

Design of an Acoustic Emission Robot Used for Preliminary Detection of Shaft Internal Cracks

Serkan Beller*

Abstract—A shaft crack is a fracture or discontinuity in a rotating shaft caused by fatigue, stress concentration, or material defects. Cracks typically begin on the surface and spread inwards. Shaft cracks are extremely dangerous in rotating machinery. Because a small, undetectable defect can develop into a complete shaft fracture within hours or days, leading to serious equipment failure. Detection of internal cracks in solid shafts is generally performed using non-destructive testing methods (Ultrasonic, magnetic particle, and radiographic testing) that do not compromise the integrity of the material. Hammer testing is another practical and traditional non-destructive method often used to detect material integrity, cracks, or loose connections. When a non-defective solid shaft is struck with a hammer to detect cracks, a clear, ringing sound is produced. If there are cracks in or on the shaft, the sound will be muffled, or the vibration will be dampened. In the present study, crack detection within a solid shaft is performed by measuring the sounds produced by four 20 mm diameter steel balls freely falling onto the shaft from a distance of 365 mm using a decibel meter. The semi-automatic robot was developed as an alternative to the hammering method for the preliminary detection of cracks. The surface areas to be tested by the steel balls can be varied using a DC motor-driven screw shaft system. Experimental results have demonstrated that the robot can produce rapid results per unit length, is improvable, and can reduce maintenance costs.

Index Terms—Acoustic Emission Robot, Crack Detection, Echo Listening, Hammering, Screw Shaft, Solid Shaft.

I. INTRODUCTION

Hammering (or acoustic emission/sound testing) is a conventional and practical non-destructive testing (NDT) method used to check the structural integrity of materials in shaft crack detection [1]. This method is commonly applied to detect fatigue cracks or internal discontinuities in parts such as large shafts, axles, and bearing housing surfaces. This method is also used for fatigue testing to check the tightness of parts such as pulleys, gears, or bearings on a shaft, or to quickly detect the onset of cracks in heavy-duty shafts. The hammering method is based on the characteristics of the sound emitted by the material. When a shaft is struck with a small hammer, a solid material produces a clear, high-frequency, and sustained ringing sound (resonance). If there is a crack in the shaft, the crack will interrupt or dampen the transmission of sound waves. In this case, when struck with a hammer, it produces a "thump," dull, or "dead" sound. This method is fast, requires no special equipment, is inexpensive, and is effective for pre-inspection of large parts. However, it may not be able to detect very small, superficial, or fatigue cracks. Because it relies on human

hearing, it is subjective; it requires experience. The hammering method is generally used for preliminary detection. For accurate results, more precise methods such as Magnetic Particle Inspection (MPI) or Ultrasonic Testing (UT) are required [1].

Detection of internal cracks in solid shafts is performed using non-destructive testing (NDT) methods, which do not compromise the integrity of the material. The most effective methods for detecting discontinuities inside (below the surface) the shaft are as follows:

1) Ultrasonic Inspection (UT)

This is the most common and sensitive method for detecting internal cracks in solid shafts. High-frequency sound waves can be used to detect structural defects within the shaft, such as cracks, voids, or pores [2].

2) Magnetic Particle Inspection (MT/MPI)

This method is used to detect surface and sub-surface cracks in shafts made from ferromagnetic (magnetizable) materials [3].

3) Radiographic Examination (RT - X-ray)

In this method, the internal structure of the shaft is visualized using X-rays or gamma rays. Although it is particularly effective for detecting deep internal cracks, it can be difficult to apply if the solid shafts are thick.

In conclusion, Ultrasonic Testing (UT) is more suitable for cracks entirely within the shaft, while Magnetic Particle Testing (MT) is more appropriate for surface and near-surface cracks [1].

Common causes of shaft cracks can be categorized into four main headings.

1) Fatigue caused by cyclical stressors

The most common causes, especially in rotary machinery, are: bending fatigue, torsional fatigue, high-cycle fatigue, and stress concentration. In bending fatigue, a rotating shaft with uneven stiffness or loads creates cyclic bending stress. In torsional fatigue, there is oscillatory torque in the power transmission shafts, while in high-cycle fatigue, millions of stress cycles accumulate over years of operation. In stress concentration, wedge paths, holes, fillets, and geometric discontinuities intensify the stress.

2) Operating conditions

These include extreme imbalance, misalignment, resonance operation, overload, and thermal stresses. Excessive imbalance is caused by high centrifugal forces, which create bending stress. Misalignment is caused by bending moments resulting from misalignment, accelerating fatigue. In resonance processing, critical speeds result in significant deviations. Overloading is caused by operating beyond design limits. Rapid heating/cooling cycles or thermal gradients are causes of thermal stress.

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3) Material and manufacturing defects

These may include material content (Presence of slag, voids, or foreign matter in the shaft material), improper heat treatment, machining defects, and corrosion pitting.

4) Operational events

These include: excessive speed incidents, severe frictions, impact loading, and previous repairs. Shaft cracks are one of the most serious potential failures in rotary machinery. The combination of vibration monitoring and periodic non-destructive testing offers the best strategy for early crack detection, enabling planned maintenance before a catastrophic failure occurs [1].

