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Novel piezoresistive high-g accelerometer geometry with very high sensitivity-bandwidth product

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ABSTRACT

This paper reports on a novel piezoresistive high-*g* accelerometer design, that partially overcomes a common drawback of shock sensor concepts, namely that their bandwidth, i.e. natural frequency, cannot be increased without sacrificing sensitivity. Its figure of merit (sensitivity multiplied by frequency squared) is about $5 \times 10^6\ \mathrm{m}^{-1}$. This is one order of magnitude higher than in existing designs in the literature or currently on the market. The increase is made possible by a design approach that focuses on displacements rather than stresses and the utilization of a spring–mass system related parameter called the "geometrical constant". The concept allows finding initial design geometries, which can be used for further optimization, and may be applied to sensors other than accelerometers. The accelerometer design presented in this paper is implemented as a MEMS device that features self-supporting piezoresistive elements. The first specimens have been characterized for shocks of up to $75{,}000 \times g$ in Hopkinson bar experiments and have sensitivities ranging from 0.035 to 0.23 $\mu\mathrm{V}/\mathrm{V}_{\mathrm{exc.}}/g$ and natural frequencies ranging from 2.7 to 3.7 MHz. Also, measurement data from a $200{,}000 \times g$ survivability check is presented.

1. Introduction

When designing accelerometers, bandwidth and sensitivity are often chosen as the defining performance characteristics and are therefore prioritized for optimization. However, since these two properties are interdependent, it is not possible to maximize both at the same time, making this optimization a non-trivial task. An early analysis has for example been conducted by Roylance and Angell [1] and Seidel and Csepregi [2] for capacitive and piezoresistive accelerometers. The interdependence is known to apply to micromachined accelerometers in general [3], but is especially important to high-*g* and shock accelerometers, which usually have rigorous requirements regarding their bandwidth and sensitivity [4,5]. The two properties are key to surviving and precisely measuring the rapidly changing signals that occur during shock events.

Two main aspects can be examined in order to optimize sensor performance: the measurement method and the accelerometer geometry. Both have been analyzed extensively. The former includes the development of new measurement methods, such as magnetic tunnel junctions [6] or silicon nanowires [7], in order to obtain very high gauge factors. The latter ranges from determining parameter sensitivities [8] and reducing package effects [9] to finding optimal dimensions [2,10] and – of course – testing different types of geometrical designs [11,12].

In this paper, a piezoresistive high-*g* accelerometer with very high sensitivity and bandwidth is presented that is based on an unconventional spring–mass geometry. The first part discusses the concept of the geometrical constant '*C*', which provides justification of said spring–mass system. It describes the mentioned frequency–sensitivity interdependence and gives insight into how accelerometer performance can be affected by choosing different initial spring–mass systems. The concept is extended by a displacement focused analysis of the most important design parameters of piezoresistive accelerometers and the first design attempt based upon this. Numerical methods are used to make a first estimate of effects not considered by the analysis and shortcomings of the approach are discussed. Initial experimental results with the first specimens are shown. Two commercial high-*g* accelerometers, the Endevco 7270 [13] and the PCB 3501 [14,15], are used as references and a performance comparison is conducted between the commercial sensors, literature designs and the new approach. The scope of generalizing the results of the approach will be discussed briefly.

2. Basic considerations

Most accelerometers are basically designed as linear spring–mass systems that are attached to a unit under test, i.e. an accelerated body, and hence experience a displacement of

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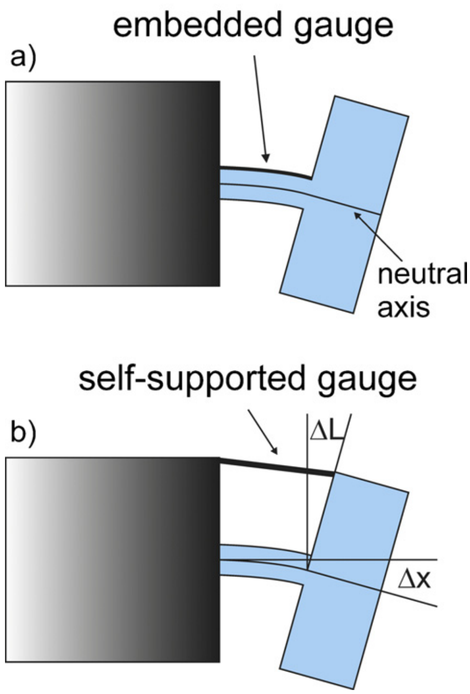

