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Review of the Air-Coupled Impact-Echo Method for Non-Destructive Testing

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Abstract. The article presents the general idea of Air-Coupled Impact-Echo (ACIE) method which is one of the non-destructive testing (NDT) techniques used in the construction industry. One of the main advantages of the general Impact Echo (IE) method is that it is sufficient to access from one side to that of the structure which greatly facilitate research in the road facilities or places which are difficult to access and diagnose. The main purpose of the article is to present state-of-the-art related to ACIE method based on the publications available at Thomson Reuters Web of Science Core Collection database (WOS) with the further analysis of the mentioned methods. Deeper analysis was also performed for the newest publications published within last 3 years related to ACIE for investigation on the subject of main focus of the researchers and scientists to try to define possible regions where additional examination and work is necessary. One of the main conclusions that comes from the performed analysis is that ACIE methods can be widely used for performing NDT of concrete structures and can be performed faster than standard IE method thanks to the Air-coupled sensors. What is more, 92.3% of the analysed recent research described in publications connected with ACIE was performed in laboratories, and only 23.1% in-situ on real structures. This indicates that method requires further research to prepare test stand ready to perform analysis on real objects outside laboratory conditions. Moreover, algorithms that are used for data processing and later presentation in ACIE method are still being developed and there is no universal solution available for all kinds of the existing and possible to find defects, which indicates possible research area for further works. Authors are of the opinion that emerging ACIE method could be good opportunity for ND testing especially for concrete structures. Development and refinement of test stands that will allow to perform in-situ tests could shorten the overall time of the research and with the connection of implementation of higher accuracy algorithms for data analysis better precision of defects localization can be achieved.

1. Introduction

Non-destructive test (NDT) and non-destructive evaluation (NDE) offer skills to engineers and owners to quickly and effectively examine and monitor structures created from variety of materials. These methods are used for detection of the damage and for local monitoring of structures. Moreover, NDT can prevent the unpredictable and premature collapse of structures by analysing the condition of construction/structure without the need to perform destructive tests [1]. One of the NDT methods is Impact-Echo methods (IE) and Air-Coupled Impact-Echo method (ACIE), which proved to be good solution for testing especially concrete structures.

The aim of the article is to present state-of-the-art related to ACIE methods available in Thomson Reuters Web of Science Core Collection Database (WOS) with the use of analysis of the publications related in this filed. What is more, authors decided to take closer look at publications from last 3 years related to ACIE and check what was the main focus of the latest research and where were they performed to find out possible areas where further examination is necessary.

2. Impact Echo and Air-Coupled Impact-Echo method of NDT

The IE method has been set up as a reliable NDT technique for detecting delamination and recognizing measurements of defects in concrete constructions, especially in decks and pavements [2]. One of the main advantages of the IE is that it is sufficient to access from one side to that of the structure to perform tests [3] which greatly facilitate research in the road facilities or places difficult to diagnose e.g., dams or sub-structures.

The equipment needed to execute effective IE test are: a contact sensor, an impactor, a data acquisition device and a computer. Example setup is presented in Figure 1a. In the standard, widely used approach, the reaction signals are acquired by physically touching the surface of the deck with a sensor. In modified approach, air-coupled detecting systems have been introduced, so that the traditional contact sensor is replaced with a contactless (air-coupled) sensor. This is the main difference between standard IE and ACIE method. The idea of air-coupled testing is that leaky waves propagate into the air that bounds the concrete deck which is caused by the generated wave motion of the surface. Although the amplitudes of these waves are very small, air sensors may have detected them with very high accuracy. Properly configured air sensors provide the same accuracy as data collecting using conventional sensors in IE methods [4, 5]. Schemes presenting the difference between IE and ACIE methods are presented in Figure 1b and 1c.

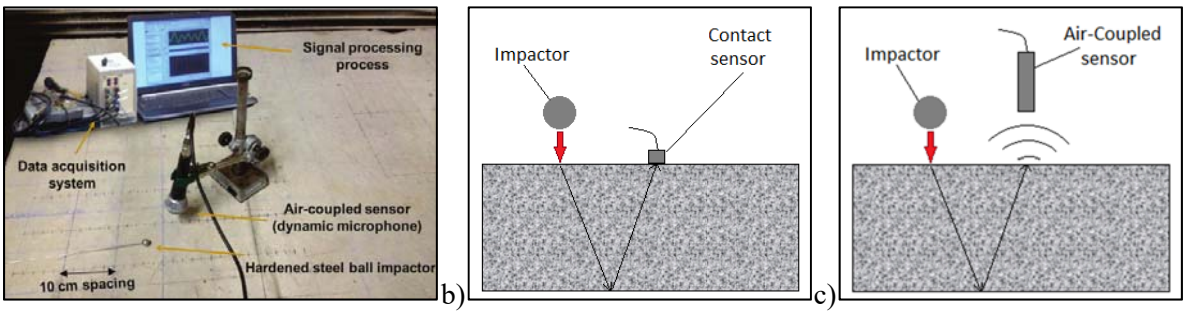


Figure 1. (a) Example Air-coupled impact-echo imaging test set-up [6]; (b) Traditional – contact test scheme; (c) Air-Coupled contactless test scheme