When previous studies are examined,

TABLE I. PREVIOUS STUDIES

Numerical Simulation and Theoretical Study	Experimental Study	Model-Based Methods (Analytical and Numerical Models)	Vibration-Based Methods
[4]–[8], [10]–[13], [15]–[19], [21], [23]–[24], [26]–[32], [35]–[36], [38]–[42], [44]–[46], [48]–[50], [52], [54]–[55]. (40/52)	[5]–[6], [8]–[10], [13]–[15], [17]–[27], [30]–[34], [37]–[44], [46]–[48], [51], [53]–[55]. (39/52)	[4]–[7], [11]–[12], [18]–[19], [21]–[24], [28]–[30], [32], [34]–[36], [38]–[40], [44]–[45], [50], [52]–[54]. (28/52)	[4]–[6], [8]–[17], [20]–[21], [23]–[27], [30]–[33], [37]–[39], [41]–[44], [46]–[49], [51], [55]. (37/52)

As shown in Table I, a total of fifty-two articles were reviewed for this study. Forty of these articles contain theoretical studies. Thirty-nine of these articles involve experimental studies. Twenty-eight of these articles involve model-based methods. Thirty-seven of these articles involve vibration-based methods. All articles fall into at least two of these four categories. Some include three, and some include all four. Only one of these articles [20] features an experimental study applying various technologies such as acoustic emission, vibration, and motor current signature analysis. In another study [26], the effects of crack depth on shaft rigidity and natural frequencies were experimentally analyzed. Natural frequencies were obtained using a vibration analyzer with impact hammer testing under static conditions. In reference [40], rotor crack detection was performed based on neural networks and modal data. In study number [42], too, crack detection was performed using the modal analysis of multiple cracks and the estimation of their features with an artificial neural network.

A. Results Obtained from the Study

1. This study was developed as an alternative to the hammering method for the preliminary detection of cracks.
2. According to the results, other non-destructive testing methods should be used for a more in-depth investigation.
3. The aim here is to develop an alternative method to the experience-based acoustic listening technique.
4. Experimental results have shown that the robot can obtain rapid results per unit length.
5. The robot's working mechanism is open to further development.

6. Maintenance costs of mechanisms can be reduced with rapid results.
7. The system can be fully automated.
8. The control block diagram can be designed as a closed loop.
9. With this study, preliminary inspection processes during short-term shutdowns in factories will be accelerated, and assistance will be provided to the technical team for future planning.

II. MATERIAL AND METHOD



Fig. 1. Acoustic emission robot experiment set: 1- DC motor (12 V), 2- Screw shaft ($\varnothing$ 16 mm x 400 mm), 3- Housing with bearing ($\varnothing$ 10 mm x 2 pieces), 4- Telescopic rail (400 mm x 2 pieces), 5- Carrier trolley, 6- Screw shaft base, wood, 7- Power supply (12V 16.7 A), 8- Solid shaft base frame (480 mm x 200 mm), 9- Bearing ($\varnothing$ 22 mm x 4 pieces), 10- Tubular frame ($\varnothing$ 22 mm), 11- Solid shaft ($\varnothing$ 50 mm x 420 mm, St 37), 12- Carrier frame, 13- Test tubes ($\varnothing$ 34 mm x 354 mm, plastic), 14- Steel balls ($\varnothing$ 20 mm, 33 g, stainless steel) 15- Decibel meter

In this study, firstly, a test hole was drilled into the first region of the solid shaft (Diameter: $\varnothing$ 50 mm, length: 420 mm, St37), measuring $\varnothing$ 10 mm in diameter, 56 mm in depth, and 16 mm off-center as seen in Figure 1. Later, four steel spheres (Diameter: $\varnothing$ 20 mm, weight: 33 g) were dropped from a certain height (365 mm) onto a solid shaft one by one. Then, the sounds produced by the steel balls were measured with a decibel meter. At the end of the tests, it was observed that the bounce of the steel sphere damped more quickly in the defective area.

A. Spindles, Shafts, and Axles

Spindles, shafts, and axles are machine elements with a circular cross-section, a length much greater than the diameter of the circle, that transfer power/torque, and are supported by bearings formed on the housing [56].

1. Spindles

The use of rotating machine elements in machines offers many advantages in terms of structure. In machine manufacturing, efforts are made to use parts and machine elements that perform rotational motion as much as possible. These machine elements need to be supported (bearings) in a way that will allow them to rotate [56].

In addition, power transmission from one rotating machine element to another is also a concern. In this case, the most common solution is to use a separate element that carries the rotating parts and allows energy flow between them. The component that performs this function is the spindle. Generally, spindles are classified according to their appearance and axis as shown in Figure 2, including

solid, hollow, flanged, elbowed (Crankshaft), articulated, and flexible spindles (In applications where low power transmission is desired, such as in automobile speedometers) [56].

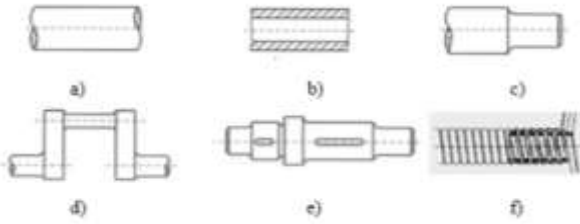


Fig. 2. Types of spindles. a) Solid, b) Hollow, c) Flanged, d) Elbowed, e) Articulated, f) Flexible

Spindles are subjected to bending due to the varying loads from the machine elements they carry, and torsion due to the torque that transmits power. As shown in Figure 3, a spindle that generates power by rotating produces torsional stress while being subjected to a constant torque. If a constant or variable radial load is applied to the spindle, a bending moment will result.



