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Geometry-Based Model for U-Shaped Strain Gauges on Medical Needles

Pierre-Loup Schaefer¹, Grégory Chagnon¹ and Alexandre Moreau-Gaudry¹

Abstract—The knowledge of needle location during insertions is essential for the success of interventional radiology procedures. As the needle is susceptible to undergo deformations during its insertion into tissues, several methods have been proposed to monitor the needle deformed shape. Thus, instrumented needles with U-shaped strain gauges are currently being developed to reconstruct the shape of the needle from gauge acquisitions. These acquisitions are used in combination with gauge model to obtain estimate of the strain of the needle. The current modeling is limited as it does not consider the geometry of the gauge. This paper introduces a more complete model for U-shaped strain gauge which, on the difference of the current model, takes into account the width of the gauge. Thus, the impact of width modeling on the strain estimate can be measured and used to improve strain estimation accuracy. Results with real characteristics of instrumented needle devices show that the differences of strain estimate are around few percents. Finally, by taking into account the width and the length of the gauge our model includes the effects of the gauge size on the strain estimation and makes the miniaturization of the gauge less necessary.

I. INTRODUCTION

Needles insertions are common procedures carried out during interventional radiology surgeries. During these insertions, the needle can be subject to deformation due to its interaction with the tissues in the patient body. The deformations can result in a loss of accuracy of the needle location which might affect the success of the surgical procedure. Different technical solutions have been proposed in order to know the deformed shape of the needle. The physician can then use medical imaging, such as echography, x-ray or CT imaging to acquire images surrounding the insertion area and visualize the deformed needle shape. A recent technique, proposed to calculate the deformed shape of the needle, involves the use of strain measures acquired from strain sensors on the surface of the needle. Different kinds of strain sensors can be used such as Fiber Bragg gratings [1], [4], [5], [7] or strain gauges as in the work of Bonvilain *et al.* [2] and Hammond *et al.* [3].

In the case of strain gauge technology, the U-shaped gauges are printed [3] or micro-etched [2] parallel to the needle in order to measure the axial strain on the surface, as illustrated in Fig. 1. As the needle undergoes deformations, the variation of the length of the gauge causes a change of its resistance. Thus, the strain $\varepsilon_{\text{gauge}}$ indicated by a gauge of initial resistance R_{gauge} and resistance change ΔR_{gauge} can be obtained using the relation:

$$\varepsilon_{\text{gauge}} = \frac{\Delta R_{\text{gauge}}}{R_{\text{gauge}} \times GF} \quad (1)$$

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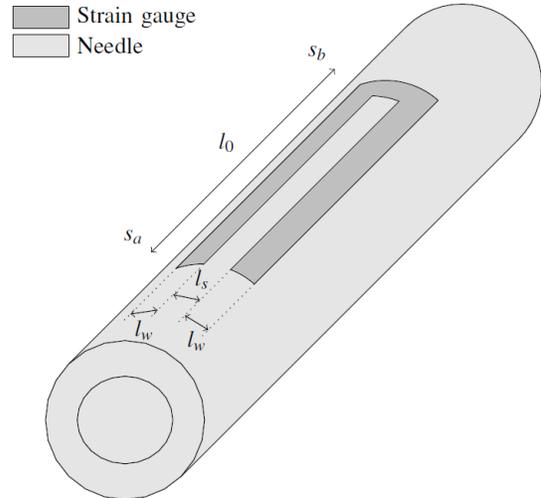


Fig. 1: Needle with a U-shaped strain gauge attached to its surface parallel to the needle length. The gauge is located between endpoints s_a and s_b and has an initial length of $l_0 = s_b - s_a$. The trace separation of the gauge is l_s and the trace width is l_w .

The term GF is the gauge factor and depends on the material characteristics of the gauge. According to the size of the gauge, hypothesis can be made on the dimensions to be considered. Thus, the length of the gauge can be taken into account [3] or not [2], depending on whether it is negligible compared to the length of the needle. The width of the gauge, however, is not taken into consideration in the work of Bonvilain *et al.* [2] and Hammond *et al.* [3].

This paper presents a model for U-shaped strain gauges which takes into account the incurred width of the gauge on the needle surface. Relations are established between the strain calculated from the gauge and the axial strain at the surface of the needle at the gauge location. Needle axial strain expressions calculated with and without the proposed model are compared and instrumented numerical characteristics from the works of Bonvilain *et al.* and Hammond *et al.* are used to quantify the impact of strain gauge width consideration on needle axial strain estimation.

A brief review of the literature is proposed in Section II. The model proposed in this paper is presented in Section III with the geometrical modeling of the strain gauge and the establishment of the strain calculated from the gauge in terms of axial strain of the needle. The results of this new model are compared with current results in Section IV and are discussed in Section V. Finally, conclusions on the presented model are summarized in Section VI.

