Effect of IDT position parameters on SAW yarn tension sensor sensitivity

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Abstract
In this paper, the effect of the interdigital transducer (IDT) position parameters on the surface acoustic wave (SAW) yarn tension sensor sensitivity is investigated. The stress–strain characteristic of substrate was studied by the combination of finite element simulation and regression analysis method. According to this characteristic, the function relationship between the SAW yarn tension sensor sensitivity and the IDT position parameters was built using the regression analysis method. The monotonicity of the regression function was also given. On this basis, a novel sensitivity optimal scheme was proposed and solved by the quadratic programming method. Its solution demonstrates that the optimum sensitivity can be obtained when the IDT is 8.9 mm to the left side of the substrate and the IDT is 0.3 mm to the top edge of the substrate within a domain of the IDT position parameters. The SAW yarn tension sensor with corresponding IDT position parameters was fabricated to validate the correctness of the sensitivity optimal scheme. The measured results indicate that the SAW yarn tension sensor sensitivity can reach 813.69 Hz/g, which confirms that the novel scheme is effective.

Keywords
IDT position parameters, yarn tension sensor, regression function, sensitivity optimal, quadratic programming

Introduction
SAW sensors, which represent the merging of acoustic theory research, piezoelectric material achievements and electronic science and technology progress, display advantages such as high precision, simple structure, small size, easy integration, passivity, and good stability.1–4 Because SAW sensors are particularly sensitive to the environmental changes on the substrate surface, they are widely used in the detection of physical,5 chemical,6 and biological7 data. With the continuous increase in SAW sensor applications, the study of the aspects of theoretical enrichment,8,9 working mechanism innovation,10 simulation model improvement,11 and working performance development12 for SAW sensors has become a hot research topic.

Yarn tension is often the key factor in the process of yarn production.12–15 If too much force is supplied, the yarn will be snapped. If there is not enough force, the yarn will become loose and curled. This will result in lower quality of yarn and less production.16,17 Yarn tension is affected by so many elements that it is difficult to measure it. As a result, the accurate measurement of yarn tension is an urgent problem.18 The SAW yarn tension sensor was proposed19 for this purpose. It exhibits advantages such as low cost, reproducibility, and anti-interference, especially compared with traditional yarn tension sensors.

The yarn tension sensor sensitivity is of great significance to yarn production and quality.20 As a result, the influence of the IDT position parameters on SAW yarn tension sensor sensitivity was investigated. After researching the substrate stress–strain characteristic, the regression function between sensor sensitivity and the IDT position parameters was established. Based on analyzing the function monotonicity, a novel scheme that can improve its sensitivity is proposed by optimizing the placement of the IDT on substrate.

Design
Figure 1 shows the design diagram of the SAW yarn tension sensor. A, B, C, Y, and S are the metal pedestal, the quartz spacer, the substrate, the yarn guide ring, and the sound absorbing adhesive, respectively. A mixture of epoxy resin and curing agent is used to glue

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them together. Y1 is a part of the Y. Glue Y1 to the bottom surface of the substrate C. The length of Y1 is about 2 mm. Because its length is small and the finite element analysis results in this paper are mainly used for qualitative analysis, it is assumed that the force bearing point of the substrate is point P. Point P is located at the midpoint of line M18N18. The substrate length is $L = 17$ mm, width is $W = 5$ mm, and height is $H = 0.5$ mm. The spacer length is $L_s = 5$ mm, and width is $W_s = 5$ mm. The sensor is fabricated as a delay line oscillator. Its physical parameters are shown in Table 1.

When the yarn guide ring is applied to yarn tension $F$, it produces strain on the substrate. Substrate strain causes variations in the substrate mechanical and electrical properties. This changes the IDT intrinsic wavelength and SAW propagation speed on the substrate. Thus, the sensor output frequency $f$ can be written as:

$$f = f_0 + \Delta f$$  \hspace{1cm} (1)$$

where $f_0$ is the sensor center frequency, and $\Delta f$ is output frequency shift.

