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A Simple Multifunctional Method to Measure Direction, Obliquity and Torsion Angle

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Abstract

Direction, obliquity and torsion angle parameters are always used to describe the movement of a widely existing structure with a conjunction between two parts, likes robot arm, human extremity and so on. A simple multifunctional method is presented in this paper to estimate three angle parameters simultaneously without modifying the structure of measured object. The estimating of these parameters is transferred to calculate length changes of several lines on a flexible tube which is regarded as the main part of this method. By analysing its geometric structure and basing on three inductances caused by generatrix length changes, the functions of three angle parameters with variables L_1, L_2 and L_3 can be obtained. With these functions and the measured data of inductances, it can be proved that using this simple multifunctional method, direction, obliquity and torsion angle can be estimated in a fast, simultaneously, non-invasive and low cost way.

Keywords: multifunctional, robot arm, direction, obliquity, torsion

1 Introduction

Various methods with ability of measuring angle have been investigated by many research groups. Angle measurement is widely needed in many fields such as robot, architecture, navigation and so on [1] ~ [3]. Most of these methods are aiming to calculate only one angle parameters. If several angles need to be measured, a common method is to combine several sensors, which makes a complex structure. In this paper, the movement of a widely existing structure which has a conjunction between two moving parts, like robot arm, human extremity and so on is researched. The movement can commonly be described with three angle parameters, which are direction, obliquity and torsion angle. As a common sense, three sensors should be used when there are three different parameters to be measured which cause a complex structure and high cost, sometimes even need to change the structure of measured object itself. The method proposed in this paper, firstly, easily fits on and removes from measured object without destroy the object structure. Secondly, three output parameters can be measured simultaneously so that three angle parameters can be estimated with a very short time. Finally, the simple structure makes the cost lower than before techniques.

Different from the popular technique, in this paper, a multifunctional method is proposed. In a simple straightforward manner, a multifunctional sensor can be defined as a sensor having more than one sensing function. That is, the quantities measured affect more than one input of the single sensor. In the last decade, various kinds of multifunctional methods have been developed [4], [5]. Our proposed multifunctional method acts much like one sensor.

The schematic structure of our proposed multifunctional sensor is shown in Fig. 1, where X_1, X_2 and X_3 are inputs of the sensor, which are the direction, obliquity and torsion angle, respectively. The final value X_1', X_2' and X_3' indicate the estimating angle parameters and are calculated by the output Y_1, Y_2, Y_3 of the sensor.

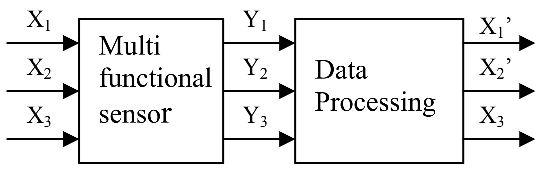


Figure 1: Measurement principle of a multifunctional sensor with three quantities.

2 Configuration and Principle

2.1 Working Principle

The main part of this method is a flexible tube, whose radius does not change with bending. As Fig. 2 shows, if the tube moves to different direction and obliquity, the generatrix lengths on tube surface change correspondingly. On the surface, three lines with 120° interval of each other are chosen for measuring. The coordinate system is shown in Fig. 2, which shows the principle of direction, obliquity and torsion angle, the symbol of which are ϕ, θ and ω respectively.

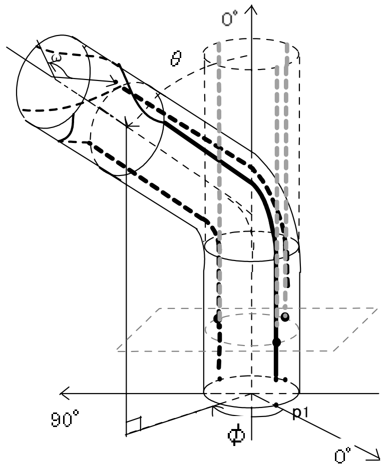


Figure 2: Principle of direction, obliquity and torsion angle

In order to estimate these angle parameters, the relationships of the length change of three lines and angle parameters need to be calculated. As shown in Fig. 3(a), the bending radiuses r_1, r_2, r_3 of three lines are different with the change of direction. The relationships are shown as below:

$$\begin{cases} r_1 = r - a \cdot \cos\phi \\ r_2 = r - a \cdot \cos(\phi + 120°) \\ r_3 = r - a \cdot \cos(\phi + 240°) \end{cases} \quad (1)$$