II. PRIOR WORKS

The Infinitesimal Width gauge model (IW) denotes the modeling where the width of the gauge, characterized by the trace separation and the trace width, is ignored, such as in Bonvilain *et al.* and Hammond *et al.* In that case, the strain indicated by a gauge is assumed to be equal to the length variation of the gauge divided by its initial length. For a gauge located between endpoints s_a and s_b whose initial length is $l_0 = s_b - s_a$, as shown in Fig. 1, this gives the following relationship [3]:

$$\epsilon_{\text{gauge}} = \frac{\Delta l}{l_0} \quad (2)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \epsilon(s) ds \quad (3)$$

where ϵ is the axial strain at the surface of the needle.

III. FINITE WIDTH GAUGE MODEL

This section proposes a geometrical modeling of a U-shaped strain gauge bonded on a needle parallel to its length taking into account the width of the gauge. The geometrical characteristics of the model are defined from the cross sections of the needle with the U-shaped strain gauge, as illustrated in Fig. 2. The outer radius of the needle is denoted

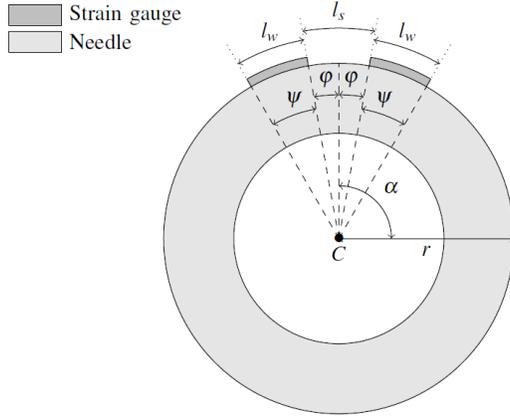


Fig. 2: Section of the needle with the U-shaped strain gauge. The center of the needle cross section is denoted C . The outer radius of the needle is denoted r . The location angle of the gauge α is measured from the center of symmetry of the gauge. The variables associated with the gauge are the trace separation l_s defined by the semi-angle ϕ and the trace width l_w defined by the angle ψ . The gauge angle range is $2(\phi + \psi)$.

r . The gauge is located at the angle α . The trace separation of the strain gauge is defined by its arc l_s and its associated semi-angle ϕ . The trace width is defined by its arc l_w and its associated angle ψ . The angles ϕ and ψ are determined by the following relationships:

$$\phi = \frac{l_s}{2r}, \quad \psi = \frac{l_w}{r} \quad (4)$$

We called this model Finite Width gauge model (FW) as the width of the gauge is taken into account. The values of the Finite Width gauge model parameters for the needles and strain gauges used by Bonvilain *et al.* and Hammond *et al.* are presented in Table I.

Under the hypothesis of linear bending deformation, the axial strain at the surface of the needle $\epsilon(s, \alpha)$ located at length s and angle α can be expressed with the curvature $\kappa(s)$ and the direction of bending $\theta(s)$:

$$\epsilon(s, \alpha) = r\kappa(s)\cos(\theta(s) - \alpha) \quad (5)$$

Equation (5) shows that ϵ varies depending on the angle α . This means that the axial strain on the circumference of a cross-section is not constant where the needle is deformed. According to Fig. 2 the strain gauge covers an angle range of $2(\phi + \psi)$. Thus, the axial strain of the surface on which the gauge is located is not constant during deformations. The problem of the strain gauge response on a non-uniform strain field was addressed by Schajer [6]. In his work, Schajer presents ϵ_{gauge} the strain indicated by a strain gauge grid as the average of the axial strain field on each of the grid lines of the strain gauge. Thus, for a strain gauge with n grid lines of respective area $\mathcal{A}_{\text{grid}_i}$ we have:

$$\epsilon_{\text{gauge}} = \frac{1}{n} \sum_{i=1}^n \frac{1}{\mathcal{A}_{\text{grid}_i}} \iint_{\text{grid}_i} \epsilon dS \quad (6)$$

As a U-shaped gauge is a gauge grid composed of 2 grid lines (the junction between them is not taken into account), the relation (6) using the FW model becomes:

$$\epsilon_{\text{gauge}} = \frac{1}{2} \times \frac{1}{l_0} \int_{s_a}^{s_b} \frac{1}{l_w} \left(\int_{\alpha-\phi-\psi}^{\alpha-\phi} \epsilon(s, \phi) r d\phi + \int_{\alpha+\phi}^{\alpha+\phi+\psi} \epsilon(s, \phi) r d\phi \right) ds \quad (7)$$

