695. Finite element model of MEMS accelerometer for accurate prediction of dynamic characteristics in biomechanical applications

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Abstract. This paper presents the developed 3D finite element model of a MEMS accelerometer with clearly defined geometry and properties, which were adjusted so as to accurately reproduce the dynamic behavior of the actual commercial seismic microsensor. Experimental characterization of the response of the actual microsensor on a vibro-stand confirmed the validity of the proposed modeling approach. Consequently, the developed numerical model enables convenient and fast determination of response of the accelerometer subjected to the real-world excitation. Implementation of the model is highly beneficial in industrial R&D applications, e.g. during testing of performance of biomechanical devices used for registration of movements of persons during fitness training, rehabilitation, etc.

Keywords: MEMS, accelerometer, dynamics, finite element model, vibrometry.

1. Introduction

MEMS [1] technology is at the center of a rapidly growing industry combining many different engineering disciplines and physics: electrical, electronic, mechanical, optical, material, chemical, and fluidic engineering. In its most conventional sense MEMS refers to a class of batch-fabricated devices that utilize both mechanical and electrical components to simulate macroscopic devices on a microscopic scale.

One of the MEMS technology outcomes is an accelerometer. Accelerometers have a high potential for use in three dimensional movement analysis systems: they are small, do not need to be attached to a reference and provide a signal, which incorporates acceleration and inclination information. However, the analysis of movements from accelerometer data is generally not straightforward, because the information comprises several components: the output signal of an accelerometer consists of an actual acceleration component and a gravitational acceleration component.

Accelerometer has many areas of application such as biomechanical, clinical, vibrational, etc. With prices dropping, availability, resolution and precision growing, new possibilities open every day. It‘s already became a matter of application and model designer to extract the benefits accelerometers can give in real world applications.

In many clinical and biomechanical applications the analysis of unconstrained movements in a natural environment for relatively long observation times (several hours) may open new perspectives. For instance, a rehabilitation treatment can be assessed by evaluating the activities of daily living (ADL) before and after a rehabilitation treatment [2]. Vibration analysis is frequently used in various industry applications as a source to determine fault conditions of some vibrating equipment. For example, excessive vibration that is produced by rotating engine might show bearings deterioration and is a primary mean to indicate when the engine must be serviced in order to have a long operation life.

Together with different wireless transmission technologies, computer development achievements these sensors allow creating small, even battery-operated systems for data aggregation and processing [3, 4]. These include creating wireless networks [5] that utilize few sensors to collect measurements and central device to do the aggregation and processing/forwarding.

However, in order to focus a research effort (especially industrial) from accelerometer to an application domain, one needs a verified accelerometer model with well-established parameters that can be used as a tool for research in application domain. Such a need was faced by joint research activities carried out by JSC Baltec CNC technologies [6] and JSC De Futuro [7] in the application of accelerometer for biomechanical movement level evaluation during the product prototype development cycle.

Human body points experiences quite big accelerations even during conventional movement. For example, during running with speed of 5 – 10 km/h the accelerations on the waist (as well as chest) can reach as high as 3*g*. Accelerations in the leg area, especially the lower one, can reach even higher (jump testing showed accelerations up to 50 – 60 m/s^2 in the ankle area). Because of the presence of such accelerations skin area of the body moves differently compared to the human skeleton depending on rheological properties of the soft tissue that is between the rigid bones and the skin.

If we take accelerometer that can track 3D accelerations and angle changes, we can exactly follow the movement of that device (assuming we know initial conditions, the measurements are very accurate and integration methods do not provide any errors). If the device would be mounted on a rigid bone inertia forces that arise because of the device mass would be neglected by the firm junction of the device and the bone. During daily physical activities this is impossible, and mounting is only possible on the skin surface. When the device having its own mass is mounted on the skin, giving described accelerations, it can have quite noticeable inertia based movements because of the rheological properties of the skin [8].

Thus, this paper presents such accelerometer model with clearly defined geometry (whole accelerometer structure fits into 1 mm^2 area and is similar to the structure used by industrial sensors though others also exists [9]) and material properties (silicon (Si) is used).

2. Model and its scope

The objective is to create an accelerometer model that would well fit industrial sensor having in mind sensor price and availability as the research is targeted to the end user application. For such a base accelerometer LIS3LV02DL by ST Microelectronics [10] was chosen. Its price is low and availability is high. The device is capable measuring acceleration range of ±2***g*** or ±6***g*** (user selectable) on all three axes (*x*, *y*, *z*). Device is digital and is capable of providing 12 bit data meaning up to 341 or 1024 steps per ***g***.

