CONSTRUCTION OF A MINIMUM CONTACT FORCE MODEL FOR VEHICLE ELECTRICAL CONNECTORS

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Abstract - Contact force is a key factor in the reliability of vehicle electrical connectors, and when the contact force is too small the connector will fail. In this paper, we investigate the effect of vibration amplitude, vibration frequency, and spring thickness on the minimum contact force of vehicle electrical connectors. Firstly, 54 sets of experiments are designed and simulated to obtain the minimum contact force values, then the influence of different factors on the minimum contact force and the requirements of the spring thickness under different vibration conditions are analyzed, and finally the minimum contact force model for vehicle electrical connectors is established by fitting the data obtained. It is verified that the model has good prediction accuracy and can provide some reference for connector design.

Keywords: Vehicle electrical connectors, Vibration, Spring thickness, Contact force, Fit forecasts.

1. Introduction

The shift towards electrification and autonomous driving in the automotive industry makes automotive wire harnesses increasingly more critical for various functions of automobiles, such as maneuvering, driving assistance, and safety system [1]. A wiring harness is a bridge for transmitting energy or exchanging information between automotive electrical systems and is mainly composed of components such as wires and connectors. Both wires and connectors can affect the reliability of wiring harness transmission under external loads [2,3]. And electrical connectors may be a weaker link in automotive electrical and communication systems compared with wires due to their harsh work conditions. Electrical connectors will gradually deteriorate and lead to system failures. According to statistics, more than half of the failures of various electrical systems are caused by components, of which the failures caused directly or indirectly by electrical connectors account for about 40%. Common failure forms of electrical connectors are mainly contact failure, insulation failure, and mechanical failure. Contact failure is the main form of electrical connector failure. The main causes of contact failure are insufficient contact force resulting in increased contact resistance, instantaneous poor contact caused by the vibration, contact surface abrasion of the oxide film resulting in increased contact resistance, contaminants between the contact body, and so on [4].

The contact surface of the electrical connector is rough and uneven, and there is a large gap between the actual conductive area and the ideal state. The vibration environment affects the contact force between the terminals of the electrical connector, which in turn affects its electrical conductivity. So, it is necessary to study the impact of vibration on the reliability of the electrical connector. Zhang et al. [5] conducted an in-depth study on frictional corrosion caused by axial vibration of electrical connectors for different cable lengths, spring forces, and coating types. Cheng et al. [6] established a dynamic model of electrical connectors to analyze how the contact resistance changes under vibration, and developed a vibration test bench and a contact resistance acquisition system for electrical connectors. Ren et al. [7] established a relevant dynamic response model to better understand the physical mechanism of fluctuation and degradation of ECR (Electrical contact resistance) in electrical connectors, and experimentally explored the relationship between the contact resistance and vibration stresses (including frequency and acceleration). Enquebecq et al. [8] investigated the effect of friction and wear caused by vibration on the transmission of microwave signals in RF connectors and developed a dedicated test rig. Ravelo [9] developed a dynamic contact Multiphysics field model for electrical connectors using a form of tensor network analysis (TAN), which integrates the relative velocity and position of the male terminals and combines it with the instantaneous contact resistance. Lyu et al. [10] analyzed the mechanism of intermittent failures of electrical connectors in the presence and absence of vibration and also conducted design and vibration experiments on electrical connectors in corrosive environments. Ji et al. [11] conducted a series of experiments using an impedance analyzer to test the internal impedance of electrical connectors with different degradation levels and carried out experimental studies and theoretical analysis of the effect of electrical connector degradation on its high-frequency behavior. Guo et al. [12] established a mathematical model of the storage life of wire spring hole type electrical connector with the change of wire spring filament inclination angle and carried out relevant experiments to achieve the storage reliability assessment of the electrical connector. Jiang et al. [13] carried out the modal analysis and random vibration analysis of electrical connectors and used orthogonal test methods to study the effects of different structural parameters of contact parts on the intrinsic frequency, maximum stress, and contact part clearance of electrical connectors. Krüger et al. [14] investigated the effects of different types of vibration loads on the failure rate of electrical connectors. Sinusoidal and random vibration loads were applied to the connectors respectively, and then the effect of the type of vibration test was determined by comparing the number of failures. Xu et al. [15] modelled the dynamic characteristics of the contact resistance of electrical connectors under vibration conditions and investigated the electrical connector contact resistance during vibration based on the Greenwood-Williamson elastic contact model and the equivalent spring model for random rough surfaces. The change of contact force between terminals during vibration was investigated. Yu et al. [16] investigated the variation of contact resistance of electrical connectors under different vibration conditions by simulation and experiment. Zhang [17] designed a multi-stress coupling test design and carried out a simulation analysis to study the variation of contact resistance of electrical connectors under the combined effect of vibration and temperature. Yang et al. [18] studied the phenomenon that the corrosion products generated during vibration lead to an increase in the contact resistance of the electrical connectors, the main purpose of which is to investigate the effect of the accumulation of corrosion products on the contact resistance. A simple model was established for the relationship between the build-up phenomenon and the characteristics of the electrical connector, the type of vibration, and the contact resistance of the electrical connector. Liu et al. [19] explored the mechanical characteristics of the electrical connector loosening process in a multi-axis random vibration environment, established a model of the electrical connector on the missile electronic segment, and simulated the change course of the contact force during the loosening and withdrawal process of the pins with respect to the jack in a random vibration environment.

