Sensitivity Enhancement of Piezoelectric Transducers for Impedance-Based Damage Detection via a Negative Capacitance Interface

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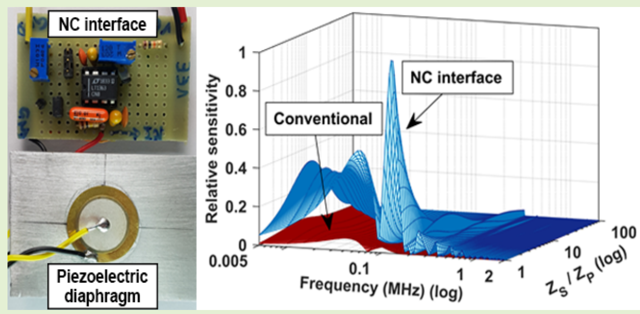
***Abstract*—Piezoelectric transducers are used in many applications due to electromechanical coupling, which allows mechanical and electrical quantities to be related. This principle is used in the development of structural damage detection techniques such as electromechanical impedance (EMI) commonly used in structural health monitoring (SHM), where structural health is monitored by measuring and analyzing the electrical impedance of a transducer. As a piezoelectric transducer is a primarily capacitive device, its reactance becomes small at high frequencies, reducing sensitivity to structural damage and increasing the excitation current required from the measuring system. Therefore, this paper proposes the use of a negative capacitance (NC) interface with the transducer to improve sensitivity to structural damage and reduce the excitation current. The improvement obtained with the NC interface is theoretically analyzed using an electromechanical model and experimentally validated with tests on an aluminum structure. The results conclusively indicate a significant improvement in the sensitivity to structural damage and a reduction in excitation current, which are critical for detecting incipient damage and developing onboard monitoring systems where the output current drive is usually low.**



***Index Terms*— Piezoelectric transducers, SHM, impedance, negative capacitance, damage detection, sensitivity.**

I. INTRODUCTION

PIEZOELECTRIC transducers have been widely investigated for the development of damage detection methods in structural health monitoring (SHM) systems whose benefits are of global interest [1], [2]. Among these benefits are increases in safety for users of large civil structures or means of transportation, such as aircraft, ships, dams, and bridges. In addition, there are maintenance-related savings, which can become predictive rather than corrective. Such benefits are achieved because SHM systems must operate in real time or periodically. The types of damage that can sensitize and alert such monitoring systems are any that change the mechanical characteristics of the structure, such as cracks, holes, corrosion, wear or loosening of connections.

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Since it is not always possible to suspend complete operation of certain structures, SHM systems must operate in a minimally invasive manner. Techniques with this characteristic, also called nondestructive testing (NDT), include acoustic emission [3], Lamb waves [4], [5], eddy currents [6] and guided ultrasonic waves [7]. In addition, the electromechanical impedance (EMI) technique [8], [9] stands out because it enables the use of low-cost, small and light piezoelectric transducers operating simultaneously as sensor and actuator, minimally interfering with the characteristics of the monitored structure [10].

The EMI technique is based on the piezoelectric effect. When a transducer is fixed to the structure to be monitored, an electromechanical coupling occurs between the transducer and the structure. Thus, any mechanical variation in the structure

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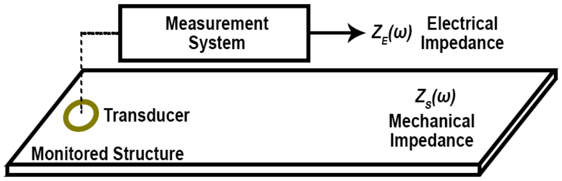

Fig. 1. Basic configuration of an impedance-based SHM system.

results in a corresponding variation in the electrical impedance of the transducer, and this impedance can be obtained in different frequency bands by an impedance analyzer.

Usually, the transducer is excited at frequencies up to 600 kHz [11], which is the region where the electrical impedance changes sufficiently to detect structural damage. As is well known, for small-thickness transducers, mechanical deformation occurs mainly in the plane orthogonal to the applied electric field, i.e., in the plane of the monitored structure. However, when the transducer is excited by high-frequency signals, typically above 1 MHz, the deformation is in the same direction as the applied electric field, that is, becomes significant in the direction of the thickness of the monitored structure, enabling the monitoring of special structural conditions not allowed at low frequencies [12].

Although high-frequency analysis is desired in some applications, it is difficult to excite the piezoelectric transducer with a high-frequency signal and measure variations in the electrical impedance due to structural damage. Since piezoelectric transducers are capacitive devices, their capacitive reactance becomes too low at high frequencies, limiting variations in electrical impedance due to structural changes. In addition, there is an increase in the excitation current required by the transducer as the electrical impedance decreases, limiting application for some embedded projects.

Thus, this paper proposes the implementation and use of a negative capacitance (NC) interface for reducing the capacitive component and thus enabling high-frequency analysis and reducing the excitation current for feasible applications in embedded systems. The next two sections present in more detail the basic principle of the EMI technique and the implementation and operation of a NC interface with piezoelectric transducers, respectively.

