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Fractal Analysis of Vibration Signals for Assessing Mechanical Material Properties Under Different Impact Forces

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Abstract Understanding the mechanical properties of materials is essential in science and engineering to enhance product durability, safety, and performance, and to prevent structural failures. This study applies fractal analysis to investigate vibration signals recorded by piezo film sensors during impact testing on four square-shaped materials: brass, copper, mild steel, and stainless steel. Using an impact hammer, each material was subjected to impact forces ranging from 300N to 800N. Vibration data was captured and analyzed in MATLAB using a box-counting algorithm to calculate fractal dimensions. The findings revealed a notable correlation between the calculated fractal dimensions and two critical mechanical properties, Poisson's ratio and Young's modulus. The fractal dimension is inversely ordered relative to the Poisson's ratio values of the materials, while the order of the fractal dimension aligns with the order of Young's modulus values. This suggests that materials with higher Young's modulus values also display higher fractal dimensions, whereas materials with higher Poissons ratios exhibit lower fractal dimensions. These insights indicate that fractal analysis of vibration signals provides a reliable, efficient, and cost-effective alternative to conventional methods for evaluating material properties. This approach holds significant potential for non-destructive testing applications, especially in fields requiring rapid and economical material assessments, such as aerospace, automotive, and construction.

Keywords Fractal dimension; box counting; vibration signal; impact force; correlation coefficient.

Mathematics Subject Classification 97R20.

1 Introduction

Characterizing material properties involves understanding a material's composition, specific form, and production methods [1]. In materials engineering, it involves evaluating various aspects like elastic modulus, hardness, tensile, compressive, and flexural properties, as well as fatigue, and fracture behavior [2]. Alfano & Pagnotta [3] stated in their study that elastic properties are fundamental for completing the characterization process of engineering materials. According to research conducted by Zhu *et al.* [4], the mechanical properties of mild steel and alloy steel have different strengths due to their different chemical compositions and manufacturing techniques. Therefore, knowledge about this is crucial and commonly applied in both complex and non-complex engineering designs and applications. The study of a material's properties and its fundamental properties can provide important information that helps prevent disasters related to engineering failures [5, 6].

Materials engineering focuses on understanding the mechanical properties of materials when subjected to forces or loads. These properties, including strength, hardness, ductility, and stiffness, are crucial for designing components that can withstand applied stresses without excessive deformation or fracture. Factors such as load type, application time, and service temperature can influence a material's mechanical behavior [7]. Understanding these properties allows engineers to select appropriate materials for specific projects and predict their performance under various conditions, ensuring the safety and efficiency of engineered structures and components [8].

Various methods have been used in studies involving the characterization of material properties, particularly to identify the elasticity and strength of a material. The elastic properties of a material play a crucial role in engineering design and applications, influencing material functionality and performance. Generally, the methods for characterizing properties are divided into two categories: static methods and dynamic methods [9]. Static methods involve the direct calculation of strain and stress under standard mechanical testing (tension, compression, bending, torsion). The specimens used in these tests must adhere to the specific size and shape prescribed in standard mechanical tests. Young's modulus and Shear modulus values are determined from the slope of the linear portion of the stress-strain curve or stress-strain graph [10]. This testing involves deforming the material until it either fails or exceeds its plastic properties. If the specimen is tested beyond its plastic properties, it is impossible for it to return to its original shape [5]. This type of testing is known as destructive testing.

Dynamic techniques, on the other hand, involve non-destructive testing. Non-destructive testing is an inspection technique that does not compromise the integrity of the material. This technique is very popular among industries and researchers because it does not require significant capital and offers a simple and clear process. According to Karim *et al.* [11], both dynamic and static techniques can measure a material's elasticity. Elasticity refers to a material's ability to return to its original shape after a load is applied and removed. Good examples include mild steel, rubber, and some plastics like nylon. Research done by Demircioglu *et al.* [12] found that fractal analysis provides a detailed understanding of surface roughness and texture, which are critical for assessing material fatigue and wear. It can identify micro-cracks and other defects that traditional non-destructive testing methods might miss.