The process of executing test run is to use measurement grid on the test element and to carry out a series of readings using the test kit. The density of the grid depends on the size of the expected defect, the amount of data that we want to be analysed and time of measurement. Recommended mesh size for the conventional method (contact) is from 15 cm to 60 cm. These distances are not sufficient to detect smaller defects. Contactless system ACIE provides the ability to implement research on denser grid, as well as the duration of each test ACIE is much shorter [7], which provides greater accuracy.

3. Web of Science Analysis

Web of Science (WOS) is the most recognizable scientific online database available for researchers. It is the product of "Thomson Reuters Institute of Scientific Information" (ISI), which arises from the Science Citation Index created by Eugene Garfield in 1960s. WOS includes about 12,000 [8] journals and comprises of seven different citation databases including different information collected from diaries, gatherings, reports, books and book arrangement [9]. WOS Core Collection includes among others [10]:

- Science Citation Index Expanded (1945-present),
- Social Sciences Citation Index (1956-present),
- Arts & Humanities Citation Index (1975-present),
- Conference Proceedings Citation Index- Science (1990-present),
- Conference Proceedings Citation Index- Social Science & Humanities (1990-present),
- Book Citation Index– Science (2010-present),
- Book Citation Index– Social Sciences & Humanities (2010-present),
- Emerging Sources Citation Index (2015-present),
- Current Chemical Reactions (2010-present),
- (Includes Institut National de la Propriete Industrielle structure data back to 1840),
- Index Chemicus (2010-present).

For the purpose of the article, authors analysed available publications in the Thomson Reuters Web of Science Core Collection database. It was chosen based on the availability and ease of access for the researchers. Two search series were performed associated with the following key-words: Impact-Echo and Air-Coupled Impact-Echo. The scheme of the carried steps is presented in Figure 2.

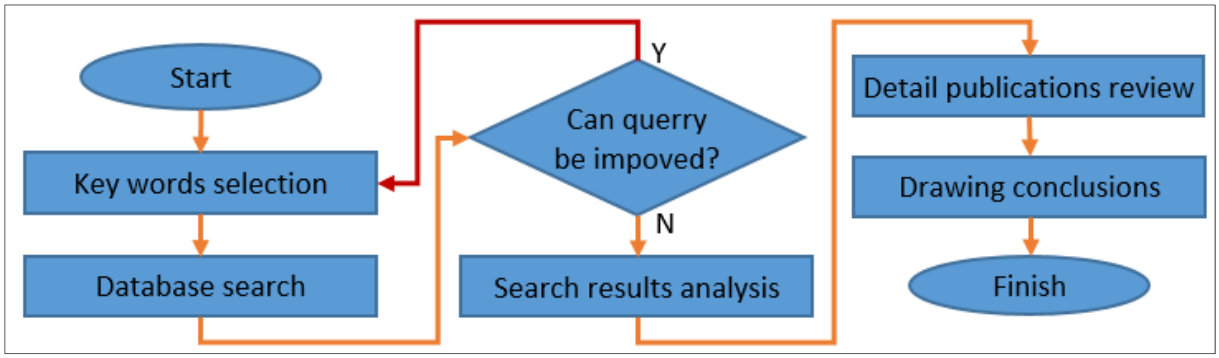


Figure 2. Research procedure for the purpose of publications review

After choosing database authors decided on key words for performing the search. Each time results were analysed taking into account their accuracy and quality. After receiving firm and final results on Impact Echo and Air-Coupled Impact-Echo queries, the results were analysed in terms of checking: publication year, country of the author, language, document type and area of research. Results are present in the points 3.1 and 3.2. After general analysis, authors decided to perform detail publication review of 13 the newest publications. Effects of this investigation are presented in Table 1. Last step was to analyse obtained data and draw the conclusions from performed works.

