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Article

A Study on Technological Dynamics in Structural Health Monitoring Using Intelligent Fault Diagnosis Techniques: A Patent-Based Approach

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Abstract: The performance and reliability of structural components are greatly influenced by the presence of any abnormality in them. To this purpose, structural health monitoring (SHM) is recognized as a necessary tool to ensure the safety precautions and efficiency of both mechanical and civil infrastructures. Till now, most of the previous work has emphasized the functioning of several SHM techniques and systematic changes in SHM execution. However, there exist insufficient data in the literature regarding the patent-based technological developments in the SHM research domain which might be a useful source of detailed information for worldwide research institutes. To address this research gap, a method based on the Co-Operative Patent Classification (CPC) codes is proposed in the current study. The proposed method includes the patent analysis of SHM in terms of its global publication trend and technology-based applications. This analysis is performed using patent database search tools, namely, IncoPat and Espacenet. The period ranging from 2005 to 2019 is selected to retrieve the required patent documents. A new approach termed as Patents' value is utilized to investigate the technological impact of a patent in the form of forward citations, technical stability, and scope of protection. The identification of emerging SHM techniques and forecasting of vacant technology is also part of current research work. The research results have revealed the increasing trend in the number of published patents each year related to various SHM technologies. In this regard, China, the United States, and South Korea are notified as to the major depositor countries, respectively. Hence, mapping of patent data in this research is an effort to illustrate the effectiveness of the proposed method to demonstrate the development trends and dynamic inventions over the time in SHM research domain to achieve the optimal damage inspections of various mechanical components.

Keywords: Structural health monitoring; mechanical components; patent analysis; technological dynamics; vacant technology forecast; publication trend analysis

Nomenclature

SHM	Structural Health Monitoring
CPC	Co-Operative Patent Classification
IPC	International Patent Classification

WIPO	World Intellectual Property Organization
EPO	European Patent Office
Non-Lin.Elas.Ws	Non-Linear Elastic Wave Spectroscopy
Comp.Vac.Monit	Comparative Vacume Monitoring
Elect.Mech.Imp	Electromechanical Impedance
AE	Acoustic Emission
Opt.Fib.Sens	Optical Fiber Sensing
Wuhan.Tec.Uni.	Wuhan University of Technology
Taiyuan.Tec.Uni.	Taiyuan University of Technology
Nanjing.Uni.	Nanjing Tniversity
Optasense.Hold.Ltd.	Optasense Holdings Limited
Qingdao.Tec.Uni.	Qingdao University of Technology
Tianjin.Uni.	Tianjin University
0K1.Elec.Ind.Co.Ltd.	0kI Electric Industry Company Limited
Shanghai.B.Fib.Sens.Te	Shanghai Boom Fiber Sensing Technology
Jiliang.CN.Uni.	Jiliang University of China
8^{th} Res.Inst.Cetc	8^{th} Research Institute China Electronics Technology Group Corporation
Dongguan.Tech.Colg.	College of Dongguan University Technology
Guangxi.P.Gr.Co.Ltd.	Guangxi Power Grid Corporate Limited
FBS.Inc.	FBS Incorporate
Petro.CN.Co.Ltd.	Petro China Company Limited
Q12 Element.LLC	Q12 Element Limited Liability Company
State.Gr.Co.Ltd.	State Grid Corporate Limited

1 Introduction

The gradual growth of a crack in the structure has a significant value to describe its integrity. The existence of any kind of defect always reduces the efficiency of the structure. Inappropriate working conditions and poor maintenance can easily cause major failures of the equipment. In the transportation and engineering structural failures, casualties and economic losses are often catastrophic. Hence, it is necessary to identify the damage initiation to enhance the service life of the mechanical and civil infrastructure. In this regard, structural health monitoring (SHM) systems are considered capable of constantly evaluating the accurate functioning of mechanical components using sensors and actuators which collect the monitored information without any interruption. A well designed SHM system detects not only the surface damages but also the inner abnormalities of the inspected specimen without executing any cutting procedure. It demonstrates the information about the current working state and assumed effectiveness of the structure, which is very useful in suggesting the compulsory maintenance operations required for the safety of structural components. Real-time SHM includes the accurate sensor's configuration, proper mechanism of crack initiation, signal processing and digital data acquisition to avoid any tragic structural failure [1,2]. The development of crack starts from the material manufacturing to the inappropriately attached components and ultimately affects the residual strength and damage tolerance of in-service structures [3–7]. In this framework, the SHM techniques not only enhance the reliability of mechanical components in all industrial applications but also reduce human errors during the damage inspection process [8–11].

The all above-mentioned study has demonstrated the major demand, scientific design and advanced research behind the SHM approaches, but it does not provide any data about the global potential impact and the current technological development trends in the SHM research domain by both countries and firms. The patent analysis gives us the opportunity to evaluate the significant features of the novel dynamics and technological developments in a certain technology and its inventing organizations [12]. The information obtained from the patent analysis can be extensively implemented in technology forecasting [13–16]. The patent is an approved document that is issued to a research scholar, and it is recognized as an authentic source of scientific advancements highlighting what research institutes assume worth protecting. Patents are classified into several groups depending on their applications, and each group contains detailed knowledge about a particular discipline and its inventors. The development trend in any technology depends on the increasing number of patents in that field [17]. Conversely, the quality of a patent is also considered a significant parameter during the evaluation period of that technology [18].

Hence, the present research aims to propose a method for the comprehensive analysis of patent documents that were filed and published from 2005 to 2019 by both countries and companies in the SHM research domain. This analysis provides useful data to forecast the emerging SHM approach and vacant technology field. Hence, the proposed method reveals not only the worldwide evolution period of SHM technologies but also the government interests and commercial policies for structural safety and reliability.

2 Literature Study

The literature study includes a description of SHM techniques and patent analysis.

2.1 SHM Techniques

Normally, the SHM is categorized as a passive approach or active approach. In the case of the passive approach, a worker observes structural health when it comes to interacting with the environment. While in the case of active approach, the current state of the structure is monitored through transducers that are attached to the examined surface [19]. Real-time SHM systems provide informative data regarding the structural design which is directly filtered and evaluated by the control station during the machine functioning hours. The whole monitoring sequence of an SHM sensing system response is demonstrated in Fig. 1. It includes damage feature extraction, signal processing, data acquisition, damage recognition and maintenance strategy.

