms of literature type, the study focused exclusively on journal articles, which typically undergo peer review and offer a complete presentation of research findings. Consequently, conference proceedings, book chapters and reviews were excluded to ensure data uniformity and quality. Only final-stage publications were selected, deliberately omitting any articles still listed as "in press." As a result of this rigorous search and screening process, a total of 883 journal articles were retrieved. This carefully curated dataset served as a strong foundation for the subsequent bibliometric analysis, ensuring that the findings were derived from high-quality, relevant and thematically coherent research outputs.

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Table 1: The Search String

Scopus	TITLE (“wave” AND “equation” AND “acoustic”) AND (LIMIT-TO (LANGUAGE , “English”)) Access date October 2025

Table 2: The Selection Criterion Is Searching

Criterion	Inclusion	Exclusion
Language	English	Non-English
Literature tpe	Journal (Article)	Conference, Book, Review

Data Analysis

VOSviewer was developed by Nees Jan van Eck and Ludo Waltman at Leiden University, Netherlands (van Eck & Waltman, 2010, 2017). It is a widely adopted bibliometric tool renowned for its user-friendly interface and advanced capabilities in visualizing and analyzing scientific literature. The software excels in generating intuitive network visualizations, clustering related items and constructing density maps that offer deep insights into the structure of scholarly domains. Its versatility allows researchers to explore co-authorship, co-citation and keyword co-occurrence networks. Through this, they can gain a deeper and more nuanced understanding of complex research landscapes. The platform’s interactive design and regular updates ensure seamless navigation and dynamic analysis of extensive bibliographic datasets. VOSviewer offers robust functionality that includes metric computation and customizable visualization. These features make it an essential tool for scholars seeking to uncover patterns within extensive scientific datasets.

A key strength of VOSviewer lies in its ability to convert complex bibliometric data into visually accessible maps and graphs. By emphasizing network-based analysis, it effectively identifies keyword co-occurrence clusters and thematic connections. This approach allows both novice and expert users to interactively explore and understand scholarly trends. Moreover, its continuous development further enhances its relevance in bibliometric research by ensuring compatibility with diverse data formats and sources. By focusing on network-based analysis, the tool can identify groups of keywords that frequently appear together. It also reveals important thematic connections across different studies. This approach helps users see how ideas are related within a field. Both new and experienced researchers can use it to explore scholarly trends interactively and insightfully. These data were analyzed using VOSviewer version 1.6.20, which applied its proprietary clustering and mapping algorithms.

Unlike traditional Multidimensional Scaling (MDS) techniques, VOSviewer emphasizes mapping items in low-dimensional space such that the proximity between any two elements accurately reflects their degree of relatedness (van Eck & Waltman, 2010). While sharing conceptual similarities with MDS (Appio et al., 2014), VOSviewer diverges by employing a more robust normalization technique tailored for co-occurrence data. Specifically, it utilizes Association Strength (AS_{ij}), calculated as:

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$$AS_{ij} = \frac{C_{ij}}{w_i w_j},$$

where C_{ij} denotes the number of co-occurrences between items i and j and $w_i w_j$ represent their total occurrences. This formulation is "proportional to the ratio between on the one hand the observed number of co-occurrences of i and j and on the other hand the expected number of co-occurrences of i and j under the assumption that co-occurrences of i and j are statistically independent" (Van Eck & Waltman, 2007). By implementing this metric, VOSviewer offers a more accurate and meaningful representation of relational strength among bibliometric entities, solidifying its role as a critical tool in scholarly network analysis.

Findings

RQ1: What Are The Research Trends In This Field Based On The Annual Distribution Of Publications?

