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Short communication

A new bi-axial cantilever beam design for biomechanics force measurements ☆

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ABSTRACT

The demand for measuring forces exerted by animals during locomotion has increased dramatically as biomechanists strive to understand and implement biomechanical control strategies. In particular, multi-axial force transducers are often required to capture animal limb coordination patterns. Most existing force transducers employ strain gages arranged in a Wheatstone bridge on a cantilever beam. Bi-axial measurements require duplicating this arrangement in the transverse direction. In this paper, we reveal a method to embed a Wheatstone bridge inside another to allow bi-axial measurements without additional strain gages or additional second beams. This hybrid configuration resolves two force components from a single bridge circuit and simplifies fabrication for the simultaneous assessment of normal and transverse loads. This design can be implemented with two-dimensional fabrication techniques and can even be used to modify a common full bridge cantilever force transducer. As a demonstration of the new design, we built a simple beam which achieved bi-axial sensing capability that outperformed a conventional half-bridge-per-axis bi-axial strain gage design. We have used this design to measure the ground reaction forces of a crawling caterpillar and a caterpillar-mimicking soft robot. The simplicity and increased sensitivity of this method could facilitate bi-axial force measurements for experimental biologists.

1. Introduction

Force measurements in biomechanics often require creative and specialized methods. For example, to measure tendon force, a metal buckle has to be implanted around the tendon (Biewener et al., 1988) and to measure joint contact forces, a force transducer has to fit around a joint (Westerhoff et al., 2009). Most applications require developing custom-made transducers for specific anatomical constraints, degrees of freedom (Dai et al., 2011), ergonomics (Isaza et al., 2009) and sensitivity requirements (Reinhardt et al., 2009). Strain gages bonded to doubly supported or cantilever beams are the basis of most force transducers used to estimate deflecting forces ranging from millinewtons to several newtons (Bartsch et al., 2007; Zumwalt et al., 2006). For the sub-millinewton range, there are various microelectromechanical devices (Park et al., 2007; Reinhardt et al., 2009) and optics based systems (Garcia-Webb et al., 2007) that also use cantilever beams as the sensing mechanism. In this paper, we present a simple manipulation of strain gage circuits which allows biaxial sensing capability better than that of the equivalent conventional design.

2. Methods

Strain gages operate under the linearly elastic condition with the change of resistance (ΔR) proportional to the strain ε:

$$\frac{\Delta R}{R_n} = G_f \varepsilon \tag{1}$$

where R_n is the nominal gage resistance and G_f is the "gage factor". As a strain gage undergoes stretching or compression, its electric resistance increases or decreases respectively, which we can measure using a "Wheatstone bridge" circuit. In the classical half-bridge configuration (Fig. 1A), matched strain gages $R1$ and $R2$ are in series with a constant excitation voltage V_{ex}. If we bond the gages on the opposite sides of a cantilever beam (as shown), then a vertical load $\mathbf{F_Y}$ (red arrow) at the beam tip produces tension in $R1$ and compression in $R2$. These opposing deformations change resistance in the strain gages and lead to a measurable voltage difference V_1 which reverses its sign with loading in the opposite direction. An alternate half-bridge works in the same way with the strain gages in parallel (Fig. 1B). A full Wheatstone bridge configuration employs two pairs of gages as shown (Fig. 1C). The same vertical load $\mathbf{F_Y}$ (red arrow) now stretches $R1$ and $R4$ while compressing $R2$ and $R3$. This produces a V_1 signal twice

☆The work presented here has been conducted under the supervision of Prof. Trimmer as part of my Ph.D. thesis. Therefore it should be attributed to Department of Biology, Tufts University, despite my current postdoctoral affiliation.