According to equation (1) and Fig. 3(b), the functions of length change of chosen lines d_1, d_2, d_3 with the variables of ϕ and θ can be deduced as below:

$$\begin{cases} d_1 = \theta \cdot (r - a \cdot \cos\phi) + d + d(\omega) \\ d_2 = \theta \cdot (r - a \cdot \cos(\phi + 120°)) + d + d(\omega) \\ d_3 = \theta \cdot (r - a \cdot \cos(\phi + 240°)) + d + d(\omega) \end{cases} \quad (2)$$

where d is the sum length of the parts with no bend acting on it. d(ω) is the length caused by torsion angle with the same affect on the three lines, the detail of which will be discussed later.

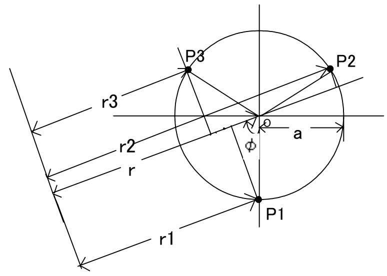
In order to get the generatrix length changes, principle of inductance is inducted into this method. As we know, the value of inductance of solenoid shape has a direct proportion with core length in the solenoid, the function of which is shown as below.

$$L = L_0 + \Delta L = L_0 + k \cdot l_c(H) \quad (3)$$

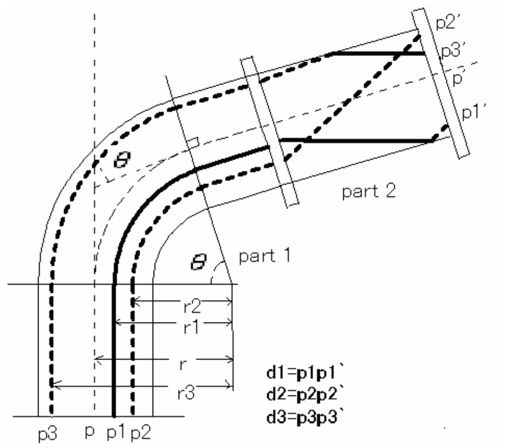
where l_c is core length in solenoid. L_0 is inductance measured without core in solenoid and k is a constant which is only related to the solenoid and material of iron core. Because l_c can be described by surface line d which changes with moving of the object. By equations (2) and (3), we can get:

$$\begin{cases} L_1 = f_1(\phi,\theta,\omega) \\ L_2 = f_2(\phi,\theta,\omega) \\ L_3 = f_3(\phi,\theta,\omega) \end{cases} \Rightarrow \begin{cases} \phi = g_1(L_1,L_2,L_3) \\ \theta = g_2(L_1,L_2,L_3) \\ \omega = g_3(L_1,L_2,L_3) \end{cases} \quad (4)$$

Each inductance is affected by three angle parameters instead of one. So we call this method multifunctional.



(a) Bending radiuses are different with direction change



(b) Generatrix change with different angle parameters

Figure 3: Geometrical analysis of working model

2.2 Configuration

Fig. 4 gives out the configuration of our proposed method for measuring angle parameters. The main part of this structure is a flexible tube which is fixed on the measured object. Three iron lines which are placed with 120° interval of each other on the tube surface are used as cores of three solenoids whose lengths in the solenoids change with the moving of measured object. In order to make lines move on the surface of tube, several small rings are used for restricting. As Fig. 3 shows, direction and obliquity act on part 1 simultaneously, while torsion angle acts on part 2. Although bending and twisting do not happen in the same part, they affect the core length simultaneously. Separating these two parts simplifies the structure of measuring system. These angles cause the length of iron lines in the solenoid different which make the inductance value change correspondingly.

Using LCR meter, we measure three inductances at different position as experiment data.