It has to be noted that all graphs that are presented in point 3 and 4 were prepared taking into account total amount of appearances of assessed features. Percentage was calculated using the real amount of publications, so for graphs presenting document type and country, as well as focus of the study and place of research, total sum of percentage may exceed 100% because the total quantity of appearances exceeded real amount of publications.

3.1 Impact Echo WOS results.

Performed examination exposed 533 works related to IE method of NDT in WOS database. The search was performed on 5.03.2017. Results related to the country of IE publications are presented in Figure 3a. They revealed that over 1/3 of all authors are from the USA, 9.5% from South Korea and 9,1% from Taiwan. It appeared that 56,5% of publications were articles (Figure 3b) and 40,1% proceedings conference papers. There was no surprise that 99.1% of articles were written in English language (Figure 4a).

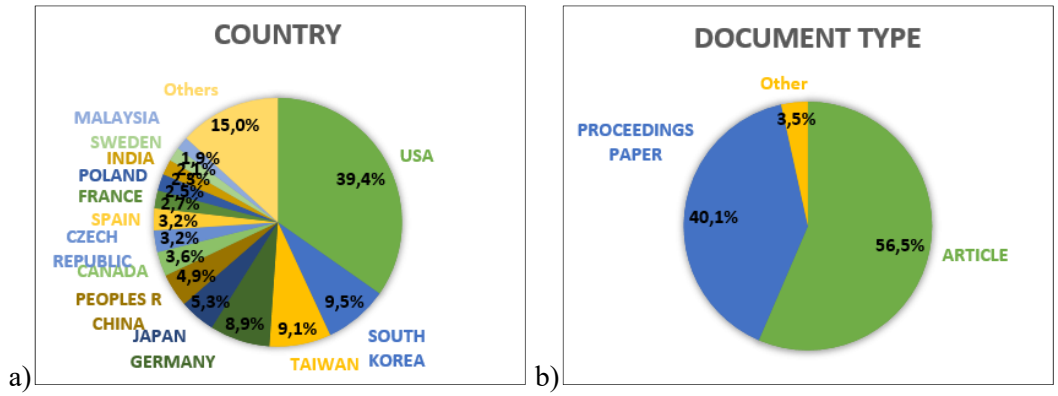


Figure 3. (a) Country of publication authors for IE results; (b) Document type for IE results

Analysis of the publication year (Figure 4b and 5) showed that first publication on IE method indexed in WOS was published in 1989, which indicates that IE research area is not new and researchers are working on this subject for over 25 years. It is also visible, that the highest number of articles was published in 2012 – 45 articles which stands for 8,5% of all publications related to IE.

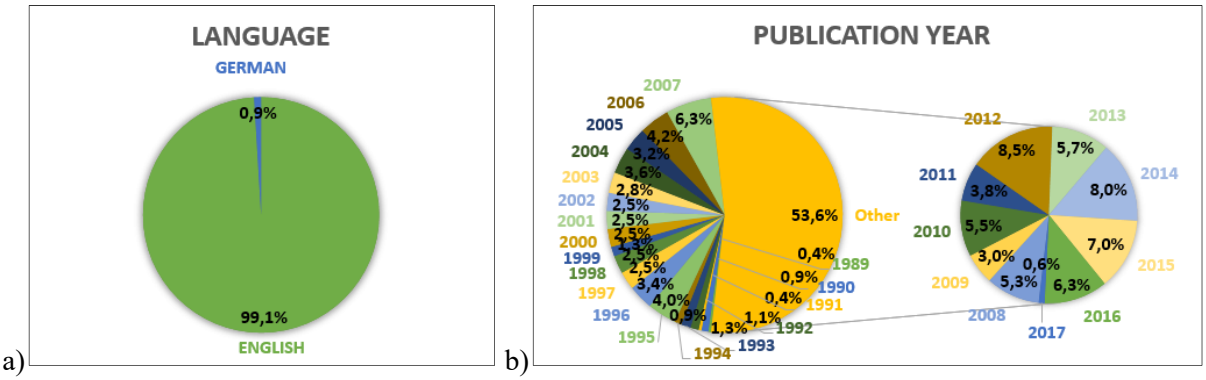


Figure 4. (a) Language of publication for IE results; (b) Publication year for IE results