As shown in Figure 2, the electrode-overlap envelope of the input IDT is weighted. Dummy electrodes are used. The output IDT is the uniform transducer. The length of the area occupied by the input and output IDTs is $L_j = 6.8$ mm, and the width is $W_j = 2.4$ mm. The area of the IDTs is $D_j$ mm to the left side of the substrate, and $D_i$ mm to the top edge of the substrate. The plane $M_0M_{17}N_{17}N_0$ is the upper surface of the substrate.

There must be a sufficient number of data samples to build the function relationship between its sensitivity and the IDT position parameters. Too many data samples may also lead to overfitting. Meanwhile, the limitation of the sensor manufacturing conditions on the difference of IDT position parameters should be considered. So we use seven SAW yarn tension sensors, whose IDTs are placed at different positions on the substrate. The diameter of quartz wafer used in the factory is 2 inches (50.8 mm). To place eight sensor substrates or more during fabrication, the substrate size parameters cannot be much larger. Nor can the IDT position parameters. The IDT position parameters are also confined by the manufacture technology of cutting substrate. In addition, these parameters are usually selected at equal intervals. The proper design parameters of these sensors are shown in Table 2. Sensors S1–S6 are used to build the regression function and sensor S7 is used to validate the function.
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Substrate stress–strain characteristic

The strain, induced by loading $F$, is so small that we assume the substrate is elongated along the SAW propagation direction. The elongation of the substrate is $\Delta L$. The substrate strain can now be written as

$$e = \frac{\Delta L}{L}$$

The substrate strain will cause the change of the sensor output frequency, so equation (1) can be expressed as

$$f = f_0 + f_0 e^{(k' - 1)}$$

where $k'$ is material coefficient, and it is a constant. Compare equations (1) and (3), and it is found

$$\Delta f = f_0 e^{(k' - 1)}$$

The substrate strain will change linearly with yarn tension because piezoelectric crystal is elastomer. Thus, we have

$$e = e' F$$

where $e'$ is the substrate strain caused by unit tension, which is called substrate strain rate.

Substituting equation (5) into equation (4)

$$\Delta f = f_0 e^{(k' - 1)} F$$

In equation (6), the term $f_0 (k' - 1) e'$ determines its frequency variation caused by unit load. The SAW yarn tension sensor sensitivity is then defined as

$$\sigma = f_0 e^{(k' - 1)}$$

In equation (7), because $f_0$ and $k'$ are constants, the value of the term $e'$ will determine the sensor sensitivity. Substitute equation (7) into equation (6)

$$\Delta f = \sigma F$$

Equation (8) needs to be solved by least square estimation. Thus, it is converted to

$$\Delta f = a + b F + e$$

where $a$, $b$ are estimation coefficients, $e$ is random error, and $b$ should equal $\sigma$.

To analyze the stress–strain characteristic of substrate, the finite element model of the substrate stress–strain is simulated. The variable $e'$ can be gained from the ANSYS simulation result. The substrate, about 17 mm long, 5 mm wide and 0.5 mm high, is called J1. The ANSYS 13 was used to set up the stress–strain simulation model of J1 using element type SOLID185. The external load of the finite element model is defined as 1 g (unit tension $F = 1$), so the ANSYS simulation results are directly the substrate strain rate $e'$ according to equation (5). The metal film is not considered in the simulation model due to its thinness. The simulation result is shown in Figure 3.

We use line $M_0M_{17}$ as an example, as shown in Figure 2. The $M_{0}M_{17}$ line was divided by 17 1-mm segments. The 16 generated points are defined as points $M_1$-$M_{16}$. $M_0$ was defined as the origin, and $M_{0}M_{17}$ as

![Figure 3. Stress–strain simulation result of substrate J1.](image-url)
the x-axis. Therefore the x coordinate at point M₀ is 0, the x coordinate at point M₁ is 1, and so on. The parameter \( x \) is defined as the x-axis coordinate. According to the simulation results shown in Figure 3, the substrate strain rate of those points can be obtained by clicking General Postproc → List Results → Nodal Solution in the ANSYS GUI.

