Dynamic response of the annular hole defect under ultrasonic in brick

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Abstract. In recent years, ultrasonic diagnostics and health monitoring of buildings have become widely used in construction. However, the accuracy of ultrasonic devices in heterogeneous media such as concrete, brick and other elements is fraught with difficulties and leads to errors. The article considers the problem of the dynamic response of a defect in the form of a cylindrical hole in a brick during ultrasonic diagnostics. The problem was simulated in the ANSYS environment using the finite element method. A dynamic stimulus with a frequency of 60 kHz is applied in the immediate vicinity of the defect and the response is numerically determined at a point symmetrically located from the defect. The results of numerical analysis in the form of fields of displacements, stresses and deformations have been obtained. It is shown that to effectively determine the geometry of a defect in the form of a hole, it is necessary to analyse data on the 3rd or 4th half-waves of the response.

1 Introduction

Nowadays, digital technologies have become widely applied in construction to detect defects [1,2]. The search for hidden defects in the form of cavities is carried out using ultrasound examinations and gives positive results [3-5]. However, the accuracy of ultrasound examinations in heterogeneous media such as concrete, brick and other elements is fraught with difficulties and leads to errors. Considering that monolithic reinforced concrete construction is always accompanied by the presence of shrinkage cracks or air cavities, monitoring of such structures is necessary and requires accurate and reliable equipment.

Algorithms for automatic diagnostics of the condition of buildings occupy leading positions in the scientific field. In Article [6], ExpoDet is introduced as a comprehensive system designed to enable autonomous buildings and structures inspection and monitoring. ExpoDet is equipped with a detector that can detect multiple objects, micro aircraft can navigate autonomously using secondary reward reinforcement learning, and there's a scheme for structural health monitoring after detection that aggregates damage. In addition, ExpoDet now incorporates EEAM+ as an attention module, enabling dynamic feature targeting and greatly enhancing its capabilities. Both on-site and field trials have thoroughly tested and evaluated ExpoDet. The use of attention modules, in conjunction with various state-of-the-

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art object detectors, led to an average enhancement of around 3% across different evaluation metrics.

Complexes of programs for visualization and segmentation of defects are being actively developed as the initial stage of predicting the condition of buildings. The paper [7] introduces HrSegNet, a specially designed network for crack segmentation that ensures real-time inference speed and preserves detailed crack information. The authors acknowledge the significance of deep learning in crack segmentation, but highlight that existing work often relies on generic or adapted models not tailored for this purpose. Additionally, they mention that high-resolution convolutional neural networks, while beneficial for crack segmentation, may impede real-time detection due to their sensitivity to object details and locations. After evaluating the CrackSeg9k dataset and scenario-specific datasets Asphalt 3k and Concrete 3k, HrSegNet outperforms other models in segmentation and performance metrics. The trade-off between high-resolution modelling and real-time detection is showcased in this approach, encouraging the adoption of advanced crack analysis devices in real-world applications.

EfficientNetV2 was the inspiration behind the study [8], which focuses on a performance convolutional neural network (CNN). The structural properties of Early EfficientNetV2 algorithms allow for faster learning rates than those of modern CNNs. StairNet, a fast CNN, was developed based on three tactics proposed from extensive research. By integrating StairNet, the faster regional CNN framework gave rise to Faster R-Stair. The represented StairNet and Faster R-Stair were tested on two datasets, respectively: Dataset1, which includes a pair of open-source datasets and a dataset of images captured in real-world environments; Dataset2, derived from Dataset1, consisting of more complex object modes, in order to simulate the coexistence of multiple cracks in real conditions. Empirical results indicate that StairNet achieves superior classification and crack detection performance compared to “…EfficientNetV2, GoogLeNet, VGG16 BN, ResNet34, and MobileNetV3” [8]. Additionally, a software platform called Faster R-Stair was developed for detecting cracks in concrete. Cracks in concrete roads were detected at a university in Nanjing, China, using a software platform and drone. System's development enables rapid detection, quick performance, and outstanding outcomes.

Creating an accurate digital representation of underground infrastructure is an important scientific challenge [9–12]. The solution to the inverse problem of restoring the shape of a buried object is preceded by an analytical or numerical solution to the direct problem of the dynamic response of the object.

Ultrasonic phased array detection is often used to detect defects. A cylindrical carbon fiber composite structure was detected using a phased array ultrasonic device in paper [13]. Using the S-scan image sequence sampling method, the length was estimated. Furthermore, the hole size depth was approximated by combining B-scan data and line identification.