II. EMI Principle

The basic principle of an SHM system based on the EMI technique is shown in Fig. 1, where a measurement system is presented measuring the electrical impedance of a piezoelectric transducer coupled to a monitored structure.

As shown in Fig. 1, with the piezoelectric transducer coupled to the monitored structure, the measurement system excites the sensor and simultaneously obtains the electrical impedance at a given frequency (ω). Piezoelectric transducers commonly used in various NDT techniques, such as EMI, consist of lead zirconate titanate (PZT) ceramics [13], and recently, piezoelectric diaphragms [10] have gained relevance because they are inexpensive and provide results that are as good as those of traditional PZT ceramics. Piezoelectric diaphragms were used in this study and typically consist of a piezoelectric material disk (active element) on a brass disk.

The relationship between the electrical impedance of a piezoelectric diaphragm ($Z_D(\omega)$) coupled to a structure of mechanical impedance $Z_S(\omega)$ was obtained in [10] by considering a one-dimensional approach and is given by

$$Z_D(\omega) = \frac{1}{j\omega C_0} \Bigg\| \left\{ \left(\frac{2s_{11}^E}{\pi \phi_P d_{31}} \right)^2 \left[Z_{P2} + \frac{1}{2} \left(Z_{P1} + Z_{B1} + \frac{Z_{B2}(Z_{B1}+Z_S)}{Z_{B1}+Z_{B2}+Z_S} \right) \right] \right\} \quad (1)$$

where $Z_D(\omega)$ is the electrical impedance of the piezoelectric diaphragm at the frequency ω; Z_{P1} and Z_{P2} are the electromechanical impedances of the piezoelectric element; Z_{B1} and Z_{B2} are the electromechanical impedances of the brass disk; Z_S is the mechanical impedance of the structure under analysis; s_{11}^E is the elastic compliance under a constant electric field; d_{31} is the piezoelectric constant; ϕ_P is the diameter of the piezoelectric element; and C_0 is the static capacitance of the piezoelectric diaphragm, where the term $1/j\omega C_0$ is the capacitive reactance. More details about the electromechanical model shown in (1) can be found in [10].

As shown in (1), any mechanical variation in the structure, such as structural damage, results in a corresponding variation in the electrical impedance $Z_D(\omega)$ of the piezoelectric diaphragm. Therefore, the condition of a structure can be monitored by regularly measuring the electrical impedance of a piezoelectric transducer coupled to the structure and comparing this impedance with the signature obtained at a known state without structural damage.

However, as shown in (1), the capacitive reactance limits the variations in the electrical impedance due to structural changes since the reactance is in parallel to the rest of the equation terms. This limitation is critical, especially at high frequencies, because the higher the frequency of analysis is, the lower the capacitive reactance and, consequently, the smaller the variations in the electrical impedance $Z_D(\omega)$ due to variations in the mechanical impedance Z_S of the monitored structure. In addition to such limitations on the electrical impedance values, a low capacitive reactance requires high excitation current, which can be drawbacks for commercial, alternative or embedded measurement systems.

Therefore, this paper presents an alternative solution to the above problems, involving the use of a negative capacitance in parallel with the piezoelectric transducer, so that the equivalent capacitance between the static capacitance C_0 of the transducer and the negative capacitance C_N presents values close to zero and, consequently, allows structural changes to be more evident in the electrical impedance of the transducer. Thus, high-frequency analysis becomes feasible, and the excitation current required by the transducer is decreased. The next section presents more details about the NC interface and how the sensitivity of the piezoelectric transducers to structural damage is improved with the use of this interface.

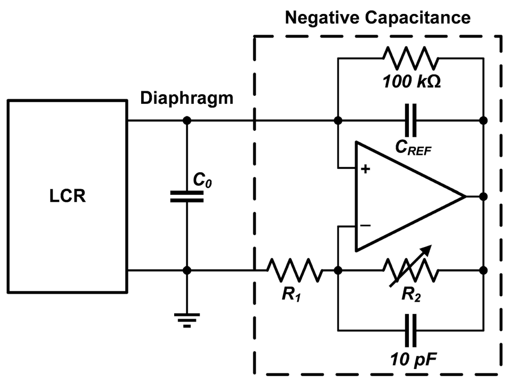

Fig. 2. Negative capacitance interface in parallel with piezoelectric transducer and impedance meter.

III. Negative Capacitance Applied in the EMI Method

The use of negative capacitance is a well-known solution, and in this section, its effectiveness is theoretically demonstrated for improving the sensitivity of piezoelectric transducers for impedance-based structural damage detection.

A. Negative Capacitance Circuit

A negative capacitance circuit is basically a negative impedance converter based on a single operational amplifier. Negative capacitance has been used with piezoelectric transducers to improve electromechanical coupling in various applications, such as vibration control [14], elastic wave manipulation [15], and micromechanical resonators [16].

As presented in Section II, the limiting component of the EMI technique at high frequencies is the static capacitance C_0 of the piezoelectric transducer due to the decreased reactance $(1/j\omega C_0)$. This capacitance has historically proven to be challenging in many applications, such as filter, oscillator and sensor designs [16]. Thus, decreasing the static capacitance value of the transducer allows structural changes to cause more evident variations in the electrical impedance signature. One way to decrease the static capacitance C_0 is to introduce, in parallel or in series with the transducer, a negative capacitance C_N. A parallel connection was used in this study, and the equivalent capacitance in a parallel connection is given by C_0+C_N. Therefore, if $C_N = -C_0$, the equivalent capacitance is ideally null.