Fig. 3. Examples of spindle applications

To ensure optimal strength, spindles are designed with a specific bending value in mind. If there are gears on the spindle and the spindle's bending exceeds an acceptable value, this will cause excessively noisy operation. If cams are present on the spindle and the torsional value exceeds the acceptable level, cam timing becomes problematic. If the bending and torsional values are high in the spindles, this problem can be solved by reducing the critical rotational speed of the spindle [56].

2. Shafts

Spindles, called shafts, transmit torque (energy) from one machine element to another and are only subjected to torsion. The spindles used between the differential and the wheel in vehicles, the hollow spindles used between the driveshaft and clutch, and the spindles used between the engine and the propeller in ships are some prime examples of shafts. The shafts are only subjected to torsion. If both torsional and bending forces act simultaneously, or only bending forces act, these machine elements are called a spindle [56].

3. Axles

Axles are spindles that resemble spindles in appearance but serve only to carry loads and are therefore only subjected to bending. Axles are machine elements that provide bearings for machine elements mounted on them that perform rotational or oscillatory motion, and they themselves do not transmit energy. The most important difference between axles and spindles is that axles do not transmit torque. Therefore, axles can be defined as spindles that do not transmit torsional moment. The axle itself can be fixed or rotary. Axles are commonly used in many

applications, such as in vehicle wheels, conveyor support rollers and drums, rope pulleys, sprockets and gear wheel assemblies, and tensioning pulleys [56].

4. Spindle, Shaft, and Axle Materials

Various types of steel, ranging from low-carbon and low-strength manufacturing steels to high-carbon and alloy steels, are used in the production of spindle, shaft, and axle material. Generally, structural steels with a carbon content of around 0.35%, such as Fe44 (St44), Fe50 (St50), Fe60 (St60), and Fe70 (St70), are used in spindle manufacturing. By adding alloys such as Mo, W, and V to these materials, materials with better strength are obtained.

In situations where high strength is required (Under heavy loads) or where surface hardening is necessary, heat-treatable steels such as C35, 40Mn4, or 34Cr4, or carburizing steels such as C15, Ck15, 16MnCr5, 25MoCr4, or heat and corrosion resistant steels such as 18CrNi8 or 42CrMo4 are the most commonly used materials for spindle, shaft, and axle. In the food and chemical industries, stainless steel is consistently preferred [56].

B. Screw Shaft

A screw shaft is a mechanical component frequently used in industrial and engineering applications. Generally, it is an element designed in the shape of a screw thread that converts rotational motion into linear motion. Screw shafts are particularly used in systems where precise positioning of moving parts is required. A screw shaft is a shaft designed in the shape of a threaded screw, typically working in conjunction with a screw thread and a nut. The screw thread has a spiral-shaped tooth structure around the shaft, while the nut fits into these threads, converting the shaft's rotational motion into linear motion. Screw shafts provide high precision and control during this conversion [57].

Driving Torque and Moment of Inertia Calculations

Driving torque;

Load converted to motor axis, moment of inertia;

Screw shaft;

$$J_B = \frac{\pi \cdot \gamma}{32} \cdot D^4 \cdot L \quad (1)$$

Moving part;

$$J_W = m \cdot \left(\frac{1}{2 \cdot \pi} \right)^2 \quad (2)$$

Coupling;

$$J_C = 0.25 \text{ kg.cm}^2 \quad (3)$$

Total moment of inertia of the screw shaft;

$$J_L = J_B + J_W + J_C \quad (4)$$

Driving torque calculation;

$$T_1 = T_a + T_{pmax} + T_u \quad (5)$$

In this formula, T_a is the driving torque at constant speed, T_{pmax} is the upper limit of the dynamic friction torque of the ball screw, and T_u is the friction torque of the support bearings.

$$T_a = \frac{F_a \cdot l}{2 \cdot \pi \cdot \eta_1} \quad (6)$$

$$F_a = \mu \cdot m \cdot g \quad (7)$$

$$T_{pmax} = 7.8 \text{ N.cm (Table 3.7)} \quad (8)$$

$$T_u = 2.1 \text{ N.cm} \cdot 2 \text{ Pieces} = 4.2 \text{ N.cm (Table 3.8, [58])} \quad (9)$$

C. System Design

In this study, four steel spheres with a diameter of $\varnothing 20$ mm and a weight of 33 g were used in the experimental setup for sound analysis. These spheres were successively dropped in free fall from a distance of 365 mm above four plastic tubes, each $\varnothing 32$ mm in diameter and 353 mm in length, in the experimental setup shown in Figure 1. At the point where the spheres fall, there is a solid shaft made of St37 material, with a diameter of $\varnothing 50$ mm and a length of 420 mm. One side of this shaft features a test hole measuring $\varnothing 10$ mm in diameter, 56 mm in depth, and 16 mm off-center. The tests were conducted in three steps. Since the total horizontal distance covered by the four tubes was 170 mm, the 420 mm-long solid shaft was examined in three steps. In this experimental setup, a screw drive system was used to move the tubes collectively. The technical data for the screw drive system are as follows.