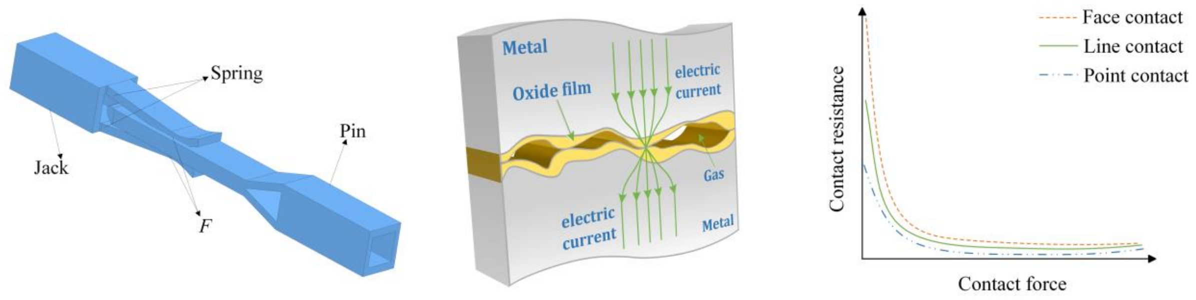
Vibration also affects the useful life of electrical connectors. Sun et al. [20] proposed a new method for predicting the remaining useful life (RUL) of electrical connectors. The method is based on the mechanism of increasing contact resistance due to vibration-induced increases in terminal oxide film thickness. Duan et al. [21] used the Wiener degradation process model with random effects to model the degradation process of the accelerated characteristics of an aerospace electrical connector under the combined temperature and vibration stresses to derive the amount of degradation and the reliability. Pan et al. [22] established a vibration model and a degradation model considering the installation of contact parts inside the connector and the connection of plug and socket to achieve a rapid assessment of the reliability of the contact parts of the electrical connector under the vibration environment [23].

The current research on the contact force of the electrical connector mainly stays in the force change under different vibration conditions, this paper mainly focuses on the relationship between the minimum contact force of the electrical connector and the vibration amplitude, vibration frequency, and spring thickness, and established a prediction model to quickly and accurately predict the minimum contact force in the research or design process.

2. Electrical Connector Terminal Structure Analysis

The electrical connector terminal composition is shown in Figure 1 (a), containing the pin and jack. Figure 1 (b) is the microscopic schematic of the electrical connector terminal contact surface. The actual contact between the terminals is composed of a number of tiny protrusions, protrusions covered with a layer of oxide film on the surface. In the initial contact force under the action of the oxide film at the point of contact will be ruptured, and the conductive metal between the pin and jack will be established to connect to the formation of a small current channel.

The electrical contact area is further reduced and the contact resistance increases due to the exposed small part of the metal will be gradually oxidized because of air, temperature, and other factors. Contact resistance is a key factor affecting the reliability of electrical connectors and it is affected by the contact force [24]. Figure 1 (c) shows the different contact forms of contact resistance with the change in contact force [25]. Regardless of the contact form, when the contact force is small, the contact resistance decreases significantly, as the contact force increases, the change tends to level off as the contact force increases.



(a) Electrical connector terminal 3D model (b) Microscopic schematic of terminal contact surface (c) Contact resistance of different contact forms

Figure 1: Components of contact resistance and their force characteristics

Contact force has a great influence on the reliability of electrical connectors. An appropriate degree of contact stress is advantageous in maintaining a stable and low electrical contact resistance (ECR) and mitigating the occurrence of instantaneous contact issues induced by external vibrations [26].