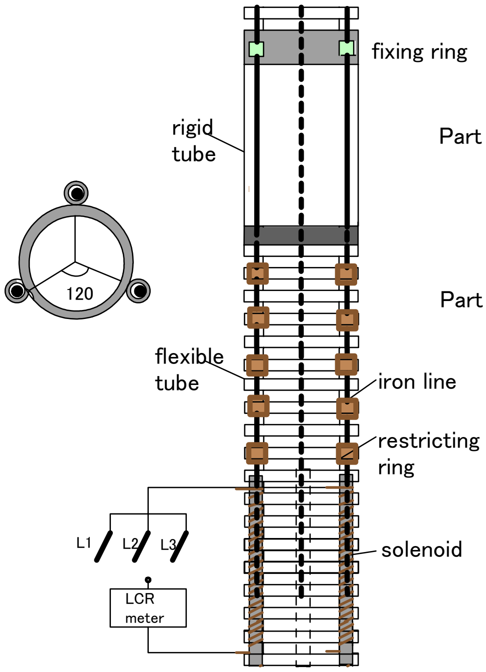


Figure 4: Working structure

2.3 Experiment Method

In order to prove the feasibility of this method and calculate the coefficients for estimating angle parameters, inductances at some positions need to be measured. As to three inductances, we measure at the points whose ϕ steps by 10° with changing from 0° to 360°, and for every ϕ, obliquity θ steps by 10°with changing from 0° to 60°. Consequently, we can get the data list as $L_x(\phi, \theta)$, where x=1,2,3; $\phi = m\cdot 10°$, m=0,1,…35; $\theta = n\cdot 10°$, n=0,1,…5. Basing on these data, coefficients for calculating angle parameters can be calculated.

In Fig. 3(b), we see torsion angle causes the same core length change of the three lines, which is independent of direction and obliquity. In order to obtain the function of torsion angle with three inductances, we measure inductance value at initial position with torsion angle changes from 0° to 180° with step about 30°.

3 Experiment Result and Data Processing

As shown in Fig. 3(b), we can express one of the core length l_{c1} as follows:

$$l_{c1} = d_1 - \theta\cdot(r - a\cdot\cos\phi) - d(\omega) \quad (5)$$

Using equations (3) and (5), equation (6) can be obtained as below:

$$L_1 = k\cdot\frac{\theta}{2\pi}\cdot 2\pi\cdot r_1 + L_0 + L(\omega)$$
$$= k\cdot a\cdot\theta\cdot\cos\phi - k\cdot\theta\cdot r + L_0 + L(\omega) \quad (6)$$

where k is a constant only depends on device itself. $L(\omega)$ is the inductance change which only relates to torsion angle, and be independent from direction and obliquity.

Because of the structure of measured object, the moving orbit of upper part is fixed with different obliquity. That means, bending radius r is the function of obliquity as variable.

$$r = g(\theta) \quad (7)$$

We suppose

$$f(\theta) = -k\cdot\theta\cdot g(\theta) + L_0 \quad (8)$$

Basing on the above analysis, we can get

$$\begin{cases} L_1 = k_0\cdot\theta\cdot\cos\phi + f(\theta) + L(\omega) \\ L_2 = k_0\cdot\theta\cdot\cos(\phi+120°) + f(\theta) + L(\omega) \\ L_3 = k_0\cdot\theta\cdot\cos(\phi+240°) + f(\theta) + L(\omega) \end{cases} \quad (9)$$

where, k_0, $f(\theta)$ and $L(\omega)$ can be estimated from our experiment data.

3.1 Estimating for Direction

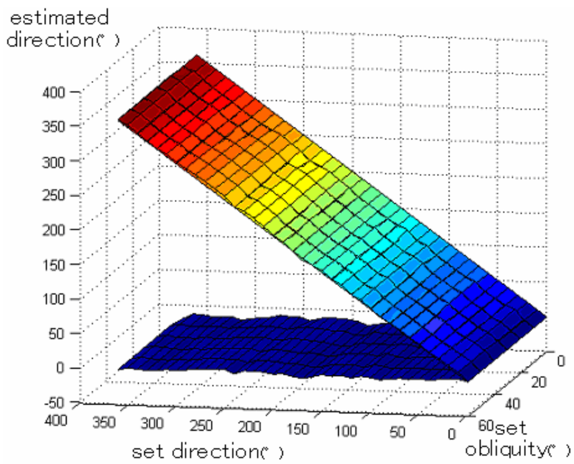


Figure 5: Calculation result of direction

Equation (10) can be obtained by (9) as

$$\frac{L_1 - L_2}{L_1 - L_3} = m = \frac{\cos\phi - \cos(\phi+120°)}{\cos\phi - \cos(\phi+240°)} \quad (10)$$