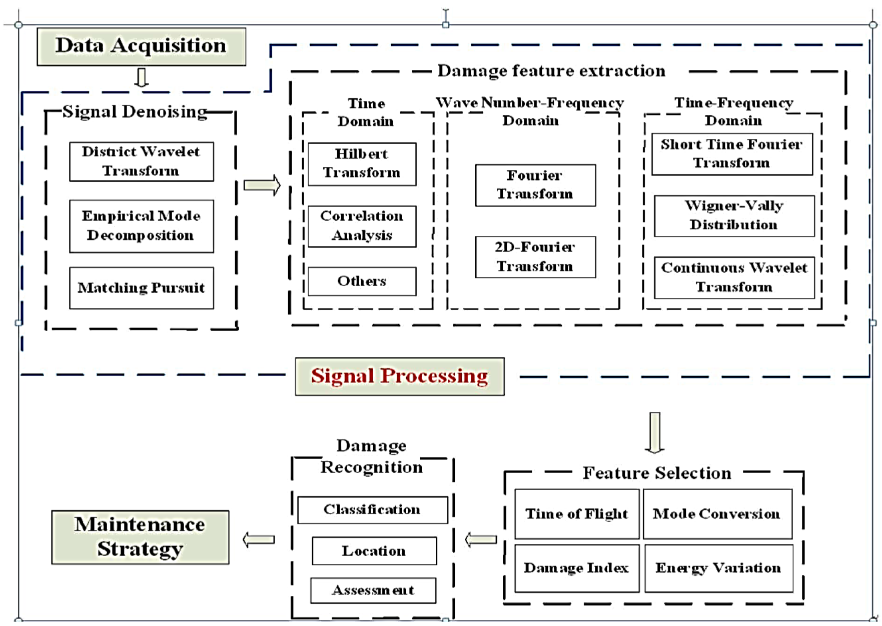

Figure 1: Monitoring sequence of an SHM system's components [20]

There exist several types of SHM techniques to monitor and ensure the reliable functioning of structural components. Based on the literature review, some significant and promising SHM sensing methods are: ultrasonic guided wave inspection, acoustic emission, electromechanical impedance method, comparative vacume monitoring approach, optical fiber sensing method, and non-linear elastic wave spectroscopy inspection [21,22]. A brief description of these damage inspection approaches is mentioned in Table 1.

Table 1: SHM techniques

Technique	Description
Ultrasonic guided wave inspection	It has the ability to directly observe any abnormality in the material's module and achieve the complete inspection of the required area of interest in just a single test. It provides more accurate data regarding structural health even in the case of complex configuration as compared to conventional NDT methods [23,24].
Acoustic emission	This approach is suitable to identify the crack or any leakage in the structure due to different phenomenon such as creep, hydrogen embrittlement, fatigue, stress corrosion, etc. For this purpose, different types of sensors are attached to the examined surface by a fluid coupling and covered with adhesive bonds tape [22].
Electromechanical impedance method (EMI)	To identify the structural abnormality by using the electromechanical coupling characteristic of piezoelectric sensors, the EMI approach is regarded to be one of the most favorable approaches. It has the ability to locate the incipient damage using the piezoelectric sensors which are light in weight and smaller in size [25].
Comparative vacume monitoring approach (CVM)	CVM is implemented in real-time health monitoring of in-situ structures. It is supposed to estimate the differential pressure between low vacuum fine galleries and the atmospheric galleries in a simple manifold [26].
Optical fiber sensing method	It consists of fiber-optic sensors (FOS) which are capable of locating the exact crack position in composite material parts used in the aviation industry. The FOS are flexible and have good thermal resistance. This sensing approach is very efficient to enhance the service life and reliable functioning of aircraft [27].
Non-linear elastic wave spectroscopy	It is used for the detection of damage initiation (delamination, cracks, deboning, and corrosion) in both metals and composites. It can determine the thickness of a thin test specimen, and its amplitude highlights the non-linear effect [22].

To enhance the significance of SHM techniques in industries, it is essential to promote the research and development work of advanced technologies and introduce global programs that encourage structural safety. A consistent policy framework is still required for the execution of SHM techniques in real-time inspections to endorse the novel research.

2.2 Patent as a Measure of Innovation and Technological Information

The main purpose of patent-based research is to illuminate the recent trends of systematic improvements in existing technologies and suggest a recommendation for future research. The novel research is compulsory to achieve the desired outcomes of development processes associated with production systems. In this framework, the technological data obtained through the patent-based research analysis provides a baseline to observe the innovative procedures before starting a new project. The patient-based information is not only an inclusive and reliable source to interpret the worldwide modern technologies but also very helpful to save both time and unnecessary expenditures in a research project. It has been investigated in the previous research that almost 70% of the technical information described in patent documents is not accessible through any other technological forum. Numerous multinational firms from China, the United States, Korea, Europe and Japan are actively contributing to present their innovations [28,29]. The patent-based analysis is very useful for these countries and companies in decision-making while introducing any new technology at the international platform [30,31].

The patent is a provisional document that is awarded to a specific scientific invention by the state, and it gives the legal rights to the inventing organization to secure the information of their invention. The data mentioned in a patent must fulfil the requirement of industrial application and it is valid for the twenty years from the date of filing. Meanwhile, accurate patent data can also be recognized as a measure of the company's real efforts in presenting the novel research [32]. Therefore, the patent document is an important source of technical and commercial information, and it can only be implemented in the countries where it is requested and approved [33–36].

Normally, the patent documents of a specific technology and its applications are accessed through the different worldwide patent search tools such as Google patent, European patent office, Espacenet, IncoPat, etc. To facilitate the researchers and companies in finding the relevant data, these documents are arranged in a proper sequence by a procedure named International Patent Classification (IPC) [37]. The information about the resources to approach some significant patent search tools is provided in Table 2.

Table 2: Resources to approach patent search tools [38]

Title	Website	Accessible data
European Patent Office	www.epo.org	Worldwide Patent data, the opportunity of printing the original data
Espacenet patent search	worldwide.espacenet.com	Free access to 90 million patent documents worldwide
World Intellectual Property Organization	www.wipo.int/	Comprehensive information and pattern of patent applications submitted via PCT
The United States Patent and Trademark Office	www.uspto.gov/	Patent data related to the United States
Japan Patent Office	www.jpo.go.jp/	Japanese patent data with bibliography
Google Patents	www.google.com/patents	To access USPTO US office
IncoPat database	www.incopat.com	Worldwide patent information source

Hence, the mapping of patent data provides comprehensive and meaningful information about the technological development trends in a particular research innovation [39]. It not only highlights the top-ranked countries and companies with the maximum number of patents filed each year but also demonstrates the scope of existing technology and forecast the future promising technologies.

3 Research Data and Methodology

In the current research work, the IncoPat patent database tool and Espacenet patent search tool are chosen to access the patent documents related to the evolution period of SHM and its techniques from the official websites of patent organizations and the private sector of different countries. IncoPat can provide more than 100 million patent documents from 112 different resources, and it covers almost 240 research domains. Moreover, it not only ensures the licensing assignment and communication standards but also accomplishes the proper functioning of the patent family including its forward citations to deliver a competitive judgment to the business and research community. On the other hand, Espacenet is an easily approachable search tool for all the field experts and new research scholars. Its data handling capability also covers more than 100 million patent documents in several research areas, and all the data is regularly modified to provide advanced and detailed information regarding the invention.

To find the patents published in the field of SHM and its techniques, a search method based on the Cooperative Patent Classification (CPC) codes is adopted in the current research. CPC has been jointly recognized by the United States Patent and Trademark Office (USPTO) and European Patent Office (EPO). The required information based on CPC is retrieved by utilizing the appropriate keywords.