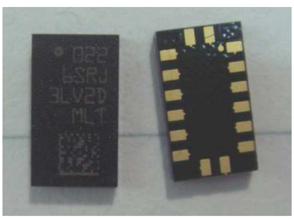


Fig. 1. LIS3LV02DL accelerometer

To simplify the things a “black box” approach was taken meaning that the goal is to get a model that can provide the same output as the actual accelerometer when given the same input without following strict specifications which are usually unknown rather than match inner structure.

In order to get some hints on the mechanical structure inside the accelerometer diamond grinding tools were used to take a look inside. Then every grinding step was captured by a lab microscope with photo shooting function. Some of the steps are given below.

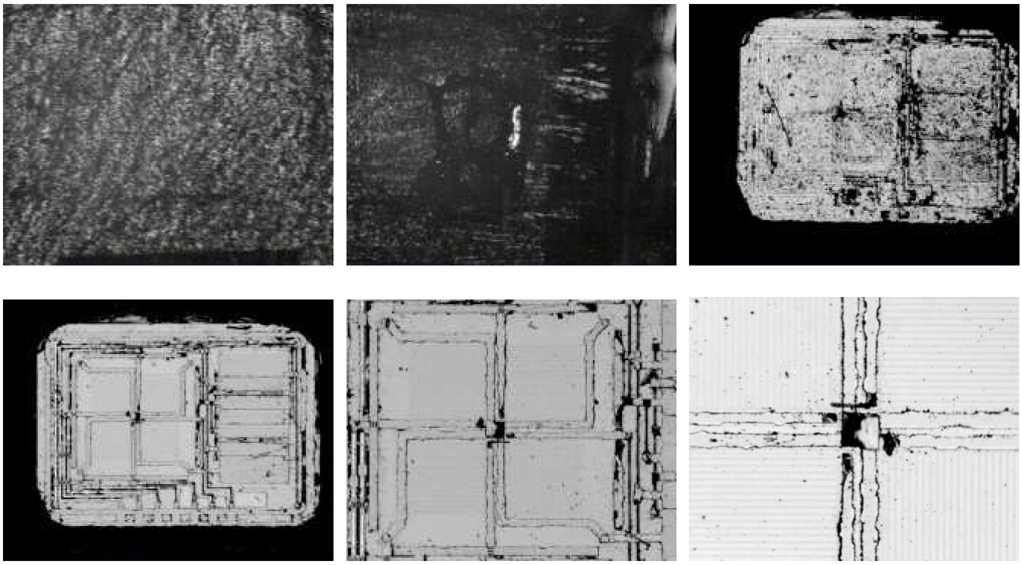


Fig. 2. Grinding process steps captured with a microscope

CAD software SolidWorks was employed to design the simplified mechanical structure of the 3D accelerometer. Overall bounding size of the sensing structure was set to 1100 µm × 1100 µm × 100 µm in order to follow industrial accelerometer dimensions. The picture below provides full view of geometrical structure with the dimensions.

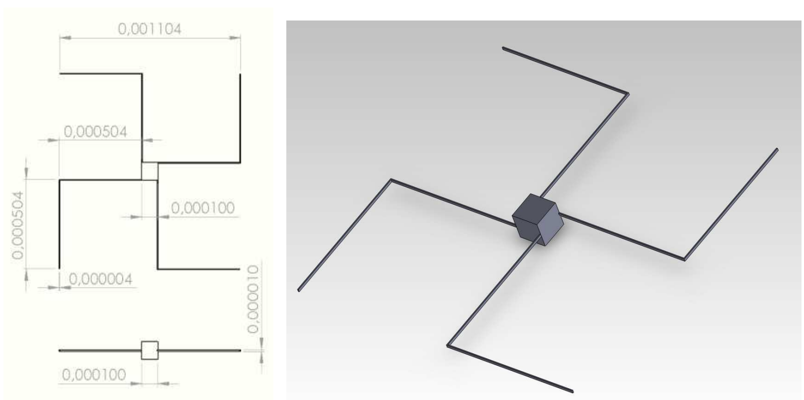
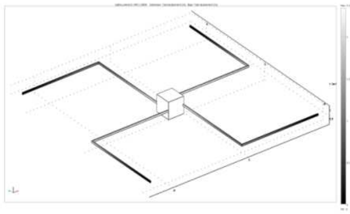


Fig. 3. Geometry of the designed accelerometer (values given in meters) and CAD model

It's worth stating that the design process was highly chained with FEM results that were extracted after importing designed CAD models to the COMSOL and modeling the experiment.

The structure presented is the result of multi-step process of *designing – modeling – adjusting* until the fit with experimental data was satisfying.