The simulation output data reveals that as these points on line \( M₀M₁₇ \) get further away from point \( M₀ \), the magnitude of strain displacement induced by unit tension at these points increases. Therefore, the parameter \( x \) is independent variable, and \( e₀ \) is dependent variable. Based on the causal relationship between the two, the substrate strain rate can be written as

\[
e₀ = k₀ + k₁D₁ + k₂D₂ + k₃D₃ + k₄D₄ + k₅D₅ + e \quad (10)
\]

where \( k₀, k₁, \ldots, k₅ \) are regression coefficients, and \( e \) is random error.

Based on the simulation output data, the regression coefficients in equation (10) are solved by the least square method.

Let \( n = 1 \), we have

\[
e₁ = -1472.32 + 442.58x \quad (11)
\]

If \( n = 2 \), it is obtained

\[
e₂ = -25.46 + 21.81x + 2.80x^2 \quad (12)
\]

Figure 4 shows the fitting curves and the data points when \( n = 1 \) and \( n = 2 \).

In Figure 4, it is clear that the blue curve fits data points better than the red curve. Therefore equation (12) should be selected to reflect their functional relationship. Moreover, equation (12) is a quadratic function, which implies that the function relationship between them is nonlinear. This indicates that the distribution of the substrate strain is not uniform in the direction of the acoustic propagation path. In conclusion, according to equation (6), it is certain that this will cause the difference change of the IDT acoustic synchronous frequency at a different x coordinate. Based on the above analysis, we conclude that the IDT position parameters will affect the SAW yarn tension sensor sensitivity.

**Function between sensor sensitivity and IDT position parameters**

As mentioned above, there should be a causal relationship between sensitivity and the IDT position parameters. This indicates that the parameter \( \sigma \) is explained variable, and the parameters \( D₁ \) and \( D₄ \) are explaining variables in the theory of multiple regression analysis. The multiple regression function between the two can be expressed as

\[
\sigma = k₀ + k₁D₁ + k₂D₂ + k₃D₃ + k₄D₄ + k₅D₅ + e \quad (13)
\]

where \( k₀, k₁, \ldots, k₅ \) are regression coefficients, and \( e \) is random error.

To build the model shown in equation (13), the data sample \( (\sigma_j, D₁_j, D₄_j, \ldots, n) \) should be given first. For this purpose, the output frequency shift of sensors S₁–S₇ is measured with yarn tension change using an Agilent E5061A network analyzer at 25°C. Their fabricated physical form is shown in Figure 5. The measured data are listed in Table 3.

To obtain equation (13), the sensitivity of sensors S₁–S₆ should be obtained first. According to Table 3, it is evident that the sensors with different placement of IDT show variations in output frequency change under the same yarn tension. This shows that the previous assumption is correct. It proves that there is a functional relationship between sensitivity \( \sigma \) and the IDT position parameters \( D₁ \) and \( D₄ \).

Using S₁ as an example, equation (9) is converted to

\[
\Delta f₁ = a₁ + b₁F \quad (14)
\]

Based on the data sample \( (\Delta f₁, F_j, j = 1, \ldots, n) \) of sensor S₁ shown in Table 3, the parameters of...
equation (14) can be solved by least square method. The solutions are

\[ a = -99.36 \]
\[ b = 668.65 \] (15)

Substitute the solutions into equation (14)

\[ \Delta f_1 = -99.36 + 668.65 F \] (16)

For \( \Delta f_1 \), its determination coefficient is

\[ R^2 = \frac{\sum_{i=1}^{11} (\Delta f'_i - \overline{\Delta f})^2}{\sum_{i=1}^{11} (\Delta f'_i - \overline{\Delta f})^2} = 0.9998 \] (17)

Equation (16) is the function between \( \Delta f_1 \) and \( F \). The decision coefficient is so close to 1 that equation (16) is considered to fit well. As shown in equation (16), the sensitivity of the sensor S1 is 668.65 Hz/g. Its fitting curve is shown in Figure 6, and the relative error is 2.9%.

In the same way, the sensitivity of the others can be derived. Their fitting curves are also shown in Figure 6. The calculated results are listed in Table 4.