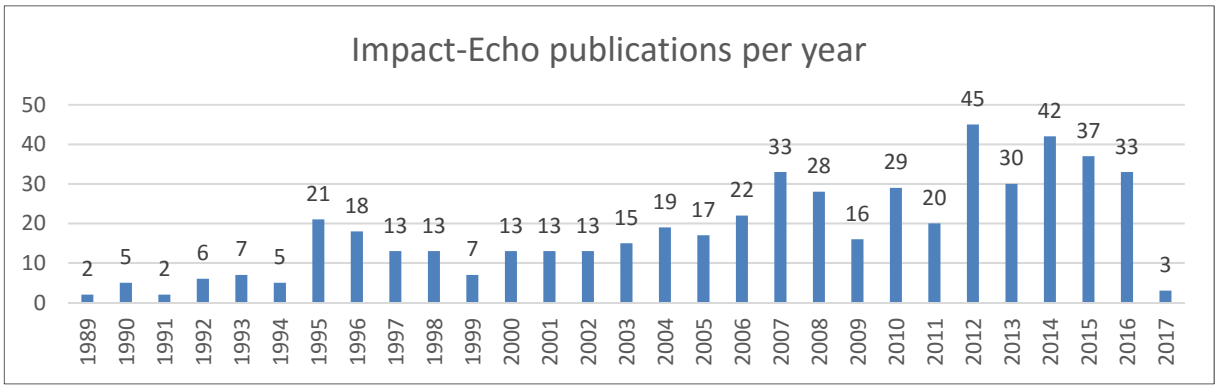


Figure 5. Amount of publication per year for the IE results

Research areas of the IE method are presented in Figure 6. It can be noted that the majority of publications are connected with Materials Science (287), Engineering (280) and Construction Building Technology (150). Other areas are far less popular that top 3 and there are overall 17 categories with the result below 10 publications.

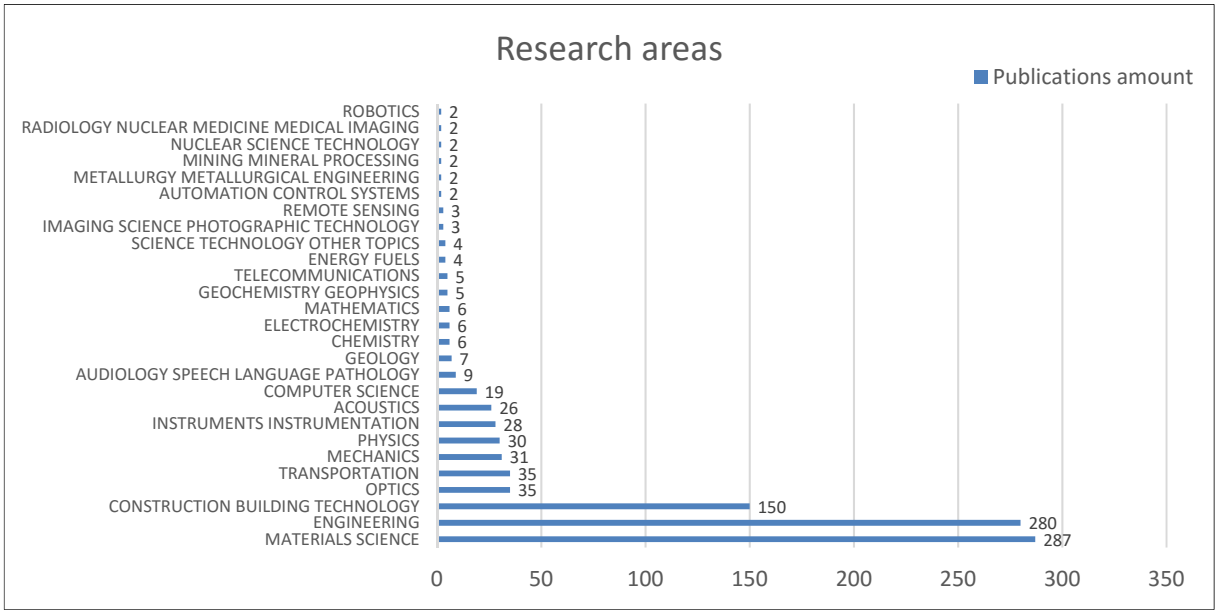
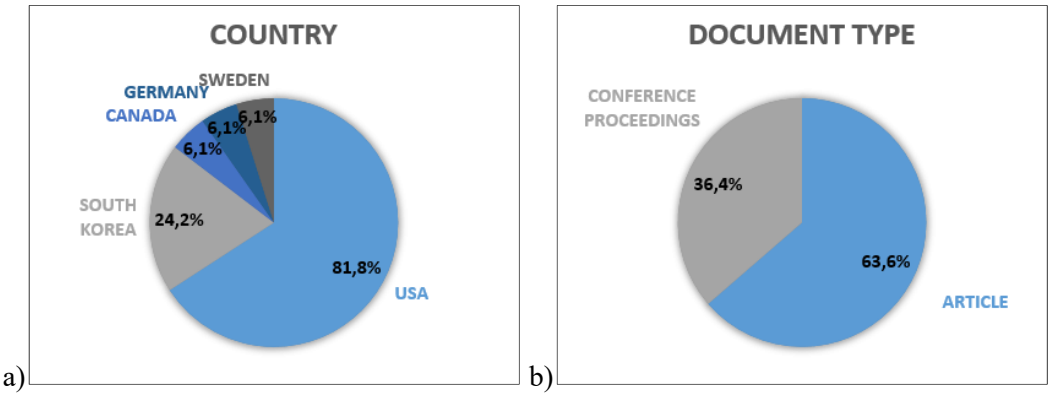


