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# MEMS Seismic Sensor with FPAA-Based Interface Circuit for Frequency-Drift Compensation Using ANN

Ramesh Pawase,[1] and
Dr. N.P. Futane[2*]

[1]Department of E&TC, SITRC Nashik, Amrutvahini CoE, Sangamner, Savitribai Phule Pune University, 422608, India.

E-mail: rameshpawase@gmail.com

[2]Department of E&TC, Government College of Engineering, Avsari, Savitribai Phule Pune University, 412405, India.

*E-mail: niteen_futane10@rediffmail.com

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## Abstract

Electrochemical micro-electro mechanical systems (MEMS) seismic sensor is limited by its nonideality of frequency dependent characteristics hence interface circuits for compensation is necessary. The conventional compensation circuits are limited by high power consumption, bulky external hardware. These digital circuits are limited by inherent analog to digital conversions which consumes significant power, acquires more size and limits processing speed. This system presents field programmable analog array (FPAA) (Anadigm AN231E04) based hardware implementation of artificial neural network (ANN) model with minimized error in frequency drift in the range of 3.68% to about 0.64% as compared to ANN simulated results in the range of 23.07% to 0.99%. Single neuron consumes power of 206.62 mW with minimum block wise resource utilization. The proposed hardware uses all analog blocks removing the requirement of analog to digital converter and digital to analog converter, reducing significant power and size of interface circuit and enhancing processing speed. It gives the reliable, SMART MEMS seismic sensor with ANN-based intelligent interface circuit implemented in FPAA hardware.

### Keywords
MEMS, Seismic sensor, Artificial neural network, FPAA, Analog signal processing.

## Introduction

Information systems getting closer to physical world which are generating new opportunities in the area of sensing and controlling environment and different devices. In order to exploit these available opportunities, miniaturized information systems must be developed. Developing miniature sensing system and making it reliable is a driving force for development of micro-electro mechanical systems (MEMS), which construct both mechanical and electrical components in miniature in size. As MEMS technology is supplementary to integrated circuits (IC) technology, the synergy between mechanical, electrical and electronic system makes it breakthrough technology. MEMS devices have application in areas ranging from automobile and telecommunication switching to printers and inertial guidance system (Bakhoum and Cheng 2012). MEMS are widely used in various sensing and actuators applications (Gabriel, 1998). In this paper, field programmable analog array (FPAA)-based design and development of interface circuit is focused for MEMS seismic sensor (MSS) output compensation. In these types of applications, the FPAA offers better solution as rapid implementation is possible. The targeted commercially available FPAA- an Anadigm AN231K04 is an IC, containing circuits from combination of very small capacitors and transistors. Recently several vendors including Anadigm, provides service for creating an application specific integrated circuit (ASIC) for user-defined application by configuring the FPAA. Development speed is time required to configure an FPAA is far less than that required to design, simulate and fabricate the ASIC. The accurate and stable design is possible due to use of switched capacitor-based analog design in FPAA, which minimizes offsets, nonlinear behavior, and component tolerances for long time with wide range of operating temperatures. The Anadigm FPAA Designer 2 tool has been used to define the architecture of Anadigm AN231K04 FPAA chips.

The major contributions of this paper are as follows:

(1) Artificial neural network (ANN)-based compensation is applied for MSS with minimum error.
(2) FPAA-based hardware implementation utilizing minimum resources and
(3) Minimum possible error is observed using FPAA-based hardware implementation giving compensation in output for MSS.

This paper is organized is as follows. Section 2 deals with literature survey and gaps in existing work along with scope for the research work. Section 3 discusses for MSS nonidealities and proposed work to compensate the nonidealities present in output of MSS, FPAA-based ANN-based frequency effect compensation scheme using neuron model. Section 4 discusses results concluded in Section 5.