Patent files relevant to the SHM and its techniques are retrieved from 2005 to 2019. Once a patent is filed, it has to pass through different comprehensive evaluation phases before the final approval and publication. Normally, this evaluation period consists of several months depending on the application, therefore, the patent data for 2019 is approximated in the current research and the patent data for 2020 has not been included. In the next step, all the retrieved patent documents associated with a specific invention and published in different countries are classified into a single patent family by an approach named "extended family merger", which is an accessible option in the original database of the IncoPat 4.0 version.

In this approach, the entire published patents of similar innovation are documented only once according to their earliest date of publication. The proposed research methodology has generated a final sample of 4089 patents associated with the evolution period of the SHM and its six prominent techniques. Hence, the significant patent classification codes obtained through the CPC search tool are demonstrated in Table 3.

Table 3: Significant CPC codes associated with the SHM [37]

CPC code	Description
G01N 29/00	Structural health monitoring
G01N 29/041/043	Ultrasonic guided wave inspection
G01N 29/045	Acoustic emission inspection
G01N 29/028	Electromechanical impedance
G01H 9/004/008	Optical fiber sensing method
G01N 29/48	Nonlinear elastic wave spectroscopy
F04D 29/0413	Comparative vacume monitoring

The term "patent count" is used in the present patent-based analysis to determine the innovative strategies over time, applicant information and the development trends of invention at the organizational level. The detailed research methodology is demonstrated in Fig. 2. The following five types of analyses have been conducted in this study to illuminate the patenting trend in the SHM research field over the period ranging from 2005–2019:

- Patent publication trend analysis;
- Technology-based publication trend analysis;
- Global technology construction analysis;
- Applicant analysis;
- Regional analysis.

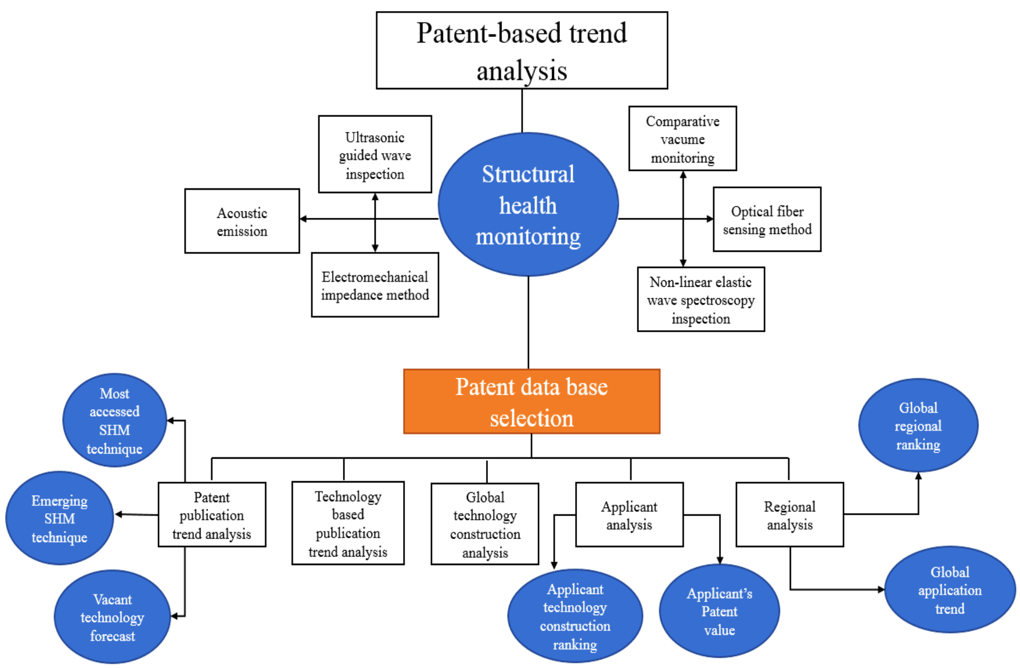

Figure 2: Research methodology process chart

4 Results and Discussion

This section is divided into two phases to demonstrate the interpretation of the obtained results. Phase-1 includes the findings of patent-based trend analysis of SHM, and Phase-2 explains the outcomes of patent-based trend analysis of six prominent SHM techniques.

4.1 Phase 1: Patent-Based Trend Analysis of SHM

The advanced research study aims to improve the working efficiency and reliability of mechanical and civil infrastructures by their regular inspection using the SHM systems. In this framework, the patent publication trend in the field of SHM has been illustrated in Fig. 3 and all the data is retrieved from 2005 to 2019. An overall increment can be observed till 2015 in the patent publication trend for SHM. A slightly declining behaviour is also perceived in the years 2016 and 2017 because of a deferment in the assessment phases of patent documents. The highest number of published patents is noticed in the year 2015, and the patent count is 477. This result indicates the maturity of global investment policies to motivate the research in SHM systems to ensure the optimal functioning of structural components.

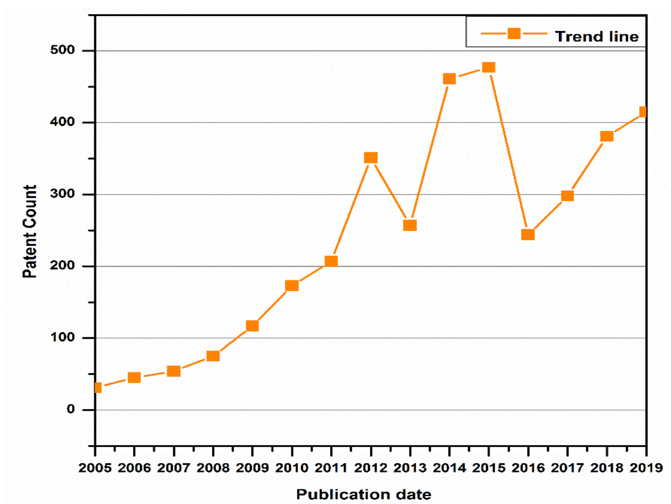

Figure 3: Publication trend analysis for SHM research domain

In the past few years, significant research efforts have been conducted to promote the concept of SHM. Table 4 reveals the technologies related to structural health monitoring. Specific IPC codes are assigned to these technologies. These codes signify the real-time applications in which the SHM system is utilized.

Table 4: Technology codes description for SHM applications

Technology code	Specification	Abbreviation
G01M	Testing of structures	TOS
G01B	Measuring irregularities of surfaces	MIOS
G01N	Analyzing materials by physical properties	Anl.Mat.PP
G01L	Measuring mechanical efficiency	MME
G01K	Measuring thermally-sensitive elements	MTSE
G06F	Electric digital data processing	EDDP
G01D	Tariff metering apparatus	T.Mt.A
G01H	Measurement of mechanical vibration	MOMV
H01L	Semiconductor devices	SCD
G02B	Testing of optical system	TOOS

Fig. 4 demonstrates the technology-based publication trend in the SHM research domain. It can be observed in Fig. 4 that the maximum number of patents is published in G01M technology, which indicates the several SHM applications such as testing of structures or apparatus, etc. The maximum patent count is observed in 2014 with 226 published patents. The second position is attained by G01B technology with the maximum patent count of 191 in 2014. This technology is mostly implemented in the measurement of surfaces irregularities and its dimensions such as length, thickness, etc. The third position is secured by G01N technology that signifies the inspection of a surface by determining its chemical or physical properties. The maximum patent count is observed in 2019 with 105 published patents. The technologies related to measuring mechanical efficiency and digital data processing (G01L and G06F) are ranked at fourth and fifth position with a maximum patent count of 176 and 64 in 2014 and 2019, respectively. Moreover, the recent emerging technology related to the measurement of mechanical vibrations (G01H) got the eighth position in this analysis with a maximum patent count of 22 in 2017. There are also some other advanced technologies that are categorized at different positions in the current analysis with the least patent count including measurement of thermally-sensitive elements (G01K), tariff metering apparatus (G01D), semiconductor devices (H01L), and testing of optical systems (G02B).