Figure 6. Research areas for IE results

3.*2 Air-Coupled Impact-Echo WOS results.*

WOS database search on ACIE key words resulted in discovering 33 publications. 81,8% of them were of the USA authorship and 24,2% were from South Korea. 63.6% of the documents were articles and the rest were conference proceedings (Figure 7a and 7b).



a) b)

Figure 7. (a) Country of publication authors for ACIE results; (b) Document type for ACIE results

There was no surprise that all of the publications were written in English which is presented in Figure 8a. Figures 8b and 9 indicates that first publication was made in 2004 and the biggest interest in the research area of ACIE was observed in 2012, when 9 publication were published which stands for 27,3% of all publication in WOS database. Moreover, between 2012 and 2015, authors of the publications prepared the majority of the texts available in ACIE area. There were also periods revealed when there was no publication at all available in database: 2006, 2009 and 2010.

Research areas for ACIE are presented in Figure 10. Totally, there are 12 categories where described methods were present. Most common ones are related to Engineering (14), Material Science (10) and Physics (10).

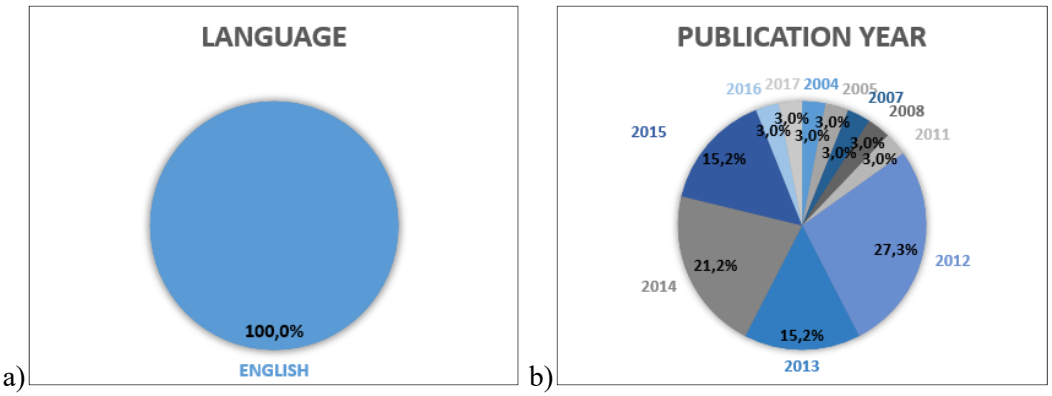


Figure 8. (a) Language of publication for ACIE results; (b) Publication year for ACIE results

