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# Damage Assessment of a 3D-Printed Plate Using Capacitance of Surface-Bonded and Embedded Piezoelectric Sensors

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## ABSTRACT

This research focuses on damage assessment based on the electromechanical impedance (EMI) method. The method uses piezoelectric transducers that excite the investigated structure and sense the response. The damage assessment is based on comparing the electrical spectra gathered for structural parts at different structural conditions. In particular, the unknown case (possibly damaged) is compared with data for known healthy (undamaged) case. In the reported research the EMI method was applied to additively manufactured samples. For several years, additive manufacturing (AM), or 3D printing, has become a popular manufacturing technique that is environmentally friendly by allowing for waste reduction. The structural parts manufactured with AM methods were introduced into the mechanical and aerospace industries. Similar to structures made from traditional metals or polymers, there is a need for structural health monitoring of 3D printed structures. This requires the development of accurate and reliable methods for evaluating and monitoring the structural integrity of such components. Additionally, the AM method gives more freedom in design and also allows for easier sensor integration for structural health monitoring. In this work, the piezoelectric sensors were embedded in a polymer 3D-printed plate and their response was compared with the surface-bonded sensor. In this study, the effective excitability of the sensors was tested with the scanning laser vibrometer. Due to high attenuation, the EMI investigation was limited to 100 kHz. In total four sensors were used for the sample assessment, and the capacitance as a function of frequency was analyzed. Firstly, the structural change was simulated by an additional mass. Secondly, a through-thickness hole was drilled to simulate damage, and the EMI responses were compared for four diameters of this hole. Traditionally, in the EMI approach resistance, conductance, or impedance is studied. However, in this study, promising results were obtained for capacitance that allowed for damage detection and later for severity assessment. The introduced data processing approach based on principal component analysis (PCA) allowed for the differentiation of all the investigated cases and showed good sensitivity to the simulated damage severity.

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## INTRODUCTION

Additive manufacturing has become a very popular manufacturing approach. The reported research focuses on damage assessment of a square 3D printed plate with the electromechanical impedance (EMI) method. The method employs piezoelectric transducers that excite the investigated structure and sense the response [1]. The piezoelectric transducers are used in current EMI-based nondestructive evaluation and structural health monitoring techniques, because they are inexpensive and lightweight [2, 3]. Sensor generates electric charges when subjected to mechanical stress and deforms when subjected to the electric field. The damage assessment is based on collecting the electrical quantities as a function of frequency and comparing the responses at different structural conditions. In particular, the unknown case (possibly damaged) is compared with data for known healthy (undamaged) cases. Four sensors were used for the study. Three sensors were embedded at three different depths in the sample material. The fourth sensor was bonded to the surface for referential purposes. Firstly, the structural change was simulated by an additional mass. Secondly, a through-thickness hole was drilled to simulate damage, and the EMI responses were compared for four diameters of this hole. In most of the application the resistance [4], conductance [5], or impedance [6] are studied. Here, promising results are shown using frequency-dependent capacitance. The introduced data processing approach based on principal component analysis (PCA) allowed for the differentiation of all of the investigated cases. The results show good sensitivity to the severity of the simulated damage. Moreover, the study focuses on the frequency range up to 100 kHz that can be achieved by impedance analyzers and simpler measurement chips [7].

## EXPERIMENTS

The investigated flat plate (150 mm × 150 mm × 5 mm) was printed from M3-X material using the ProJet 3500 HD Max printer. One the sample surface one sensor was bonded with Super Glue. The remaining three sensors were placed at slots panned during printing at 1 mm, 2 mm and 3 mm from the top surface, respectively for the shallow, middle and deepest sensor. The slots after printing had an extra 0.15 mm depth that was filled with liquid printing material before sensor placement. Next the sensors were covered with additional material to obtain even surface. Each use of the liquid material was followed by curing with an UV lamp. All the used sensors were piezoelectric disc of 10 mm diameter and 0.5 mm thickness placed at the middle of each of the sample edges. The effective excitability of the sensors was tested with the scanning laser vibrometer. Due to high attenuation, the EMI investigation was limited to lower frequencies. The electromechanical measurements were conducted in the range of 1 kHz to 100 kHz with 20 Hz step. The measurements were made with a HIOKI IM 3570 impedance analyzer with five volts excitation voltage. First set of measurements comprised of the data collection for the healthy condition. These measurements were labeled as ‘h1’ and ‘h2’. Second set involved three added mass cases - a magnetic mass was added at three positions: 12 mm, 32 mm, and 68 mm away from the sensor edge. These three measurements were labelled as ‘close’, ‘medium’ and ‘far’, respectively. Third case involved hole drilling. A through-thickness hole of 4 mm diameter was drilled at the center of the sample. Next the whole diameter was enlarged to 5, 6 and 7 mm. Summarizing, the whole measurement campaign resulted in 9 measurements for each sensor.

