Based on Pearson correlation coefficient and Monte Carlo simulation method, the calculation formula of frictional resistance is optimized for soft shaft bending and pulling of steel wire

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Abstract: The main content of this study is based on Pearson correlation coefficient and Monte Carlo simulation method to optimize the frictional resistance calculation formula for pushing and pulling flexible wire shafts in different bending states. According to the calculation formula and experimental data of the frictional resistance of the soft shaft bending of the wire, in order to improve the calculation accuracy, the Pearson correlation coefficient test is carried out by SPSS software, and the coefficient β and the corresponding friction f between the shaft core and the sheath are very relevant at all angles, so the size of the β can be adjusted to make the calculation of friction f more accurate. The parameters and parameters of the formula β modified by the Monte Carlo simulation method, and the frictional resistance formula of the flexible wire rope shaft at different angles is optimized. The optimized formula is calculated with an overall error of 2.3260%, which is 1.5637% lower than the original total error of 3.8898%, and is suitable for soft shaft friction with different diameters at a certain calculation angle.

1. introduction
Wire soft shafts are mainly composed of inner wire shafts and outer rubber sleeves, commonly used in automobiles, motorcycles and odometer remote control and other transmissions. In the state of repeated push and pull, the shaft core is in contact with the outer wall and recursive movement, thus generating friction, long-term friction will inevitably lead to wear. Therefore, it is very important to study the friction of soft shafts of different specifications in different states, and the theory can guide people to give different strategies in the use and maintenance of soft shafts.

For the classic traditional Eura friction formula: \( T = T_o \cdot e^{\mu \theta} \), it can only be used in the pulleys status,
because the initial force $T_0$ is difficult to solve, resulting in this calculation method is difficult to use. So far, there are a lot of domestic research on soft shaft force: Li Jian, Zhang Bao [1] etc. based on the least-multiplication method and particle group search algorithm and combined with experimental data to put forward the soft axis in the push-pull state to calculate friction experience formula. Zhang Nan, Yan Dongxu [2] and others comprehensively analyzed that the aircraft engine operating soft shaft installation channel design has a more than the domestic soft shaft adaptation range and the domestic soft shaft core part of the slide rod friction coefficient is larger than the imported soft shaft, and the domestic soft shaft adapts to bending capacity is not as good as the imported soft shaft caused by the domestic soft shaft installation problems. Based on the ANSYS Workbench platform, Zhang Wei [3] has studied and simulated the force of the wire soft shaft. Wang Hui[4] Used Solidworks software to model the elastic shafts connected to the hollow shafts of aerial generators, and to calculate the torque of the elastic shafts under pulse load impact on THESYS Workbench platform, this pre-simulated simulation experiment provides a theoretical basis for the adaptability of the elastic shafts that the motor supports in replacing the new platform, and the experimental results prove that the conclusions are effective and effectively avoid the repeated experimental design. Kondratenko V E, Sedykh L V [5], et al., by comparing the ratio of the operating angle velocity of the hard axis running in the subcritical zone with the flexible axis running in the supercritical zone, they give a reasonable method of what axle speed the hard shaft and the soft axis use when designing the operating state. Babak Bozorgmehri, Vesa-Ville Hurskainen [6], etc. carried out dynamic analysis of the hinges through the node coordinate formula, and came up with the cross-sectional deformation of the hinges under the formulaic framework of absolute node coordinates.

The above-mentioned paper shows the achievements made by people in the study of soft shafts, but on the other hand, there are few studies on the theoretical calculation method of frictional resistance in the soft axis push-pull state at home and abroad, and this paper optimizes the soft-axis bending thrust calculation formula proposed by Yisheng Liu [7] and others based on the existing literature base materials. The error between the formula and the calculation formula is 2.3260 percent, which is 1.5637 percent less than the original error of 3.8898 percent, and is applicable to the soft shafts of different axis diameters, so this paper is very theoretical and practical.

