Characterizing an elastomeric strain sensor at large strains and strain rates

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***Abstract*—Soft sensors are a necessary part of developing agile soft robots, but have not been adequately characterized at high strains and strain rates. Liquid-metal-in-elastomer sensors exhibit nonlinear hysteresis that has yet to be characterized or quantified. Preliminary experiments point to this hysteresis and suggest the need for systematic study of dynamics of soft-material robotic devices. Examining the high strain response of a strain sensor at 1.0 and 4.8 Hz we find the sensor signal expresses a large increase in hysteresis, from 0.696% to 55.8%, but only a modest increase in the stress response hysteresis from 7.69% to 29.3%. Accurately identifying and characterizing the nonlinear dynamics of soft materials will enable better soft sensors and more agile soft robots.**

I. INTRODUCTION

Making robots softer will make them resistant to everyday contact and better at matching the compliance of biological tissue [1]. In addition to these gains, robots made from elastomers can exhibit large deformations [2]. The biological examples that serve as inspiration for deformable compliant robots, such as squid and octopus, are also astoundingly agile. Agility can be characterized by ”a rapid whole-body movement with change of velocity or direction in response to a stimulus”. Defined thus, agility can be broken into three characteristics: (i) whole-body coordination, (ii) high mechanical power output, and (iii) high speed sensing of stimuli. All three characteristics are ultimately necessary for agile soft robots. Here we provide a framework for assessing the third point, high speed sensing with soft sensors.

Soft sensors have been made from a variety of extensible conductors [3, 4] and have demonstrated sensing in various modes [5]. Though sensors have previously been stretched to five times their initial lengths before failure [6], generally they have been tested at strain rates less than 100 $\%/s$ and oscillatory frequencies less than 1 Hz. Using sensors for soft wearable robots demonstrated a need for biomechanically relevant strain rates, above 300 $\%/s$, and frequencies, above 3 Hz. If soft sensors can be used for accurate stimulus sensing at such strains and strain rates then we will be able to achieve reliable wearable sensing and will be able to fulfill one characteristic of soft agile robots.

Here we introduce an experimental method to characterize an elastomeric strain sensor at high strains and strain rates. We use a simple strain sensor and an experimental setup based on traditional materials testing, see Fig. 1.

II. METHODOLOGY

The strain sensor design and fabrication is based on previous demonstrations of liquid-metal-in-elastomer sensors [7]. The sensing element is 6 cm long with a strain-gauge pattern of microchannels positioned mid-plane within the thickness of the sensor, see Fig. 1A. The experimental setup uses a materials tester as a rigid platform and to capture forces and sensor signals at 1000 Hz. A backlight and high speed camera are used to capture sensor extension information at 600 Hz, see captured video stills in Fig. 2. Actuation of the sensor extension is achieved using a simple pulley system and human-input. The use of human actuation is a stop-gap solution for the broader practical need for high extension and high speed materials testers.

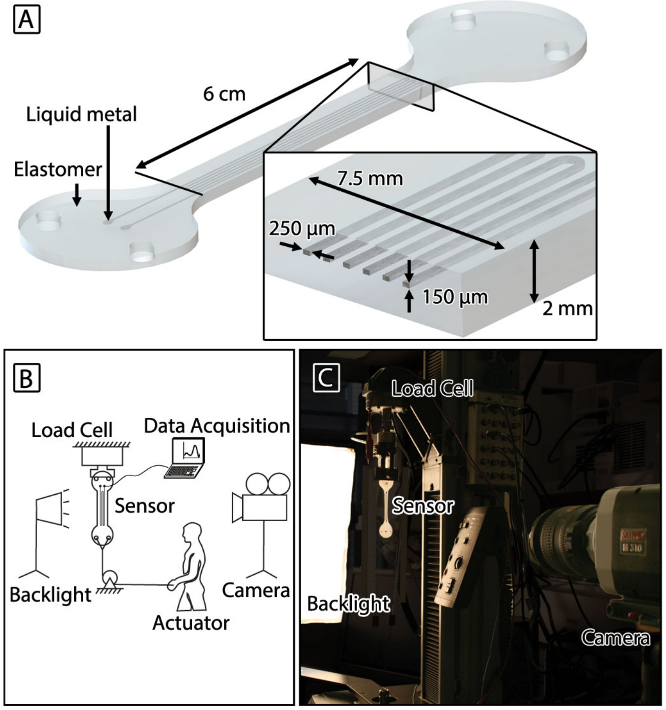

Fig. 1. Rendering of the strain sensor with inset depicting relevant dimensions of the sensor and microchannels, (A). Schematic, (B), and photograph, (C), of the experimental setup.