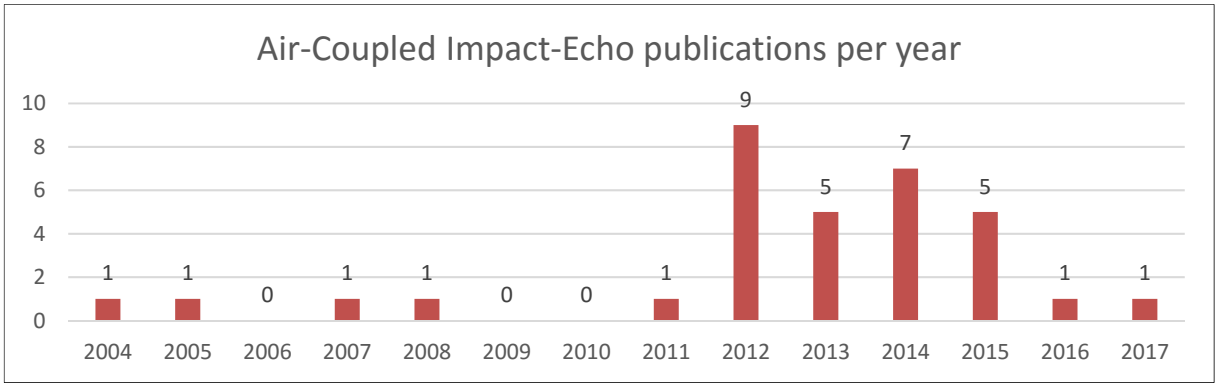


Figure 9. Amount of publication per year for ACIE results

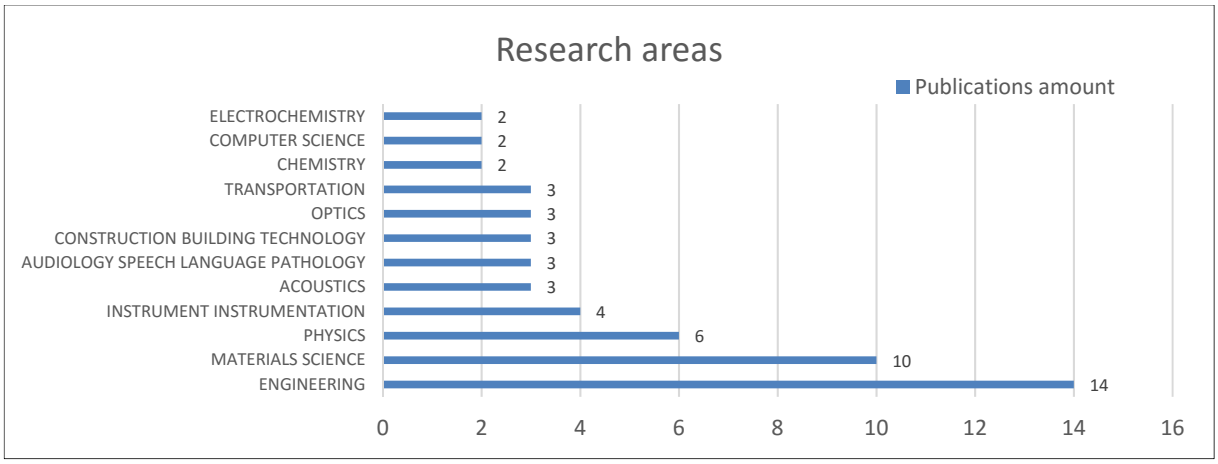


Figure 10. Research areas for ACIE results

ACIE and IE publications were put on the same graph for visualizing the % of ACIE publication in IE research papers. The result is presented in Figure 11. It has to be noted that year 2012 was significant for both methods, because 20% of all research paper were connected with ACIE method. It is also evident that in 2017, 33% are related to ACIE. This is result of very limited number of publications in the WOS database in 2017.