2. method

2.1. Theoretical model
For the force situation in the soft shaft push-pull state, Yisheng Liu and others arrived at the solution by a simple process of deduction for the wire soft-axis bending push-pull friction resistance calculation:

$$f = \mu D \beta P \int_{a}^{b} \frac{y''}{1 + y'^2} dx$$

(1)

The reasoning process is as follows: when the soft shaft is bent, the shaft core is in close contact with the protective sleeve, resulting in positive pressure. According to the actual situation, the smaller the bending radius when the soft shaft bends, the greater the positive pressure generated, assuming that the positive pressure of the shaft and the protective sleeve is proportional to curvature, $N = \beta \cdot K$ i.e. $(\beta$:proportional; K:curvature, $K = \frac{|y''|}{(1 + y'^2)^{\frac{3}{2}}}$, According to the soft shaft force in the bending state),

the $ds$ friction force on the unit arc length when bending and pushing can be as:

$$df = \mu_1 \cdot \beta \cdot dN = \mu_1 \cdot \beta \cdot D \cdot ds \cdot p_0 \cdot k = \mu_1 \cdot \beta \cdot D \cdot p_0 \cdot ds \cdot \frac{d\alpha}{ds} = u_1 \cdot \beta \cdot D \cdot p_0 \cdot d\alpha = u_1 \cdot \beta \cdot D \cdot p_0 \cdot \frac{y''}{1 + y'^2} dx$$

(2)

On the friction $f$ integral: $f = \mu D \beta P_0 \int_{a}^{b} \frac{y''}{1 + y'^2} , among which P_0 = \frac{mg}{DL}$
It indicates that the shaft core is under pressure throughout the contact surface. The friction can be obtained by the curve equation \( y \) generation formula obtained by the soft axis after it is traced under the coordinate system.

The symbol description is as table 1 follows:

| Symbol | Description                             | Unit          |
|--------|----------------------------------------|---------------|
| \( F \) | Frictional resistance between the shaft core and the sheath | N             |
| \( M \) | The coefficient of friction is pushed and pulled in a straight line by the soft axis | Constant     |
| \( f_{180} \) | Frictional resistance at 180 degrees in a straight line on a soft axis | N             |
| \( G \) | The weight of the wire | Kg            |
| \( D \) | Soft shaft diameter | Mm           |
| \( L \) | Soft shaft length | Mm           |
| Beta | Proportional coefficient, let a diameter soft shaft experimental data obtained | Constant     |
| \( P_0 \) | Initial pressure | N/mm²        |
| \( Y \) | Soft axis curve equation | The function variable |
| \( S \) | The integral of the curve equation on the interval | Constant     |

2.2. Pearson correlation coefficient

Pearson correlation coefficients [8] [9] are used to measure the degree of correlation between two variables, with values between -1 and 1, and are widely used in the field of natural science. An idea put forward by Francis Colton in the 1880s evolved from Carl Pearson to become the Pearson correlation coefficient, also known as the Pearson moment correlation coefficient. The experimental data in this study are to select the frictional forces of the representative different shaft diameter cores at various angles, so the sample Pearson correlation coefficient is used in the search for the relationship between \( F \) and \( \beta \). Combined with the relevant definition of the Pearson correlation coefficient of the sample, the calculation formula can be written.

There are two sets of variables: \( F = \{ F_1, F_2, \ldots, F_n \} \) and \( \beta = \{ \beta_1, \beta_2, \ldots, \beta_n \} \)

\[
F = \sum_{i=1}^{n} F_i, \quad \bar{\beta} = \frac{1}{n} \sum_{i=1}^{n} \beta_i
\] (3) Sample co-variance

\[
\text{cov}(F, \beta) = \frac{1}{n-1} \sum_{i=1}^{n} (F_i - \bar{F})(\beta_i - \bar{\beta})
\] (4)