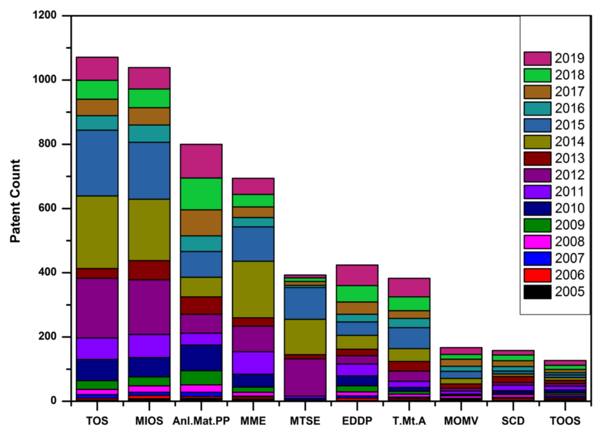

Figure 4: Technology-based publication trend in SHM [Abbreviations explained in Table 4]

All the SHM technologies are affiliated with relevant research institutes and companies. In this regard, Fig. 5 demonstrates the global distribution trend of SHM technologies and classifies the most advanced countries in this research field.

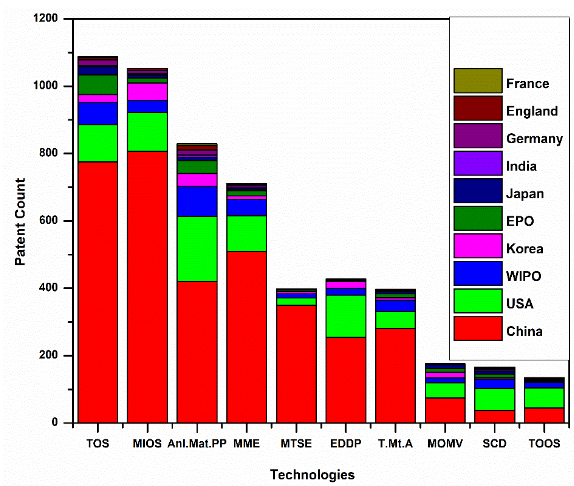

Figure 5: Technology global distribution trend in SHM research domain [Abbreviations explained in Table 4]

Fig. 5 reveals that China is among the top-ranked countries for introducing innovation in SHM applications and worldwide technologies distribution. China is followed by the United States of America (USA) and the World Intellectuals of Patent Organization (WIPO). This analysis reveals the incentive policy of China to endorse the concept of SHM in different mechanical and civil engineering research fields. Numerous programs have been introduced by the Chinese government in particular industrial zones to prompt the trend of patent filing for technological development. To support these programs, the China Intellectual Property Service has issued its national patent development strategy (2011–2020). According to this strategy, the government has declared the tax rebate for the companies with outstanding scientific infrastructure and the maximum number of deposits each year, meanwhile, this policy also encourages awareness about entrepreneurship [40]. Hence, Fig. 5 has revealed the keen interest of several countries in the development of the latest SHM technologies related to damage detection, signal processing, measurement of vibration and surface irregularities, mechanical efficiency of structural components, etc.

There are several multinational firms and research institutes that are presenting their research on SHM technologies through the patent publication method. To categorize these organizations, applicant analysis is conducted and shown in Fig. 6. It can be noticed that the Southeast University of China is recognized as a leading research institute in introducing various SHM technologies. It mostly deals with research on the inspection of structural components in practical applications. The second position is also earned by the Chinese research institute named Dalian University of Technology (DUT). The third position is secured by an American company named Boeing. These all top-ranked research institutes and companies have focused on the four main applications specified in Table 4 with codes (G01M, G01B, G01N and G01L). Hence, it is clear from Fig. 6 that the modern research on SHM is mostly directed towards its implementation in real-world practical applications for an accurate and reliable inspection process.

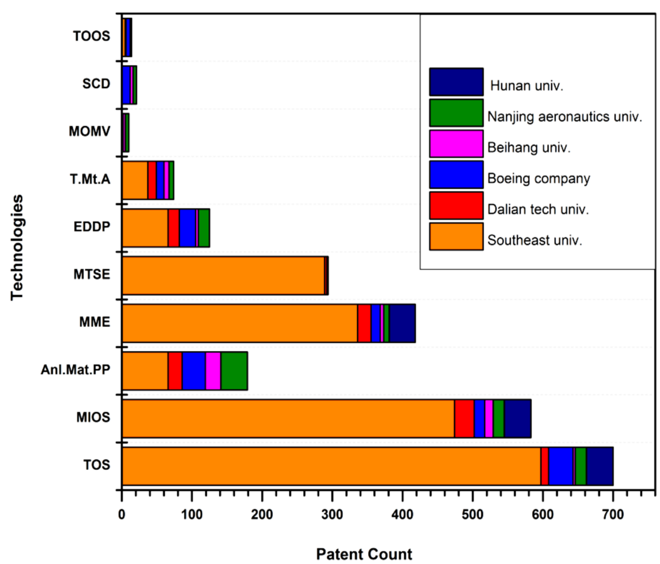

Figure 6: Applicant technology construction ranking in SHM research domain [Abbreviations explained Table 4]

It is also significant to quantify the technological impact of the leading research institutes and companies to differentiate low-quality patents from highly cited patents. To this purpose, the overall technological impact of the well-known organizations is measured by their patents' value in the current research work. The patent value analysis utilizes the patent count to distinguish the institutes that publish the high technological impact patents as shown in Fig. 7. It measures the impact of a patent in terms of its forward citations, the scope of protection and technical constancy. In this regard, the patent with the significant forward citations, reasonable scope of protection and extreme technical constancy is granted with the highest patent value of 10, and there exist very few patents that secure the patent value of 10.

Therefore, the patent value always lies between the maximum value of 10 to a minimum value of 1 depending upon the organizations' innovative efforts.