A negative capacitance can be obtained by using an impedance converter circuit based on an operational amplifier [14]. A negative capacitance circuit C_N, in conjunction with a piezoelectric transducer with static capacitance C_0 and an impedance measuring instrument (LCR), is shown in Fig. 2.

As shown in Fig. 2, the negative capacitance C_N is given by [14]

$$C_N = -\frac{R_2}{R_1} C_{REF} \tag{2}$$

where C_{REF} is the reference capacitance used to obtain the negative capacitance; R_1 is a fixed value resistor; and R_2 is a potentiometer for regulating the negative capacitance value.

It is noteworthy that the circuit of Fig. 2 has stability problems that depend on the dynamic response of the operational amplifier and the parasitic capacitances. In this way, the 10 pF capacitor and the 100 kΩ resistor are used for the stable operation of the circuit, properly detailed in Section IV.

As stated above, the value of the negative capacitance C_N should be as close as possible to the static capacitance of the transducer C_0, so that the resulting capacitance is ideally zero; therefore, the electrical impedance of the piezoelectric diaphragm shown in (1) is changed as follows:

$$Z_{D_{NC}}(\omega) = \left\{ \left(\frac{2s_{11}^E}{\pi \phi_P d_{31}} \right)^2 \times \left[Z_{P2} + \frac{1}{2} \left(Z_{P1} + Z_{B1} + \frac{Z_{B2}(Z_{B1}+Z_S)}{Z_{B1}+Z_{B2}+Z_S} \right) \right] \right\} \tag{3}$$

where $Z_{D_{NC}}(\omega)$ is the electrical impedance of the piezoelectric diaphragm in parallel with a negative capacitance with a value ideally equal to the static capacitance of the diaphragm, i.e., $C_N = -C_0$. As shown in (3), the new equivalent impedance does not have any capacitive components. Thus, structural changes are no longer attenuated by the capacitive reactance and present high corresponding electrical impedance variations.

B. Damage Sensitivity Improvement

The sensitivity of a given transducer to structural damage can be theoretically obtained by analyzing the changes in its electrical impedance, as shown by (1) and (3), caused by variations in the mechanical impedance Z_S of a given structure [10]. For this approach, the partial derivative with respect to the mechanical impedance of the monitored structure Z_S is applied to the electrical impedance as follows:

$$\eta(\omega) = \left| \frac{\partial |Z(\omega)|}{\partial Z_S} \right| \tag{4}$$

where $Z(\omega)$ is the electrical impedance, as given by (1) and (3).

For this study, we considered a 7BB-20-6 piezoelectric diaphragm, manufactured by Murata Electronics North America, Inc. (Smyrna, GA, USA). The dimensions and properties of the diaphragm are as follows [17]: piezoelectric constant (d_{31}) of -207 × 10^{-12}m/V; elastic compliance (s_{11}^E) of 15.8 × 10^{-12}m^2/N; capacitance (C_0) of 10 nF; ceramic disk diameter (ϕ_P) of 14.0 mm; brass plate diameter of 20 mm; brass plate thickness of 0.20 mm; brass mass density of 8500 kg/m^3; brass compliance of 9.1 × 10^{-12}m^2/N; ceramic disk thickness (h_p) of 0.22 mm; and ceramic mass density (ρ_p) of 7800 kg/m^3.

The electrical impedances of transducers without and with negative capacitance can be obtained by substituting such values in (1) and (3), respectively. In addition, the electromechanical impedances Z_{P1}, Z_{P2}, Z_{B1} and Z_{B2} can be calculated using the other values according to the one-dimensional electromechanical model [10] of piezoelectric diaphragms. Thus, the structural damage sensitivities of a conventional

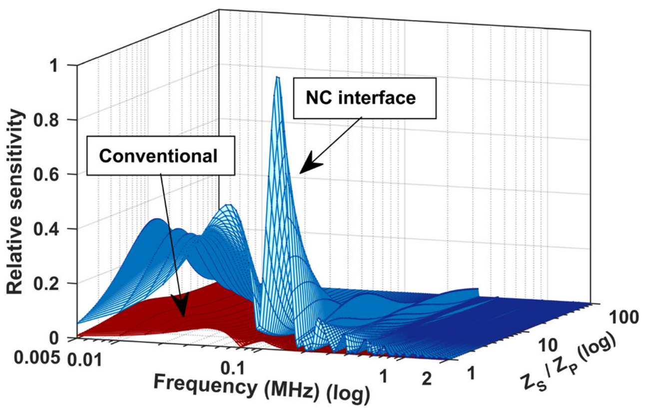

Fig. 3. Comparison of relative sensitivities of a piezoelectric diaphragm and a piezoelectric diaphragm in parallel with a NC interface.

transducer and a transducer with negative capacitance can be calculated and compared using (4).