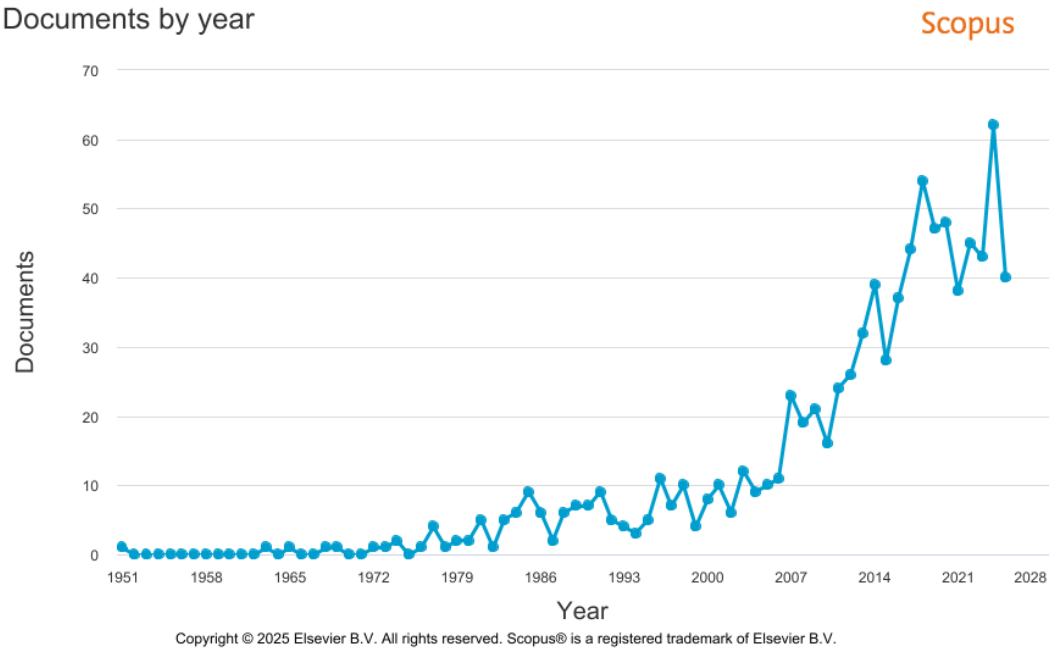

Figure 2: Number of Documents Based on Year of Publication
Source: (Scopus, Fri Oct 03 2025)

The bibliometric analysis of scholarly publications from 1951 to 2025 on the application of the wave equation in acoustic and vibration engineering reveals a distinct upward trend in research activity, especially in the past two decades. In the earlier years, the field produced only a small number of publications, averaging fewer than five per year between 1951 and the mid-1990s. During the early 2000s, a period of moderate growth began to emerge. After 2010, the number of publications increased steadily and showed a clear upward trend. Notably, publication volumes began to exceed 40 papers per year starting in 2017 and peaking at 62 articles in 2024. This trend is clearly visualized in Figure 2, which illustrates the annual distribution of publications over time. The steady growth is closely linked to technological advancements and

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the increasing global focus on precision engineering, noise control and smart materials. In these areas, wave-based modeling plays a crucial and influential role. The increase also reflects the broader accessibility of computational tools and simulation software that facilitate more sophisticated wave equation analyses in real-world acoustic and vibration systems. Additionally, growing interdisciplinary interest from fields such as mechanical engineering, materials science and applied physics has helped drive the expansion of this field.

Beginning in 2020, there was a noticeable increase in the number of publications. This rise may be partly linked to changes in research priorities after the pandemic. During that period, laboratory access was limited, and many researchers turned to virtual simulations and computational modeling. Note that these approaches became more common as alternatives to traditional experimental work. Researchers increasingly turned to theoretical and numerical investigations like wave propagation modeling to continue their work remotely. In recent years, research activity in this field has continued to grow. One reason is the increasing global interest in developing sustainable and quiet infrastructure. There is also a growing focus on precision acoustics for medical devices. In addition, new advancements in vibration control for autonomous and aerospace systems have further stimulated research in this area. As illustrated in Figure 2, the dominance of recent years in publication volume justifies the growing recognition of the wave equation as a critical mathematical tool across engineering domains. The upward trend in research demonstrates that the field has reached a higher level of maturity, indicating that development in this area is still ongoing. Therefore, future studies are expected to explore nonlinear wave behavior in greater depth. Researchers are also likely to focus on hybrid modeling techniques and the use of wave-based methods in smart and adaptive structures.