The determination coefficients shown in Table 4 are close to 1, indicating that the data are reliable. Thus, the experimental data sample \(((\sigma_i, D_{li}, D_{ti}), i = 1, \ldots, 6)\) is acquired as shown in Table 4. The software tool MATLAB is used to solve the least square estimation of the parameters in equation (13). The solutions are \( k_0 = 640.87 \), \( k_1 = 29.86 \), \( k_2 = -44.29 \), \( k_3 = -0.97 \), \( k_4 = 2.99 \), and \( k_5 = -1.09 \). Those parameters are put in equation (13), which can be written as

\[ \sigma = 640.87 + 29.86D_{li} - 44.29D_{ti} - 0.97D_{li}^2 
+ 2.99D_{li}D_{ti} - 1.09D_{ti}^2 \] (18)

For parameter \( \sigma \), its \( R^2 \) is

\[ R^2 = \frac{\sum_{i=1}^{6} (\sigma'_i - \overline{\sigma})^2}{\sum_{i=1}^{6} (\sigma'_i - \overline{\sigma})^2} = 0.9998 \] (19)

The \( R^2 \) is close to 1, which indicates that equation (18) can appropriately reflect the effect of the IDT position parameters on the sensor sensitivity. Its fitting surface is shown in Figure 7.

However, the limitation of the substrate actual size and manufacture technology to the IDT position parameters also needs to be considered. The domain of definition for equation (18) should be

\[ 1.4 \leq D_{li} \leq 8.9 \]
\[ 0.3 \leq D_{ti} \leq 2.3 \] (20)

Sensor S7 is made to verify the functional relationship shown in equation (18). First, we obtain parameters \( D_{li} = 1.4 \) and \( D_{ti} = 2.3 \) of S7 from Table 2. Then, it is calculated that the estimated value \( \hat{\sigma} \) is 783.36 Hz/
g according to equation (18). Finally, the data sample \(((\Delta f_j, F_j), j = 1, \ldots, 11\) of sensor S7 shown in Table 3 is used to solve equation (9). It is obtained as
\[
\Delta f = -97.27 + 765.25F
\]

For \(\Delta f\), its determination coefficient is \(R^2 = 0.9998\). Its fitting curve is shown in Figure 6. The actual sensitivity is 765.25 Hz/g. The relative error of sensor S7 is 2.9%. It can be seen that the estimated value is almost equal to the measured value. For sensor S7, the relative error between its actual sensitivity and estimated sensitivity is
\[
\delta = \frac{783.36 - 765.25}{765.25} = 2.4\%\]

The value \(\delta\) is small, which demonstrates that the sensor sensitivity can be represented by the IDT position parameters. That is to say, the model shown in equation (18) can be used to express the functional relationship between parameter \(\sigma\) and parameters \(D_t\) and \(D_l\) with \(\{(D_t, D_l) | 1.4 \leq D_t \leq 8.9, 0.3 \leq D_l \leq 2.3\}\).

It is found that equation (18) can be set up based on the IDT position parameters and the sensors sensitivity using the regression analysis method. For the other SAW force sensors, if we had related parameters, we could build the regression function too. Therefore, it can be concluded that the novel scheme can be applicable to SAW sensors with the different types of substrate material.

**Effect of IDT position parameters on sensor sensitivity**

For equation (18), the partial derivative \(\sigma'\) is given
\[
\sigma' = \frac{\partial \sigma}{\partial D_t} = 29.86 - 1.94D_t + 2.99D_l
\]

It is calculated that the parameter \(\sigma'\) is greater than zero because of \(\{(D_t, D_l) | 1.4 \leq D_t \leq 8.9, 0.3 \leq D_l \leq 2.3\}\).

This illustrates that the parameter \(\sigma\) will monotonically increase with the parameter \(D_t\). Consequently, we can make \(D_t\) larger to obtain higher sensitivity within the interval \(\{(D_t, D_l) | 1.4 \leq D_t \leq 8.9, 0.3 \leq D_l \leq 2.3\}\).