## Related work

MEMS-based electrochemical seismic sensor device characterization performed on a vibration table recorded in Chen et al. (2013) It has been reported overall linear relationship between applied velocities and output voltage amplitudes with a sensitivity of 274 V/(m/s) in the range of 20 to 80 Hz but these characteristics are not purely linear. Ideally the characteristics of MSS should be independent of input vibrating frequency for the experiment reported in Chen et al. (2013). The purpose of this work is to study the limitations of the experimentation of MEMS-based Seismic sensor such as frequency dependence and ANN-based soft computing model have been proposed to compensate these errors. Compared to other seismometers relying on solid proof masses for environmental vibration monitoring, the electrochemical approach was reported to enable low-frequency vibration signal characterization (Lia et al., 2012; Chen et al., 2013). Chen et al. reported micro-electrochemical seismic sensor which have input vibrating frequency dependent characteristics. Figure 1 shows these characteristics (Lia et al., 2012; Chen et al., 2013). All of these reviewed work attempted to compensate different types of nonidealities of MEMS sensors; however, all these techniques require external hardware circuits or computer to compensate the errors (Futane et al., 2010). Our previous work focused on the development of the ANN-based soft computing model (Pawase and Futane, 2015) which results in frequency drift compensation with mean square error of 7.74 e-2 (Pawase and Futane, 2015). Similar kind of compensation method applied to MEMS-based gyroscope for minimizing angular rate error (Pawase and Futane, 2015). Recently, FPAA is becoming popular for sensing and controlling systems as most of them process analog signals (Dias Pereira et al., 2000). Majhi et al. performed DC servo position is control using FPAA in real-time application and its results shows the applicability of FPAA for reconfigurable systems in industries (Majhi et al., 2012). FPAA proved the variety of applications for control and measurement systems, biomedical signal processing, audio applications as explained in Malcher and Falkowski (2014). FPAA is also used for controller design to compensate vibration, hysteresis and time delay in a high-speed serial-kinematic X–Y nanopositioner (Wadikhaye et al., 2014). FPAA based analog emulation of electric power system dynamics is reported in Deese and Nwankpa, 2014.

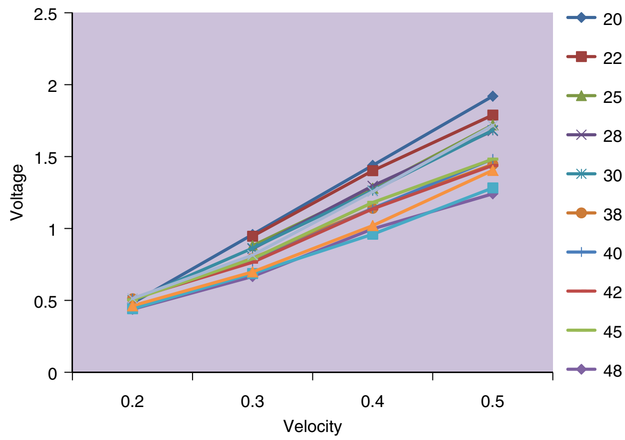


Figure 1: MEMS seismic sensor characteristics—velocity V/S output voltage of before vibrating frequency compensation.

## Proposed work

### ANN model description

Researchers have attempted for minimizing the nonidealities in MEMS-based sensors like humidity sensors, porous silicon pressure sensors with external hardware or computer programme. But these applications are limited by more size and more power requirement which is not acceptable for highly compact circuits and system. Hence small size, less powered solution should be proposed for MSS. To characterize the parameters of commercially available MSS (MET2003), the devices were positioned on a vibrating table with the vibrating velocity and frequency adjusted systematically. Figure 1 records the output voltage of a MSS device as a function of the vibration velocity. It demonstrates the different output voltages for different vibrating frequencies which show linear relationship however these must be independent of input vibrating frequencies having purely linear relation. Hence this problem must be attempted by developing the interface circuit for drift compensation in output voltage.

In our previous work, the feed forward ANN model with hyperbolic tan sigmoid activation function is trained with back propagation algorithm and the simulations are carried out in MATLAB, with ANN tool box. The frequency dependent output voltage is taken as input to ANN model which yields compensated output (Pawase and Futane, 2015). It results in frequency drift compensation with minimum mean square error (MSE) of 7.74 e-2. Figure 2 shows a neuron in ANN model. The input layer has two inputs and bias. Two neurons are selected for hidden layer. In this paper, work is focused on FPAA-based hardware implementation of input vibrating frequency independent interface circuit development.

