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Tester for space micro-accelerometer

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Abstract

Micro-accelerometer MAC04 has been developed in order to measure very low accelerations such as those caused to satellites by atmospheric drag and other non-gravitational forces. The instrument uses a cubic proof-mass inside a small cavity. In an open loop the change of capacitance between the cube and 12 electrodes on the inner cavity surface is a measure of the applied acceleration. It is very difficult to ground test and calibrate such a device due to gravity. The tester simulates the change of capacitances (base capacitance 13,5pF, changes in a range of ±1.5pF). Complete closed loop system is presented.

Keywords: micro-accelerometer, tester, simulator

1. Introduction

Micro-accelerometer MAC04 has been developed in order to measure very low accelerations such as those caused to satellites by atmospheric drag and other non-gravitational forces (range 1.2×10^{-4} m.s^{-2}, resolution 2×10^{-9} m.s^{-2} and 2σ accuracy 1.3×10^{-8} m.s^{-2} - after in-flight calibration using Precise Orbit Determination data). The instrument uses a cubic proof-mass inside a small cavity. The cube is kept in the middle of the cavity by electrostatic forces. When the measured acceleration is present, the cube is displaced and this displacement is measured by the change of capacitance between the cube and 12 electrodes on the inner cavity surface. Multiple feedback loops keep electrostatically the cube in the center between the electrodes. It is very difficult to ground test and calibrate such a device due to gravity. The tester simulates the change of capacitances (base capacitance 13,5pF, changes in a range of ±1.5pF). Complete closed loop system is presented. The system consists of three basic parts: high resolution (16-bit) digital to capacitance converter, analog to digital converter and MATLAB-Simulink based model of the physical sensor.

2. Motivation

The MAC04 Micro-Accelerometer is planed to be one of the scientific instruments onboard of the oncoming ESA's SWARM mission. The functionality of the concept has been proved during the Atlantis Space Shuttle

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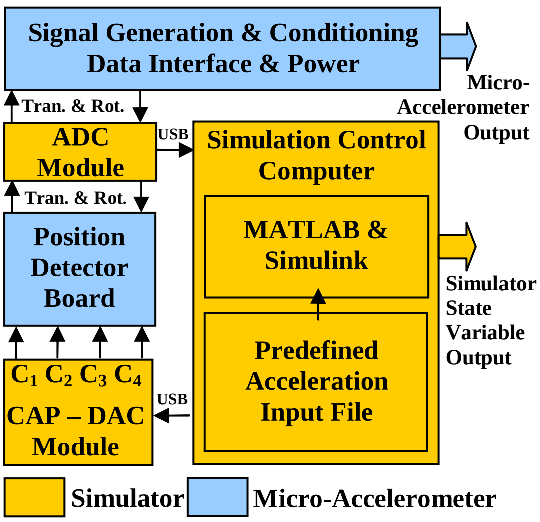
mission STS-79[1]. The latest development of the instrument for SWARM mission brought changes to the construction that have to be verified. It is almost impossible to completely test the accelerometer because the gravity force is 100000 times higher than is the measurement range of the instrument. With the presented design it is possible to test all the electronic circuits of the micro-accelerometer, only the physical acceleration sensor itself is replaced by digital-to-capacitance converters (CAPDAC). The tester represents one possible approach how to calibrate the micro-accelerometer (the capacitance differences produced by the CAPDACs can be measured very precisely).

3. Tester

Figure 1a shows the concept of the test setup. The CAPDACs are connected to “Position Detector Board” which converts the four capacitances to voltage outputs that correspond to translation and rotation of the cube in one axis (see Fig.1b). The conversion is based on analog processing of a differential transformer output signal. The feedback voltages which electrostatically compensate the movements of the cube are measured by ADC. Closed loop simulator-tester uses mathematical simulation of the physical sensor to complete the loop. The proof-mass sensor is simulated in two steps. First calculation is used to transform the feedback voltages to a virtual movement of the proof-mass. The second step is to calculate the capacitances from the cube position. Third step is added to introduce an external action (applied acceleration) to the system (we can calculate how the acceleration affects the proof-mass position).