- 1) Screw shaft diameter; $D_b = \varnothing 16$ mm
- 2) Screw shaft length; $L_b = 400$ mm
- 3) Screw shaft material (iron); $\rho = 7900 \text{ kg/m}^3$
- 4) Screw pitch; $P_B = 5$ mm
- 5) Screw shaft efficiency; $\eta = 0.9$
- 6) Instantaneous traverse speed; $V_{\max} = 250 \text{ mm/s}$ (Table 3.1)
- 7) Position accuracy; $\pm 0.05 \text{ mm}$ [58]–[59] (NSK catalog, page B87)

- 8) Repeatability; $\pm 0.005 \text{ mm}$ [58]–[59], (NSK catalog, page B87)
- 9) Coefficient of friction of sliding surfaces; $\mu = 0.05$ [60]
- 10) Motor type; DC motor ($N_{\max} = 3000 \text{ RPM}$) (Table 3.2)

In the experimental setup, a DC motor drives the screw shaft mechanism. This motor, operating at 12V, can rotate at 600 RPM [61]. Additionally, the experimental setup utilized two 400 mm telescopic rails with a load capacity of 45 kg each, and ASAHI, Japanese brand UCP series ball bearings with a $\varnothing 10$ mm bore diameter. The power supply was a Globex GXA1216 (12 V, 16.7 A).

A. Control Block Diagram

Figure 4 shows that the system control has an open-loop mechanism. The control block was designed in the MATLAB/Simulink environment. In this semi-automatic system, a decibel meter is used to analyze the sounds produced by spheres manually dropped from tubes as they strike the shaft surface. If the results are satisfactory, the screw shaft is moved by a DC motor, and the other surfaces on the solid shaft are inspected. The process here is only a preliminary assessment of internal shaft cracks. Further analysis of suspected areas requires the use of other methods. The designed experimental setup is developed as an alternative to the classic hammering method. The aim here is to save the user time and reduce maintenance costs.

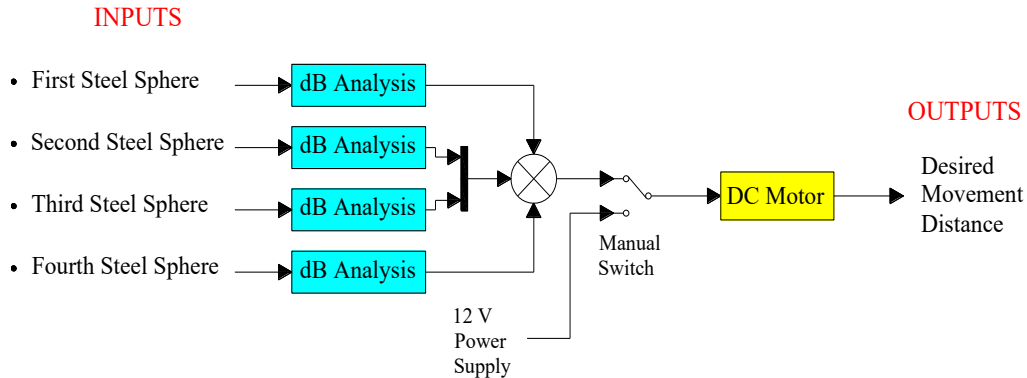


Fig. 4. Control block diagram

III. EXPERIMENT STUDIES

As shown in Figure 5, the solid shaft was investigated in three stages in this study. The horizontal inspection distance of the four tubes is 170 mm, and the distance between the axes of the outermost tubes is 140 mm. The distance between the axes of the tubes is 47 mm, and if desired, more than three inspection steps can be chosen. The $\varnothing 50$ mm diameter solid shaft to be tested is supported by four bearings. This allows for 360° inspection of the shaft. Because the diameters of the tubes through which the steel spheres pass are larger than the diameters of the spheres, these tubes prevent the spheres from scattering when they bounce off the surface. The first section of the solid shaft contains a horizontal test hole with a diameter of $\varnothing 10$ mm, a depth of 56 mm, and an offset of 16 mm from the center. The center of this hole is located 9 mm from the surface. The remaining wall thickness is only 4 mm. Four different tests were performed in this section,

while only one test was performed in the second and third sections, which consisted of problem-free areas. The test results are shown in the results section.

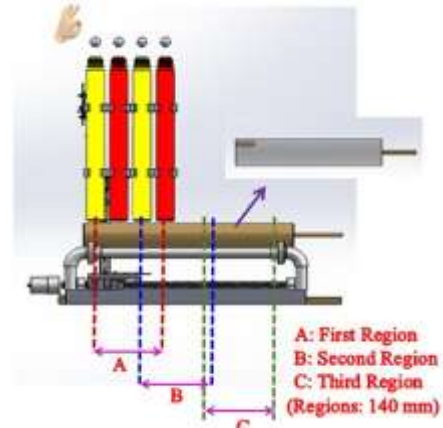
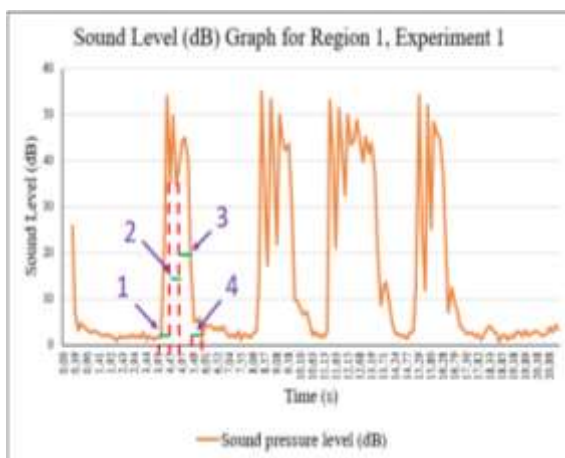