Fractal analysis is a valuable tool for evaluating mechanical material properties, as evidenced by various research studies. Hlushkova *et al.* [13] applied fractal analysis to estimate the mechanical properties of hydraulic hammer parts after detonation spraying. This approach demonstrated a method for assessing the effectiveness of strengthening technologies based on fractal analysis. Li *et al.* [14] fractal analysis methods to quantitatively measure fractal dimensions of various types of fracture surfaces in composite materials and found that the fractal dimensions relate differently to the impact energy and fracture properties of the materials. In research conducted by Aouit and Ouahabi [15], the authors employed multifractal analysis using the continuous Wavelet Transform Modulus Maxima method (WTMM) to characterize and differentiate the irregular fracture signals of materials. This approach provides a powerful diagnostic tool to identify the crack initiation site and determine the causes of material cracking. In investigating the mechanical properties of metals, fractal analysis has also emerged as a promising method. Studies have shown that fractal dimensions correlate with various mechanical properties across metal alloys. For aluminum alloys, increasing fractal dimensions were associated with decreased tensile strength [16]. In steel, fractal analysis of non-metallic inclusions revealed a strong correlation with impact toughness [17]. Meanwhile, based on the research conducted by Wu *et al.* [18], it was found that the mechanical properties of materials, specifically Poisson's ratio, decrease with the increase in fractal dimensions.

Conventional testing machines are fundamental for accurately measuring the mechanical properties of materials [19], but their use is often costly and time-consuming. Innovations such as fractal analysis of vibration signals offer complementary methods to provide additional insights for the material characterization process. This innovation could provide a quick, economical, and practical method for assessing material properties, especially valuable in industrial settings where rapid testing is essential. Therefore, this study aims to explore an alternative method for assessing mechanical properties by analyzing time series signals from experiments using piezo film sensors through fractal analysis and to investigate the mechanical properties of materials subjected to different impact forces using fractal dimensions. This study is particularly significant for industrial applications where quick material assessment is crucial. By establishing correlations between fractal dimensions and mechanical properties across different metals, this research opens new possibilities for rapid, non-traditional material testing methods that could complement existing techniques.

2 Methodology

In that study, vibration signals were obtained from experiments using an impact hammer on selected square-shaped metals with different impact forces. The metals used were copper, brass, mild steel, and stainless steel. Four piezo film sensors were employed in that study and used simultaneously to get the vibration signals. Those sensors were placed on each side of the rectangular material, with one sensor on each side. The impact force was applied manually using a hammer. The resulting signals were observed and recorded in an Excel file.

2.1 Box Counting Method

In this study, fractal analysis is used in the characterization of mechanical materials. One commonly used method in fractal analysis is the box-counting algorithm. In this method, the vibration signal is covered with a number of boxes of a specific side length. The number of boxes needed to cover the vibration signal is counted, and this process is repeated for different box sizes. Therefore, the number of boxes used to cover the vibration signal will vary, and the fractal dimension value can be calculated [20]. This box-counting algorithm is programmed using MATLAB software. The vibration signal obtained will be analyzed using the fractal dimension obtained from the box counting method [20]. First, the vibration signal image in the form of a time domain is covered with several boxes of size δ. The number of boxes, $N(\delta)$ needed to cover the signal image is counted. This step is repeated with different sizes of boxes. Therefore, the number of boxes that can be used to cover the signal image will vary for each step. Then, by using the following equation

$$FD = \lim_{\delta \to 0} \frac{\log N(\delta)}{\log\left(\frac{1}{\delta}\right)} \tag{1}$$

the fractal dimension can be calculated from the slope of the best-fitted straight line of the plot $\log[N(\delta)]$ versus $\log(\delta)$.

3 Result and Discussion

3.1 Vibration Signal

The vibration signals generated from four piezo film sensors placed on each side of all the square-shaped materials used in this study will be analyzed using the fractal method. These piezo film sensors are frequently used to detect vibration signals. The resulting signals are in the time domain, measured in seconds. For example, the vibration signals image for brass stainless steel material in the time domain is shown in Figure 1 and Figure 2. These time-domain signals show that piezo film sensors are suitable for helping identify and characterize the properties of selected metal material.