## FPAA structure

Recently, like field programmable gate array (FPGA) in digital design, Anadigm provided FPAAs with on board dynamic configuration capability gives designers user friendly platform in analog design. FPAA has fully differential architecture which is suitable and advantageous for low voltage analog signal processing. FPAA consist of four configurable analog block (CAB) blocks in which implementation of analog circuits is simpler, easier and less time taking. It uses the switched capacitance technology at the backend in which electrical charge through capacitor is controlled. Figure 3 shows the internal basic structure of the FPAA model AN231E04. The biggest advantage of FPAA is dynamic reconfiguration ability which provides on board parameter changing facility reducing time for development. It has seven configurable input-output cells and two dedicated output for interfacing. The main features including, low input offset through chopper stabilized amplifiers leading to better performance. The main four analog independent modules consisting of the look-up table (LUT), input and output interfaces having the analog functions crating facility. LUT having 256 Byte capacities can be more suitable for sensor characteristics linearization and arbitrary signal generation. The typical frequency range for operation is from DC to 2 MHz having broadband signal to noise ratio of 90 dB and Narrowband (audio) S/N ratio of 120 dB (Anadigm FPAA).

## FPAA-based implementation

The vibrating frequency dependent output voltage (0-2.5 V) of seismic sensor for vibrating velocity (0-0.5 cm/s) is used as input for FPAA-based interface circuit which provides frequency independent output voltage. Figure 4 shows the basic working model of our research which has two parts consisting online

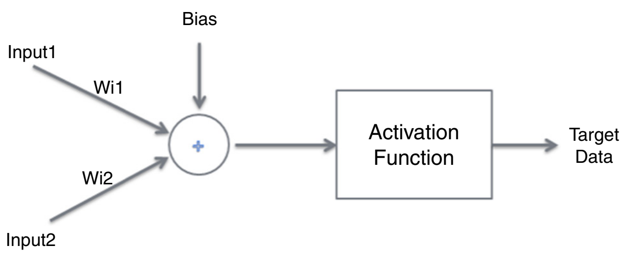


Figure 2: Basic single neuron model.

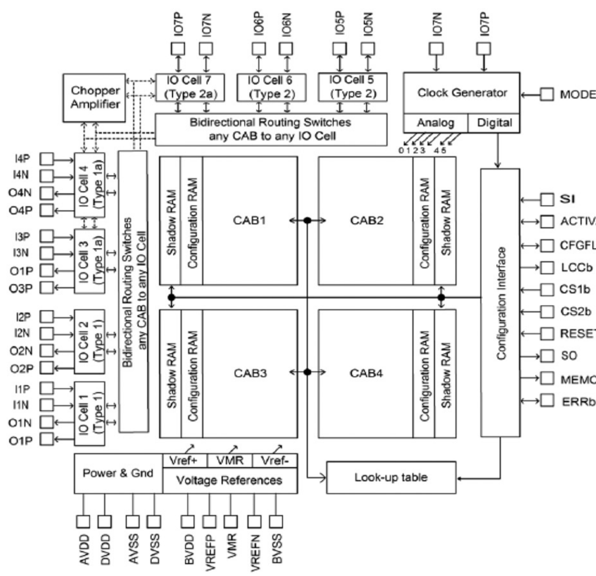


Figure 3: Internal block diagram of FPAA (Anadigm FPAA).

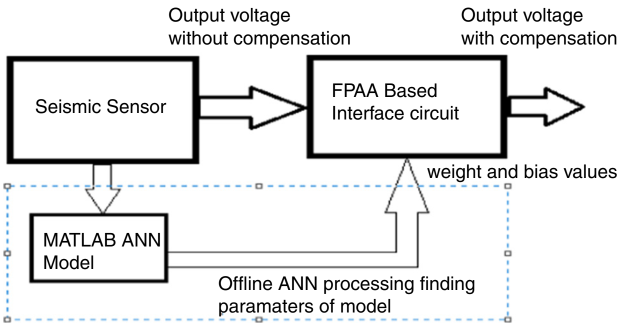


Figure 4: Block diagram of sensor with FPAA based interface circuit.

sensor output processed by interface circuit and other having offline ANN model finding optimum parameters like weights and bias which are then taken into account while design of FPAA-based interface circuit. Figure 5 depicts the single neuron implementation of FPAA-based interface circuit in Anadigm Designer 2 simulator (Anadigm FPAA) which is then implemented in FPAA hardware development kit as shown in Figure 6 (Manolov et al., 2009, Anadigm Designer®2). The output of MSS is given to FPAA directly through function generator and output of FPAA is observed on oscilloscope. The one neuron is analysed in FPAA hardware which uses 3.3 V as supply voltage for operation. The hyperbolic tan transfer function is implemented in look up table as shown in Figure 7.