The complete calculation of (7) is presented in Fig. 3 for convenience. Finally, the expression of the strain indicated by the gauge ϵ_{gauge} with the FW model is:

$$\epsilon_{\text{gauge}} = F(\phi, \psi) \times \frac{1}{l_0} \int_{s_a}^{s_b} \epsilon(s) ds \quad (17)$$

$$\text{where } F(\phi, \psi) = \cos\left(\phi + \frac{\psi}{2}\right) \text{sinc}\left(\frac{\psi}{2}\right) \quad (18)$$

IV. STRAIN ESTIMATE COMPARISON

The expressions of ϵ_{gauge} in (3) and (17) are directly proportional, with the function $F(\phi, \psi)$ defined in (18) as the coefficient of proportionality.¹ The estimates of the axial strain ϵ with the IW and FW models are denoted respectively $[\epsilon]_{IW}$ and $[\epsilon]_{FW}$. From relations (3) and (17) it results that:

$$[\epsilon]_{IW} = F(\phi, \psi)[\epsilon]_{FW} \quad (19)$$

Equation (19) shows that the axial strain estimate with the IW model is equal to the axial strain estimate with the

¹If $\phi \rightarrow 0$ and $\psi \rightarrow 0$ then the width of the gauge becomes infinitesimal and $F(\phi, \psi) \rightarrow 1$. As a consequence, (3) and (17) are identical and the FW model is equivalent to the IW model in this case.

$$\varepsilon_{\text{gauge}} = \frac{1}{2} \times \frac{1}{l_0} \int_{s_a}^{s_b} \frac{1}{l_w} \left(\int_{\alpha-\varphi-\psi}^{\alpha-\varphi} \varepsilon(s, \phi) r d\phi + \int_{\alpha+\varphi}^{\alpha+\varphi+\psi} \varepsilon(s, \phi) r d\phi \right) ds \quad (8)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \frac{1}{2\psi} \left(\int_{\alpha-\varphi-\psi}^{\alpha-\varphi} \varepsilon(s, \phi) d\phi + \int_{\alpha+\varphi}^{\alpha+\varphi+\psi} \varepsilon(s, \phi) d\phi \right) ds \quad (9)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \frac{r\kappa(s)}{2\psi} \left(\int_{\alpha-\varphi-\psi}^{\alpha-\varphi} \cos(\theta(s) - \phi) d\phi + \int_{\alpha+\varphi}^{\alpha+\varphi+\psi} \cos(\theta(s) - \phi) d\phi \right) ds \quad (10)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \frac{r\kappa(s)}{2\psi} \left([\sin(\phi - \theta(s))]_{\alpha-\varphi-\psi}^{\alpha-\varphi} + [\sin(\phi - \theta(s))]_{\alpha+\varphi}^{\alpha+\varphi+\psi} \right) ds \quad (11)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \frac{r\kappa(s)}{2\psi} (\sin(\alpha - \varphi - \theta(s)) - \sin(\alpha - \varphi - \psi - \theta(s)) + \sin(\alpha + \varphi + \psi - \theta(s)) - \sin(\alpha + \varphi - \theta(s))) ds \quad (12)$$

$$= \frac{1}{l_0} \int_{s_a}^{s_b} \frac{r\kappa(s)}{2\psi} (-2 \cos(\theta(s) - \alpha) \sin(\varphi) + 2 \cos(\theta(s) - \alpha) \sin(\varphi + \psi)) ds \quad (13)$$

$$= \left(\frac{\sin(\varphi + \psi) - \sin(\varphi)}{\psi} \right) \frac{1}{l_0} \int_{s_a}^{s_b} r\kappa(s) \cos(\theta(s) - \alpha) ds \quad (14)$$

$$= \left(\frac{2 \cos(\varphi + \frac{\psi}{2}) \sin(\frac{\psi}{2})}{\psi} \right) \frac{1}{l_0} \int_{s_a}^{s_b} \varepsilon(s) ds \quad (15)$$

$$= \cos\left(\varphi + \frac{\psi}{2}\right) \text{sinc}\left(\frac{\psi}{2}\right) \times \frac{1}{l_0} \int_{s_a}^{s_b} \varepsilon(s) ds \quad (16)$$

Fig. 3: Expression of strain response $\varepsilon_{\text{gauge}}$ in terms of axial strain ε for a strain gauge located between positions s_a and s_b on the needle at angle α .