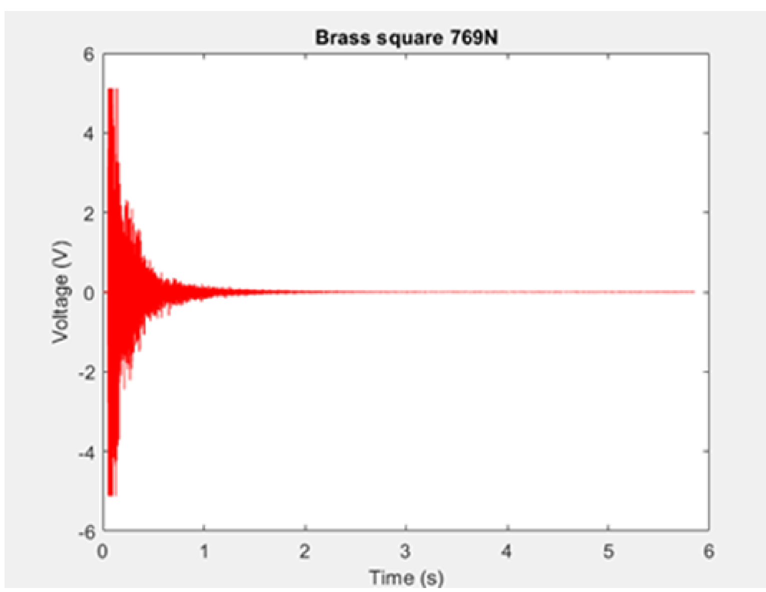

Figure 1: Vibration Signal of Square-shaped Brass Material at the Impact Force 769N.

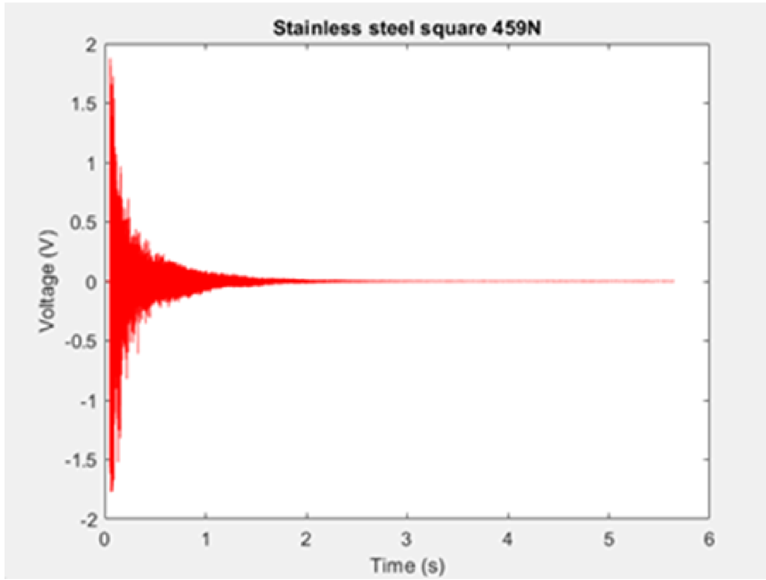

Figure 2: Vibration Signal of Square-shaped Stainless Steel Material at the Impact Force 459N.

3.2 Fractal Dimension

Next, the fractal dimension of each vibration signal produced on all metal materials will be calculated using equation (1). Figure 3 shows the relationship between impact forces and fractal dimension values for brass, copper, mild steel, and stainless steel materials. It was found that for all the materials used in this experiment, the value of the fractal dimension is different for different impact forces. The result from Figure 3 also shows a positive correlation between the impact force and the fractal dimension, meaning as the impact forces increase, the fractal dimensions also increase for all the materials: brass, copper, mild steel, and stainless steel. These results are consistent with the findings obtained by Sun *et al.* [21], who found that the fractal dimension increases as the applied load increases.

3.3 Relationship of fractal dimensions and mechanical properties of materials

In determining the mechanical properties of brass, copper, mild steel, and stainless steel materials, Poisson's ratio plays a crucial role alongside Young's Modulus. Poisson's ratio is a fundamental mechanical property affecting material characterization; meanwhile, Young's Modulus is a crucial parameter that significantly influences material strength and mechanical behavior.

The fractal dimension obtained from the box counting method will be used to determine the material's mechanical properties. Table 1 shows Poisson's ratio values and Young's Modulus in CES Edupack2012 for brass, copper, mild steel, and stainless steel.