By calculating (10) inversely, direction ϕ can be estimated as equation (11) shows.

$$\phi = \tan^{-1}\left(\frac{\sqrt{3}\cdot(m-1)}{m+1}\right) + n\cdot\pi = \phi' + n\cdot\pi$$

$$\phi' = \tan^{-1}\left(\frac{\sqrt{3}\cdot(m-1)}{m+1}\right) \quad (11)$$

Using the relationship of three inductances, we can estimate ϕ as equation (12) shows.

$$\phi = \begin{cases} 120° & (L_1 = L_3, L_1 - L_2 < 0) \\ 240° & (L_1 = L_3, L_1 - L_2 > 0) \\ \phi' & (\phi' > 0, L_3 = \min(L_1, L_2, L_3)) \\ \phi' + \pi & (L_2 or L_3 = \max(L_1, L_2, L_3)) \\ \phi' + 2\pi & (\phi' < 0, L_2 = \min(L_1, L_2, L_3)) \end{cases} \quad (12)$$

Basing on our experiment data and using (12), the direction of every point can be calculated inversely. The result as shown in Fig. 5 indicates this method is possible to estimate direction. It can be known that the calculation of direction is independent to other angle parameters.

3.2 Estimating for Obliquity

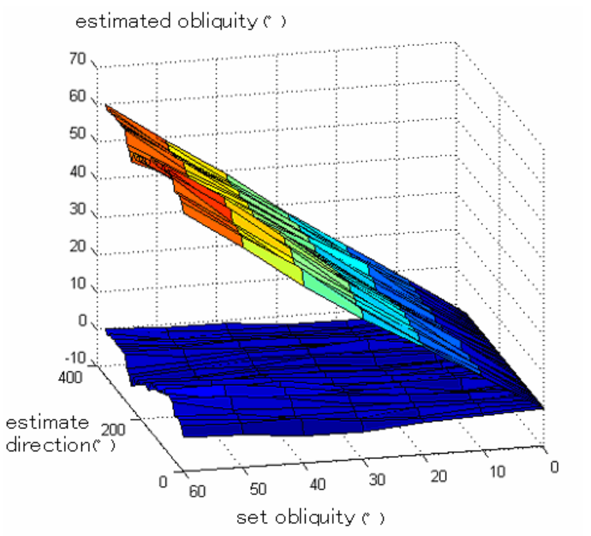


Figure 6: Calculation result of obliquity

After having estimated direction as shown above, obliquity calculating is possible using estimated direction and equation (9).

$$L_1 - L_2 = k_0 \cdot \theta \cdot [\cos\phi - \cos(\phi + 120°)] \quad (13)$$

In order to get the function to estimate θ, the coefficient k_0 must be estimated firstly basing on our experiment data. With ideal obliquity θ stepping by $10°$ with changing from $0°$ to $60°$, coefficient k_0 can be calculated as shown in equation (14).

$$k_0 = \frac{1}{2n}\cdot\left[\sum_n\left(\frac{L_1 - L_2}{\theta\cdot(\cos\phi - \cos(\phi+120°))}\right) + \sum_n\left(\frac{L_1 - L_3}{\theta(\cos\phi - \cos(\phi + 240°))}\right)\right] \quad (14)$$

where n is the number of points except for whose numerator and denominator are equal to zero. k_0 is an average value of its calculation at every measuring point and is calculated as 5.3388 by (14). With this value, θ can be obtained as

$$\theta = \frac{L_1 - L_2}{5.3388\cdot[\cos\phi - \cos(\phi+120°)]}(L_1 - L_2 \neq 0)$$

$$\theta = \frac{L_1 - L_3}{5.3388\cdot[\cos\phi - \cos(\phi+240°)]}(L_1 - L_2 = 0) \quad (15)$$

The estimated obliquity is shown in Fig. 6.