Although (3) represents the ideal electrical impedance when using negative capacitance to cancel the static capacitance of the transducer, in practice, such an equivalent capacitance value is not achieved due to the frequency response and other limitations of the operational amplifier. Thus, for this theoretical analysis, two capacitance values were considered: $C_0 = 10$ nF, which is the capacitance of the diaphragm model 7BB-20-6 previously described, and $C_0 + C_N = 1.3$ nF, which is the equivalent capacitance value obtained using the negative capacitance interface during experimental tests for a wide frequency band, as described in Section IV.

In addition, the mechanical impedance value Z_S of the monitored structure was not set, causing the value to vary according to the mechanical impedance of the transducer Z_P according to the Z_S/Z_P ratio. The mechanical impedance of the transducer is approximately given by [10]

$$Z_P \cong \frac{\pi \phi_p h_P}{2} \sqrt{\frac{\rho_P}{s_{11}^E}} \tag{5}$$

The damage sensitivities as a function of frequency and the Z_S/Z_P ratio obtained for the conventional transducer and the transducer using the NC interface are shown in Fig. 3. The theoretical analysis was performed up to 2 MHz because the circuit of Fig. 2 operated stable up to this frequency, as described in detail in Section IV.

As shown in Fig. 3, the curves are normalized between the values of 0 and 1 for a proper comparison. The sensitivity obtained by the transducer using negative capacitance is significantly higher than that of the conventional transducer. This behavior is observed throughout the frequency range and for all considered structure sizes (Z_S/Z_P ratios). Although the improvement in the sensitivity is more noticeable for low frequencies, high-frequency peaks appear with the use of negative capacitance, indicating improvement in this region as well.

Therefore, this theoretical result indicates that the use of a piezoelectric transducer in conjunction with a NC interface, aiming to nullify the static capacitance, brings benefits in terms of sensitivity to structural variations when applied to impedance-based SHM systems. In addition, as the capacitance is reduced and, consequently, the capacitive reactance increases, high-frequency analysis becomes feasible, especially for autonomous embedded systems.

It is important to note that the transducer sensitivity improvement from using the negative capacitance interface not only can be applied to detect structural damage in engineering structures but also can be extended to other fields of research that monitor variations in mechanical quantities by means of corresponding variations in the electrical impedance of transducers. Other fields of research that may employ the results presented here are biomedicine and dentistry with applications such as biomedical diagnostics [18], [19] and dental implant monitoring [20].

The improvement in sensitivity for detecting structural damage was experimentally validated by tests on an aluminum bar. The experimental setup is presented in the next section.

IV. Experimental Setup

All tests were performed on a thin, narrow aluminum bar with dimensions of 500 mm x 38 mm x 3 mm, appropriately representing a one-dimensional propagation model, which was considered for the development of (1) and (3) and, consequently, the results shown in Fig. 3. As a piezoelectric transducer, a piezoelectric diaphragm was used with the characteristics presented in the previous section. The diaphragm was fixed to the structure by cyanoacrylate-based adhesive, with the center 25 mm from one end of the aluminum bar.

As mentioned before, the stability and operating frequency range of the NC interface shown in Fig. 2 depends on the dynamic response of the operational amplifier. In this study, the LT1363 operational amplifier from Analog Devices, Inc., was chosen due to its high bandwidth and slew rate. The 10 pF capacitor and 100 kΩ resistor shown in Fig. 2 are used to cancel the input pole and optimize dynamic performance, as recommended by the manufacturer. In addition, a 10 nF capacitor was used as the reference capacitance C_{REF}, a 10 kΩ resistor as the fixed resistor R_1 and a 20 kΩ potentiometer as R_2. The circuit was powered with a ±15 V supply and 1 μF bypass tantalum capacitors were used.

With this configuration, the NC interface operated stable in a frequency range from 50 kHz to 2 MHz and with an excitation signal of 0.5 V_{RMS}. The stable equivalent capacitance obtained from the parallel association between the piezoelectric transducer and the NC interface is approximately 1.3 nF, i.e., $C_0 + C_N \cong 1.3$ nF, and as shown in Section V, the equivalent capacitance varies slightly according to the dynamic response of the operational amplifier. It is important to note that wider operating frequency band and lower equivalent capacitance can be obtained according to the operational amplifier used in the NC interface.

The experimental tests performed in this study consisted of comparing the structural damage sensitivities of the conventional transducer and the transducer with the NC interface. Initially, the two conditions (with and without the NC interface) were analyzed and compared by the pencil lead break (PLB) test. The PLB test is a known tool for generating an acoustic emission source [21] and can also be used to evaluate the sensitivity of piezoelectric transducers for impedance-based damage detection [22]. This test consists of breaking a pencil lead against the structure under analysis. By performing the break, an elastic wave with a wide frequency spectrum is released and is then acquired from the transducer using a data acquisition (DAQ) device. The obtained signal is then processed in the frequency domain by the power spectral density (PSD) calculation. In addition to the aluminum bar and piezoelectric diaphragm already described, an NI PXIe-5105 acquisition module with an acquisition rate of 60 MHz was used for this test. In addition, the tests were performed with a lead of 0.5 mm diameter and a length of 3 mm in contact with the structure at an angle of 40°, according to [23]. Five breaks were performed without using negative capacitance, and another 5 breaks were performed using negative capacitance, all 100 mm from the piezoelectric diaphragm.

