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Free-PZT Calibrated AD5933 Impedance Board for Structural Health Monitoring and Minimal Loading Damage Detection

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Introduction

Structural Health Monitoring (SHM) systems are critical for maintaining the safety and performance of weight-sensitive structures in aerospace (aircraft wings) and renewable energy (wind turbine blades, solar arrays) applications[1]. While lightweight aluminum alloys dominate these domains due to their strength-to-weight ratio and cost efficiency, their susceptibility to environmental overloads - particularly ice accumulation causing 12-15% mass increase - demands robust monitoring solutions[2]. Electromechanical impedance (EMI) methods using piezoelectric transducers (PZTs) have shown exceptional sensitivity in detecting sub-millimeter cracks, bolt loosening and composite delaminations [3] . However, conventional impedance analyzers (e.g., Agilent 4294A) remain impractical for field deployment due to their bulk (>10 kg) and cost (>$10k).To overcome these limitations, compact alternatives such as the AD5933 impedance converter (Analog Devices Inc.) have been developed. This device integrates a frequency generator and a digital signal processor in a portable, cost-effective IC package capable of impedance measurements up to 100 kHz. Previous research has demonstrated its successful application in detecting defects such as debonding and cracking in composite materials, with performance comparable to that of professional analyzers when properly calibrated. While promising, challenges remain regarding calibration accuracy, frequency segmentation, and feedback resistor selection, which must be addressed to achieve measurement precision comparable to professional-grade analyzers.
This study explores the experimental of the AD5933 for detecting weight-induced overloads in aluminum structures, simulating real-world ice accumulation through the strategic placement of solid glass elements. Unlike prior works that used simplified geometries (e.g., hollow nuts) to mimic added mass[4], this study aims for higher realism and relevance to environmental loading scenarios. The primary objectives are: (1) to develop a refined calibration protocol that mitigates response discontinuities and reduces dependence on professional analyzers, and (2) to evaluate the system's performance on aluminum specimens subjected to incrementally applied static loads.

Results

- The comparison between PV520A(Fig a) and AD5933(Fig c) responses under identical conditions shows excellent agreement when optimized feedback resistor used.
-A robust calibration protocol was developed for the AD5933 using free-standing PZT patches, accurately reproducing EMI responses over the 10–100 kHz range (Fig d).
-Experimental loading using glass weights (20g increments, up to 100g) revealed measurable impedance shifts, with downward trends in amplitude and resonant frequency across key frequency bands (Fig e).
- Statistical analysis with RMSD and CCDM indices demonstrated sensitivity to both amplitude changes and waveform distortions, confirming the system’s ability to track damage-like perturbations under low-mass influence.

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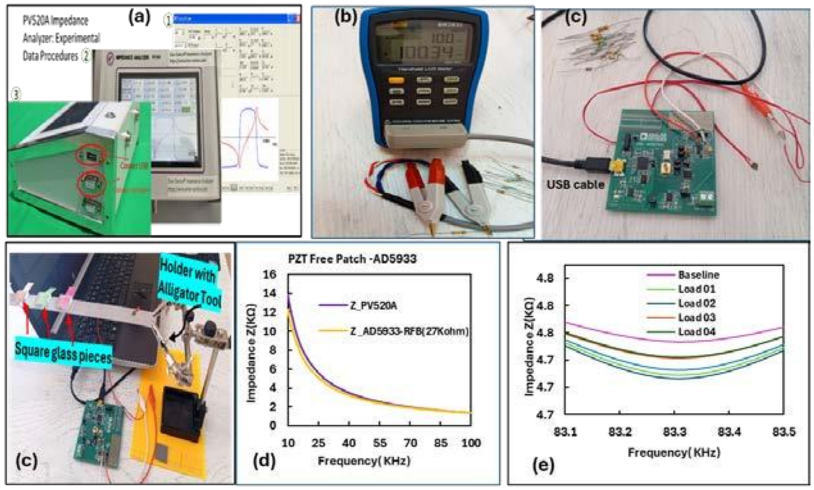

Figure 1.(a) PV520A-impedance analyzer, (b) BR2832 Handheld LCR Meter, (c) AD5933 Evaluation Board, (d) EMI calibration of a free PZT (AD5933 & PV520A). (e) Effect of incremental lightweight loading on EMI response.

Mathematical Model

The AD5933 does not allow direct input of the end frequency; instead, it is defined through the start frequency ff_{start}, where $ff_{\text{end}} = ff_{\text{start}} + (NN - 1) \cdot \Delta ff$, In this case, a start frequency of 10 kHz and a target end frequency of 100 kHz were selected with 202 total measurement points, resulting in 201 increments. Rearranging Equation (1), the frequency increment was calculated as: $\Delta ff = \frac{ff_{\text{end}} - ff_{\text{start}}}{N-1} = \frac{100{,}000-10{,}000}{201} \approx 447.76\text{Hz}.$

Conclusion

This study demonstrates that the AD5933 board, when calibrated with free PZT patches and analyzed using RMSD and CCDM, offers a reliable, cost-effective EMI-based SHM method. Its high sensitivity to minimal loading makes it ideal for detecting early damage in lightweight structures such as lightweight aluminum used in wind turbine blades and solar arrays. Future improvements will focus on automating damage classification using machine learning.

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