## DATA ANALYSIS AND PROCESSING

The studies reported in [4] showed that the root mean square (RMSD) index based on resistance can differentiate the added mass and detect the smallest hole (4 mm in diameter) presence. However, when other hole diameters were considered there was no increase of the RMSD index value observed as the hole diameter was increased. The same was observed for the conductance values, so new quantity analysis was proposed. The capacitance (C) as a function of frequency was calculated from the measured imaginary part of admittance (the susceptance). The obtained capacitance values for the measured healthy cases are depicted in Figure 1 . The values for each case slightly vary across the measured frequencies (1 kHz – 100 kHz) with small negative and positive peaks visible throughout the range. More pronounced peaks are visible for the surface bonded sensor above 60 kHz. The capacitance values obtained for surface bonded sensors are the highest next are the values for the shallow, middle and deepest sensor, respectively. So, the deeper is the sensor the capacitance is lower for each frequency value.

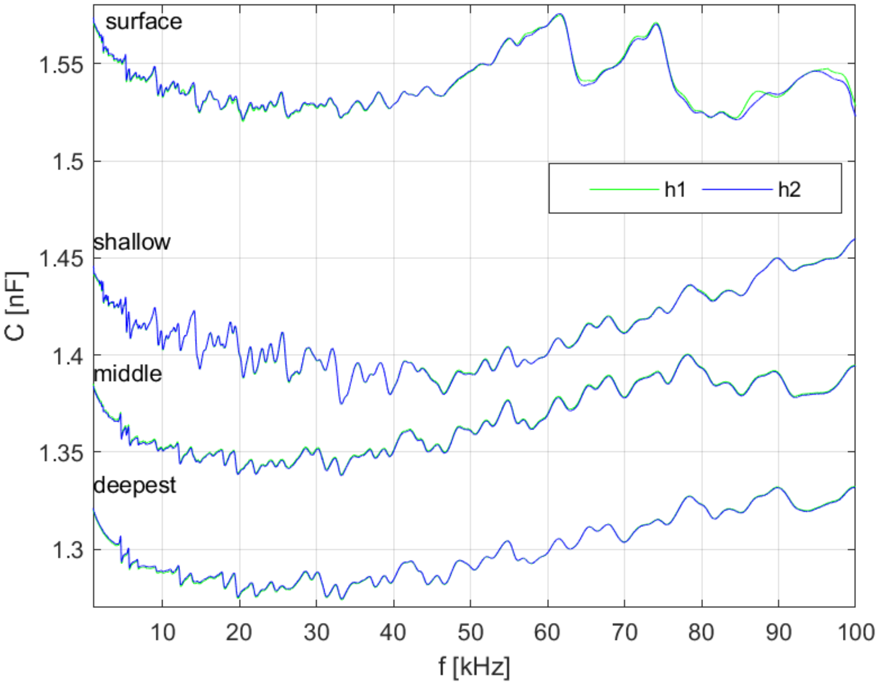

Figure 1. Measured capacitance values for healthy cases for all four sensors.

These values are lower than for a free sesnor. This is in agreement with observations reported in [8] where the susceptance of the free sensor had the highest values in the frequency range up to 20 kHz, when compared to bonded sensors. Since the capacitance is the frequency rescaled susceptance we observe here the same behavior up to 100 kHz. The values of the capacitance for embedded sensors drop even more (Figure 1). Even though the  capacitance values vary a bit through the frequencies, it is easy to separate the responses from individual sensors using the mean value (Figure 2). The mean values of capacitance can be used to distinguish the mass cases for the surface-bonded sensor (Figure 3). The farther the mass is placed from the sensor, the more the mean capacitance value tends to the value observed for the healthy cases ('h1' and 'h2'). This behavior was not observed for the remaining sensors, indicating their lower sensitivity. In the case of drilled holes none of the sensors showed an increase of the mean capacitance value with the increase of the hole diameter.