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2 Materials and methods

This work utilizes ceramic bricks measuring 250x100x50 mm, which are of standard size. Sound travels at a speed of 2680 m/s in brick. Fig. 1. illustrates the force application scheme and geometric features of the brick.

Fig. 1. Model of a brick with a through-wall cylindrical hole in ANSYS environment

The finite element method is used to model the problem in the ANSYS environment. The cracked structural element is a 500x100x50 mm parallelogram. The material used is brick. Point 1 in Figure 1 shows the application of a force with an amplitude of 10 N and a frequency of 60 kHz on the upper surface, 60 mm away from the crack to the right. The ultrasonic radiation receiver measures the signal response at a point 2, which is located 60 mm to the left of the crack. Between the application of load 1 and the determination of signal response 2, there is a centrally positioned hole in the brick that is symmetrically placed.

The problem is resolved by dividing the body into finite elements, as shown in Figure 2.
The following boundary conditions were used to solve the problem. The nodes on the lower surface are constrained in the Y direction with $U_Y=0$. The bottom surface nodes with $x=0$ are fixed in the Z direction, specifically $U_Z=0$. The nodes on the bottom face with an X value of 250 mm are fixed in the X direction, specifically with a UX value of 0.

### 3 Results and discussion

The problem solution provides fields of stress, deformation, and displacement.

Fig. 3. Dynamic influence on the displacement fields (increased by a factor of $10^5$).
When an ultrasonic wave is applied, Figure 3 demonstrates that the edges of the hole become deformed and the signal is transmitted through the upper surface to the opposite edge. To reach point 2 of the receiver, the signal needs to go around the hole.

Graphs in Figure 4 show the displacements of the signal at the received point 2. It can be seen that for a buried defect there is no signal shift at the reception point for bricks without a defect and with 10mm and 30mm holes. However, the amplitude values of the curves differ between the 2nd and up to the 4th half-waves.

![Graph](image)

**Fig. 4.** Displacement versus time graph for bricks: 10mm (blue), 30mm (red), defect-free (green).

It is obvious that a disturbance wave propagated over the surface arrives at the signal reception point simultaneously for a brick without a defect and with defects. At the same time, it is clear that the maximum amplitude value of the oscillations differs in the second and subsequent half-waves. At the point 45 µs, 50 µs and 57 µs the amplitudes differ noticeably by about 7%.

This fact can be explained by the fact that the hole resonates at certain frequencies determined by the size of the cylinder and the properties of the material. This allows us to develop a method for effectively diagnosing the presence of cylindrical cavities in construction objects.

At $t=0.15$ µs, Figure 5 displays the von Mises stress fields during the initial stage of load application.
Mises stress fields shown in Fig. 5 show that the disturbance from the ultrasonic signal is transmitted to the receiving point, both along the surface and reflected from the brick wall. It can be seen that the hole is also deformed. Vibrations of the hole walls are transmitted to the receiving point and are determined by the geometry of the hole, as well as the properties of the brick material. That is, at certain frequencies the hole resonates and these resonant phenomena affect the shape of the signal at the receiving point.

The obtained results align well with the findings of other researchers [9, 10]. For example, in article [9] a group-penetrating radar is used, used for non-destructive 3D reconstruction techniques. The signal reflected from the cylindrical hole is captured by an array of sensors and restores the geometry of the object. It should be noted that such a radar takes up a lot of space and needs to be redesigned for construction sites.

In article [17], defect detection is carried out based on a combination of various methods and through the use of machine learning algorithms. The accuracy of the algorithms used is thoroughly analyzed before conducting the experiment, including Accuracy (A), Intersection over Union (IoU), Precision (P), and Recall (R).

4 Conclusion

The focus of this study was on the 3-D propagation of ultrasonic waves in building elements with cylindrical cavities. Ceramic was selected as the building brick material due to its common usage. An FEM model of wave propagation in brickwork has been constructed, which simulates the behaviour of an object in the form of a cylindrical hole in a brick during the passage of an ultrasonic wave. It is shown that at the reception point; the signal has a difference in amplitude for bricks with holes compared to bricks without defects.

To construct a methodology for estimating the parameters of a hole, it is necessary to use the amplitude-frequency characteristic of the signal and determine the geometry of the hole from changes in amplitudes.

Further development of this research is connected with the study of Fourier transforms of the signal and comparison of the frequency response for intact and defective objects. To solve
the inverse problem, it seems promising to construct neural networks to restore the geometry of the defect based on the results of ultrasonic signal processing.

References

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