Fig. 1. (a) Typical design concept for a piezoresistive accelerometer with the strain gauge embedded into a flexural element. (b) Design concept with increased sensitivity due to self-supported strain gauges placed further away from the neutral axis.

their mass due to inertial forces [3]. The displacement can then be detected by various means,[1] resulting in the measurement signal. Sensitivity, which is defined as the measurement signal (usually a voltage) per unit acceleration, and bandwidth, which is given by the mechanical resonant frequency of the spring–mass system, are often prioritized in the design process. The two properties are related to each other by the following well-known equation [3,16]:

$$S\omega^2 = \phi_{\text{sensor}} \tag{1}$$

Here ω denotes the (lowest) resonant frequency of the spring–mass system, S denotes sensitivity and ϕ_{sensor} is a design constant that depends on the measurement method and the geometry of the system. Obviously, increasing sensitivity and bandwidth simultaneously is only possible by maximizing ϕ_{sensor}, making this constant a figure of merit. It has been used as an optimization goal in various designs (see for example [16] or [17]). Also, if the measurement method is identical, which is the case for the piezoresistive sensors discussed in this paper, this figure of merit makes geometries intended for different measurement ranges, i.e. varying resonant frequencies and sensitivities, comparable.

In many piezoresistive accelerometer designs, the strain gauges are embedded into a flexural component of the sensor's spring mass system (see schematic example in Fig. 1a) and the sensitivity is increased by maximizing the stress at the location of the gauges [10]. Other designs obtain higher sensitivities by using self-supporting elements (as shown in Fig. 1b) that are further away from the neutral axis and thus have a better strain per displacement ratio ($\propto \Delta L/\Delta x$) [12,16]. The idea of both design variants is to maximize the strain energy in the piezoresistive elements. In contrast to this, an approach focusing on displacement rather than stress is presented in this paper. It leads to a new initial geometry that is implemented as a self-supporting gauge design.

3. Geometrical constant of continuous oscillatory systems

The basic consideration needed for the displacement focused analysis of the figure of merit of piezoresistive accelerometers, is the interdependency of the displacement of a spring–mass system under acceleration load and its first resonant frequency. The interdependency is described by a dimensionless constant 'C', called geometrical constant in the following. This is well known and was first discussed by Jones [18,19] for elastic plates, before Sundararajan [20] and later Bert and Stephen [21,22] provided derivations and further examples.[2] Hoffmann and Wertheimer [23] analyzed tapered beams. However, to the authors' knowledge, the implications of the geometrical constant have not been explicitly used in an accelerometer design process yet.

For a single-degree-of-freedom oscillatory system, the resonant frequency ω_0 and the static displacement Δx per unit acceleration a can be related to each other by the simple equation:

$$\frac{\Delta x}{a}{\omega_0}^2 = 1 \tag{2}$$

For continuous systems, e.g. plates or beams, a similar equation can be formulated:

$$\frac{\Delta x_{\max}}{a}{\omega_1}^2 = C \tag{3}$$

Here, ω_1 is the first eigenfrequency of the system, $\Delta x_{\max}$ is the displacement at the point of maximum deflection of the system, when a static acceleration load a, e.g. dead weight, is applied. C is the previously mentioned dimensionless geometrical constant.

An important implication of C being dimensionless is that any given spring–mass system can be scaled in size without changing the value of its geometrical constant. This means, once an advantageous geometry has been developed, it can in principle be scaled to have the desired bandwidth, while having optimal sensitivity (or vice versa). Obviously, this method has limits in design processes where manufacturing constraints or size specifications need to be met.

Since most accelerometers contain continuous spring–mass systems, formula (3) is fundamental to optimizing bandwidth, which is given by ω_1, and sensitivity, which is related to $\Delta x_{\max}/a$, simultaneously. By improving the geometrical constant, it is possible to increase both quantities. Typical values for C range[3] from 1 to 3 [21], which means performance variations of up to 200% can be potentially be realized in different geometries.

4. Calculation of the geometrical constant

The geometrical constant of a system can be calculated by determining its static deflection curve and the first eigenfrequency analytically, experimentally or numerically. If determined analytically, C can be optimized accordingly. However, for complex geometries, analytic solutions usually do not exist, rendering experimental or numerical parameter studies the method of choice. Though this may be successful, it does not provide insight on why certain geometries can be beneficial for optimizing C. In order to develop a general understanding of the magnitude of the geometrical constant for different geometries, it is helpful to consider the

[1] Different readout mechanisms may include piezoresistive and piezoelectric effects, capacitive measurements and magnetic methods.

[2] In all cited references the equation is shown in slightly dissimilar forms.
[3] No theoretical restriction on the range of values is known.