It is important to know that according to the device datasheet its data sampling frequency can be 40 Hz, 160 Hz, 640 Hz and 2560 Hz. According to digital signal processing theory Nyquist criterion states that the sampling frequency must be at least two times bigger than the bandwidth we want to measure. According to the datasheet accelerometers bandwidth is limited to ¼ of sampling frequency and can be 10 Hz, 40 Hz, 160 Hz and 640 Hz. That is why we must do Eigen frequency analysis in order to make sure that model resonances are far from the maximum bandwidth. Figure below presents the first five Eigen frequencies and their forms on the model.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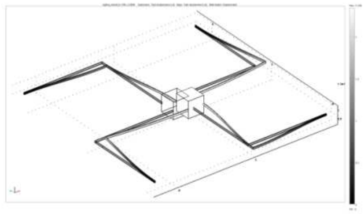
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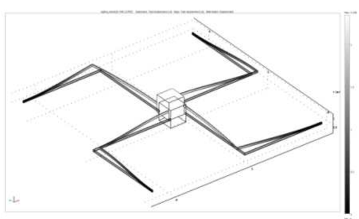
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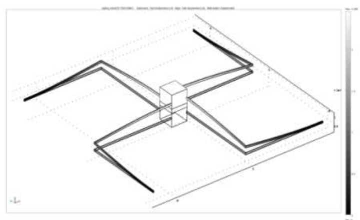
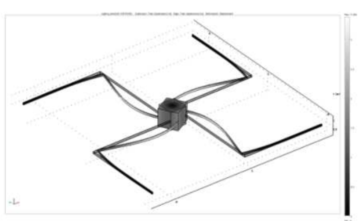

d)


e)

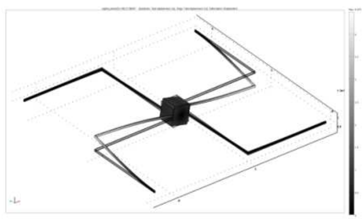
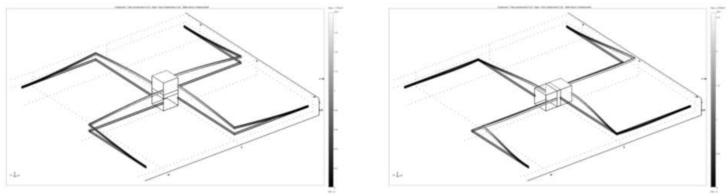

f)

Fig. 4. Steady state (a) and first five eigenfrequencies (b – 2451 Hz; c – 2451 Hz; d – 2919 Hz; e – 21079 Hz; f – 24213 Hz)

Given eigenfrequencies are only available with specific material properties that are associated with the model. „Legs“ (folded springs holding the proof mass) were chosen to be silicon (Young‘s modulus - 170 GPa, Poisson‘s ratio - 0.28, density - 2329 kg/m^3) and center mass was chosen to be copper (Young‘s modulus - 120 GPa, Poisson‘s ratio - 0.34, density - 8960 kg/m^3). Also, first eigenfrequency is over 2.4 kHz, which is almost four times bigger than the accelerometer’s bandwidth meaning the model should be adequate for modeling in the given bandwidth without manifestation of resonance effects.

Given material combination and geometrical shape guaranteed almost equal sensitivity on all three axes (it is very important as this is a 3D accelerometer). For example, when the acceleration of 60 m/s^2 was applied to the model on all three axis, resulted displacement in *z* axis was 1.79e-7 m and 2.55e-7 m in *x* and *y* axis. Both displacements are of the same order and difference is only 0.76e-7 m (42.5% of *z* displacement and 31.0% of *x* and *y* displacement).



a) b)

Fig. 5. Displacement in *z* and *x* axis when 60 m/s^2 acceleration is applied to the model

3. Experimental setup and validation

An experiment was conducted in order to evaluate how well the model conforms to the actual accelerometer. Experimental setup consists of waveform generator Tabor Electronics WW5064 producing 50 Ms/s (a), 50 W power amplifier LV102 from PFT (b), an electrodynamic shaker Robotron 11077 (c), our measuring prototype device (d) and Robotron 00032 with low frequency acceleration sensor KB12 with resolution of 300 mV per 1 m/s^2 (e).