Fig. 5. Robot inspection distances

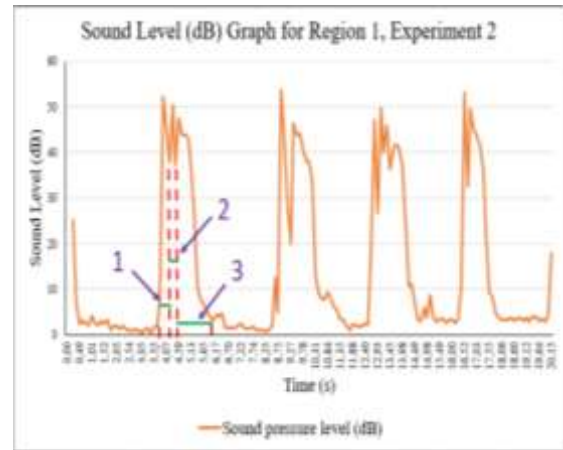
IV. RESULTS

The results of the experiments are shown in Figure 6. In each graph, the decibel values of the sounds produced by four different spheres were plotted by a decibel meter. In these experiments, the measurement areas on the solid shaft were divided into three regions. On the side where the first region is located, there is a test hole with a diameter of $\varnothing 10$ mm, a depth of 56 mm, and 16 mm off-center. This hole represents the horizontal crack inside the shaft. The movable part of the experimental setup on the shaft has four vertical tubes. These tubes are placed 47 mm apart. In the first region, only the steel sphere falling from the first tube can test the crack region. Due to the test hole in the first region, more experiments were conducted in this region, and the results are presented in Figure 6 (a, b, c, d). When these four graphs are examined, what they all have in common is this: The first sphere's number of bounces and sound amplitude are both lower and over shorter distances compared to the results of the other spheres. This indicates that there is an internal shaft defect in the first 27 mm of the first region of this shaft. Here, the vibration is damped. Although the sound is muffled, it was not very noticeable in terms of decibel value. The other spheres bounced more often and had longer sound amplitude values compared to the first sphere. This shows that no problems were found in these regions of the shaft near the surface. The experimental results of the remaining second and third regions of the shaft are shown in Figure 6(e, f), respectively.

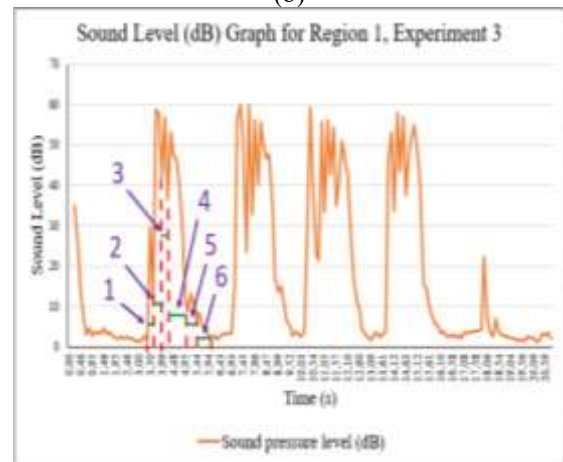
In these regions, the number of bounces and the amplitude of the bounces of all four spheres are similar. This indicates that no shaft defects are found near the surface. If desired, experiments can be conducted over shorter distances with more precise DC motor control. This would allow for the precise determination of the defective region's length. The system operates in a semi-automatic. If automatic positioning of the steel spheres is enabled, the system can also transition to full automation. Furthermore, the control block of the system can be designed as a closed-loop system.



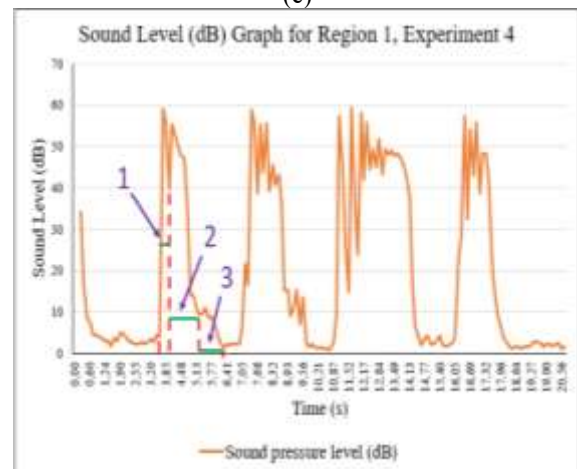
(a)



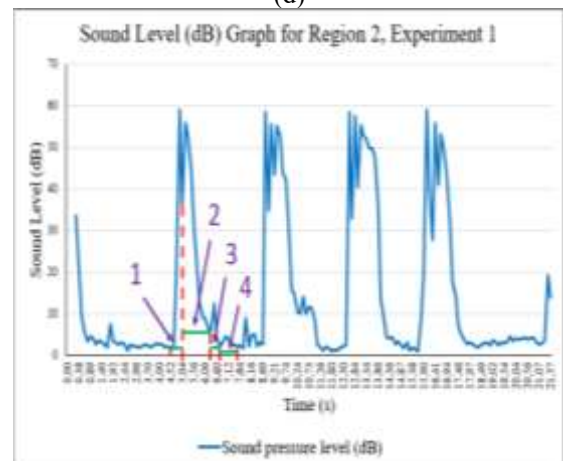
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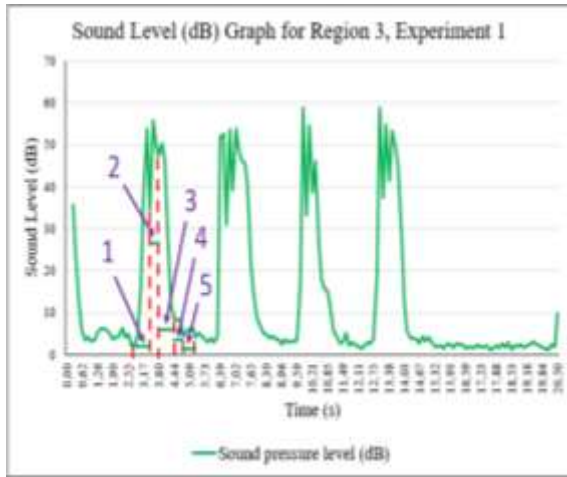
(c)