III. RESULTS

In interpreting the results, we characterized several parameters: engineering strain, engineering stress, stretch ratio, signal ratio, elastic modulus, and hysteresis. Engineering strain is defined as $e = (L - L_0)/L_0$, where L_0 is the unstretched sensor length and L is the stretched length. Engineering stress is defined as $s = F/A_0$, where F is the applied force measured at the load cell and A_0 is the undeformed sensor

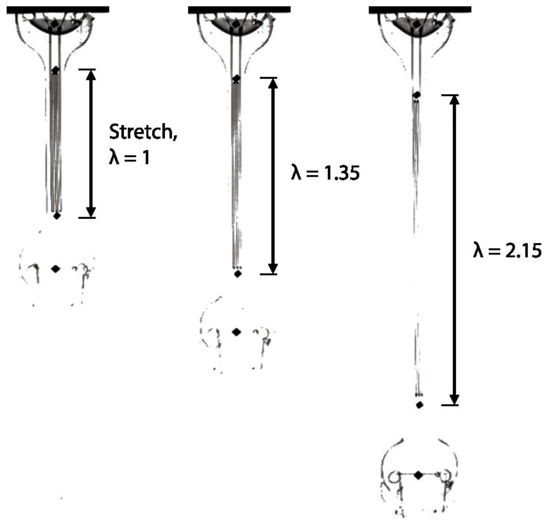

Fig. 2. Three video stills from the high speed camera. Sensor strains are measured with opaque marks placed at the ends of the length of sensing microchannels.

cross section. Stretch ratio is defined as the ratio of stretched, L, to unstretched length, L_0, as $\lambda = L/L_0$. The stretch ratio has historically been used instead of engineering strain when describing materials that can stretch many times their initial length, such as elastomers, and so we will use stretch in our analysis. Note that the stretch ratio can be mathematically expressed in terms of engineering strain as $\lambda = e + 1$. We consider the sensor response in terms of its signal ratio, $SR = R/R_0$ where R is the stretched sensor resistance, R_0 is the unstretched resistance. The elastic modulus is defined as the ratio of stress to strain, $E = s/e$, and is also called the Young's modulus when, as in our case, the loading is uniaxial tension. Hysteresis is a slightly more complex consideration.

Hysteresis is the dependence of the system output on the history of system inputs. We define a simple measure of hysteresis as the range of system output between loading and unloading as seen at the midpoint of ranges of input. In our experiment the system input is the applied axial stretch ratio and the system output is either sensor signal ratio or engineering stress. We mathematically express signal hysteresis, H_{SR}, as

$$H_{SR} = \left| \frac{SR_{unload}(\lambda_{mid}) - SR_{load}(\lambda_{mid})}{SR_{max} - SR_{min}} \right|, \tag{1}$$

where SR_{max} and SR_{min} are the maximum and minimum observed signal ratios, and $\lambda_{mid} = (\lambda_{max} - \lambda_{min})/2$, where λ_{max} and λ_{min} are the maximum and minimum observed stretch ratios. The stress hysteresis, H_s, is similarly defined as,

$$H_s = \left| \frac{s_{unload}(\lambda_{mid}) - s_{load}(\lambda_{mid})}{s_{max} - s_{min}} \right|. \tag{2}$$

When the sensor is loaded at an oscillatory frequency of 1.0 Hz it expresses very low hysteresis of 0.696%, see gray line in Fig. 3A. When the loading frequency increases to 4.8 Hz, the hysteresis increases to 55.8%, see black line in Fig. 3A. The stress hysteresis also increases with increasing loading frequency, from 7.69% to 29.3%, see Fig. 3.

