Measurement 46 (2013) 3372–3388

Contents lists available at SciVerse ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

A simple analytical design approach based on computer aided analysis of bulk micromachined piezoresistive MEMS accelerometer for concrete SHM applications

S. Kavitha [a], R.Joseph Daniel [a,*], K. Sumangala [b]

[a] NPMaSS National MEMS Design Centre, Department of Instrumentation Engineering, Annamalai University, Annamalainagar, 608 002 Chidambaram, Tamil Nadu, India

[b] Department of Civil and Structural Engineering, Annamalai University, Annamalainagar, 608 002 Chidambaram, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 5 July 2012
Received in revised form 8 April 2013
Accepted 13 May 2013
Available online 1 June 2013

Keywords:
Structural health monitoring
MEMS
Piezoresistor
Single axis accelerometer
Cross axis sensitivity

ABSTRACT

Structural Health Monitoring (SHM) using non destructive testing generally involves measurement of shift in natural frequency of the monitored structure. This paper presents the simulation using CoventorWare MEMS design tool and analysis of three bulk micromachined piezoresistive MEMS accelerometers namely device A, B and C that are specifically intended for SHM applications. The devices A and B have been designed for the same natural frequency (100 Hz) but with different geometries. The device C has the maximum deflection sensitivity. The modal, piezoresistive and stress analyses show that beam length (L) must be less than the half side length (a) of the proof mass for achieving maximum voltage sensitivity. Thus Device-A has been selected for further analysis and the various performance factors for the Device-A have been obtained using simulation experiments and the results show that this device has excellent voltage sensitivity (3.56 mV/g/V), appreciably smaller cross axes sensitivities (32.8 μV/g/V), very low noise floor ($4.53\,\mu g/\sqrt{Hz}$) and high resolution (12.72 μg) compared with the already reported piezoresistive accelerometer designed for SHM applications and certain general purpose accelerometers available in the global market. The frequency analysis on two devices (Devices A and D) show that the resonant frequency of the sensor should be low for achieving maximum sensitivity and the damping factor (ξ) must be 0.7 for getting the maximum bandwidth over which the sensitivity remains constant (60 Hz). Finally, a standard analytical design procedure for the design of piezoresistive MEMS accelerometers has been developed and presented based on the various observations and results of this study. Further, the design approach for high packing density has also evolved.

1. Introduction

Structural Health Monitoring (SHM) involves determination of structural health status of the concrete structures and potentially predicts the damage of the structure. Conventionally wired sensors are installed to manually acquire the vibration data and natural frequency is obtained from the vibration data using FFT analysis. The shift in the natural frequency indicates damage and the magnitude of the frequency shift can be used to quantify the damage levels [1]. This kind of health monitoring is restricted by either the cost of permanently installed sensors or of manual collection of structural data using portable equipment. Further the traditional SHM systems are less effective with bulky sensors of poor capabilities and needs large electrical power. In the recent past, wireless sensors have been considered as a potential alternative to the

* Corresponding author. Tel.: +91 4144 239802 (R), mobile: +91 09445112208; fax: +91 4144 238080/238275.

E-mail addresses: kaviraj_2003@rediffmail.com (S. Kavitha), josuma.au@gmail.com (R. Daniel), josuma@rediffmail.com (K. Sumangala).

0263-2241/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.measurement.2013.05.013

wired sensors since it offers a more cost effective approach for capturing the vibration data from the structure in addition to high performance and less power for their operation.