Similarly, the partial derivative \(\sigma'\) is
\[
\sigma' = \frac{\partial \sigma}{\partial D_l} = -44.29 + 2.99D_l - 2.18D_t \tag{24}
\]

Since the value range of the parameters is \(\{(D_t, D_l) | 1.4 \leq D_t \leq 8.9, 0.3 \leq D_l \leq 2.3\}\), we can calculate that \(\sigma' < 0\). This shows the relationship between them is negative correlated. Then we put forward that the sensor sensitivity will increase with the parameter \(D_t\) decreasing.

**Sensitivity optimization induced by IDT position parameters**

Sensor sensitivity will vary with the change of the IDT position parameters. Therefore, sensitivity optimization was achieved by optimizing the IDT location parameters. The quadratic programming method was used to implement this scheme.

The function relationship between the dependent variable \(\sigma\) and the independent variables \(D_t\) and \(D_l\) is shown in equation (18). Parameter \(\sigma\) should be maximized, making it possible to gain optimization sensitivity. Hence, the objective function is given by
\[
\max \sigma = 640.87 + 29.86D_t - 44.29D_l - 0.97D_t^2 + 2.99D_lD_t - 1.09D_t^2 \tag{25}
\]

Due to the restrictions of substrate size and manufacturing technology, we choose equation (20) as the constraint condition.

The quadratic programming model shown in equations (25) and (20) is solved by Lingo software. The optimal solution is \(\sigma = 824.35\), where \(D_t = 8.9\) and \(D_l = 0.3\). This means the maximum sensor sensitivity 824.35 Hz/g could be obtained when the IDT is 8.9 mm to left side of the substrate and the IDT is 0.3 mm to top edge of the substrate.

Sensor S8 was fabricated to verify the correctness of our scheme. Its design parameters are \(L = 17, W = 5, H = 0.5, L_{s} = 5, W_{s} = 5, D_t = 8.9,\) and \(D_l = 0.3\). Its fabricated physical form is shown in Figure 8. In the same way, the fitting curve between \(\Delta f_s\) and \(F\) is shown in Figure 9. Its sensitivity is given by
\[
\Delta f_s = 139.18 + 813.69F \tag{26}
\]

The \(R^2\) of \(\Delta f_s\) is greater than 0.999, which proves that equation (26) fits the data well. Its measured sensitivity is 813.69 Hz/g, while the estimated value is 824.35 Hz/g. The difference is 10.66 Hz/g. Compared with the value 813.69 Hz/g, the difference is so small that the scheme can be considered effective. In addition, the sensitivity of sensor S8 is the largest of sensors S1-S8. Compared with the lowest sensitivity 582.75 Hz/
g (S6), this will improve sensitivity by 39%. This means that the scheme presented in this study can be used to improve sensor sensitivity by optimizing the IDT position parameters. In summary, the goal of obtaining greater sensitivity was achieved.

**Conclusion**

Through theoretical research and finite element simulation analysis, it is found that there is uneven distribution of the substrate strain rate in the direction of acoustic propagation path. Based on this conclusion, the regression function between SAW yarn tension sensor sensitivity and the IDT position parameters is established and validated. Using this model, the influence of the IDT position parameters on yarn tension sensor sensitivity was analyzed. The results suggest that if IDT is farther to the left side or closer to the top edge of the substrate, higher sensor sensitivity could be achieved. According to this regression function, the optimization of sensor sensitivity was achieved through a quadratic programming model. The results show that the maximum sensitivity of 813.69 Hz/g was realized through optimizing the IDT position parameters. The modeling of substrate stress-strain characteristic is a subject worthy of further research.

**Declaration of conflicting interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This article was supported by the Natural Science Foundation of Ningxia Province of China (Grant No.NZ1711, and No. 2020AAC02028), the National Natural Science Foundation of China (Grant No.61461003), the Scientific Research Project of North Minzu University(Grant No. 2020XYZJK01), the Ningxia Key Discipline Projects of “Computer Application Technology” (Grant No. PY1607) and Major Projects of North Minzu University in 2018 (Grant No. 31519040263).

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