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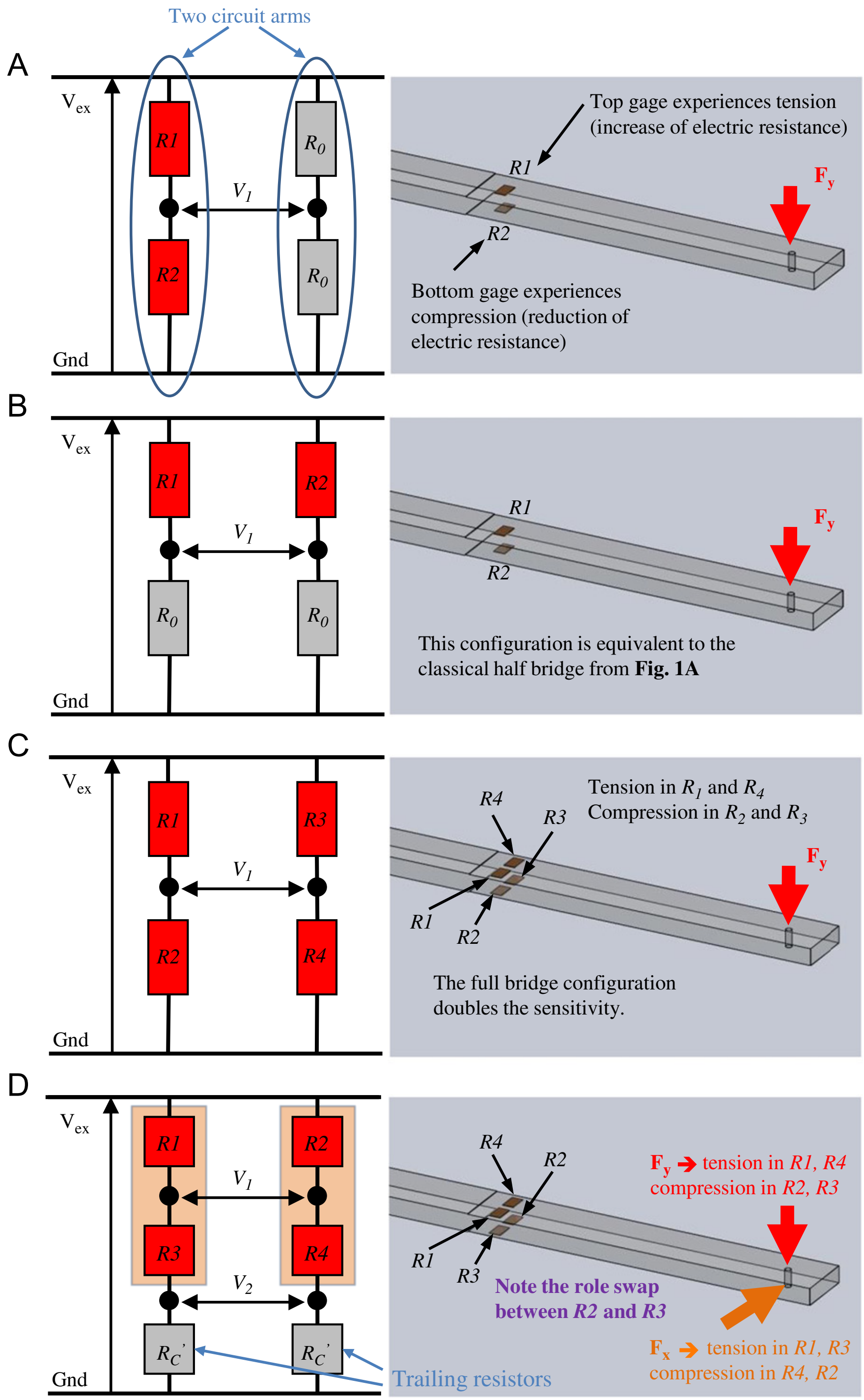

Fig. 1. (A) The classical Wheatstone half-bridge strain gage circuit consists of two voltage divider arms. One arm has two strain gages in series (red rectangles). Under vertical loading (red arrow), a cantilever beam undergoes tension on the top surface and compression on the underside. By installing the two strain gages (e.g. *R*1 and *R*2) on the opposite sides, one can quantify beam loading from the V_1 signal. (B) An equivalent alternate half-bridge configuration is shown. (C) The full Wheatstone bridge incorporates four strain gages and therefore doubles the sensitivity of a cantilever force beam. Under the same vertical load, the strain gages *R*1 and *R*4 increase while the gages *R*2 and *R*3 decrease, causing a V_1 signal again. (D) A hybrid-bridge circuit embeds a full bridge setup within a half-bridge configuration for bi-axial sensing. Signal $\boldsymbol{V_1}$ reflects the resistance difference due to vertical loading $\mathbf{F_Y}$ (red) with gage *R*1 to *R*4 acting as a full bridge (similar to panel **C**). Signal V_2 represents horizontal loading $\mathbf{F_X}$ (orange) using gage *R*1–*R*3 and gage *R*2–*R*4 as a half bridge (comparable to panel B). In addition to swapping the wiring sequence of *R*2 and *R*3, this new design requires only adding a pair of trailing resistors R_c and R_c'. The result is a biaxial sensing configuration with a one-way induced crosstalk.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

that of a half-bridge arrangement. This configuration is commonly used in precision laboratory transducers (*e.g.*, Grass Products Group, West Warwick, RI).

Here, we propose a new design that enables a full bridge to operate inside a half bridge for bi-axial sensing. To begin, we add a pair of matched trailing resistors R_C and R_C' after the full bridge (Fig. 1D), creating two additional voltage nodes. Then we swap the wiring sequence of *R*2 and *R*3 (Fig. 1D). These two changes allow the four strain gages to act as a full Wheatstone bridge inside a collective half bridge. As the cantilever deflects downward upon vertical load, $\mathbf{F_Y}$, gages *R*1 and *R*4 increase while gages *R*2 and *R*3 decrease. The V_1 signal represents the vertical load just as in Fig. 1(**C**). As we apply a load $\mathbf{F_X}$ (orange arrow) in the horizontal direction, the gages *R*1 and *R*3 are stretched while the gages *R*4 and *R*2 compress. This leads to another voltage difference V_2. In effect, we can treat