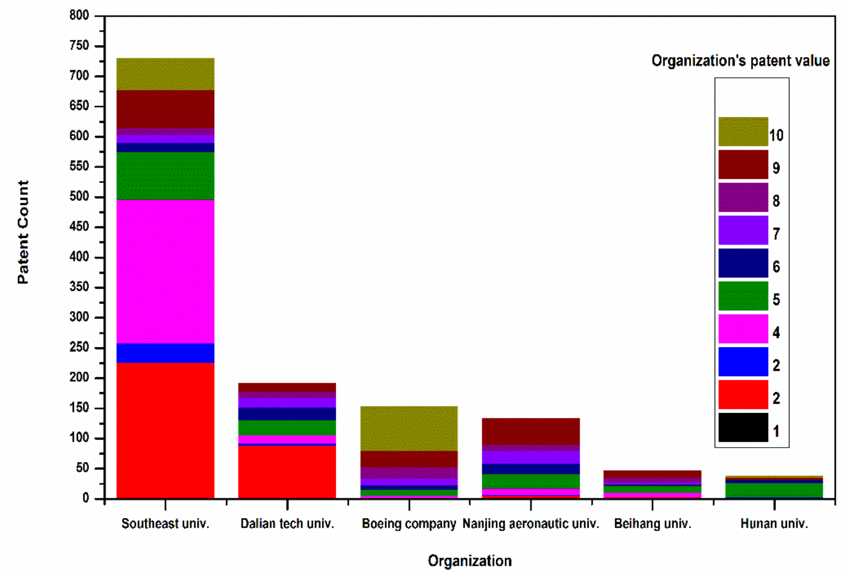

Figure 7: Organizations' technological impact based on their patents' value for innovative research in SHM

It is clear from Fig. 7 that the Southeast University of China and Dalian University of Technology (DUT) China possess the maximum number of patents with a patent value ranging from 1 to 10, and these institutes have respectively secured the first and second position in the overall technological impact among the top-ranked organizations working for the innovative research strategies in the SHM field. Meanwhile, it can also be noticed in Fig. 7 that the American company named Boeing obtained an overall third position in that analysis but it is succeeded in securing the highest patent value of 10 with a maximum 73 patent count as compared to the Southeast University of China (53 patent count with patent value of 10) and DUT China (0 patent count with patent value of 10). Hence, the patent value analysis is very helpful to choose the high-quality patent for the research work on a specific topic among the thousands of relevant patents in that field.

To determine the global region ranking of the countries in term of the maximum percentage of published patents, regional analysis is performed from 2005–2019 as shown in Fig. 8.

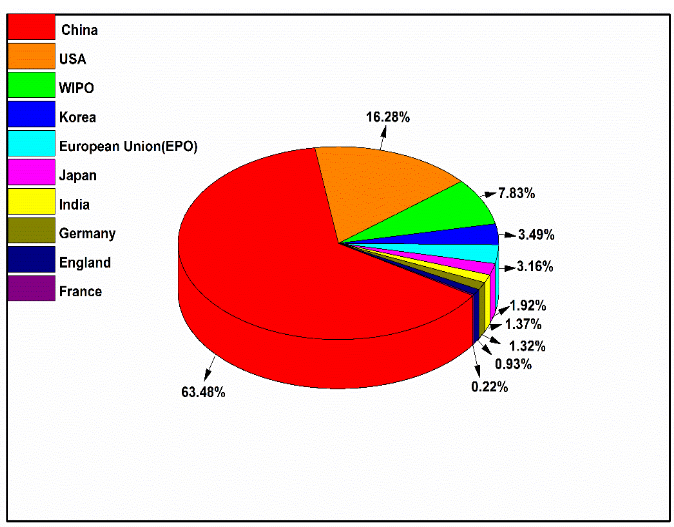

Figure 8: Global regional ranking for innovative research in SHM

The results illustrate that China is the top leading country for innovative research in SHM systems with a maximum share of 63.48%. China is followed by the USA and WIPO with a percentage of 16.28% and 7.83%, respectively. South Korea has a bit high percentage of published patents as compared to the European patent organization. In the framework of regional analysis, it can be perceived that China and South Korea surpasses European countries in the patenting activity related to the development trend in SHM. It may be assumed that these European countries have started to work on SHM patenting activity later than China and South Korea. The countries possessing a higher percentage of patent publications indicate their mature patent filing infrastructure to provide advanced scientific information to international research and the business community. Fig. 9 demonstrates the global application trend analysis of the countries with the maximum patent count from 2005 to 2019.

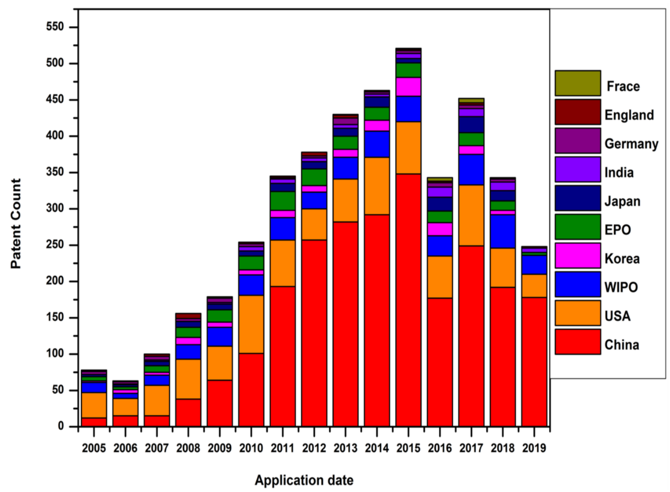

Figure 9: Global application trend for innovative research in SHM

Two important aspects can be noticed in Fig. 9. Firstly, it shows that China is the leading country in applying the maximum number of patents each year followed by the USA and WIPO for the innovative research in SHM systems. Secondly, this analysis signifies the year 2015 with the highest applied patent count. A decreasing trend is also observed in the year 2016 and onwards because of the delay in the assessment phases of patents.

Hence, the overall patent-based analysis for the SHM system promotes the concept of advanced scientific research related to structural safety in several practical fields such as transportations, power plants, industrial and architectural applications.

4.2 Phase-2: Patent-Based Trend Analysis of Intelligent Fault Diagnosis Techniques

It is extremely necessary to study the extracted features from raw data using advanced artificial intelligence techniques such as artificial neural networks, optical fiber sensing, support vector machine and ultrasonic guided wave inspection, etc., instead of extracting and selecting features manually. This would make intelligent fault diagnosis methods less dependent on prior knowledge or human labor, so that novel applications could be done faster, and more importantly, to make mechanical fault diagnosis towards real artificial intelligence [41]. As mentioned before, numerous SHM techniques can be utilized to monitor structural health. Patent-based publication trend analysis can help us to provide significant information about the following some questions related to the evaluation period of SHM techniques:

- Which SHM technique has mostly been accessed and utilized by several research institutes, companies and countries from 2005 to 2019;
- Which technique has the emerging scope;
- What is the vacant technology forecasting.

Based on the literature review, six promising SHM sensing techniques are selected for the patent-based publication trend analysis, including, ultrasonic guided wave inspection, acoustic emission, electromechanical impedance method, comparative vacume monitoring approach, optical fiber sensing method, and non-linear elastic wave spectroscopy inspection [21,22]. Fig. 10 demonstrates the patent publication trend in SHM techniques.