The second test consisted of analyses using the EMI method. The tests were performed in two different frequency bands (55 kHz to 70 kHz and 1.11 MHz to 1.26 MHz), and for both, piezoelectric diaphragm electrical impedance signatures were obtained with and without using the NC interface. As is well known, the detection of damage in the EMI method is typically based on a comparison between two impedance signatures, one of which is known to be in a healthy state (baseline) and the second is after any damage. Usually, such a comparison is made by calculating damage indices. This study used the root-mean-square deviation (RMSD), which is given by [1]

$$RMSD = \sum_{\omega=\omega_I}^{\omega_F} \sqrt{\frac{[Re\,(Z_2\,(\omega)) - Re\,(Z_1\,(\omega))]^2}{Re\,(Z_1\,(\omega))^2}} \tag{6}$$

where RMSD is the calculated index between the initial frequency ω_I and the final frequency ω_F, $Re\,(Z_1\,(\omega))$ is the real part of the baseline impedance signature and $Re\,(Z_2\,(\omega))$ is the real part of the impedance after the damage. The damage applied to the structure was a hole 100 mm away from the piezoelectric transducer using a 1.5 mm diameter drill. This damage corresponds to a mass variation of approximately 0.0093%.

To obtain the impedance signatures, an IM3536 LCR Meter from HIOKI, equipped with the test fixture HIOKI 9262, was used. The transducer was excited with a 0.5 V_{RMS} signal and the impedance signatures were obtained with 10 Hz steps for low frequency band (55 kHz to 70 kHz) and 100 Hz steps for high frequency band (1.11 MHz to 1.26 MHz). Measurements of baseline signatures were obtained for both configurations (without and with the NC interface) for both frequency ranges and, after drilling, were obtained again for both configurations in both frequency ranges. The experimental setup is shown in Fig. 4. It is important to note that the interface shown in Fig. 4 is just a prototype for evaluating the proposed methodology and not a final product. A more compact interface for use with autonomous sensors can be easily achieved using specific printed circuit board and surface mounting devices.

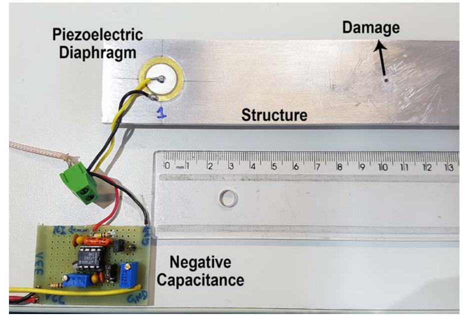

Fig. 4. Experimental setup.

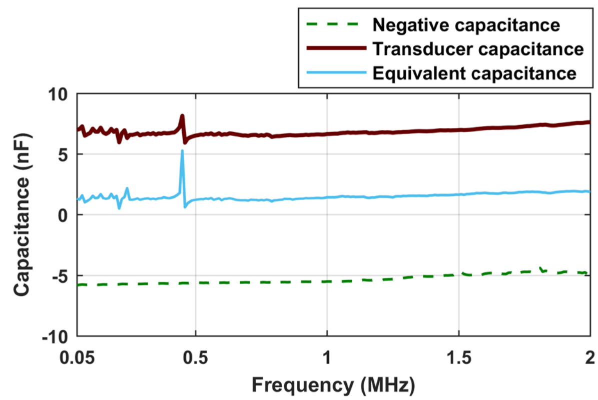

Fig. 5. Experimental capacitances.

In addition to the tests already described, the current supplied by the LCR and the capacitance of the piezoelectric diaphragm with and without the NC interface were measured. All tests were performed at a controlled room temperature of approximately 25 °C and with the structure supported by rubber blocks. As is well known, the EMI method is significantly sensitive to temperature variation [24], and temperature control is necessary to ensure that the observed variations in impedance signatures are due to structural damage rather than temperature effects. The results are presented in the next section.

V. Experimental Results

A. Capacitance Decrease

Initially, as a demonstration of the negative capacitance operation to reduce the capacitance value of the piezoelectric transducer, Fig. 5 shows the experimental capacitances for the whole operating frequency range from 50 kHz to 2 MHz obtained for the NC interface (C_N), conventional piezoelectric transducer (C_0), and the equivalent capacitance of the piezoelectric transducer using the NC interface ($C_0 + C_N$). The capacitances were measured with the IM3536 LCR Meter with 10 kHz frequency steps and 0.5 V_{RMS} excitation signal.