Even among the wireless sensors being developed, the MEMS vibration sensors are beginning to play crucial role since the sensing and data transmission can be integrated as a single chip. Lynch et al. [2] has conducted extensive research on structural health monitoring integrating off-the-shelves accelerometers for sensing the vibration and wireless communication equipment for transmission of acquired vibration data to explore the benefits of wireless structural monitoring systems. To date, the standard practice in the SHM community has been to adapt commercial off-the-shelf (COTS) sensing technologies to the particular proof-of concept experiment at hand. In the recent past, COTS MEMS accelerometers have been used for SHM [2,6,7]. Micro electro-mechanical systems (MEMS) sensor is fabricated through micro-fabrication techniques. In MEMS sensors, electro-mechanical transduction mechanisms can be combined with micro-circuitry thereby forming a sensor. The sensor is now a miniaturized version of the traditional transduction element along with substantial circuitry for signal processing and computation [3,4]. Vogl et al. [3] reported the design and implementation of a novel wireless MEMS piezoresistive accelerometer sensor with a sensitivity of 0.19 mV/g/V for condition monitoring of AC motors. However, little attention has been paid to the development and implementation of MEMS sensors with the intent of specifically addressing issues related to concrete SHM.

The fundamental building blocks of structural monitoring systems are the sensing transducers. The quality and completeness of the data set collected for a given structure largely depends upon the capabilities and quality of the transducers used to record structural responses. Especially, the MEMS sensors used for concrete structure health monitoring should be of high sensitivity with ultra noise floor since most ambient vibrations in civil structures are characterized by low-amplitude accelerations. Secondly, the natural frequencies of civil structures are relatively small and hence the MEMS accelerometers designed for Civil SHM need not have larger band width. Ultimately, such sensors should be of low cost and consume low power. The authors of this present paper have made an attempt to design a piezoresistive MEMS accelerometer that satisfies the requirements of an accelerometer meant for concrete SHM applications. The results of such a design and the details of modal analysis on the designed accelerometer obtained through CoventorWare simulation tool are presented in this paper. The various analyses carried out on the sensors described in this paper have brought out a simple analytical design approach for the design of high performance piezoresistive MEMS accelerometers specially intended for SHM applications.

2. Proposed MEMS accelerometer (vibration sensor)

The cross sectional view of the MEMS accelerometer considered in this study for concrete SHM applications is shown in Fig. 1 and the top view of the MEMS accelerometer and view of the structure created for analysis by CoventerWare are presented in Fig. 2a and b respectively.

The seismic mass (m) is suspended by four symmetrical beams that determine the stiffness constant 'k'. This structure with the seismic mass (m) suspended by four symmetrical cantilever beams has been preferred in this study to reduce the cross-axis sensitivity. The other advantage is that this device can be realized using bulk micromachining and hence it paves way for using a large mass which is typically required for achieving higher sensitivity at low frequency vibrations. Four silicon piezoresistors strategically embedded on these four beams gives the vibration in terms of change in their resistances. The strategic locations at which these resistors are placed will be discussed in a later section. The four piezoresistors were organized in a Wheatstone bridge to sense single axis (z-direction) vibration. Considering the fact that this accelerometer is intended for concrete SHM applications, the device parameters are specified as given in Table 1.

3. Analytical model for natural frequency

The natural frequency of this accelerometer can be estimated from the well known equation

$$\omega_o = \sqrt{k/m} \tag{1}$$

where k is the effective stiffness of the beams and m is the mass of the effective seismic mass and the stiffness constant (k) of the present beam structure is obtained as

$$k = \frac{48EI}{L^3} \tag{2}$$

where E is the young's modulus of the beam material and the moment of inertia, I is thus

$$I = \frac{1}{12}bt^3 \tag{3}$$

where b and t are the breadth and thickness of a beam respectively. The existing analytical model for natural frequency of such an accelerometer [3,4] has been given as

$$f_o = \frac{1}{2\pi}\sqrt{\frac{4Ebt^3}{mL^3}} \tag{4}$$

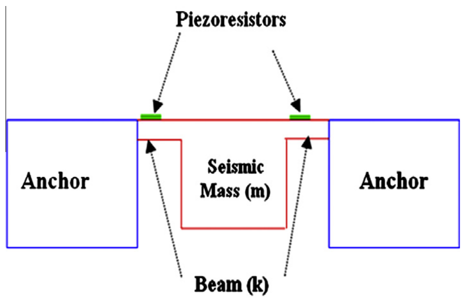

Fig. 1. Cross sectional view of the MEMS accelerometer.