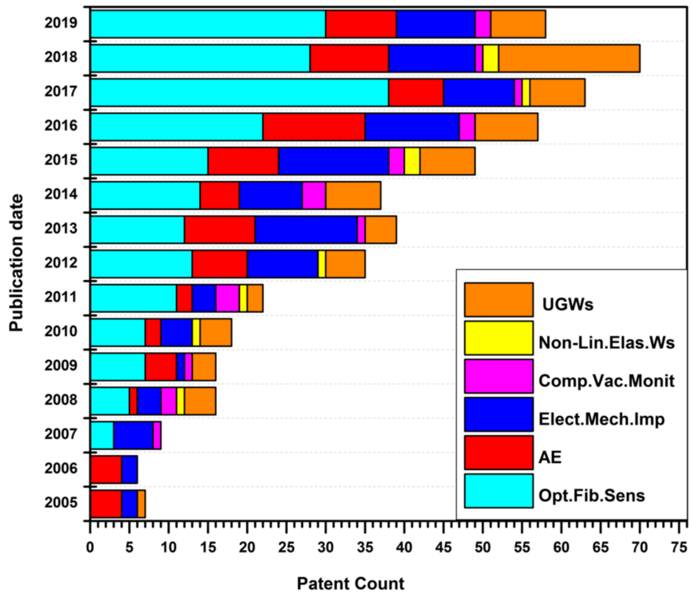

Figure 10: Publication trend analysis for SHM techniques

Following results have been interpreted from Fig. 10:

- Optical fiber sensing technique with maximum patent count 205 is found to be mostly accessed and utilized SHM technique in overall publication trend analysis followed by the electromechanical impedance method (patent count 107) and acoustic emission (patent count 86).
- Ultrasonic guided wave inspection has secured the second position in the publication trend analysis for the year 2018. This result reveals that ultrasonic guided wave inspection has an emerging scope in the advanced scientific research related to structural safety as it possesses the ability to accomplish the inspection of a complete area of interest in just a single test.
- Vacant technology forecasting is generally used to investigate the target technology that is required in the future related research field. According to the current publication trend analysis, non-linear elastic wave spectroscopy inspection with least patent count 9 is forecasted as a vacant technology. Hence, this analysis provides a baseline to all of the research institutes, companies and countries to initiate the work on this research gap to achieve an optimal non-linear spectroscopy inspection.

Based on the findings of Fig. 10, optical fiber sensing technique and ultrasonic guided wave inspection are chosen for further analysis. The basis of these intelligent fault diagnosis techniques includes three main steps: signal acquisition, feature extraction and selection, and fault classification. In the signal acquisition step, vibration signals have been extensively utilized since they provide the most intrinsic information about mechanical faults. In the second step, feature extraction aims to extract representative features from the collected signals based on signal processing techniques, like time-domain statistical analysis, Fourier spectral analysis and wavelet transformation. Although these features characterize the mechanical health conditions, they may contain useless or insensitive information and affect the diagnosis results as well as computational efficiency. So feature selection is used to select sensitive features through dimension reduction strategies, such as principal component analysis (PCA), distance evaluation technique and feature discriminant analysis. In the fault classification step, the selected features are used to train artificial intelligence techniques and the mechanical health conditions are finally determined by these techniques [41,42].

4.2.1 Optical Fiber Sensing Technique

Several international companies and research institutes are working to publish the patents for the technological development of optical fiber sensing damage inspection approach. In this framework, Fig. 11 represents the applicants ranking based on their published patents from 2005 to 2019.

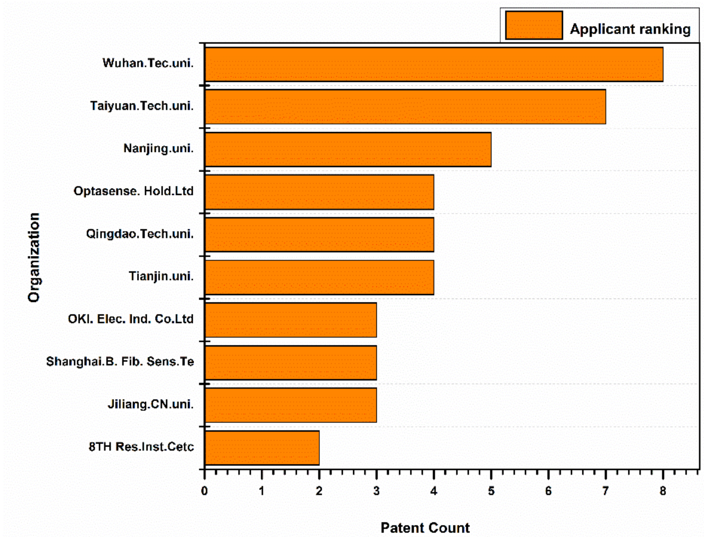

Figure 11: Applicants ranking based on published patents in optical fiber sensing technique

It can be observed in Fig. 11 that the top three positions are secured by the Wuhan University of Technology, Taiyuan University of Technology and Nanjing University, respectively. It is interesting to note that all these top three research institutes belong to China. Fig. 12 displays the global region ranking of the countries contributing to the innovative research for the advancement in optical fiber sensing approach in terms of the maximum percentage of published patents from 2005 to 2019.

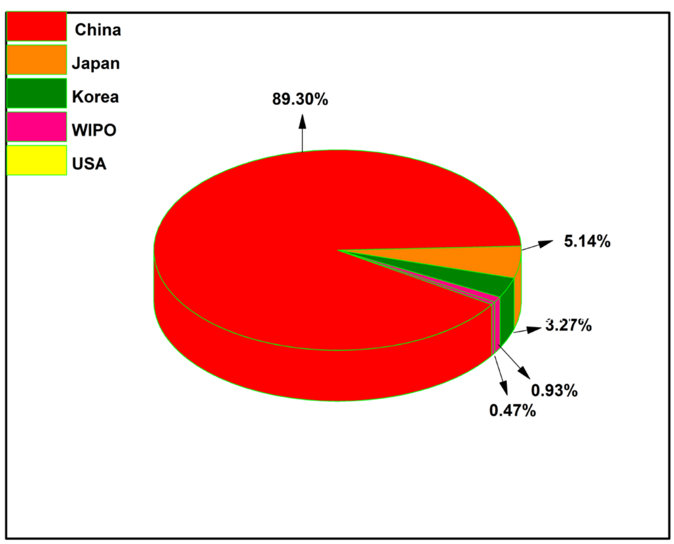

Figure 12: Global regional ranking for innovative research in optical fiber sensing technique

This analysis signifies China as the top-ranked country for the research and development in optical fiber sensing technique with a maximum share of 89.25%. China is followed by Japan and Korea with a percentage of 5.14% and 3.27%, respectively. Hence, it is clear that China is providing outstanding scientific infrastructure and sufficient opportunities to different companies with incentives to enhance the technological development trend in the optical fiber sensing damage inspection approach.

4.2.2 Ultrasonic Guided Wave Inspection

Since ultrasonic guided wave inspection is distinguished as an emerging SHM technique in the current research based on the publication trend analysis, a lot of companies and research institutes are working to enhance its practicality and availability in the coming years through technological developments. Hence, Fig. 13 represents the applicants ranking based on their published patents to promote the innovation trend in ultrasonic guided wave inspection from 2005 to 2019.