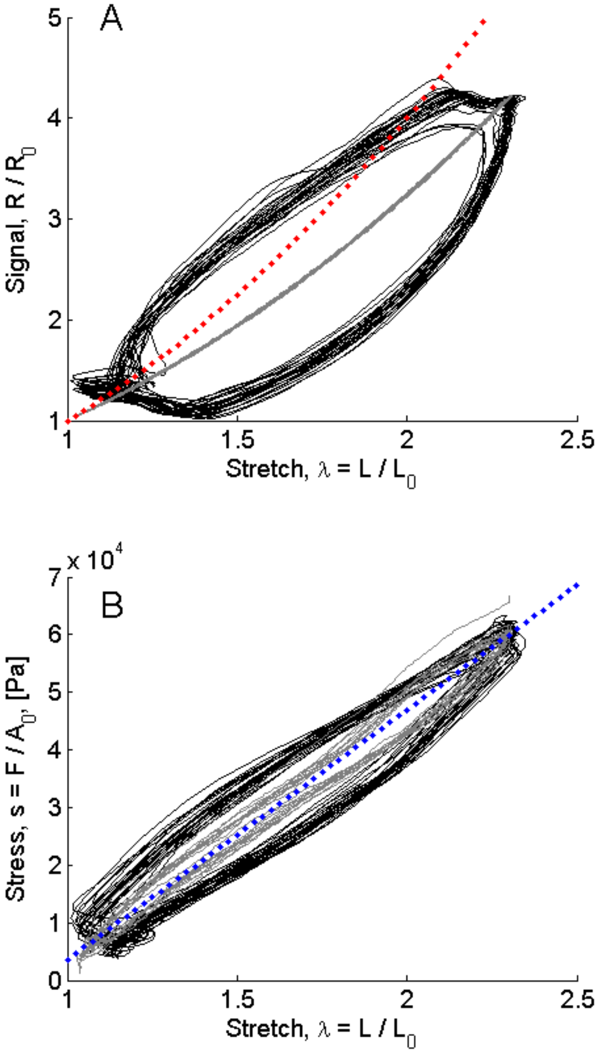

Fig. 3. Sensor behaviors characterized at oscillatory loading frequencies of 1.0 Hz in gray and 4.8 Hz in black. Sensor signal has a large hysteretic response at high loading rates as seen in the difference of the thin grey line and broad loop-like black line, (A). The ideal elastic conductor response, $R/R_0 \propto \lambda^2$, is plotted as a red dashed line in (A). The stress response expresses a smaller apparent dependence to increasing loading rate, seen as similarly broad loops in (B). The linear fit to the stress response gives an elastic modulus of 43.4 kPa, seen as a dashed blue line in (B).

IV. DISCUSSION

The results of our analysis clearly show a distinct relationship between the sensor signal and loading frequency, and thus strain rate. Interestingly, the sensor signal seems more sensitive to loading rate than sensor stress is to the loading rate. We interpret this difference in sensitivity as the relative change in hysteresis, which can be seen via a cursory visual examination of the loop-like plots in Fig 3. Specifically, the sensor signal output for a 1.0 Hz loading input appears to have almost no difference in its loading and unloading responses, so it appears as a thin line, plotted in grey in Fig. 3A. Increasing the loading input to 4.8 Hz leads to a vastly different loading and unloading signal response, as seen in the broad loop-like plot of the black line in Fig. 3A. If we instead look at the stress response, the change in behavior is much more modest from 1.0 Hz to 4.8 Hz, seen in Fig. 3B.

Ignoring dynamics for a moment, idealized sensor signal can be described as the deformation of the microchannels according to a rate-independent equation $R/R_0 \propto \lambda^2$, plotted as a dotted red-line on Fig. 3A. At low frequency loading, our sensor signal does not fit this idealized signal response, indicating room for improving our sensor sensitivity.

We can also identify our sensor's elastic modulus by applying a linear fitting to the stress response plot, seen as the dashed blue line in Fig. 3B. The slope of this linear fitting gives an elastic modulus of E = 43.4 kPa.

V. CONCLUSION

The current experiment succeeds in highlighting the drastic stretch rate dependence of liquid-metal-in-elastomer sensors. The distinct behavior of liquid-metal-in-elastomer indicates a need for systematic characterization under dynamic loading conditions. The non-linear dynamics of soft materials have already proven crucial for creating reservoir computing systems [8], but the material characterization and selection has not yet been emphasized. To adequately asses the dynamic behavior of soft sensor in particular and soft materials in general, future work will have to borrow from the analysis of biomaterials and viscoelastic fluids [9]. Applying large amplitude oscillatory strains to biomaterials fluids using rheometric techniques can reveal the fluids' nonlinear response. Similarly, engineering materials such as elastomers reveal their nonlinear viscoelastic behavior only under large stretches and high frequency oscillatory loading conditions. By using the techniques of the study of biomaterials, it will be possible to better quantify the materials used in soft robotics research and systematically design soft-material robots.

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