To establish the relationship between the vibration signal and the material's mechanical properties, the trend line of the graph of fractal dimension against impact forces (N) will be calculated. The chosen trend line is a polynomial equation with degree 2 since it has a correlation coefficient (R^2) that approaches one. Figure 4 shows the graph of the polynomial function based on the obtained fractal dimension against impact forces (N). Meanwhile, Table 2 shows the quadratic equation and correlation coefficient obtained from the graph. Based on

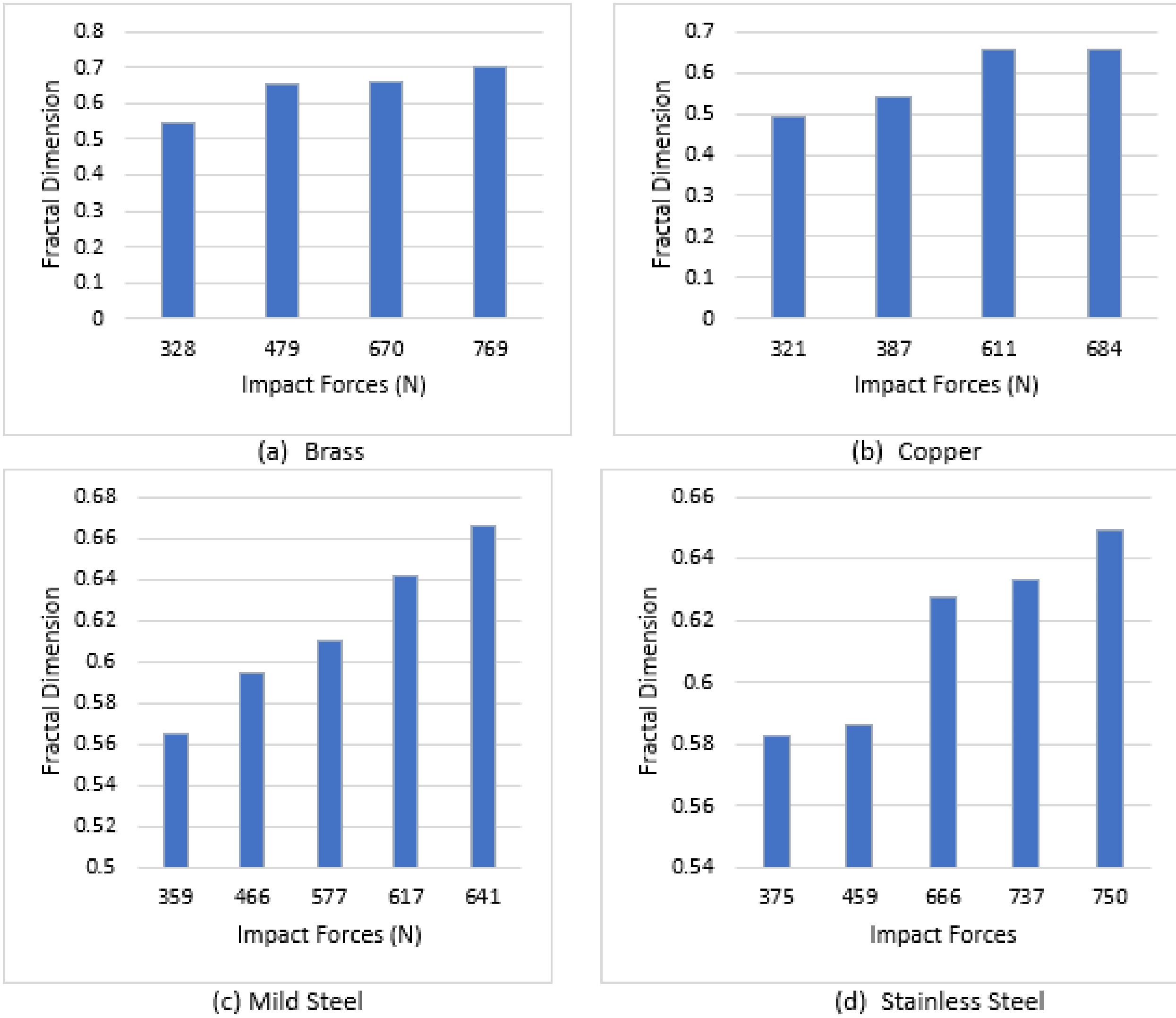

Figure 3: Fractal Dimensions for Brass, Copper, Mild Steel, and Stainless Steel Materials.

Table 2, the correlation coefficient (R^2) values obtained are in the range of 0.8889 to 0.9978. High (R^2) values in this study show that the quadratic model is a strong and reliable predictor of the relationship between impact force and fractal dimension, especially for copper and stainless steel, making fractal analysis a promising approach for material characterization.