(d)



(e)



(f)

Fig. 6. Decibel meter test results: a, b, c, d) First region tests, e) Second region tests, f) Third region tests

TABLE II. NUMERICAL RESULTS OF THE EXPERIMENTS

		Total Experiment Duration (s)	Number of Bounces of the Spheres	Average Interval Time (s)
Region 1, Experiment nt 1	First Sphere	1.80	4	0.45
	Second Sphere	2.70	4	0.68
	Third Sphere	3.37	7	0.48
	Fourth Sphere	3.69	7	0.53
Region 1, Experiment nt 2	First Sphere	2.36	3	0.79
	Second Sphere	3.50	5	0.70
	Third Sphere	3.22	8	0.40
	Fourth Sphere	2.48	3	0.83
Region 1, Experiment nt 3	First Sphere	2.68	6	0.45
	Second Sphere	3.33	7	0.48
	Third Sphere	3.06	5	0.61
	Fourth Sphere	2.99	5	0.60
Region 1, Experiment nt 4	First Sphere	2.68	3	0.89
	Second Sphere	2.90	9	0.32
	Third Sphere	3.90	9	0.43
	Fourth Sphere	2.81	4	0.70
Region 2, Experiment nt 1	First Sphere	2.99	4	0.75
	Second Sphere	2.71	5	0.54
	Third Sphere	2.56	5	0.51
	Fourth Sphere	2.73	4	0.68
Region 3, Experiment nt 1	First Sphere	2.67	5	0.53
	Second Sphere	2.31	3	0.77
	Third Sphere	2.27	4	0.57
	Fourth Sphere	2.30	5	0.46

A. Comparison of Experiment Results

Figure 1 shows that the existing robot has two degrees of freedom. One degree of freedom is in the horizontal direction thanks to the screw shaft, while the other is in the vertical direction where the spheres move. Since no mechanism has been added to the robot for vertical movements, the existing robot structure is called semi-automatic. The data in Table 2 consists of the total durations of the experiments shown in Figure 6. For a sine wave, the period represents the time interval between two peaks or two troughs. A total of four experiments were conducted in the first region on the solid shaft, while one experiment was conducted in each of the other regions.

Detailed data regarding the experiments are included in Appendix 1.

During the experiments, four steel spheres were successively dropped on the test shaft, and the decibel values of the resulting sounds were recorded. The first four experiments in Figure 6 are located in the first region where the shaft crack is present. Of the four spheres, the first sphere falls onto the surface containing the shaft crack, while the other three spheres fall onto surfaces without shaft defects. Looking at the decibel values produced by the first sphere in the first four experiments, it is observed that the number of bounces and amplitude values of the spheres are lower compared to the results of the other spheres (Appendix 1). The motion is damped more quickly. The total motion times of the first sphere in the four experiments are shown in Table 2 as 1.8 (A total of four amplitudes), 2.36 (A total of three amplitudes), 2.68 (A total of six amplitudes), and 2.68 seconds (A total of three amplitudes), respectively. This indicates the presence of a crack near the surface within the solid shaft. Meanwhile, the decibel values of the sounds produced by the first sphere are similar to those of the other spheres. Differences in tone were observed during the tests, but these differences were not reflected in the numerical results. This is thought to be due to the large diameter ($\varnothing$ 10 mm) of the test hole and its openness to the external environment. When the graphical results are examined, it can be seen from the numerical results in Table 2 that the damping ratios and durations of the other spheres, except the first one, are close to each other. The first column in Appendix 1 lists the names of the spheres that underwent the test. The second and third columns show the start and end times of the tests, respectively. The fourth column shows how many different amplitudes (Sine waves) were generated during the tests and their period durations. It is seen in both the graphs and the table that each sphere performed a different number of bounces. The fifth column shows the total test duration for each sphere. In tests conducted in the second and third zones, it was observed that the test completion times of each sphere were quite similar. This indicates that a clear defect could not be detected near the outer surface of the solid shaft. This robot was developed for the preliminary detection of internal shaft cracks. It is seen as an alternative to the hammering method. The aim here is to speed up preliminary inspection processes during short shutdowns in factories and to assist the technical team in future planning. To obtain definitive results in the tests, other non-destructive testing methods (Ultrasonic, magnetic particle, and radiographic testing) should be used.