3.3 Estimating for torsion angle

Known from equation (9), torsion angle gives the same effect on all three inductances. When a torsion angle happens, the iron line moves in spiralled orbit on the surface of part 2, which causes a same change L(ω) of inductance as proved in Fig. 7. By equation (9), we can get

$$L(\omega) = L_1 - k_0 \cdot \theta \cdot \cos\phi - f(\theta) \quad (16)$$

where L(ω) is the inductance change caused by the core length change d(ω), which is inducted by orsion angle. We can get ω by calculating L(ω) inversely.

$$\omega = L^{-1}(\omega) \quad (17)$$

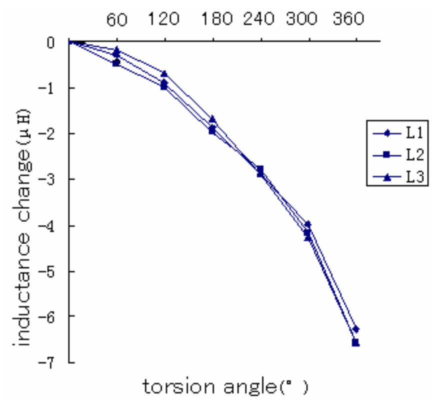


Figure 7: Twisting has the same effects on three inductances

In order to reconstruct equation (17), first the function of f(θ) need to be got. The generating of f(θ) comes from the length changing of bending radius with obliquity, as we have discussed before. Basing on the our experimented data without torsion angle what means L(ω)=0 at this situation and the estimated direction and obliquity, the function of f(θ) can be deduced by quadratic polynomial.

$$f(\theta) = 0.8112\theta^2 + 1.15\theta + 50.46 \quad (18)$$

Therefore, from (16) and (18), we can get

$$L(\omega) = L_1 - 5.3388 \cdot \theta \cdot \cos\phi - 0.8112\theta^2 - 1.15\theta - 50.46 \quad (19)$$

To get the function of ω with variable of L(ω), there are two methods can be used. One is using the geometry of spiral line. Here we reconstruct this function by experimental data. The inductance value measured at initial position with torsion angle changes from 0° to 180° with step about 30° .

The measured data are shown in Fig. 8. Using quadratic polynomial, the function can be obtained as

$$\omega = -0.06386 L(\omega)^2 - 0.8675 L(\omega) + 0.1721 \quad (20)$$

where L(ω) has obtained from (19).

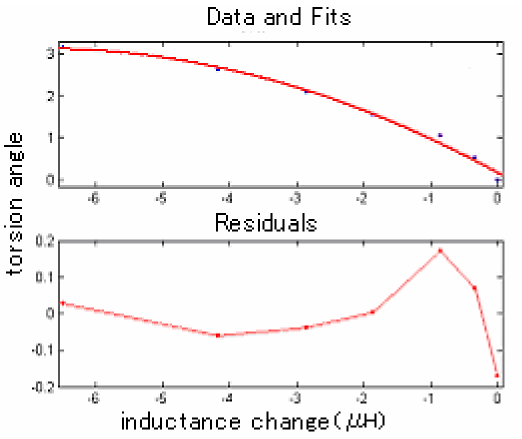


Figure 8: Fitting of torsion angle and inductance change

4 Discussion

The response of the measuring system to different angle parameters is satisfactory. Although this experiment was acted without real measured object in it, the activity should be the same. In order to be used on measured object, only adding some rings for fixing will be sufficient, which will be shown in future research. Besides the simple measuring, this structure also shows a possibility of non-invasive measuring.

The small rings to restrict the moving of line and the solenoid have a little space around lines which cause the error happened. But this can be solved by precise structure. In this experiment, inductance was used to measure length change which needs the solenoid length should be longer than the maximum change of generatrix. In order to make the measuring system more sophisticate, different shape of solenoid such as spiral can be chosen. The data processing of this paper are mainly basing on the value of L_1. For more accuracy, every one of these three inductances can be chosen as calculating basement at different situation.

5 Conclusion

A simple multifunctional method for estimating direction, obliquity, and torsion angle parameters which are always used to describe the movement of a common structure with a conjunction between two parts is proposed in this research. The measuring structure basing on our proposed method permits a simultaneous and non-invasive measurement. By analysing the generatrix length change of a flexible tube which was regarded as the main part of this method, equations (12), (15) and (19) which are the functions of three angle parameters with variables L_1, L_2 and L_3 can be obtained.

Firstly, L_1, L_2 and L_3 which indicate the length change of generatrix are measured simultaneously. Secondly, the differences of L1-L2 and L1-L3 are used to calculate direction. Then obliquity is calculated basing on the previous result. Finally, torsion angle is obtained using the estimating direction and obliquity parameters. As a result, the proposed multifunctional method can realize the aim of measuring three angle parameters of the measured object in a fast, simultaneously, non-invasive and low cost way.

6 References

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