To get the variation of contact force under different spring thicknesses, this study proposes the research idea shown in Figure 2.

Firstly, the model required for the analysis is established, and the contact force values under different loading conditions are obtained by transient dynamics analysis. And then, the obtained data are sorted and fitted to establish the relationship model between vibration amplitude, vibration frequency, spring thickness, and minimum contact force. Finally, a reasonable prediction is proposed and the error is analyzed.

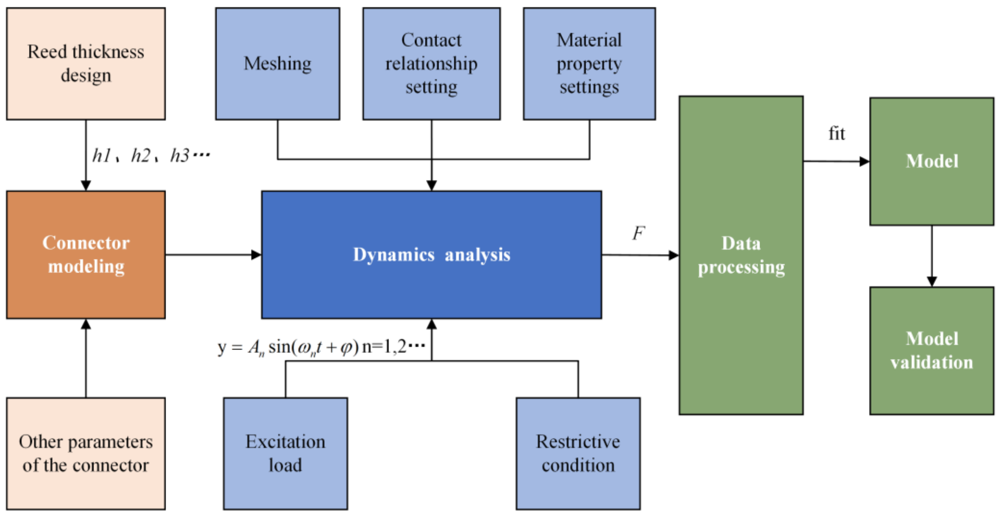


Figure 2: Study idea of contact force values for different spring thicknesses

3. Dynamic Analysis

3.1 Theoretical Minimum Contact Force

The basic material properties of the electrical connector terminals used in this study are shown in Table 1.

Table 1. Basic material properties of a commonly used electrical connector

Parts	Material	ρ/(g·cm^{-3})	E/GPa	ν
Pin	QSn6.5-01	8.8	118	0.33

To ensure the reliability of the connector during operation, the contact force between the terminals must not be less than a certain critical value, which can be obtained by the empirical formula for contact resistance [27]:

$$R = \frac{K}{(0.102F)^m} \tag{1}$$

Where R is the contact resistance, mΩ, according to QC_T 1067.1-2017, the maximum contact resistance of the connector selected in this paper cannot be higher than 10mΩ; k is related to the material of the electrical connector terminals and its surface condition, and other factors, take k = 240; *56* is related to the actual number of contact points, force range, contact form, and other factors, the connector terminals are considered to be the surface contact, take m = 0.7, *F* is the contact force between the electrical connector terminals, N. After calculation, to meet the requirements of the theoretical minimum contact force is 0.1357N.

Vehicle electrical connector is usually in the vibration environment, therefore the contact force in the static case differs from the magnitude in actual operation. In order to get more accurate results, the following is a dynamic analysis of the electrical connector with the thickness of the spring as the object of study.

3.2 Dynamic Model

The electrical connector is fixed on the equipment through the insulating shell, and the vibration excitation from the outside of the car in the driving process is transmitted to the inside of the electrical connector through the shell, so that the pins and jacks occur between each other's movement, thus affecting the normal operation of the electrical connector. The vibration excitation transmission path is shown in Figure 3.