# Performance evaluation

## Performance metrics

Error in percentage is calculated and analysed for the range of input velocity, 0-0.5 cm/s. The second

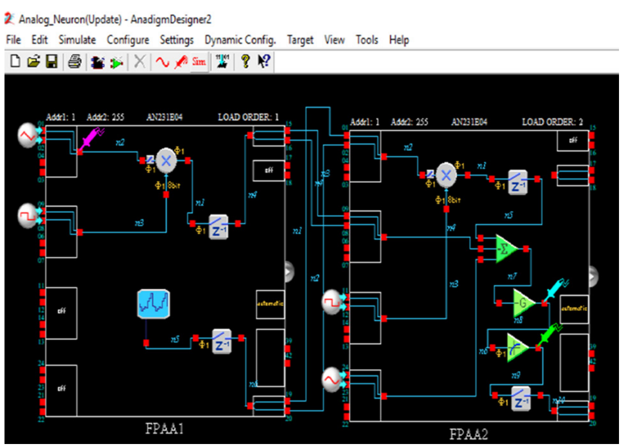


Figure 5: Implementation of FPAA based interface circuit in anadigm designer 2.

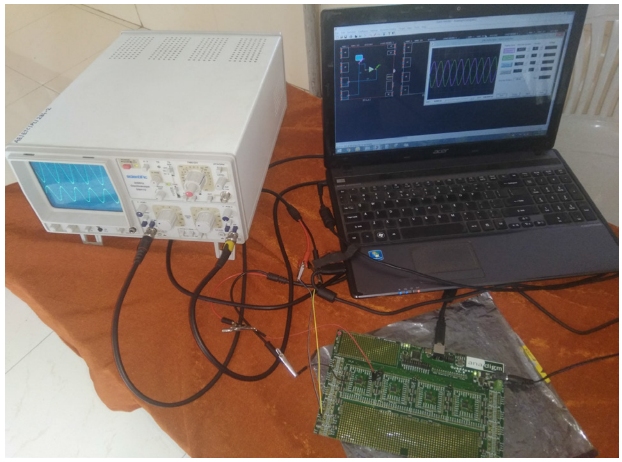

Figure 6: FPAA based implementation.

metrics is used as the resource utilization in FPAA hardware which is also expressed in percentage.

## Discussion on results

In proposed system, the frequency dependent output voltage is taken as input to ANN model which yields compensated output. Our previous work focused on developing ANN model and finding optimum values of weights and biases which are used in simulation and then implemented in FPAA-based hardware. The input layer has two inputs and bias. For experimentation two neurons in hidden layer are used implement the circuit with simplicity. The selected method of training is back propagation algorithm and the simulations are carried out in MATLAB, with ANN tool box. Figure 8 shows minimized error with reference to velocity and Figure 9 shows the output voltage for different vibrating frequency, after applying ANN-based compensation model in FPAA.

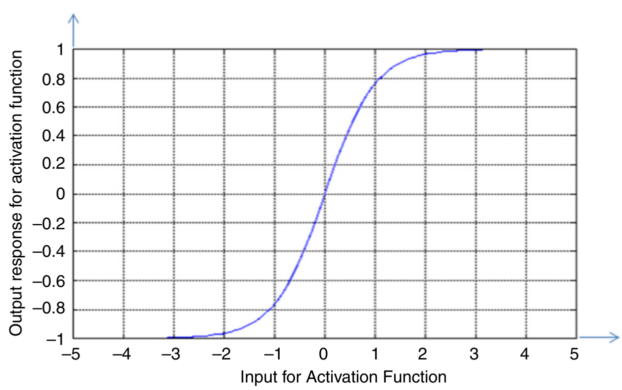


Figure 7: Hyperbolic tan transfer function implemented in look up table.

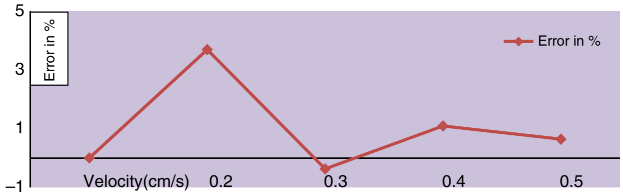


Figure 8: Compensated Error in Percentage.

After applying FPAA-based compensation circuit, the compensated output is obtained with minimum possible error in frequency drift in the range of 3.68% to about 0.64% as compared to ANN simulated results in the range of 23.07% to 0.99%. Figure 8 shows the compensated errors in percentage for different velocity. Overall the MSS finds best fit compensation circuit in terms of FPAA which reduces the requirements of analog to digital converter (ADC), digital to analog converter (DAC) and processing original signal in few required steps. Results are achieving compensation using new approach of analog signal processing improving the reliability of MSS for seismic applications. The overall usage of resources in FPAA is about 50% which is advantageous (Fig. 10 and Table 1).