RQ2: Which are The Top 10 Most Cited Articles in This Area of Study?

Table 1: Most Cited Author

No	Authors	Title	Year	Source title	Cited by
1.	Alkhalifah (2000)	An acoustic wave equation for anisotropic media	2000	Geophysics	696
2.	Pratt & Worthington (1990)	Inverse theory applied to multi-source cross-hole tomography. Part 1: acoustic wave-equation method	1990	Geophysical Prospecting	545
3.	Schamel (1973)	A modified Korteweg-de Vries equation for ion acoustic waves due to resonant electrons	1973	Journal of Plasma Physics	513
4.	Seadawy (2014)	Stability analysis for Zakharov-Kuznetsov equation of weakly nonlinear ion-acoustic waves in a plasma	2014	Computers and Mathematics with Applications	370
5.	Duveneck et al. (2008)	Acoustic VTI wave equations and their application for anisotropic reverse-time migration	2008	SEG Technical Program Expanded Abstracts	272

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6.	Y. Liu & Sen (2009)	A new time-space domain high-order finite-difference method for the acoustic wave equation	2009	Journal of Computational Physics	258
7.	Krishnasamy et al. (1990)	Hypersingular boundary integral equations: Some applications in acoustic and elastic wave scattering	1990	Journal of Applied Mechanics	250
8.	Sugimoto (1991)	Burgers' equation with a fractional derivative; hereditary effects on nonlinear acoustic waves	1991	Journal of Fluid Mechanics	218
9.	De Basabe & Sen (2007)	Grid dispersion and stability criteria of some common finite-element methods for acoustic and elastic wave equations	2007	Geophysics	209
10.	Brown (1980)	Connection between formation factor for electrical resistivity and fluid-solid coupling factor in Biot's equations for acoustic waves in fluid-filled porous media.	1980	Geophysics	197

Source: (Scopus, Fri Oct 03 2025)

The ten most cited articles show a strong emphasis on acoustic wave theory. Many of these works are closely related to studies in geophysics and plasma physics. Their influence demonstrates the fundamental role these areas play in advancing theoretical understanding. The findings have also contributed significantly to practical applications such as seismic imaging, tomography and wave propagation modeling. The most cited study in the dataset is by Alkhalifah (2000), which has received 696 citations, introducing an acoustic wave equation designed for anisotropic media. The study represents a major advancement in accurately modeling geological formations as they exist in the real world. Similarly, the studies by Pratt and Worthington (1990) and Schamel (1973) have maintained a strong influence over time. Their research introduced mathematically rigorous models that remain highly relevant today. Even decades after their publication, these models continue to form the foundation for much of the modern research in the field. The high citation counts of older papers (1970s - 1990s) suggest they introduced fundamental methods still widely referenced.

More recent studies, such as those by Seadawy (2014) and Liu and Sen (2009), are also among the most frequently cited works. Their inclusion shows that research in this area continues to evolve. These newer studies focus on improving and refining wave equation models. The goal is to make the models more suitable for analyzing complex media and for integration with advanced computational methods. This trend reflects the growing demand for higher accuracy in simulations, driven by advancements in computing power and increasing applications in energy exploration and plasma studies. Note that articles published in reputable journals such as Geophysics, Journal of Computational Physics and Journal of Fluid Mechanics tend to receive greater attention from researchers. Their high visibility and credibility contribute significantly to their frequent citation. Overall, the results highlight the enduring relevance of

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foundational mathematical physics in acoustics and the continuing innovation in numerical methods that build upon this base.

RQ3: Which Countries Are the Top 10 Contributors Based on The Number of Publications?

Figure 3 depicts that China leads in the number of published documents with 211, followed by the United States (US) with 189. These two countries show a much higher level of research productivity compared to others. This reflects their strong investment in research and development, well-established academic institutions and substantial funding for scientific advancement. India, Saudi Arabia and South Korea come next in the ranking. However, their publication numbers are noticeably lower, placing them in a secondary tier of emerging research contributors. The remaining countries in the list are Brazil, Russia, Egypt, France and the United Kingdom. These nations show a moderate level of research activity in this field. The number of publications from each country ranges between 29 and 41. This indicates that while they are active contributors, their output is not as high as that of the leading countries.