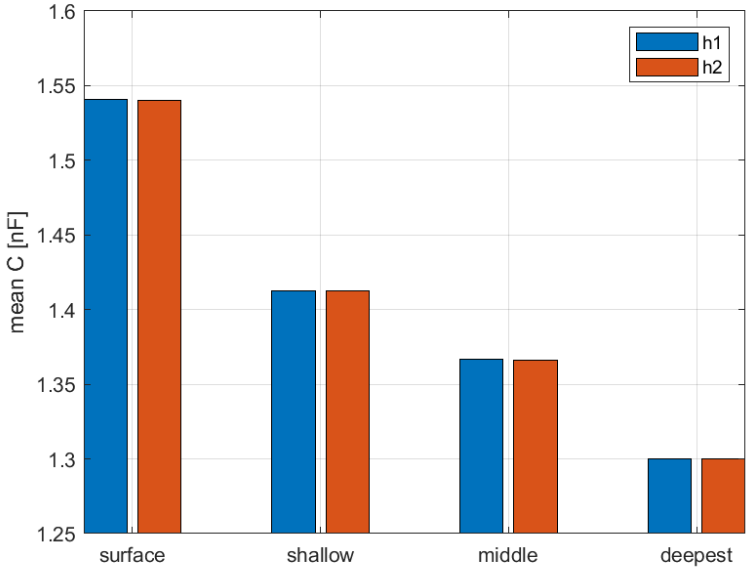

Figure 2. The mean values of capacitance in the frequency range 1 kHz-100 kHz for the healthy cases.

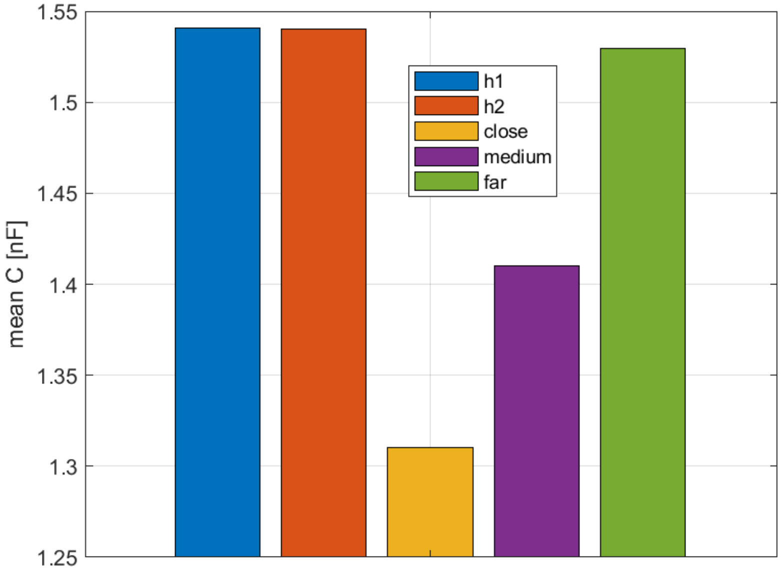

Figure 3. The mean values of capacitance in the frequency range 1 kHz-100 kHz for the healthy and mass cases measured by surface-placed sensor.

## DAMAGE ASSESSMENT

The mean capacitance value over the 1 kHz-100 kHz range allowed to separate the responses from individual sensors and differentiate the mass cases for surface-bonded sensor. In order to assess remaining cases, the vertical difference of the capacitance curves was removed by using polynomial fit. Further, the data classification was made employing principal component analysis (PCA) [8]. Each capacitance vector is treated as an observation and the capacitance value for given frequency is a variable. The representation of the original data in the new PC space that explain at least 95% of the variance is analyzed to find differences between the healthy cases and the simulated damage cases. For the mass cases five principal components were taken, while for the hole cases four principal components were enough. The representation in the new space is compared by calculating the Euclidean distance (ED) between all the case and the first healthy case (h1). Since the healthy cases are similar, the results were presented as relative to the Euclidean distance of the h2 case. The results of mass cases are shown in Figure 4. All the sensors indicate dropping ED value as the mass is moved farther from the sensor. There is a clear difference in sensitivity to the mass depending on the sensor depth. The surface-bonded sensor is characterized by a moderate drop in the ED values when the mass is moved farther away from the sensors. The other sensors show high values for closely placed mass and low values the mass placed farthest. The results for the second set of data show that the larger  the hole diameter is, the ED value is larger (Figure 5).