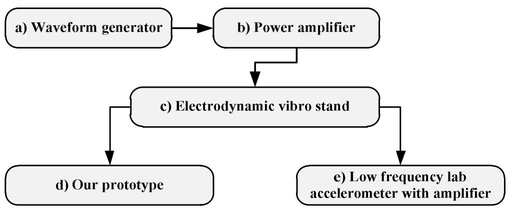


Fig. 6. Experimental setup scheme and data flow

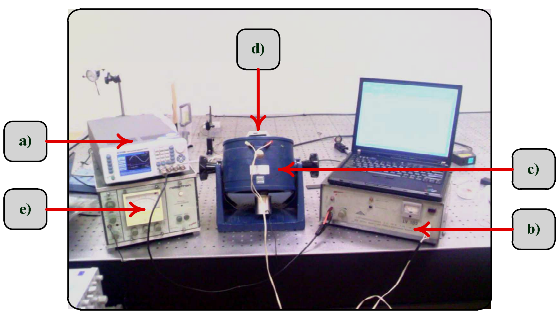


Fig. 7. Experimental setup for testing of MEMS accelerometer

Waveform generator (a) was set to generate 20 Hz sine wave. Resulting vibrations were captured both with our prototype (d) and low frequency acceleration sensor (e) (it indicated ~5.9 m/s^2). Captured data chart is given below. Because industrial accelerometers always include ***g*** in their measurements it is needed to filter it out. The process is not straightforward, but taking into account our experimental setup, it was possible. Detailed description of how this is achieved can be found in [11].

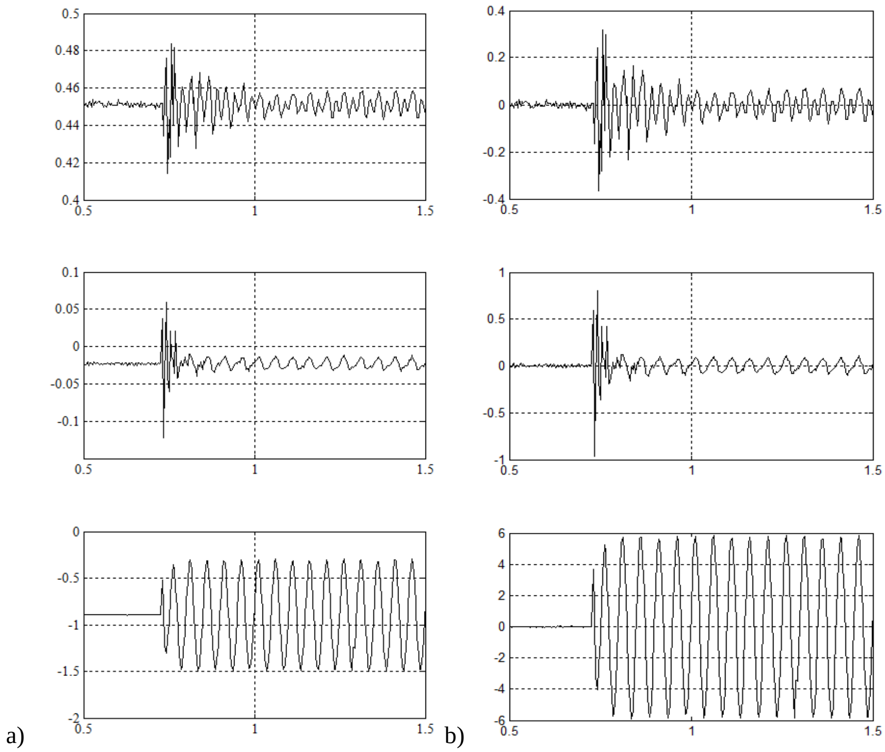


Fig. 8. a) *X*, *Y* and *Z* acceleration values captured by our prototype (d), b) vector ***g*** filtered from the measurements (notice amplitude changes while the character remains the same and the fact that amplitude only after filtering ***g*** is in line with generated amplitude which was 5,9 m/s^2)

Next step was to feed experimental data into the COMSOL in order to determine how well the model represents the actual data. A number of comparisons were made to define the "black-box" relationship between the measured and modeled data. It was observed that the increase in the acceleration both during experiment and in the model gives the same increase ratio towards what is measured when operating on the same frequency and direct relationship is defined only by the scale factor. For example, for 40 Hz the scale factor is 5274, and for 20 Hz the scale factor is 2107. The scale factor dependency from frequency, however, can be considered to be linear and does not pose any further restrictions.

4. Conclusions

Conducted work indicates that the constructed model of MEMS accelerometer together with the employed "black box" modeling approach can provide results equivalent to the actual device. The proposed modeling approach can speed up research process in the other fields by substituting resource-intensive experimental investigations in order to measure the accelerations. The proposed approach is also needed when it is necessary to analyze other data but the analysis is based on acceleration measurements by industrial sensors which always include ***g*** data in their output, which can be very frustrating as the filtering is not straightforward and sometimes even impossible.

The developed model was verified and was demonstrated to be in good agreement with the experimental data with less than 5% error when the base frequency is 20 Hz and the scale factor is 2107. Scale factor dependency on frequency was found to be linear and the linearity is valid at least in the frequency range from 10 Hz to 40 Hz.

Acknowledgements

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