China and the US clearly dominate in terms of research output, suggesting that this dominance is linked to several important factors. Both countries have strong economies that enable large-scale investment in research and innovation. They also maintain extensive global research collaborations that enhance visibility and impact. In addition, consistent support from government agencies and the private sector has further strengthened their position in science and technology. China's emphasis on becoming a global leader in innovation has led to aggressive expansion in research output, while the US benefits from a long-standing tradition of high-impact research institutions. At the same time, countries such as India and Saudi Arabia have focused their investments on education and research. Their emphasis on advancing technology and energy-related fields helps explain their growing presence in the research landscape. In contrast, the relatively lower output from traditionally strong academic countries such as the UK and France may be influenced by several factors. These include limitations in the dataset's scope, recent changes in research funding priorities and a more specialized focus within the publications that were included.

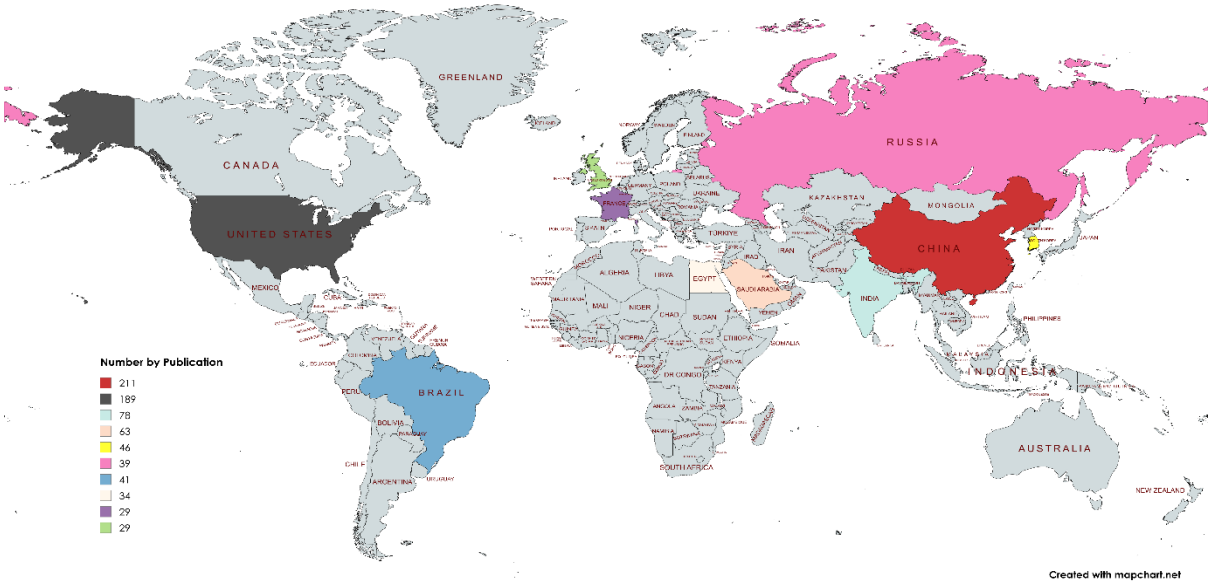

Figure 3: Country Mapping Based on The Number of Published Documents

Source: (Scopus, Fri Oct 03 2025)

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RQ4: What Are the Most Frequently Used Keywords Associated with This Research Field?