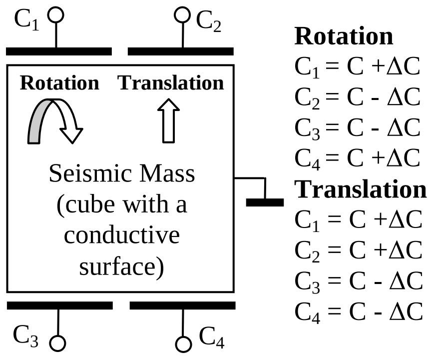


Fig. 1 (a) Block diagram of the micro-accelerometer test setup; (b) Principle of acceleration sensing

Fig.2a shows the block diagram of the first version of CAPDAC. The change of output voltage of the amplifier is equivalent to a change of virtual capacitance between e_1 and e_2 terminals. This circuit is very simple but its weak point is a time and temperature stability of the input capacitance of the first op-amp. More sophisticated but complicated method would be to use an external reference signal to drive the multiplying DAC.

The second CAPDAC (Fig.2b) uses MAXIM's MAX1474 "Miniature Electronically Trimmable Capacitor". Two of them (C_A, C_B) together with passive variable capacitors (C_1, C_2, C_3) form a circuit which has non-linear transfer function and can achieve up to 10 bits of resolution. We could partially deal with the non-linearity using a look-up table in the control software. Practically the measurements of the transfer function are affected by the test setup (measured capacitance is very low ~13±1.5pF) and the linearization is therefore difficult. For this reason the first circuit was selected for further development. There is limitation for both presented circuits - the signal amplitude applied to CAPDACs has to be within their power supply range.

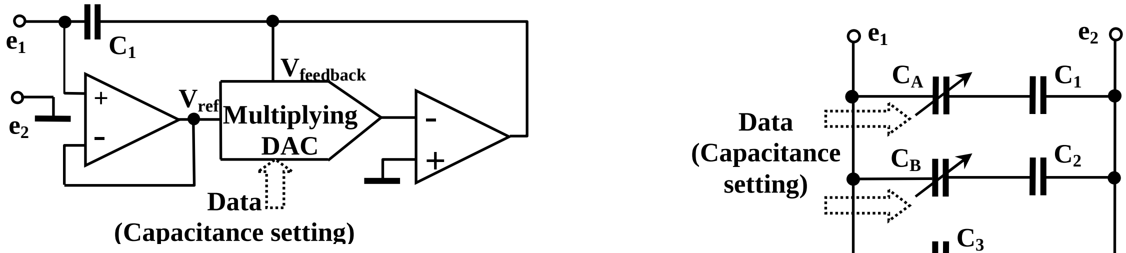


Fig. 2 (a) CAPDAC with multiplying DAC; (b) CAPDAC based on a digital trimmable capacitor

4. Results

At first both CAPDACs modules were evaluated with a precise LCR meter (Hewlett Packard 4284a). It is possible to measure the capacitance change with a very good accuracy (0.1%; 0.1fF resolution), but the absolute value of capacitance is heavily influenced by the geometry of the shielding and grounding. The transfer function of the first circuit (Fig.2a) is highly linear, see Fig.3b (linearity <±0.15%). The overall non-linear transfer function of Fig.2b circuit is composed of 32 non-linear parts (MAX1474 has 5 bits resolution). It is possible but very difficult to tune-up the characteristic by the variable capacitors.

Both translation and rotation movements of the proof-mass were simulated (Fig.4,5,6). The simulation was started with center value of capacitance and one step corresponds to 100 LSBs (100 LSB ~ 5fF) change of C_1 to C_4 (see Fig.1b). Results (output voltages from the Position Detector Board) for the Fig.2a circuit are presented. The linearity error is better than ±0.3% for translation (Fig.5) and <±0.6% for rotation movement (Fig.6). Higher non-linearity in this measurement is partly caused by the non-linearity of the Position Detector and by combination of all four non-linearities of the CAPDAC.

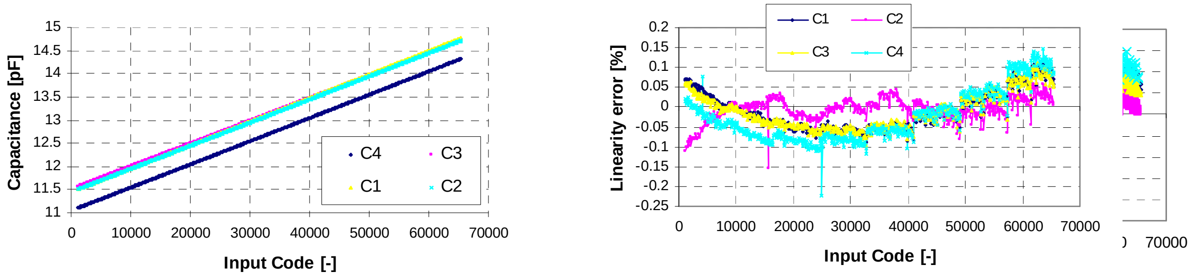


Fig. 3 (a) Output capacitance versus input code (Fig.2a circuit); (b) Linearity error of this CAPDAC