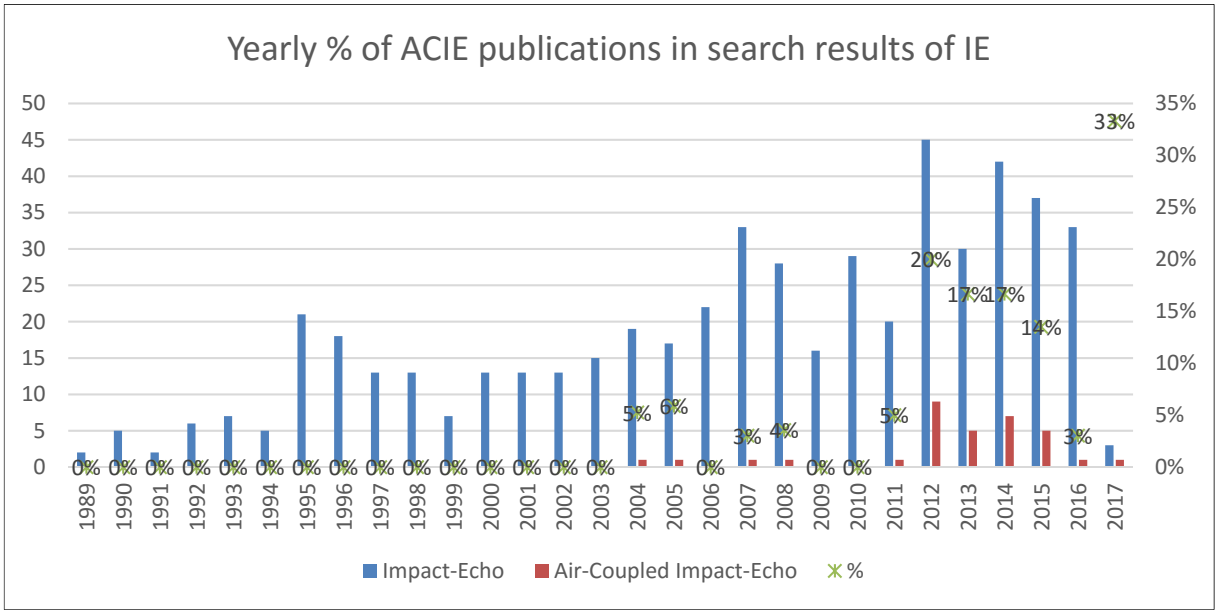


Figure 11. Yearly % of ACIE publication within IE results

4. Detailed review of 13 newest publications

For the purpose of this publication, authors performed deep literature review on selected 13 newest publication form last 3 years in terms of what areas were researched and what approach was used. Table 1 was prepared to summarise performed analysis presenting: short description of each work, focus of the study and place of the research performance.

In Figure 12, focus of the study and place of research are shown from 13 analysed publications for better visualization of the results. It appeared that majority of performed tests were done in laboratory and only 3 publications describe test in-situ related to ACIE method. What is more, 61.5% of authors were focused on research connected with methods and 30.8 with sensors, which are main part of the test equipment. Results showed that there is only small amount of research done in-situ, which may lead to the conclusion that ACIE method requires further research to prepare test stand 100% ready to execute tests in the field. Enormous part of testing procedure is step connected with data analysis. While working with selected 13 publication, it appeared that algorithms used for data presentation are still being developed and there does not exist universal solution for this step, which opens another possible area for the research.

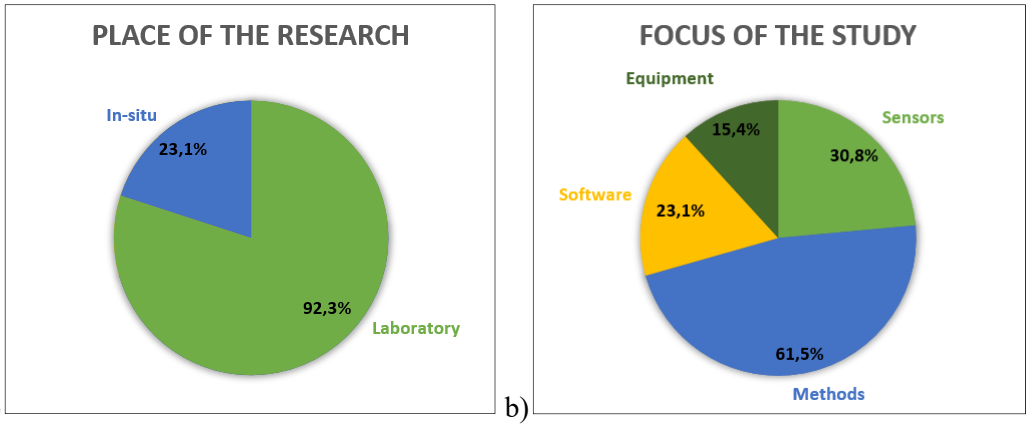


Figure 12. For articles on ACIE form last 3 years: (a) place of the research; (b) focus of the study

Table 1. Selected publications related to IE method.