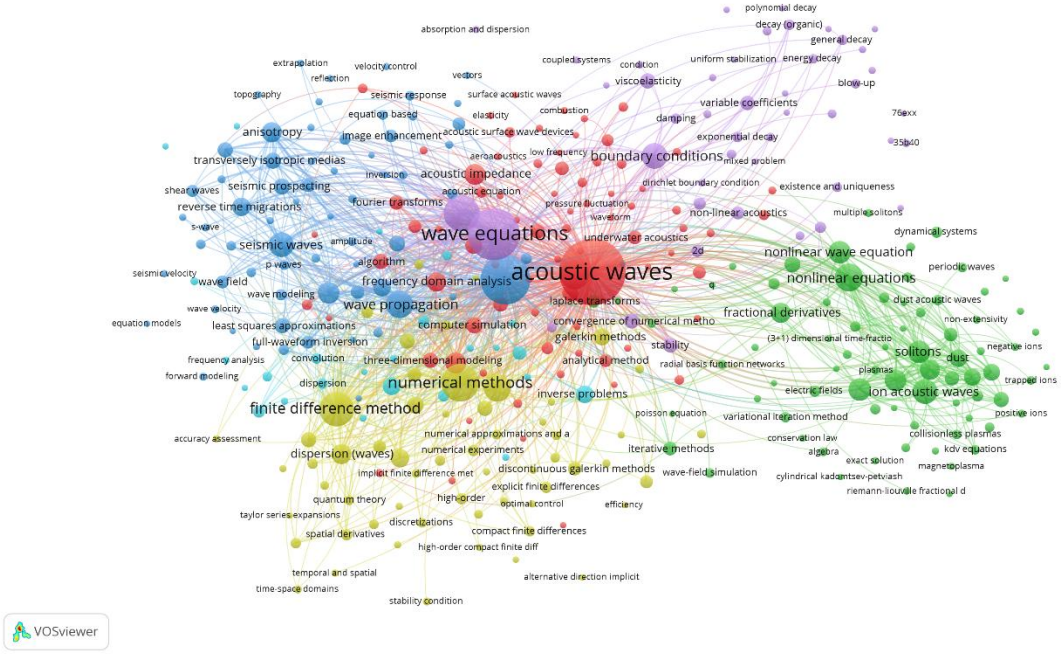

Figure 4: Network Visualization Map of Keywords' Co-Occurrence

Source: (Scopus, Fri Oct 03 2025)

Co-occurrence analysis of author keywords using VOSviewer identifies patterns and relationships among key research terms based on how often they appear together in scientific publications. By applying full counting and setting a minimum threshold of 5 keyword occurrences, the analysis narrowed down 2,431 keywords to 348, which were grouped into six distinct clusters. These clusters encompass key research themes that define the field. They include acoustic wave theory, numerical and computational techniques, seismology and geophysics, and nonlinear wave phenomena in plasma physics. Other major themes involve advanced mathematical modeling and the study of complex wave behavior under real-world conditions, particularly in anisotropic and heterogeneous media.

The findings highlight a well-structured and mature research landscape that integrates physics, mathematics, geoscience and engineering. The strong presence of numerical methods and theoretical modeling shows the field's emphasis on precision and computational efficiency, while applications range from seismic imaging to plasma wave dynamics. This analysis contributes to the body of knowledge by mapping the thematic structure of the field, revealing interdisciplinary links and identifying areas of research concentration and emerging trends.

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RQ5: What Are the Patterns of International Collaboration Based on Co-Authorship Among Countries?