Find the sample Pearson coefficient

\[
r_{F\beta} = \frac{\text{cov}(F, \beta)}{S_F S_\beta}
\] (5)

Where \( S_F \) (sigma \( F \)) is the sample standard deviation of friction \( F \) measured by the experiment:

\[
S_F = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (F_i - \bar{F})^2}, \quad S_\beta = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (\beta_i - \bar{\beta})^2}
\] (6)

The symmetric matrix of Pearson correlation coefficient between each two variables is as follows:

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & \cdots & r_{1n} \\
    r_{21} & r_{22} & \cdots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nn}
\end{bmatrix}
\] (7)

Each \( r_{ij} = r_{ji}, i, j = 1, 2, \cdots, n \), of them is calculated according to the calculation formula \( r_{ij} = r_{F\beta} \).
2.3. Monte Carlo simulation

Monte Carlo method [10] [11], also known as statistical simulation, is a random simulation method, based on probability theory and the theoretical method of statistical statistics, based on known conditions to calculate according to the set goals, in the calculation process, this method makes random numbers (or more often pseudo-random numbers) to solve many computational class problems. With the progress of computer technology [12] and the continuous enhancement of calculation, people can connect the solved problem with a defined probability model, using the computer to achieve multiple statistical models or sampling, in order to obtain an approximate solution to the problem. Because this method has the distinctive characteristics of probability statistics, the famous mathematician von Neumann named it after the world-famous casino, Monte Carlo of Monaco, and covered it with a layer of mystery. S.M Ulam and J. Ulam, members of the Manhattan Project, which developed the original bomb during the Second World War in the United States in the 1940s Von Neumann first proposed the Mont Caro method. In fact, before that, the Monte Carlo law existed. In 1777, the French Buffon [13] proposed the method of needle experiments to find the circumference rate, which is believed to be the origin of monte Carlo law. In this paper, Monte Carlo method is used to β optimization process of the system is described in mathematical language as follows:

$$\min ER = ER\left\{ e_1, e_2, \ldots, e_n \right\}$$  \hspace{1cm} (8)

$$\text{s.t.} \begin{cases} n \leq 20000 \\ 2 \leq \beta \leq 5 \\ e_n = \sum_{i=1}^{k} \left[ \mu_i \cdot D_i \cdot \beta_i \cdot P_{Di} \cdot S_i - F_i \right] / \frac{1}{k} \cdot 100\% \end{cases}$$  \hspace{1cm} (9)

Description of constraints:

When the important parameters in the formula β into the overall error calculation formula of friction at various angles, the overall error ER can be obtained. Taking into account the impact of computer performance and calculation time, this simulation takes 20,000 simulations to find the minimum value of the overall error, and accordingly, we can know the size of β the important parameters β to be used by the spindle at the same angle in calculating friction.

3. Experiments

3.1. Experimental data

Soft shafts with diameters of 3mm, 4mm, 5mm, 6mm, 8mm, 10mm and 12mm are selected, each with a length of 1400mm, so that the spindles are measured at different angles and their friction is measured separately. Take a flexible shaft with a diameter of 3mm as an example, the experimental data are shown in the table2 below.

| Spindle diameter (mm) | Angle (°) | Curve equation | The integral of curve in (-5,5). | Level 180f(N) | Measured Friction (N) |
|----------------------|-----------|----------------|----------------------------------|---------------|----------------------|
| 3                    | 45        | \(y = 0.1443x^2\) | 1.9296                           | 4.35          | 15.7                 |
| 3                    | 60        | \(y = 0.1233x^2\) | 1.7787                           | 4.35          | 14.6                 |
| 3                    | 75        | \(y = 0.0901x^2\) | 1.4667                           | 4.35          | 12.9                 |
| 3                    | 90        | \(y = 0.0712x^2\) | 1.2375                           | 4.35          | 11                   |
| 3                    | 105       | \(y = 0.0595x^2\) | 1.0735                           | 4.35          | 10                   |
| 3                    | 120       | \(y = 0.0411x^2\) | 0.7799                           | 4.35          | 8                    |
| 3                    | 135       | \(y = 0.0318x^2\) | 0.6158                           | 4.35          | 7                    |
| 3                    | 150       | \(y = 0.0219x^2\) | 0.4318                           | 4.35          | 5.5                  |
The experimental data measured by the experiment is plotted to the following figure 1 according to the soft axis friction with the change of angle without the same axis diameter:

Figure 1 frictional map of the soft axis at the same axis diameter that varies with the angle

3.2. Calculating important parameters $\beta$

Set the friction of the same spindle at different angles $F = [F_1, F_2, ..., F_n]^T$ Its coefficient of friction $\mu$, diameter $D$, initial $P_0$ pressure, integral part $S = [S_1, S_2, ..., S_n]^T$

You can find it: 

$$ [\beta] = [F^{-1} \cdot \mu^{-1} \cdot D^{-1} \cdot P_0^{-1} \cdot S^{-1}] $$

(10)

According to the formula to calculate the different diameters of the spindles at each angle corresponding to the $\beta$ table 3 below:

| Angle | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_8$ | $\beta_{10}$ | $\beta_{12}$ |
|-------|-----------|-----------|-----------|-----------|-----------|-------------|-------------|
| 45    | 2.6187    | 2.6491    | 2.5811    | 2.5740    | 2.5291    | 2.6080      | 2.6373      |
| 60    | 2.6417    | 2.5196    | 2.6183    | 2.6095    | 2.4879    | 2.6363      | 2.5236      |
| 75    | 2.8306    | 2.7981    | 2.8414    | 3.1514    | 2.9024    | 2.8089      | 2.8442      |
| 90    | 2.8609    | 3.0018    | 2.9426    | 3.0630    | 3.0009    | 3.0059      | 2.9222      |
| 105   | 2.9981    | 2.9387    | 3.0340    | 2.9478    | 3.0658    | 2.9611      | 2.9493      |
| 120   | 3.3013    | 3.0940    | 3.4802    | 3.3773    | 3.5419    | 3.5028      | 3.4760      |
| 135   | 3.6586    | 2.9819    | 3.6493    | 3.6934    | 4.1402    | 3.6473      | 3.8441      |
| 150   | 4.0997    | 4.1214    | 4.0874    | 4.0975    | 4.0749    | 3.9092      | 4.1581      |

The coefficients of the above table $\beta$ are descriptively counted as table 4 follows:

| Category | 45 degrees corresponds $\beta$ | 60 degrees corresponds $\beta$ | 75 degrees corresponds $\beta$ | 90 degrees corresponds $\beta$ |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| The minimum value | 2.5291 | 2.4879 | 2.7981 | 2.8609 |
| The maximum value | 2.6491 | 2.6417 | 3.1514 | 3.063 |
| The average | 2.5996 | 2.5767 | 2.8824 | 2.971 |
| Median | 2.608 | 2.6095 | 2.8414 | 3.0009 |
| Bias | -0.4866 | -0.3049 | 1.7521 | -0.3623 |
| peak | 2.2174 | 1.3409 | 4.4934 | 2.2183 |
| Standard deviation | 0.0414 | 0.064 | 0.1232 | 0.0669 |

Continued Table:

| Category | 105 degrees corresponds $\beta$ | 120 degrees corresponds $\beta$ | 135 degrees corresponds $\beta$ | 150 degrees corresponds $\beta$ |
|----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| The minimum value | 2.9387 | 3.094 | 2.9819 | 3.9092 |
| The maximum value | 3.0658 | 3.5419 | 4.1402 | 4.1581 |
| The average | 2.985 | 3.3962 | 3.6593 | 4.0783 |
| Median | 2.9611 | 3.476 | 3.6586 | 4.0975 |
| Bias | 0.6663 | -1.086 | -0.8268 | -1.527 |
It can be seen from the table 4 that the corresponding $\beta$ under the same angle has little difference. You can select other groups of $\beta$ to substitute into the calculation formula of a group of diameter flexible shaft friction, and calculate the absolute error and relative error, so as to reflect the error of the formula itself. Taking 3mm as an example, the absolute and relative errors are calculated by using 4mm and 5mm $\beta$ into the 3mm diameter friction calculation formula, respectively. $F_{mn}$ represents the friction calculated by the soft shaft with a diameter of $m$ calculated at different angles $\beta$, with a soft shaft with a diameter of $n$ corresponding to the angle friction calculation formula. According to the above method, the error of the friction calculation formula for each axis diameter is calculated, the average of the population error is 3.8898%.

4. Optimize the friction calculation formula

4.1. Using Pearson correlation coefficients to determine whether $\beta$ and friction $F$ are linearly related

Before using Pearson correlation coefficients, it is possible to determine whether the two variables are linearly related. After drawing the scatter chart of the cores of different shaft diameters corresponding to friction $F$ at different angles using SPSS24, we can see whether there is a correlation between them by observing the friction size of the cores of different shaft diameters at different angles and the calculated parameters $\beta$.

![Figure 2 friction and coefficient of the soft axis at different angles $\beta$ matrix scattering chart of the value](image)

Symbolic meaning: $F_m$ represents the friction corresponding to the core shaft with a diameter of $m$ at different angles, and beta $m$ represents the spindle with a diameter of $m$ the coefficient calculated by the experimental data at different angle.

As we can see from the figure 2 above, there is a linear correlation between $F_3$ and $\beta_3$, $F_4$ and $\beta_4$, $F_5$ and $\beta_5$, $F_6$ and $\beta_6$, $F_8$ and $\beta_8$, $F_{12}$ and $\beta_{12}$, so the Pearson correlation coefficient is used to calculate. The correlation coefficients between them are calculated as shown in table 5.

Table 5 Correlation coefficients of $F$ and $\beta$

| $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_8$ | $\beta_{10}$ | $\beta_{12}$ |
|-----------|-----------|-----------|-----------|-----------|-------------|-------------|
| $F_3$     | -0.9361   | -0.8044   | -0.9653   | -0.9278   | -0.9579     | -0.9684     | -0.9448     |
| $F_4$     | -0.9235   | -0.7572   | -0.9477   | -0.9199   | -0.9625     | -0.9527     | -0.9321     |
| $F_5$     | -0.9677   | -0.8489   | -0.9840   | -0.9345   | -0.9590     | -0.9796     | -0.9657     |
| $F_6$     | -0.9219   | -0.7696   | -0.9538   | -0.9840   | -0.9492     | -0.9602     | -0.9340     |
| $F_8$     | -0.9533   | -0.8811   | -0.9712   | -0.9263   | -0.9264     | -0.9580     | -0.9406     |
From the table we can see that the coefficients of F3 and β3, F4 and β4, F5 and β5, F6 and β6, F8 and β8, F12 and β12 are -0.9361, -0.7572, -0.9840, -0.9840, -0.9264, -0.9631, -0.9332. The correlation coefficient table shows that there is a strong correlation between friction and β from each angle, so that the size of the β can be adjusted to make the friction F calculation more accurate.

4.2. Monte Carlo Simulation
The results of descriptive statistics can be analyzed to show that the minimum value of β is 2.4875171400000000 and the maximum value is 4.1580896360000001, so the interval of the selected β is [2,5]. Taking into account computer performance and time constraints, this time on them at lab platform using the Monte Carlo simulation method for 20,000 searches, the flowchart is as follows:

![Monte Carlo Simulation Flowchart](image)