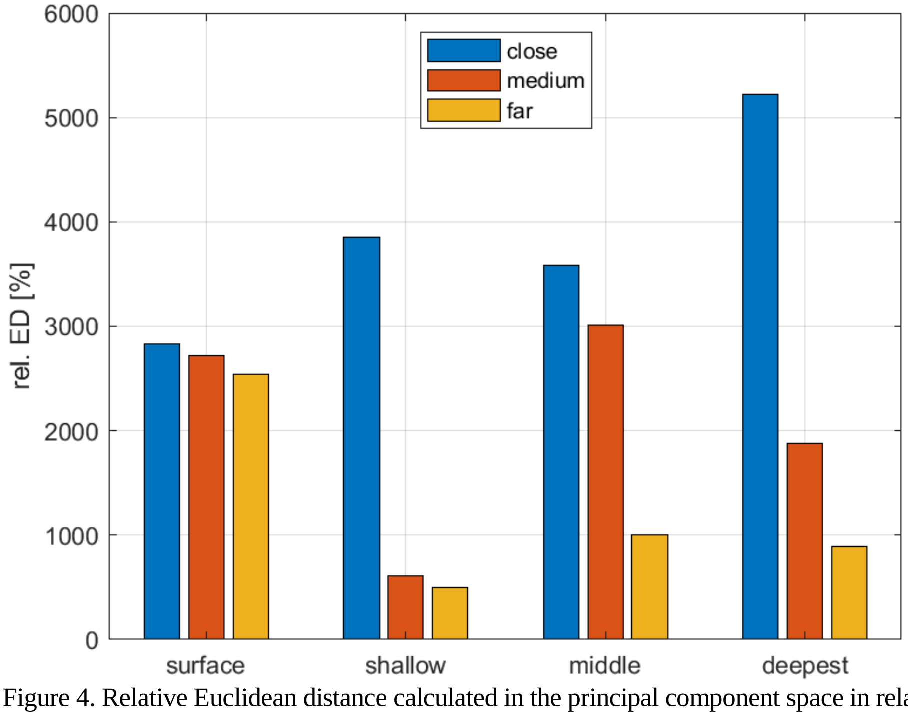

Figure 4. Relative Euclidean distance calculated in the principal component space in relation to the value of h2 case for the additional mass measurements.

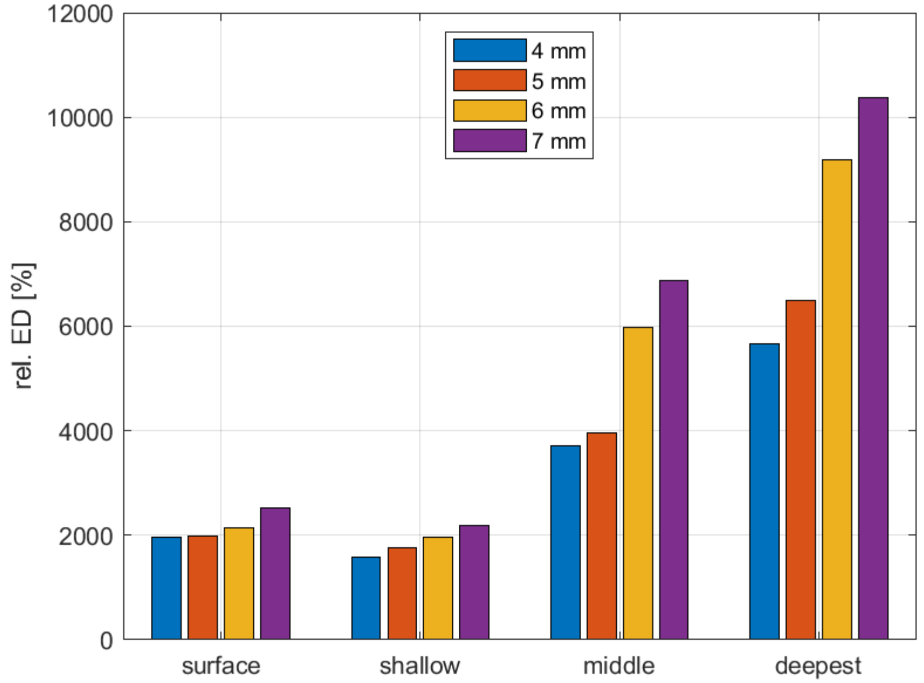

Figure 5. Relative Euclidean distance calculated in the principal component space in relation to the value of h2 case for the through thickness hole measurments.

## CONCLUSIONS

The study reported here showed the behavior of capacitance of surface-bonded and material-embedded piezoelectric sensors. Data processing based on principal component analysis was proposed and the Euclidean distance served as a good index for differentiating the investigated cases. Sensitivity to distance of surface-placed mass was observed as well as to the diameter of a drilled hole. The study showed that the structural damage assessment using EMI can be realized by embedded sensors. Due to the limited range of the method, the inspection of larger structural parts would require a dedicated sensor network.

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