V. DISCUSSIONS

Cracks in shafts are important structural defects because they can progressively reduce the integrity and dynamic stability of rotating machinery. Such cracks may originate from material fatigue, stress concentration, manufacturing imperfections, or defects that develop during prolonged operation. Fatigue-related damage is particularly important because repeated cyclic loading can initiate small surface cracks that subsequently propagate toward the interior of the shaft [15], [22], [25]. Previous

experimental and analytical investigations have demonstrated that even relatively small cracks can modify the dynamic behavior of a shaft and, when they remain undetected, may ultimately contribute to severe rotor damage or complete mechanical failure [4], [10], [31]. Consequently, early crack detection is essential for preventing unexpected shutdowns, secondary equipment damage, and potentially hazardous shaft fracture.

Several non-destructive testing (NDT) techniques are available for detecting cracks in shafts. Ultrasonic testing is widely applied to identify internal discontinuities by analyzing the propagation and reflection of ultrasonic waves within a material [2], while magnetic particle testing is particularly useful for detecting surface and near-surface discontinuities in ferromagnetic components [3]. In rotating machinery research, vibration-based methods have also received considerable attention because a crack changes local stiffness and consequently influences natural frequency, modal response, harmonic components, and other dynamic characteristics of a rotor system [4]–[9], [16]–[20]. Experimental studies have shown that crack location and severity can be identified through changes in vibration response, modal parameters, frequency response functions, and vibration energy distribution [8], [9], [17], [19], [33], [37]. These findings provide the theoretical basis for using changes in mechanical and acoustic responses as preliminary indicators of shaft defects.

The method investigated in the present study is based on the same fundamental principle, but applies a relatively simple controlled-impact approach as an alternative to conventional manual hammer testing. In a traditional hammering test, the condition of a solid component is preliminarily assessed from the sound and vibration generated after impact. A structurally intact shaft is expected to produce a relatively sharp and sustained response, whereas the presence of a discontinuity may alter stiffness and energy transmission, producing greater damping or a less sustained response. This principle is consistent with previous studies showing that cracks can affect vibration amplitude, modal properties, frequency characteristics, and energy distribution within a shaft [5], [12], [16], [25], [37]. However, manual hammer testing is intrinsically dependent on the experience of the operator, the magnitude and location of the impact, and subjective interpretation of the resulting sound. The present robotic system was therefore developed to provide a more repeatable impact mechanism for preliminary crack screening.

To examine this concept experimentally, a solid St37 steel shaft with a diameter of 50 mm and a length of 420 mm was used. A simulated defective region was produced by drilling a hole with a diameter of 10 mm and a depth of 56 mm at an off-center distance of 16 mm. Four steel spheres, each 20 mm in diameter and weighing approximately 33 g, were subsequently dropped individually from a height of 365 mm onto the shaft. The acoustic responses generated by these impacts were recorded using a decibel meter, while the behavior and damping of the spheres after impact were observed. The use of standardized spheres and a fixed dropping height was intended to reduce variations associated with

manually applied hammer impacts and to establish a more consistent excitation condition. This approach is conceptually compatible with previous crack-detection techniques in which controlled excitation is used to reveal structural differences between intact and damaged shafts [5], [6], [28], [30].

The experimental observations indicate that the defective region produced a systematically different damping response from the non-defective regions. In the four experiments conducted over defective regions, the damping times associated with the first sphere were 44.66%, 23.05%, 14.29%, and 16.33% shorter than the corresponding mean damping times of the second, third, and fourth spheres. In contrast, in the two experiments performed over non-defective regions, the damping times of the first sphere were 10.80% and 9.48% longer than the respective averages of the remaining spheres. Thus, the principal experimental pattern was not merely a difference in measured sound level, but a more rapid attenuation of the impact response when the sphere interacted with a defective section of the shaft. This observation is consistent with the general findings of vibration-based crack-detection research, in which the presence of structural discontinuities modifies stiffness, vibration transmission, energy distribution, and damping-related characteristics [12], [25], [33], [37]. Similar studies have demonstrated that crack-induced changes in dynamic response can be sufficiently systematic to distinguish damaged from undamaged shaft conditions [17], [34], [39].

From a mechanical perspective, the shorter damping time observed in the defective region may indicate that the artificially introduced discontinuity modifies the local transfer and dissipation of impact energy. A crack or crack-like defect changes the local structural characteristics of the shaft and can consequently influence its dynamic response. Previous studies have demonstrated that crack depth, crack location, and crack geometry affect measured rotor responses and can therefore influence the sensitivity of diagnostic procedures [9], [34], [36], [41]. Accordingly, the present results should not be interpreted as evidence that a single damping threshold can identify every possible shaft crack. Rather, they provide preliminary experimental evidence that controlled impact and damping behavior may serve as a relatively simple screening indicator for distinguishing potentially defective regions from intact regions. Further experiments involving different crack depths, orientations, locations, shaft diameters, and materials would be necessary before a generalized diagnostic threshold could be established.

The robotic configuration also provides an important practical advantage over purely manual hammer testing. The current prototype operates in a semi-automatic mode and has two degrees of freedom. The shaft can be rotated through 360°, enabling different circumferential surfaces to be examined, while a DC motor-driven screw-shaft mechanism allows the longitudinal position of the impact area to be varied. This arrangement potentially enables systematic scanning of multiple positions along the shaft rather than relying on manually selected impact locations. Such controlled positioning is relevant because previous

investigations have shown that diagnostic response depends strongly on crack position and depth [9], [35], [36], [53]. The combination of repeatable impact conditions and controlled spatial positioning therefore represents an important feature of the proposed system.