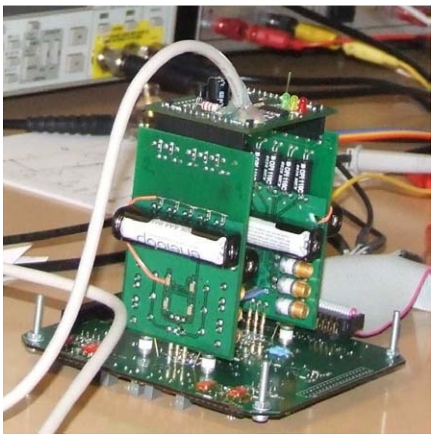


Fig. 4 MAX1474 based CAPDAC connected to Position Detector Board

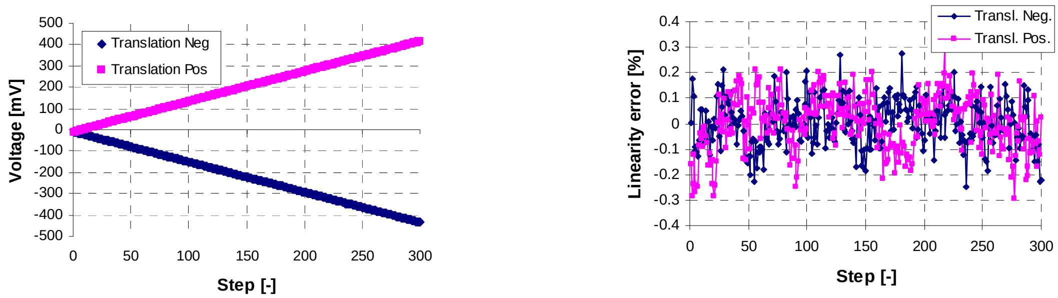


Fig. 5 (a) Position detector output voltages (translation); (b) Position detector output voltages linearity error

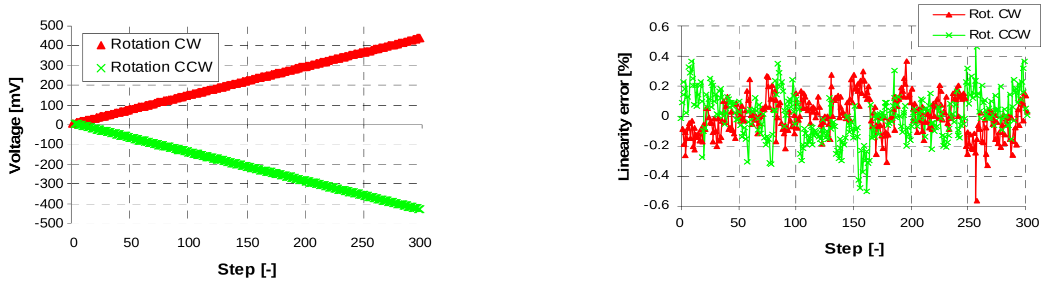


Fig. 6 (a) Position detector output voltages (rotation); (b) Position detector output voltages linearity error

The frequency range of the micro-accelerometer is 0.1 to 10^{-4} Hz. The Position Detector Board has a time constant about 50ms (derived from a step response). The projected refresh rate of the simulator is 100Hz, which turned to be too high for standard PC with MATLAB-Simulink. NI LabView Real-Time Module running under real-time operating system in the target computer is the proposal for the final solution.

5. Conclusions

The tester brings new possibilities to the development and testing process of the micro-accelerometer. The design could also be useful for other electrostatically compensated systems with capacitive sensing[2,3]. The 16-bit resolution CAPDAC provides an excellent dynamic range for testing of all possible applied accelerations. In order to maximize its potential the electro-mechanical construction of the micro-accelerometer should be adjusted to accept the simulator hardware. Full (three axes) simulator will be made after successful testing of the single axis tester in a closed loop. The simplicity of the simulator circuits allows us to build all the required electronics into the space of the physical sensor (proof-mass with cage). Newly developed MEMS based (e.g. WiSpry) variable capacitors could improve the simulator properties (the limitation of applied signal voltage is not so strict for MEMS based devices), however these devices are still not available.

The presented CAPDAC circuit (Fig.2a) can be easily modified for a different base capacitance and tuning range. This can be useful for testing of signal evaluation circuits for any sensor which provides a change of capacitance as its output value.

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