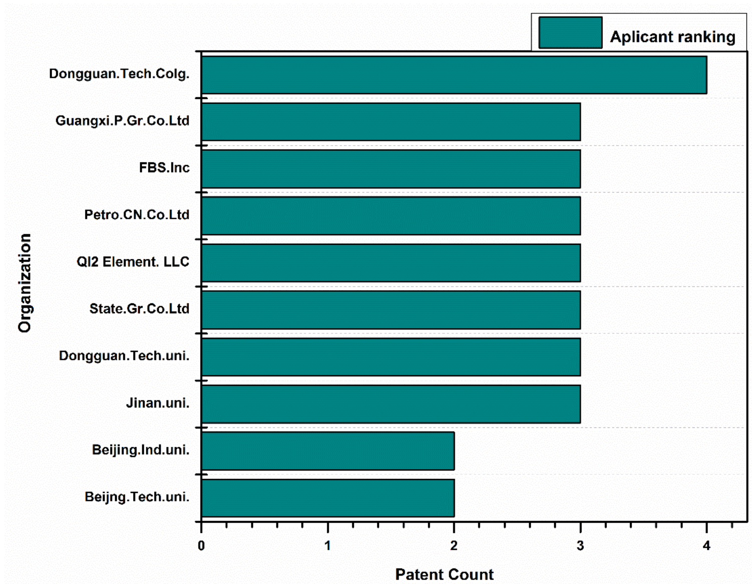

Figure 13: Applicant ranking based on published patents in ultrasonic guided wave inspection

Fig. 13 shows that the top three positions are secured by College of Dongguan University Technology, Guangxi Power Grid Co., Ltd. (China), and FBS INC, respectively. The organizations ranked at the first and second position are from China, while the organization at third position belongs to the USA. Fig. 14 illustrates the global region ranking of the countries introducing the modern research trend based on the maximum percentage of published patents.

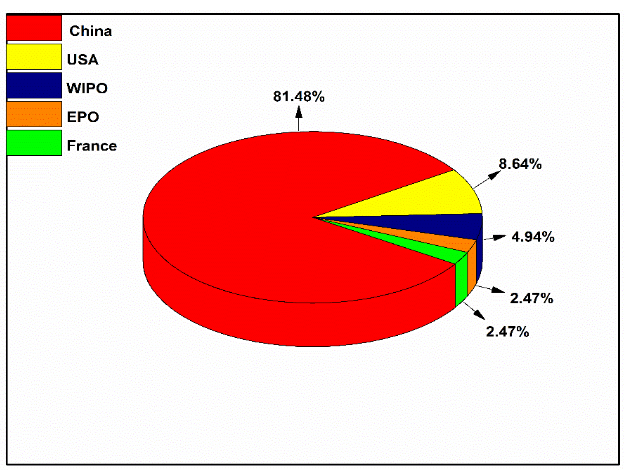

Figure 14: Global regional ranking for innovative research in ultrasonic guided wave inspection

The analysis in Fig. 14 signifies China as a leading country for performing innovative research in ultrasonic guided wave inspection with a maximum share of 81.48% followed by the USA and WIPO with a percentage of 8.64% and 4.94%, respectively. This result highlights the fact that China is playing a key role in the technical and commercial advancements in the emerging SHM technique (ultrasonic guided wave inspection).

5 Conclusions

In the current research work, a method based on patent analysis is proposed to investigate the innovative efforts and patenting activity trends in the field of SHM. This analysis is performed over the period of 2005 to 2019 at the regional and organizational levels. The research results have revealed that the number of published patents on SHM is gradually increasing every year, and China, the United States, and South Korea are found to be the top depositor countries, respectively. The research institutes/companies working on the technological development of SHM systems are mostly the Chinese and American ones, and the core areas of knowledge are testing of structures, measurement of surface irregularities, structural damage and mechanical efficiency of components. It is necessary to state that China and South Korea surpasses European countries in the patenting activity related to the development trend in the SHM. It may be expected that these European countries have started to work on SHM patenting activity later than China and South Korea. The countries possessing a higher percentage of patent publications indicate their mature patent filing infrastructure to provide advanced scientific information to international research and the business community.

To investigate the overall technological impact of the famous organization, a new analysis called Patents' value was performed. This analysis has revealed the technological impact of a patent in the form of forward citations, the scope of protection and technical constancy. According to this analysis, top two positions were secured by the Chinese research institutes named Southeast University of China and Dalian University of Technology (DUT) in terms of the maximum patent count with a patent value ranging from 1 to 10. American company named Boeing obtained an overall third position in that analysis but it has achieved success in securing the highest patent value of 10 with 73 patent count as compared to Southeast University of China (53 patent count with patent value of 10) and DUT, China (0 patent count with patent value of 10).

According to the patent-based publication trend analysis of SHM techniques, it has been found that the optical fiber sensing technique with the maximum patent count is mostly accessed and utilized approach in SHM applications. Ultrasonic guided wave inspection is identified as an emerging technique in advanced scientific research related to structural safety. While non-linear elastic wave spectroscopy inspection with the least patent count is forecasted as vacant technology.

Hence, the patent-based trend analysis of SHM and its techniques provides a baseline to observe the innovative procedures before starting a new research project. The proposed patent-based information is not only an inclusive and reliable source to interpret the worldwide modern technologies but also very helpful to save both time and unnecessary expenditures. For future research work, it is suggested to evaluate the relationship between the level of patent registration and its implementation in real-world applications.

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References

[1] C. J. Lissenden and J. L. Rose, "Structural health monitoring of composite laminates through ultrasonic guided wave beam forming," *NATO Applied Vehicle Technology*, pp. 1–14, 2008.

[2] S. S. Kessler and S. M. Spearing, "Design of a piezoelectric-based structural health monitoring system for damage detection in composite materials," in *SPIE's Ninth Int. Sym. on Smart Structures and Materials*, San Diego, CA, pp. 86–96, 2002.

[3] V. Vasiliev and E. Morozov, *Mechanics and Analysis of Composite Materials*. Elsevier Science, 2001. [Online]. Available: https://www.elsevier.com/books/mechanics-and-analysis-of-composite-materials/vasiliev/978-0-08-042702-7.

[4] J. Krautkrämer and H. Krautkrämer, *Ultrasonic Testing of Materials*. Springer, Berlin, Heidelber, 1983. [Online]. Available: https://link.springer.com/book/10.1007%2F978-3-662-02357-0#about.

[5] O. J. Løkberg and J. T. Malmo, "Detection of defects in composite materials by TV holography," *NDT International*, vol. 21, no. 4, pp. 223–228, 1988.

[6] D. O.Thompson and D. E. Chimenti, "Review of progress in quantitative nondestructive evaluation," *Optica Acta: International Journal of Optics*, vol. 32, no. 7, pp. 747, 1993.

[7] J. Prasad and C. G. K. Nair, *Non-Destructive Test and Evaluation of Materials*, 2nd edition. New York: McGraw.-Hill Education, 2011.

[8] W. J. Staszewski, C. Boller and G. R. Tomlinson, *Health Monitoring of Aerospace Structures: Smart Sensor Technologies and Signal Processing*. 2003. [Online]. Available: https://onlinelibrary.wiley.com/doi/book/10.1002/0470092866.

[9] C. R. Farrar and K. Worden, "An introduction to structural health monitoring," *New Trends in Vibration Based Structural Health Monitoring*, vol. 520, pp. 1–17, 2010.