## Conclusion and future scope

In this paper we proposed input vibrating frequency dependent compensation model with minimum error and its implementation in the range of 0 to 0.5 velocities against the expected frequency independent compensation. FPAA-based neuron implementation

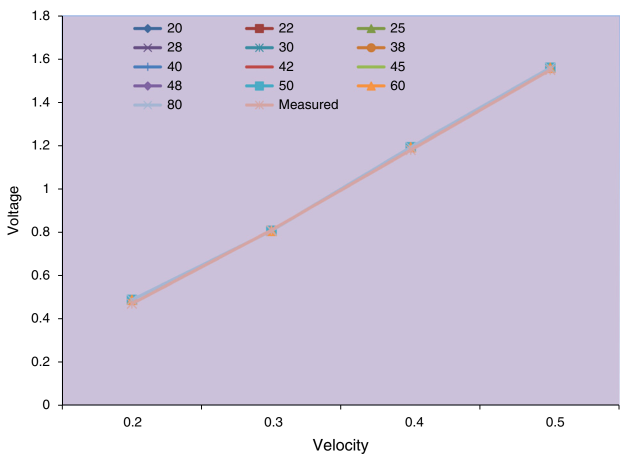


Figure 9: MEMS seismic sensor characteristics—velocity v/s output voltage of after vibrating frequency compensation.

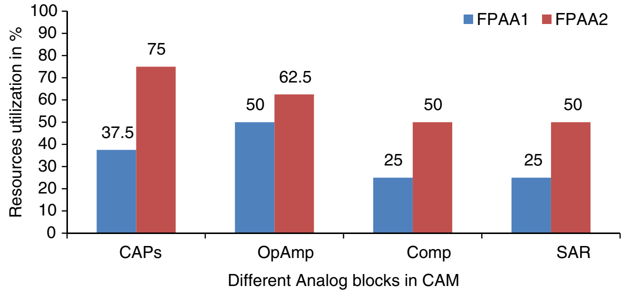


Figure 10: Comparison of FPAA resource utilization in percentage.

is proposed with quick prototype for interface circuit. This single neuron consumes of power of 206.62 mW. The available resources are not fully utilized for one neuron implementation. Developed prototype gives advantages in terms of less time to implement, interactive hardware and simulation design environment however same circuit implementation in ASIC may take much time for implementation. Using this FPAA-based compensation circuit, the error in frequency drift have been minimized in the range of 3.68% to about 0.64% as compared to ANN simulated results in the range of 23.07% to 0.99%. As the proposed hardware consists all analog environment which removes the requirement of ADC and DAC reducing significant power and size of interface circuit. This work gives the SMART MSS with reliable output and it also highlights the use of FPAA for implementing ANN-based intelligent interface circuit hardware. In this work, the advantage of rapid

### Table 1. Resource utilization

| | FPAA1 | | | | FPAA2 | | | |
|---|---|---|---|---|---|---|---|---|
| Resources | C | Op | Co | SAR | C | Op | Co | SAR |
| CAB 1 | 06 | 02 | 01 | 01 | 06 | 02 | 01 | 01 |
| CAB 2 | 06 | 02 | -- | -- | 08 | 01 | -- | -- |
| CAB 3 | -- | -- | -- | -- | 04 | 01 | -- | -- |
| CAB 4 | -- | -- | -- | -- | 06 | 01 | 01 | 01 |
| Total used | 12 | 04 | 01 | 01 | 24 | 05 | 02 | 02 |
| Available | 32 | 08 | 04 | 04 | 32 | 08 | 04 | 04 |
| Utilization in % | 37.5 | 50 | 25 | 25 | 75 | 62.5 | 50 | 50 |
| Power | 94.28 mW | | | | 112.34 mW | | | |

Note: C: Capacitors, Op: No of Operational Amplifiers, Co: Comparators, SAR: Successive approximation resistors.

prototyping of FPAA has been utilized. This FPAA-based work can be upgraded with new ANN parameters and can be used for improvement of any MEMS sensor which has nonideal characteristics. Our further work will be focused on the Complementary Metal Oxide Semiconductor (CMOS)-based ASIC solution in which analog multipliers, adders and activation functions implemented using CMOS circuits.

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