By using the coefficient of x^2 in the quadratic equation obtained (Table 2), an investigation will be conducted on the relationship between the vibration signal and the material properties using Poisson's ratio and Young's Modulus. Table 3 shows the coefficient of x^2, the Poissons Ratio and Young Modulus (CES Edupack 2012) for brass, copper mild steel and stainless steel. Here, the coefficient of x^2 are arranged in ascending order. Materials with higher Poisson's ratio values correspond to lower coefficients of x^2, suggesting an inverse relationship between Poissons ratio and the coefficient of Meanwhile, the order (ascending order) of the coefficient of x^2 is similar to the order of Young's Modulus of the tested material. Stainless steel has the lowest Poisson's and the highest Young Module and has the highest (positive) coefficient

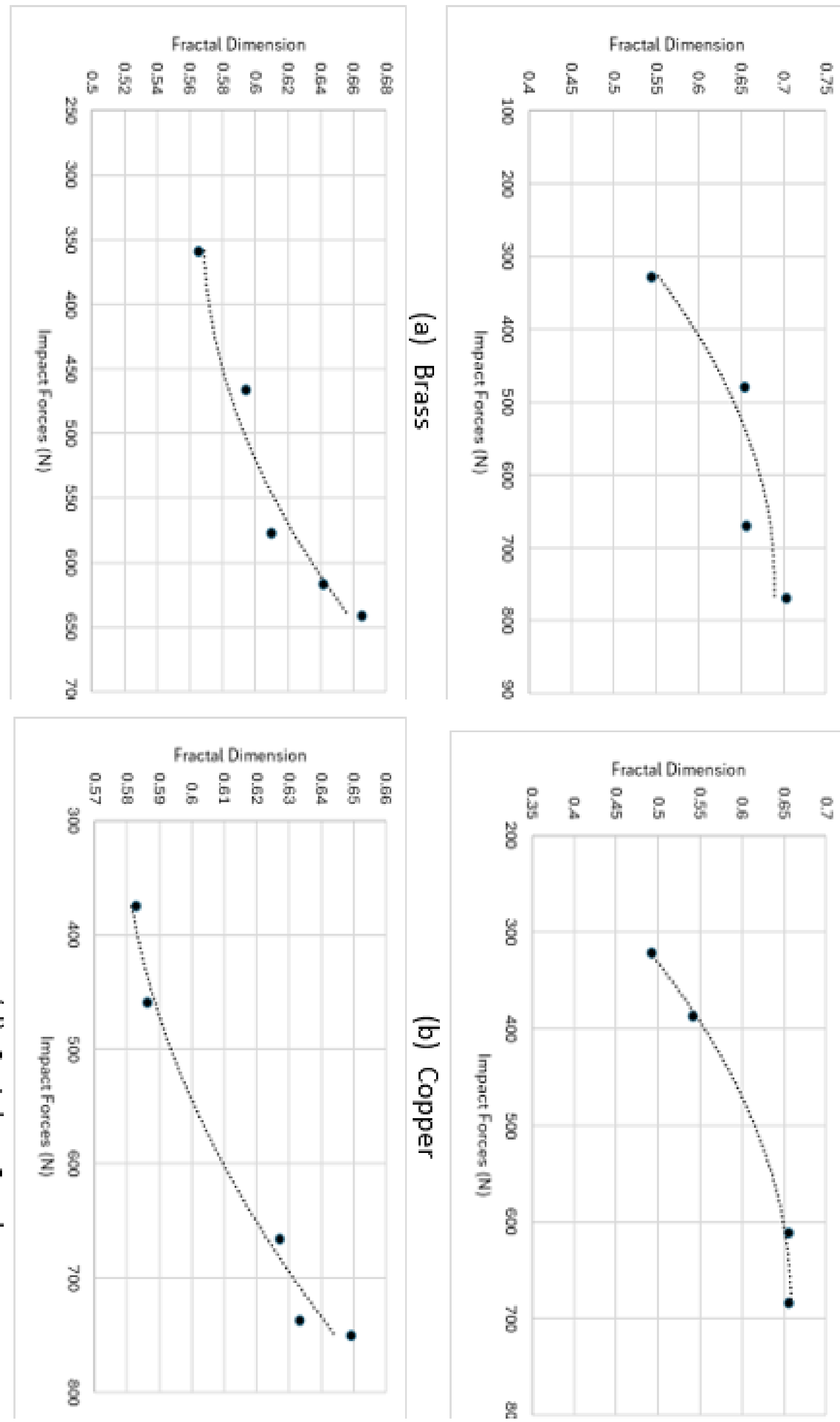

Figure 4: Graph for the Quadratic Equation Against Impact Forces (N) for Brass, Copper, Mild Steel, and Stainless Steel

Table 1: Poisson's ratio values in CES Edupack2012.