As shown in Fig. 5, the negative capacitance (C_N) ranges from approximately -5.8 nF to -4.4 nF over the entire analyzed frequency range. This variation depends on the dynamic response of the operational amplifier. Despite the observed variation, the NC interface operated stable, decreasing the

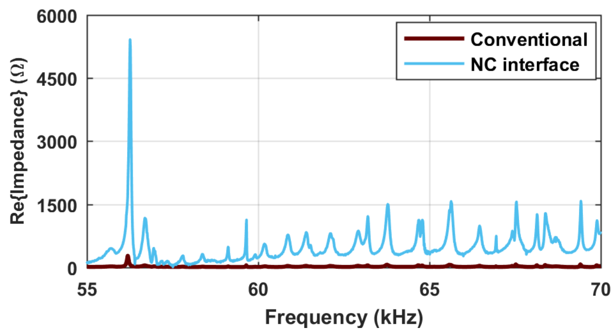

Fig. 6. Electrical impedances with conventional and NC interface at low frequency.

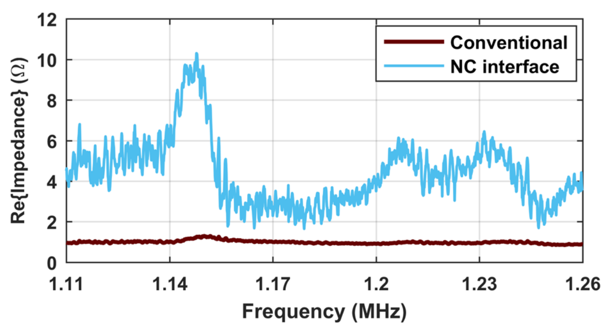

Fig. 7. Electrical impedances with conventional and NC interface at high frequency.

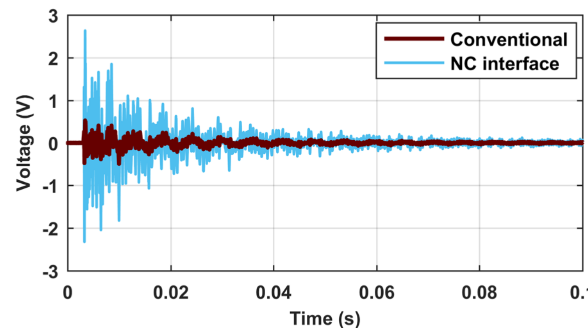

Fig. 8. Signals from conventional transducer and with NC interface.

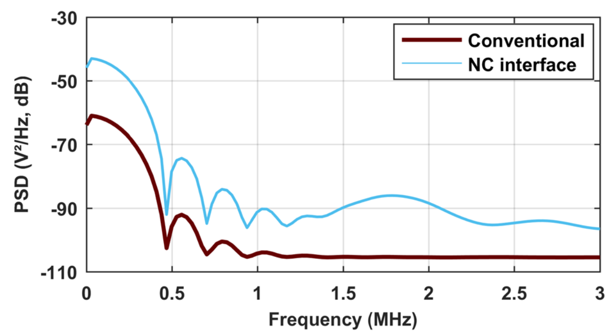

Fig. 9. PSD signals obtained for conventional and NC interface.

transducer equivalent capacitance $(C_0 + C_N)$ as desired. As noted, the transducer alone has an average capacitance (C_0) around 7 nF. Using the interface, the equivalent capacitance $(C_0 + C_N)$ is reduced to an average around 1.3 nF. The reduction in capacitance averages approximately 80%. It is important to note that it is possible to reduce the equivalent capacitance to a few pF, but the compensation is not effective by exciting the transducer over wide frequency ranges, as considered in this study. In addition, this result depends on the frequency response of the operational amplifier used. Therefore, in applications requiring narrow ranges, a very small equivalent capacitance can be obtained. Finally, it is important to note that the pronounced variations observed in the capacitance curves of the transducer alone and the transducer using the NC interface are due to resonant peaks, which are expected in the EMI method.

The benefits of reducing the capacitance are those theoretically analyzed in Section III, such as improving the electromechanical coupling and sensitivity to structural damage, as well as reducing the electrical current required by the transducer. As an example, decreasing the equivalent capacitance causes a significant change in the impedance signatures. Figs. 6 and 7 show the real parts of the impedance signatures obtained for both conditions, with and without the NC interface, for frequency bands of 55 kHz – 70 kHz (low frequency) and 1.11 MHz – 1.26 MHz (high frequency), respectively. Although the NC interface has been characterized for a wide frequency range from 50 kHz to 2 MHz, narrow ranges are presented for an appropriate comparison between the two conditions.

As shown in Figs. 6 and 7, for both low- and high-frequency ranges, the signatures obtained using negative capacitance show greater amplitude than the signatures obtained using the piezoelectric transducer alone. However, it is worth noting that the behavior of the signatures and the variations, such as resonance peaks, occur in the same frequency regions. This result indicates that the use of the NC interface makes the variations in the resonance peaks more significant, making this approach more sensitive for detecting structural damage or mechanical changes in the structure. The next results confirm this conjecture.

B. Pencil Lead Break (PLB) Test

As mentioned before, the PLB test allows for evaluation of the sensitivity of the piezoelectric transducer. The transducer response signals due to lead break for both conditions, with and without the NC interface, are shown in Fig. 8, and the corresponding PSDs are shown in Fig. 9. It should be noted that the PSD curves were obtained by averaging 5 measurements.