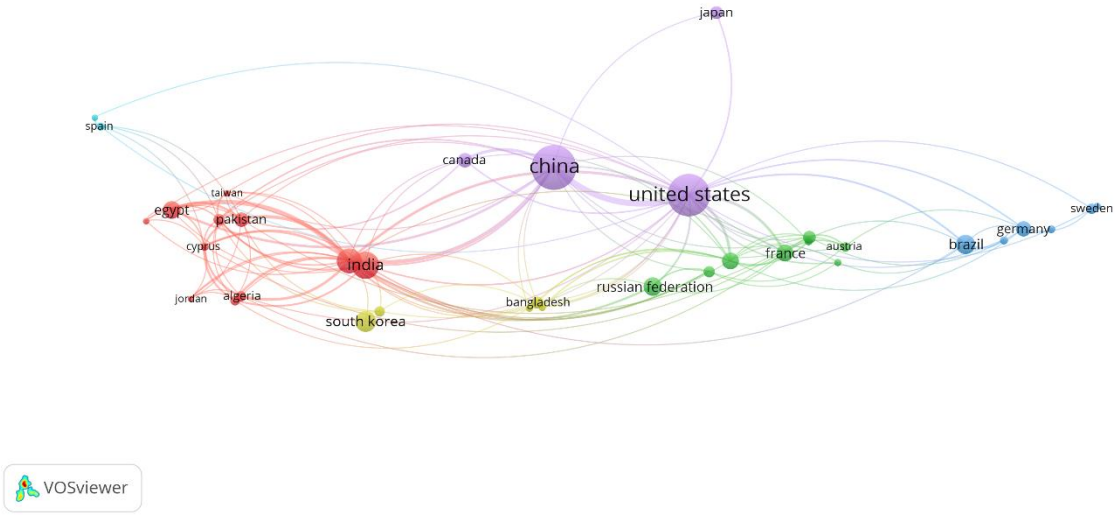

Figure 5: Network Visualization Map of Co-Authorship by Countries' Collaboration
Source: (VOSviewer, Fri Oct 03 2025)

Co-authorship analysis by countries using VOSviewer is a bibliometric method that maps and visualizes the collaborative relationships between countries based on shared authorship of scientific publications. Each country is represented as a node, and links are established when authors from different countries co-author a paper. The strength of these links reflects the frequency and intensity of collaboration. Using the full counting method, every co-authorship between countries is counted equally. With a minimum threshold of 5 publications per country, the analysis focused on 36 out of 78 countries, grouping them into six clusters based on their collaboration patterns and network strength.

The results reveal a structured global collaboration landscape in the field, highlighting key countries that serve as major hubs of international research activity. Countries with strong scientific infrastructures and high publication output tend to form central nodes, facilitating cross-border knowledge exchange. On the other hand, the six clusters reflect regional or strategic alliances such as shared research priorities or historical academic ties. These findings add valuable insights to the existing body of knowledge. They help identify which countries play the most influential roles in the field and reveal important collaboration networks among researchers. The results can be used to guide future strategies for international cooperation and research capacity building. They also provide useful input for policymakers aiming to strengthen global research impact.

Conclusion

The purpose of this study was to map the global research landscape on the application of the wave equation in acoustic and vibration engineering through bibliometric analysis. The analysis sought to examine research trends, identify the most influential articles, determine the leading contributing countries and institutions, explore keyword patterns, and assess international collaboration networks.

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Consequently, the findings revealed a steady increase in scholarly output since the mid-20th century, with significant growth in the last two decades. China and the US emerged as the most productive countries, supported by strong institutional capacities and collaborative networks. Highly cited works continue to focus on acoustic wave modeling, geophysics and numerical methods, demonstrating the enduring relevance of foundational theories alongside recent advances. Keyword co-occurrence analysis highlighted six thematic clusters, including acoustic wave theory, computational methods, nonlinear wave behavior, and interdisciplinary applications, reflecting both established and emerging areas of inquiry. Furthermore, international collaboration patterns showed that research in this field benefits from cross-border partnerships with certain countries serving as central hubs in global cooperation.

This study contributes to the field by providing a comprehensive overview of the intellectual and collaborative structures that define research on the wave equation in acoustics and vibrations. The results underscore the importance of bibliometric mapping as a tool for identifying knowledge gaps, recognizing influential themes and informing future directions. The implications of this study are relevant to academic researchers, industry professionals and policymakers alike. The insights gained can help advance simulation techniques, improve noise and vibration control strategies, and support the development of new and innovative materials.

The present research has several limitations that should be acknowledged. It relies on only one database, which may limit the coverage of relevant studies. The analysis also focuses only on journal articles written in English. Conference papers and other types of literature were not included. For future research, the scope can be widened by using more than one database and including studies written in other languages. Other than that, researchers could conduct long-term analyses to observe how research themes change and develop over time.

In summary, bibliometric analysis demonstrates the central role of the wave equation in advancing acoustic and vibration engineering and provides a structured foundation for future scientific development. By clarifying patterns, highlighting collaborations, and mapping research evolution, this study reinforces the significance of bibliometrics in guiding progress in this important area of engineering.

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