Finally, the error average between the corresponding β at different angles and the corresponding friction calculated with β and the friction measured by the experiment is shown in the following table:

| Optimized β | The error average | The average of the population error | Reduce |
|-------------|-------------------|------------------------------------|--------|
| 2.6081      | 1.2194%           |                                    |        |
| 2.6097      | 2.0620%           |                                    |        |
| 2.8415      | 2.1622%           |                                    |        |
| 3.0009      | 1.6862%           |                                    |        |
| 2.9614      | 1.2377%           | 2.3260%                            | 1.5637%|
| 3.4759      | 3.3328%           |                                    |        |
| 3.6584      | 5.8088%           |                                    |        |
| 4.0977      | 1.0993%           |                                    |        |
Therefore, after optimization, the calculation formulas for each angle are respectively:

\[
\text{Angle(45 degrees): } f = \mu D2.608135P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(60 degrees): } f = \mu D2.609656P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(75 degrees): } f = \mu D2.841479P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(90 degrees): } f = \mu D3.000863P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(105 degrees): } f = \mu D2.961416P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(120 degrees): } f = \mu D3.475946P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(135 degrees): } f = \mu D3.658369P \int_0^b \frac{y'}{1 + y'^2} \, dy' \\
\text{Angle(150 degrees): } f = \mu D4.097696P \int_0^b \frac{y'}{1 + y'^2} \, dy'
\]

At the same angle, the friction (dotted line) calculated using the above formula for the soft axis of the different axis diameters is shown in Figure 4, with a top-down distribution of 45 degrees, 60 degrees, 75 degrees, 90 degrees, 105 degrees, 120 degrees, 135 degrees, 150 degrees corresponding to the experimental data points and optimized curve distribution.

![Figure 4](image1)

Figure 4 The soft axis friction at the same angle is optimized with the diameter

![Figure 5](image2)

Figure 5 Compared to the calculated friction and experimental values

As can be seen from Figure 4, in the 3-6mm range, friction is distributed exponentially as the diameter of the spindle increases, and in the 6-12mm range, the friction is linearly distributed as the diameter of the spindle increases, and the optimized friction calculation formula curve fits well with the experimental data, reflecting the applicability of the optimized formula. Figure 5 shows a comparison of the friction distribution between the corresponding friction at the same spindle diameter and after the optimization of the angle, and it can be seen that the optimized formula is equally applicable to the spindle at different angles.

5. Conclusions

1. Analysis of the current research on the soft axis, pointed out that people in the soft axis friction theory calculation formula is insufficient, explained Yisheng Liu and others put forward the soft axis bending push and pull calculation formula reasoning process.

2. Through the different specifications of the spindle at different angles of friction experimental data after drawing, found that: for the same specification of the spindle, with the extension angle of the longer, in the corresponding state of the friction is smaller; The larger the diameter of the core shaft at the same angle, the greater the friction in the corresponding state.

3. Through the experimental data to calculate the important parameters in the formula $\beta$ statistical, calculated the error of the formula itself. After drawing the matrix scatter chart of friction and coefficient $\beta$ using SPSS software, the Pearson correlation coefficient between the two can be inferred from the
same angle by adjusting the parameters in the formula $\beta$ which can make the friction calculation formula more accurate.

4. Through the Monte Carlo method of the formula $\beta$ of the formula, so that the formula for different angles of the spindle has a good applicability. The data shows that the average error of the calculation formula optimized by Monte Carlo simulation is 1.56372% smaller than the 3.88977% before optimization, and only 2.32604%, which is significantly improved in accuracy.

5. The friction calculation formula of flexible shaft is optimized by Monte Carlo simulation, which provides a basis for people to calculate the friction of the spindle in the state of push and pull, so as to better guide people's application of the shaft research, installation and maintenance to provide reference. In addition, Yisheng Liu and others mentioned in this paper put forward the soft axis bending push and pull calculation formula of the reasoning process reflected in the calculus thought can provide future scholars in the study of soft axis friction in other aspects of thinking, such as how to reverse the soft axis calculation of its friction and other issues.

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