The results show that the NC interface significantly improves the transducer response. In the time-domain response signal shown in Fig. 8, the peak value is close to 3 V using negative capacitance, whereas for the conventional transducer, the peak is only approximately 0.5 V. In the frequency-domain response shown in Fig. 9, the difference between the two PSDs averages approximately 20 dB. For high frequencies above 1.5 MHz, the use of negative capacitance shows sensitivity not observable without its use.

This experimental result matches well with the theoretical result presented in Fig. 3 and the improvement in

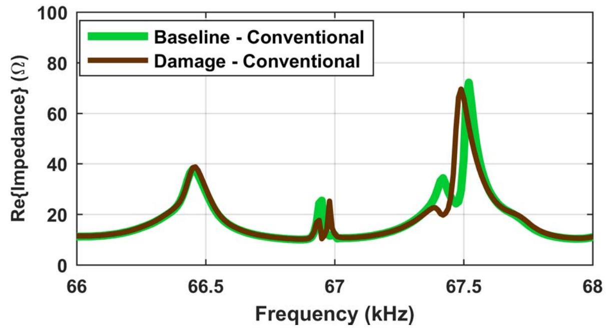

Fig. 10. Electrical impedance signatures obtained with conventional interface at low frequency.

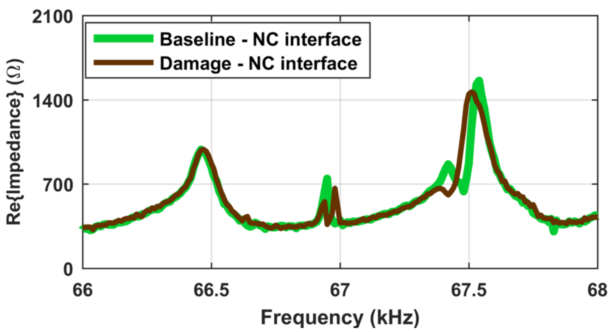

Fig. 11. Electrical impedance signatures obtained with NC interface at low frequency.

impedance signatures observed in Figs. 6 and 7. Therefore, the results indicate that the negative capacitance interface can improve transducer sensitivity for structural damage detection, as shown in the next subsection.

C. Improvement in Damage Sensitivity

As described in Section IV, a small hole corresponding to only 0.0093% mass variation was drilled into the structure to simulate minor damage. The real parts of the impedance signatures obtained in the low-frequency range for the conventional configuration and that using the NC interface are shown in Figs. 10 and 11, respectively. Although a wide band of 55 kHz - 70 kHz was analyzed, a narrow band is displayed to ensure a satisfactory comparison.

The behaviors of the impedance signatures obtained for both conditions (with and without negative capacitance) are similar, indicating that negative capacitance does not alter the correct analysis of the structural conditions but improves the electromechanical coupling and damage sensitivity. As shown in Fig. 11, the use of the NC interface makes the amplitudes of the variations more significant, with peaks close to 1600 **Ω** in the displayed range, whereas in the conventional method, the peaks are below 80 **Ω**. In addition, extra variations are observed between healthy and damaged conditions that were not detected without the use of the NC interface, clearly indicating an improvement in sensitivity to structural damage.

Damage sensitivity can be quantitatively analyzed by calculating the RMSD index using (6). The RMSD index was calculated in 3 kHz subbands, as shown in Fig. 12.

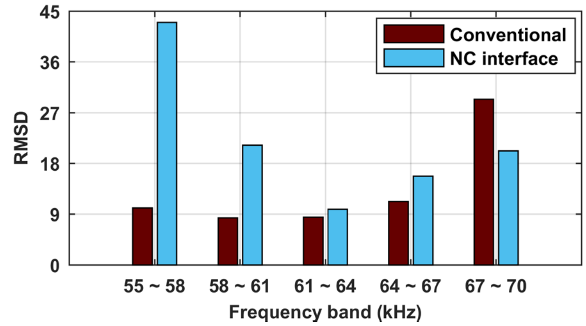

Fig. 12. RMSD indices with conventional and NC interface at low frequency.

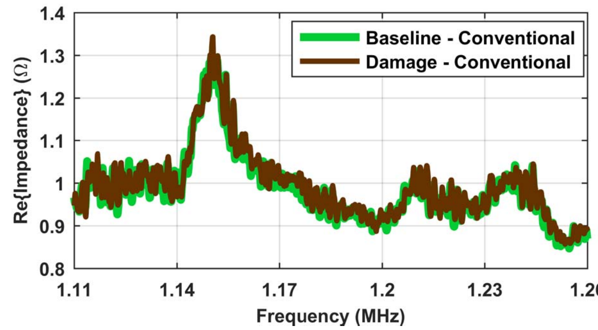

Fig. 13. Electrical impedance signatures obtained with conventional interface at high frequency.

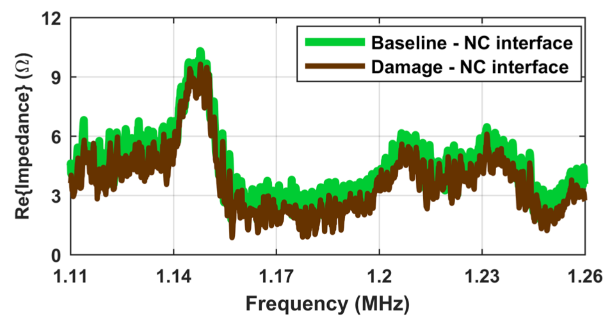

Fig. 14. Electrical impedance signatures obtained with NC interface at high frequency.