Material	Poisson's ratio,μ	Young's Modulus (GPa)
Brass	0.345	98
Copper	0.335	117
Mild Steel	0.300	200
Stainless Steel	0.280	203

compared to the other three materials. In contrast, brass, which has the highest Poisson's ratio and the lowest Young's modulus, has the lowest (negative) coefficient of x^2.

Table 2: Quadratic Equations and Correlation Coefficients for All the Materials.

Material	Quadratic Equation	Correlation Coefficient (R^2)
Brass	$y = (-8 + 10^{-7})x^2 + 0.0012x + 0.2555$	0.8889
Copper	$y = (-1 + 10^{-6})x^2 + 0.0017x + 0.062$	0.9978
Mild Steel	$y = (1 + 10^{-6})x^2 + 0.0007x + 0.6831$	0.9404
Stainless Steel	$y = (3 + 10^{-7})x^2 + 0.0001x + 0.5979$	0.9706

Table 3: Slope Coefficient of the Linear Line and Poissons Ratio.

Material	Coefficient of x^2 x 10^{-7}	Poisson's ratio, μ (CES Edupack 2012)	Young Modulus (GPa)
Brass	-8.0	0.345	98
Copper	-0.1	0.335	117
Mild Steel	0.1	0.300	200
Stainless Steel	3.0	0.280	203

The demonstrated correlation between fractal dimensions and mechanical properties like Poisson's ratio and Young's modulus, establishes fractal analysis as a promising advancement in material characterization. This innovative approach offers a practical alternative to conventional testing methods, distinguishing itself through its non-destructive nature. Fractal analysis of vibration signals could be incorporated into routine quality control procedures to quickly assess the mechanical integrity of materials without requiring extensive testing equipment or damaging the material. This method allows for rapid, on-the-spot testing, reducing the need for expensive conventional testing machines and long processing times. This approach could potentially reshape standards for material testing, making it more accessible and practical for a wide range of applications.

4 Conclusion

Determining the mechanical properties of materials is crucial in various fields, such as material science and mechanical engineering. Traditionally, methods like destructive testing have been employed to assess these properties accurately. However, these conventional methods are often expensive and time-consuming. In this study, the identification of mechanical property characteristics of a material using vibration signals obtained from piezo film sensors has proven successful. The recorded data and analysis that was conducted have demonstrated that vibration signal is a mechanical factor that can serve as an alternative to conventional methods for identifying and characterization of material mechanical properties.

One of this study's significant findings is the correlation between impact forces and the fractal dimensions of the vibration signals. The study found that higher impact forces tend to result in higher fractal dimensions. The increase in fractal dimension with impact force could indicate the complexity or irregularity of the system. Since traditional testing methods might not always reveal the complex behavior of composite materials under stress, fractal analysis provides an alternative that could better capture their mechanical characteristics, enabling more effective design and application of these advanced materials.

By using the coefficient of x^2 of the fractal dimension, the relationship between the fractal dimension and the material's mechanical properties, specifically Poisson's ratio and Young Modulus, was established. It was identified that a relationship exists between the fractal dimension of the vibration signals and Poisson's ratio and Young Modulus. This relationship can be useful in fields like material science or mechanical engineering to understand how materials respond to varying levels of force and to possibly predict their behavior under different stress conditions. Additionally, the use of fractal analysis via box counting method can provide valuable insights into the behavior of materials under varying impact forces, offering a unique perspective on material characterization beyond traditional methods.

Future research could broaden the applications of fractal analysis in material testing by examining a wider range of materials, including polymers, ceramics, and advanced alloys, and exploring correlations with microstructural properties such as fracture patterns. Researchers might focus on multi-scale fractal analysis, and applications for additively manufactured materials, which have unique structural characteristics. These directions could establish fractal analysis as a reliable, non-destructive method for predicting material properties across industries, benefiting quality control, maintenance, and material optimization.

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