Publication title and year	Description	Focus of the study	Research place
Air-coupled impact-echo damage detection in reinforced concrete using wavelet transform. (2017)	The study proposes a new impact-echo analysis method using wavelet transforms with dual microphones with 20 kHz resolution to improve damage detection capabilities [11].	Sensors	Laboratory
Detecting the thickness mode frequency in a concrete plate using backward wave propagation. (2016)	The study confirms that it is possible to detect the wave traveling with a negative phase velocity using both accelerometers and air-coupled microphones as receivers and that this approach is alternative technique that can be used in non-contact scanning measurements based on air coupled microphones [12].	Sensors method	Laboratory
Validation of Benefits of Automated Depth Correction Method Improving Accuracy of Ground-Penetrating Radar Deck Deter. Maps. (2015)	Article presents 3 processes for depth correction which compare favourably with one another on several mapped concrete decks. One of the methods was proved to be as accurate as manual methods on numerous decks [13].	Software method	In-situ
Practical Visualization of Local Vibration Data Collected over Large Concrete Elements (2015)	Article presents the idea of original multidimensional presentation format for non-destructive evaluation point test spectral data. Application of proposed data of manipulation and visualization technique to IE data collected from two different reinforced concrete samples demonstrates improved near-surface delamination detection as compared with conventional data formats [7].	Software method	In situ and Laboratory
Application of Impact Resonance C-Scan Stack Images to Evaluate Bridge Deck Conditions (2015)	Study presents a practical approach for imaging concrete pavement and bridge deck slabs for the presence of delamination defects in conjunction with the stacked C-scan imaging approach [14].	Method	In situ and Laboratory
Application of Micro-Electro-Mechanical Sensors Contactless NDT of Concrete Structures (2015)	Article presents the utility of micro-electro-mechanical sensors (MEMS) for application in air-coupled (contactless or noncontact) sensing to concrete non-destructive testing (NDT) [15].	Sensors	Laboratory
MEMS Microphone Array Sensor for Air-Coupled Impact-Echo (2015)	Article proposes new sensor concept for air-coupled IE measurements with the use of an array of MEMS (micro-electro-mechanical system) microphones, instead of a single receiver. In his way, several operational advantages compared to conventional sensing strategies in IE are achieved [3].	Sensors	Laboratory
Comparison of Synthetic Aperture Radar and IE Imaging for Detecting Delamination in Concrete (2014)	The paper evaluates the utility of microwave and mechanical wave non-destructive testing techniques to detect delamination in reinforced concrete bridge deck mock-up samples [4].	Method	Laboratory
Effective Presentation of Impact-Echo Data for Bridge Deck NDE(2014)	Article proposes an imaging technique that combines flexural and thickness stretch (IE) vibration modes from air-coupled impact-echo tests collected across the surface of concrete structure [16].	Method	Laboratory
Comparison of Data-Processing Methods by Air-Coupled Impact Echo Testing for the Assessment of a Concrete Slab (2014)	The practical application of three different processing methods for impact-echo test data-the classical impact-echo method, the peak frequency map, and the 4D-spectrum technique-is performed is analysed in the presented work. The results showed that 4D spectrum technique is more effective and accurate for the detection of shallow defects in the slab [17].	Method	Laboratory
Numerical Simulations and Experimental Measurements of Steel and Ice Impacts on Concrete for Acoustic Interrogation of Delaminations in Bridge Decks (2014)	Article presents numerical simulations that are used to characterize the flexural response of a model concrete bridge deck subject to both steel and ice impactors and the results are compared with similar experiments performed in the laboratory on a partially delaminated concrete bridge deck slab [18].	Software	Laboratory

Air-Coupled Impact-Echo Delamination Detection in Concrete Using Spheres of Ice for Excitation.(2014)	The aim of the paper is to demonstrate that ice can be used as a suitable impactor to excite the acoustic modes in concrete associated with delamination and to compare ice sphere impacts with traditional steel ball impacts [19].	Equipment (impactor)	Laboratory
Surface Wave Transmission across a Partially Closed Surface-Breaking Crack in Concrete (2014)	Study investigates surface waves propagating across a partially closed surface-breaking crack in concrete. Findings provide useful information for studying stress wave propagation across a partially closed crack and for applying, the surface wave based non-destructive testing methods to actual concrete structures [20].	Method	Laboratory
Air-coupled ultrasonic system for fusion of impact-echo tests and surface wave measurements (2014)	The main objective of this study was to develop a prototype air-coupled ultrasonic system (ACUS) for simultaneous data collection of impact-echo tests and surface wave measurements in concrete bridge decks. It was demonstrated that the ACUS is very effective for improving speed of data collection, and that the innovative fusion algorithm enables more accurate data interpretation[21].	Equipment	Laboratory

5. Conclusions

Performed analysis on the current state-of-the art connected with publication related to Impact Echo and Air-Coupled Impact-Echo methods available in Thomson Reuters Web of Science Core Collection database with analysis of recent publications allows to draw the following conclusions:

1. ACIE methods can be widely used for performing ND testing of concrete structures and can be performed faster than standard IE method.
2. The majority of articles related to IE were published between 2012-2014 and first publication is dated back to 1989.
3. There is limited amount of publications related to ACIE (33 out of 517) and majority of them were published between 2012-2015.
4. 92,3% of the recent research described in publications connected with ACIE were performed in laboratories, and only 23,1% in-situ. This method requires further research to prepare test stand 100% ready perform analysis on real objects.
5. Algorithms that are used for data presentation in ACIE method are still being developed and it is possible area for further, deeper research in this field.

Authors are of the opinion that emerging ACIE method could be good opportunity for ND testing especially for concrete structures. Development and refinement of test stands that will allow to perform in-situ tests could shorten the overall time of the research and with the connection with the implementation of higher accuracy algorithm for data analysis could result in the better accuracy of the defects localization.

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