As shown in Fig. 12, the RMSD index obtained using negative capacitance was higher for all frequency subbands, except for the 67 - 70 kHz subband. At high frequencies above 1 MHz, the improvement in sensitivity to damage was more significant. The impedance signatures obtained for the conventional transducer and that using the NC interface are shown in Figs. 13 and 14, respectively.

As with the lower frequencies, the behaviors of the signatures obtained with and without negative capacitance are similar, preserving the same tendencies. However, using the NC interface makes the healthy and damaged structure signatures more distinguishable, as shown in Fig. 14. In contrast, the healthy and damaged structure signatures obtained by the transducer in the conventional configuration approximately overlap, as shown in Fig. 13.

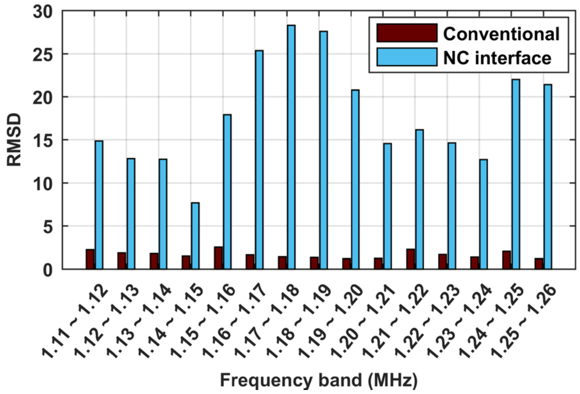

Fig. 15. RMSD indices with conventional and NC interface at high frequency.

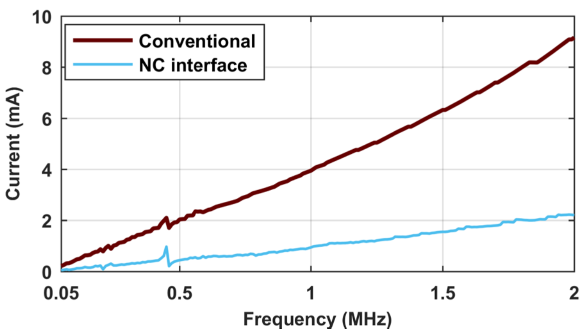

Fig. 16. Excitation current with conventional transducer and NC interface.

Therefore, the NC interface makes the transducer significantly more sensitive to structural damage, as can be quantitatively verified by the RMSD indices calculated for 10 kHz subbands, as shown in Fig. 15.

According to Fig. 15, the RMSD indices obtained with the negative capacitance interface are significantly higher over the entire frequency band analyzed. The difference in some subbands is approximately 1900%. This experimental result matches well with the theoretical analysis presented in Section III, indicating the effectiveness of using the negative capacitance interface to improve sensitivity to structural damage, especially at high frequencies.

D. Reduction in Excitation Current

In addition to greater sensitivity to structural variations at low and high frequencies, reducing the equivalent capacitance of the system has another benefit, which is reducing the required excitation current from the measuring system. Fig. 16 shows the rms electric current required by the transducer as a function of frequency for the conventional configuration and that using the NC interface.

In the conventional configuration, the current required by the transducer increases with frequency to a maximum of 9.5 mA for a 2 MHz frequency. In contrast, using the NC interface, the current is reduced to only 2.2 mA at the same frequency, and this result represents a savings of approximately 77%. Although a current on the order of milliamperes may seem low in many applications, this reduction may be important in autonomous monitoring systems, especially those with multiple transducers. Typically, alternative measurement and autonomous systems have low output current drive. Despite this improvement in the excitation current, it is important to note that the NC interface requires additional power consumption, which depends on the operational amplifier used.

Therefore, the experimental results confirm the conjectures pointed out in the theoretical analysis, indicating the effectiveness of the NC interface for impedance-based structural damage detection. Reductions in equivalent capacitance and required current excitation, and improved sensitivity to structural damage were clearly observed.

VI. Conclusion

This paper proposes the use of a negative capacitance interface with piezoelectric transducers to improve sensitivity for detecting structural damage based on electromechanical impedance. The use of negative capacitance was theoretically analyzed, and the results were validated by experimental tests.

The experimental tests were performed in a thin and narrow structure to guarantee the one-dimensional condition applied in the theoretical analysis. The PLB test was performed, and with the PSD calculation, the behavior observed in the theoretical analysis was confirmed. In addition, tests were performed by measuring the electrical impedance of a transducer at low and high frequencies for healthy and damaged structure. The experimental results conclusively confirmed a significant increase in sensitivity to structural damage, especially at high frequencies, validating the theoretical analysis.

Therefore, the theoretical analysis and experimental results demonstrate the effectiveness of using negative capacitance with piezoelectric transducers for impedance-based damage detection, bringing advantages such as improved sensitivity to structural variations and lower excitation current required by the transducer.

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