FW model multiplied by the coefficient $F(\varphi, \psi)$. Therefore, the difference between the axial strain estimates for IW and FW models depends exclusively of the gauge width parameters and is independant of the deformation. As the strain gauges modeled have an angle range smaller than half of the circumference of the needle, the following inequalities for F can be established:

$$0 < F(\varphi, \psi) < 1 \quad (20)$$

which associated with (19) gives:

$$|[\varepsilon]_{IW}| < |[\varepsilon]_{FW}| \quad (21)$$

Thus, the amplitude of the strain estimate is inferior when the width of the U-shaped gauge is not considered. The relative difference of strain estimation between the FW and IW models expressed in percent, denoted η , is given as:

$$\eta(\varphi, \psi) = \frac{[\varepsilon]_{FW} - [\varepsilon]_{IW}}{[\varepsilon]_{FW}} \times 100\% \quad (22)$$

$$= (1 - F(\varphi, \psi)) \times 100\% \quad (23)$$

The values of the function F and the relative difference of strain estimation η for the needle instrumentations used by Bonvilain *et al.* and Hammond *et al.* are presented in Table I and Table II. These results show that the relative difference of the strain between the IW and FW model is 0.4 % for Bonvilain *et al.* and 3.0 % for Hammond *et al.*

Figure 4 presents the plot of $\eta(\varphi, \psi)$ according to the previously defined trace separation semi-angle φ and trace width angle ψ .

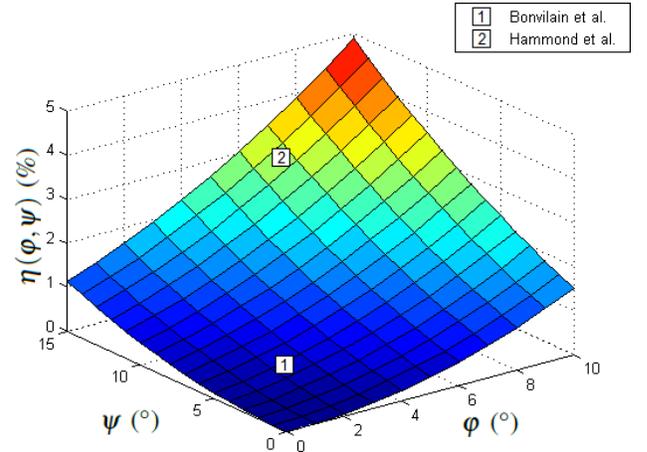


Fig. 4: Relative difference of strain estimation $\eta(\varphi, \psi)$ between FW and IW gauge models according to angles φ and ψ . The angles φ and ψ are expressed in degrees. The values of η for Bonvilain *et al.* and Hammond *et al.* are plotted on the function graph of η .

V. DISCUSSION

This paper proposed a new model for U-shaped strain gauge attached on a needle which takes into account the width of the gauge and the non-uniform aspect of the strain field of the surface where the needle is located. By including these specificities, the model presented is more complete than the model of Bonvilain *et al.* and Hammond *et al.* The terms resulting of these additional geometrical and physical hypothesis are present in the expression of the strain

TABLE I: Needle and U-shaped strain gauge characteristics for instrumented needles devices of the literature.

Author	Needle radius r	Trace separation l_s	Trace width l_w	Trace separation semi-angle ϕ	Trace width angle ψ	$F(\phi, \psi)$
Bonvilain et al.	600 μm	50 μm	50 μm	2.39 $^\circ$	4.77 $^\circ$	0.996
Hammond et al.	635 μm	150 μm	150 μm	6.77 $^\circ$	13.53 $^\circ$	0.970

TABLE II: Effect of the gauge width consideration on strain estimation. Numerical values of the relative strain difference of strain estimation η are presented for instrumented needles devices of the literature.

Article	Gauge angle range	Relative difference of strain estimation $\eta(\phi, \psi)$
Bonvilain et al.	14 $^\circ$	0.4 %
Hammond et al.	40 $^\circ$	3.0 %

indicated by the gauge. It is then believed that this expression coming from a more complete model increases the accuracy of the needle axial strain estimate.

Results show that when the gauge width is not taken into account the larger the strain gauge is, the larger the amplitude of the axial strain is underestimated. Thus, for the needle instrumented in Bonvilain *et al.* where the range angle of the strain gauge is 14 $^\circ$ the relative difference of strain is only of 0.4 % whereas it reaches 3.0% in the case of Hammond *et al.* where the range angle is 40 $^\circ$.

Therefore, the proposed model allows to estimate the impact of width modeling by quantifying the difference in strain estimation. It can then be used to correct the strain estimate value and then improve the accuracy. Moreover, as our model offers the possibility to take into account the length and the width of the gauge, the miniaturization of the gauge becomes less necessary as it is possible to correct the bias induced by both of these dimensions with our model.

VI. CONCLUSION

This paper introduced a new model for U-shaped gauge taking the width of the gauge into account. It is assumed that improving the strain gauge model is improving as well the accuracy of the strain estimation. Thus, the difference of strain estimation with the new model has been quantified and strain correction can be applied on instrumented needle from their characteristics.

VII. ACKNOWLEDGMENTS

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