[10] T. Mickens, M. Schulz, M. Sundaresan, A. Ghoshal, A. S. Naser *et al.,* "Structural health monitoring of an aircraft joint," *Mechanical Systems and Signal Processing*, vol. 17, no. 2, pp. 285–303, 2003.

[11] W. Baker, I. McKenzie and R. Jones, "Development of life extension strategies for Australian military aircraft, using structural health monitoring of composite repairs and joints," *Composite Structures*, vol. 66, no. 1–4, pp. 133–143, 2004.

[12] L. Ardito, A. M. Petruzzelli, U. Panniello and A. C. Garavelli, "Towards industry 4.0: Mapping digital technologies for supply chain management-marketing integration," *Business Process Management Journal*, vol. 25, no. 2, pp. 323–346, 2019.

[13] M. Karvonen and T. Kässi, "Patent citations as a tool for analyzing the early stages of convergence," *Technological Forecasting and Social Change*, vol. 80, no. 6, pp. 1094–1107, 2013.

[14] J. H. Kwakkel, S. C. Carley, C. John and W. Scott, "Visualizing geo-spatial data in science, technology and innovation," *Technological Forecasting and Social Change*, vol. 81, pp. 67–81, 2014.

[15] J. Choi and Y. S. Hwang, "Patent keyword network analysis for improving technology development efficiency," *Technological Forecasting and Social Change*, vol. 83, pp. 170–82, 2013.

[16] M. Lee, K. Kim and Y. Cho, "A study on the relationship between technology diffusion and new product diffusion," *Technological Forecasting and Social Change*, vol. 77, no. 5, pp. 796–802, 2010.

[17] J. S. Liu, C. Kuan, S. Cha, W. Chuang, G. Gau *et al.,* "Photovoltaic technology development: A perspective from patent growth analysis," *Solar Energy Materials & Solar Cells*, vol. 95, no. 11, pp. 3130–3136, 2011.

[18] S. Lizin, J. Leroy, C. Delvenne, M. Dijk, E. Schepper *et al.,* "A patent landscape analysis for organic photovoltaic solar cells: Identifying the technology's development phase," *Renew Energy*, vol. 57, no. C, pp. 5–11, 2013.

[19] C. Boller, "Structural health management of ageing aircraft and other infrastructure," *Monograph on Structural Health Monitoring*, Institute of Smart Structures and Systems (ISSS), pp. 1–59, 2002.

[20] F. Li, Z. Su, L. Ye and G. Meng, "A correlation filtering-based matching pursuit (CF-MP) for damage identification using lamb waves," *Smart Materials and Structures*, vol. 15, no. 6, pp. 1585–1594, 2006.

[21] I. Herszberg, M. K. Bannister, H. C. H. Li, R. S. Thomson and C. White, "Structural health monitoring for advanced composite structures," in *Sixteenth Int. Conf. on Composite Materials*, Tokyo, Japan, 2007.

[22] O. S. David-West, D. M. Amafabia, G. Haritos and D. Montalvão, "A review of structural health monitoring techniques as applied to composite structures," *Structural Durability and Health Monitoring*, vol. 11, no. 2, pp.

91–147, 2017.

[23] D. Samaratunga, R. Jha and S. Gopalakrishnan, "Wave propagation analysis in adhesively bonded composite joints using the wavelet spectral finite element method," *Composite Structures*, vol. 122, pp. 271–283, 2015.

[24] L. Maio, V. Memmolo, F. Ricci, N. D. Boffa, E. Monaco *et al.,* "Ultrasonic wave propagation in composite laminates by numerical simulation," *Composite Structures*, vol. 121, pp. 64–74, 2015.

[25] F. P. Sun, Z. Chaudhry, C. Liang and C. A. Rogers, "Truss structure integrity identification using PZT sensor-actuator," *Journal of Intelligent Material Systems and Structures*, vol. 6, no. 1, pp. 134–139, 1995.

[26] D. Roach, "Real-time crack detection using mountable comparative vacuum monitoring sensors," *Smart Structures and Systems*, vol. 5, pp. 317–328, 2009.

[27] S. Abbas, F. Li and J. Qiu, "A review on SHM techniques and current challenges for characteristic investigation of damage in composite material components of the aviation industry," *Materials Performance and Characterization*, vol. 7, pp. 224–258, 2018.

[28] Instituto Nacional de Propriedade Industrial, 2017. [Online]. Available: http://www.inpi.gov.br/ portal/.

[29] World Intellectual Property Organization, 2017. [Online]. Available: http://www.wipo.int/portal/en/ index.html.

[30] J. Yoon, W. Seo, B. Y. Coh, I. Song and J. M. Lee, "Identifying product opportunities using collaborative filtering-based patent analysis," *Computers & Industrial Engineering*, vol. 107, pp. 376–387, 2017.

[31] G. Kim and J. Bae, "A novel approach to forecast promising technology through patent analysis," *Technol Forecast Social Change*, vol. 117, pp. 228–037, 2017.

[32] E. Rugraff, "A patent analysis of foreign direct innovative R&D activities in Central Europe: the czech case," *International Journal of Innovation Management*, vol. 21, no. 2, 2017.

[33] P. Sampaio, M. O. A. González, R. Vasconcelos, M. Santos, J. C. D. Toledo *et al.,* "Photovoltaic technologies: mapping from patent analysis," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 215–224, 2018.

[34] B. V. Pottelsberghe, H. Dernis and D. Guellec, "Using patent counts for cross-country comparisons of technology output," *STI Review*, vol. 27, pp. 129–146, 2002.

[35] H. Dernis and M. Khan, "Triadic patent families methodology," *OECD Science, Technology and Industry Working Papers*, 2004.

[36] H. J. Leu, C. C. Wu and C. Y. Lin, "Technology exploration and forecasting of biofuels and biohydrogen energy from patent analysis," *International Journal of Hydrogen Energy*, vol. 37, pp. 15719–15725, 2012.

[37] Espacenet Patent Classification Search, European Patent Office, 2018. [Online]. Available: https://worldwide.espacenet.com/classification.

[38] K. C. H. Bittencourt, R. C. Pedrosa, *Intellectual Property Guide*. UFSC: Florianópolis, 2010.

[39] EC/EACI. Boosting Green Business. Executive Agency for Competitiveness and Innovation and European Commission, Luxembourg, 2011.

[40] P. Yokota, *Desafios Tecnológicos Vindos da Asia*, 2011. [Online]. Available:
http:// www.asiacomentada.com.br/2011/01/desafios-tecnologicosvindos- da-asia.

[41] Y. Lei, F. Jia, J. Lin, S. Xing and S. Ding, "An intelligent fault diagnosis method using unsupervised feature learning towards mechanical big data," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 5, pp. 3137–3147, 2016.

[42] M. Kang, J. Kim, M. Kim, A. C. Tan, E. Y. Kim *et al.,* "Reliable fault diagnosis for low-speed bearings using Individually trained support vector machines with Kernel discriminative feature analysis," *IEEE Transactions on Power Electronics*, vol. 30, no. 5, pp. 2786–2797, 2015.