Nevertheless, the present study should be regarded as a proof-of-concept investigation rather than a complete replacement for established NDT procedures. Only longitudinal crack control was considered, the defect was artificially introduced, and only six experimental measurements were evaluated, comprising four measurements involving defective regions and two involving non-defective regions. The number of shaft specimens, defect geometries, and operational conditions was therefore limited. Moreover, the current system remains semi-automatic and the acoustic signal was assessed using a relatively simple decibel-based measurement rather than a more comprehensive frequency-domain or time-frequency signal analysis. Previous research has demonstrated that advanced methods involving modal analysis, spectral characteristics, wavelet analysis, principal component analysis, and combined lateral and torsional vibration measurements can improve crack characterization and localization [19], [39], [46], [47], [54], [55]. Integration of such signal-processing techniques into future versions of the system could therefore improve diagnostic sensitivity and reduce dependence on simple acoustic amplitude or damping observations.

Overall, the experimental findings support the feasibility of using a robotic controlled-impact mechanism as a preliminary alternative to manual hammering for shaft crack screening. The substantially shorter damping times observed in the experimentally defective regions, together with the opposite pattern found in the non-defective regions, suggest that impact-response damping contains potentially useful information regarding shaft integrity. The proposed robot should not be viewed as a substitute for ultrasonic, magnetic particle, radiographic, or other established NDT procedures when definitive defect characterization is required. Instead, its principal potential lies in rapid preliminary inspection, particularly during short maintenance shutdowns, where suspicious shaft regions could first be identified through automated impact testing and subsequently examined using more sophisticated NDT techniques. Further validation with larger sample sizes, naturally occurring cracks, different materials and shaft geometries, and automated signal analysis will be required to determine the reliability, sensitivity, specificity, and practical applicability of the proposed method.

IV. CONCLUSION

This current study is designed for factory workers to check the solid shaft health of machines during short shutdowns. Because using other methods is time-consuming, requires a team of experts for use and interpretation of results, and is also costly. The aim is to enable workers, some of whom may lack experience, to make informed decisions based on graphical results. Interpreting the results here is easier compared to other

methods. Furthermore, this method eliminates the need for experienced workers to interpret the results. The current experimental setup is a prototype. Design modifications can be made depending on the application. The robot can operate more quickly and pinpoint the problem. In this study, only a longitudinal crack in one shaft was detected. Future studies will conduct trials for the preliminary detection of other crack types. Furthermore, it is planned to apply artificial intelligence methods to the robot's movements in crack detection studies to both pinpoint the problematic area and obtain faster results.

DECLARATION OF COMPETING INTEREST

The author confirms the absence of any financial conflicts of interest or personal relationships that might have affected the outcomes of this study.

ACKNOWLEDGMENT

This research received support from the Scientific Research Projects Unit of Çukurova University (Project code: FBA-2023–16425).

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Appendix 1. Total duration the spheres spend in the air.

Region One. Experiment One.				
	Start Time (s)	End Time (s)	Durations of Amplitude Periods (s)	Total Experiment Duration (s)
First Sphere	4.08	5.88	0.39-0.25-0.77-0.39	1.8
Second Sphere	8.18	10.88	0.51-0.39-0.37-1.43	2.7
Third Sphere	11.13	14.5	0.5-0.39-0.27-0.52-0.26-0.52-0.91	3.37
Fourth Sphere	15.03	18.72	0.51-0.26-0.74-0.89-0.25-0.26-0.78	3.69
Region One. Experiment Two.				

First Sphere	3.68	6.04	0.52-0.26-1.58	2.36
Second Sphere	8.25	11.75	0.5-0.52-0.25-1.18-1.05	3.5
Third Sphere	12.14	15.36	0.4-0.39-0.26-0.26-0.78-0.52-0.23-0.38	3.22
Fourth Sphere	16.12	18.6	0.53-1.54-0.41	2.48
Region One. Experiment Three.				
First Sphere	3.37	6.05	0.25-0.37-0.24-0.85-0.36-0.61	2.68
Second Sphere	6.31	9.64	0.49-0.78-0.26-0.25-0.38-0.52-0.65	3.33
Third Sphere	10.03	13.09	0.77-0.25-0.26-0.26-1.52	3.06
Fourth Sphere	13.47	16.46	0.65-0.25-0.26-1.47-0.36	2.99
Region One. Experiment Four.				
First Sphere	3.6	6.28	0.37-1.29-1.02	2.68
Second Sphere	6.92	9.82	0.39-0.37-0.26-0.25-0.26-0.36-0.25-0.38-0.38	2.9
Third Sphere	10.74	14.64	0.78-0.39-0.26-0.27-0.28-0.25-0.25-0.27-1.15	3.9
Fourth Sphere	15.66	18.47	0.91-0.25-0.25-1.4	2.81
Region Two. Experiment One.				
First Sphere	4.52	7.51	0.52-1.3-0.39-0.78	2.99
Second Sphere	8.69	11.4	0.26-0.26-1.15-0.25-0.79	2.71
Third Sphere	12.05	14.61	0.66-0.25-0.51-0.89-0.25	2.56
Fourth Sphere	15.64	18.37	0.65-0.25-1.31-0.52	2.73
Region Three. Experiment One.				
First Sphere	2.68	5.35	0.74-0.38-0.64-0.4-0.51	2.67
Second Sphere	6.12	8.43	0.53-0.25-1.53	2.31
Third Sphere	9.47	11.74	0.49-0.25-1.15-0.38	2.27
Fourth Sphere	12.62	14.92	0.51-0.25-0.9-0.39-0.25	2.3



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