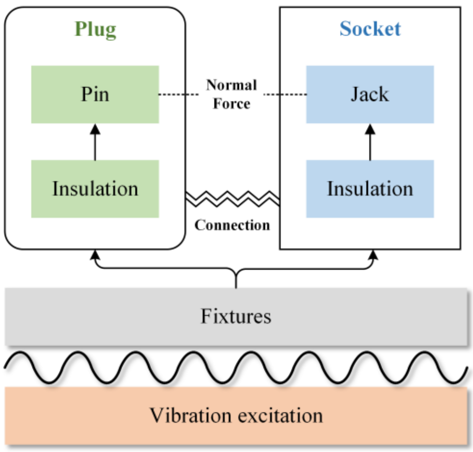


Figure 3: Vibration excitation transmission path

Based on Fig. 3, a sketch of the dynamics model of the electrical connector contact can be established as shown in Fig. 4. In this study, the effect of the shell is ignored, and the terminals are considered to be rigidly connected to the shell. Fixed constraints are directly applied at the end of the jack, and excitation is applied at the end of the pin.

$$y = A(\omega t + \varphi) \tag{2}$$

Where A is the vibration amplitude; ω is the vibration frequency; φ is the initial phase; this is used to obtain the change of contact force between the terminals in the vibration state.

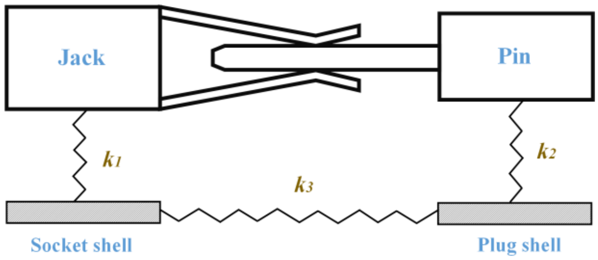


Figure 4: Dynamic model of contactor

Refer to GJB 1217A-2009 "Test Methods for Electrical Connectors" to develop vibration test excitation conditions, as shown in Table 2.

Table 2. Excitation conditions for vibration analysis

Group	A/mm	ω/Hz
1	0.25	50
2		100
3		200
4	0.5	50
5		100
6		200
7	0.75	50
8		100
9		200

3.3 Simulation Process

As shown in Figure 5, the established 3D model is imported into Ansys transient dynamics analysis module. Fixed constraints are applied to the end of the jack, and a sinusoidal displacement load is applied to the end of the pin. As the gap between springs is smaller than the thickness of the pin, the contact part is in the state of penetration when the assembly is completed. So, the whole analysis process will be set up in two load steps. The first load step does not apply the external load, and the springs undergo a certain amount of deformation and generate holding force with the penetration between the terminals becomes normal contact. The second load step applies a sinusoidal displacement excitation at the end of the pin and then extracts the contact force between the terminals during vibration. The contact force between terminals under the conditions of spring thickness of 0.32mm, vibration amplitude of 0.75mm, and vibration frequency of 100Hz is shown in Figure 6.

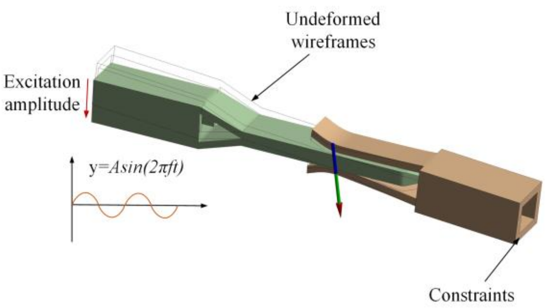


Figure 5: Simulation analysis setup

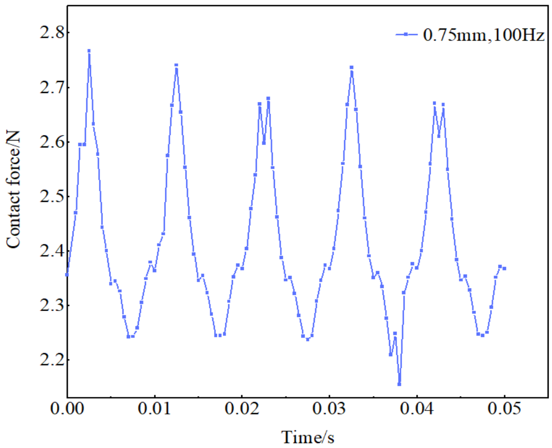


Figure 6: Contact force values

It can be seen that the contact force varies periodically from Figure 6, the period is the same as the excitation period. The limit position of the pin movement corresponds to the minimum force which determines whether the connector is reliable or not. The variation of the minimum force under different conditions will be the focus of subsequent studies.

3.4 Analysis of Simulation Results

The transient dynamics of the electrical connector terminals with six different spring thicknesses *h* shown in Table 3 were analyzed according to the excitation conditions set in Table 2, and the results are shown in Figs. 7~9.

Table 3. Analyzing six spring thicknesses

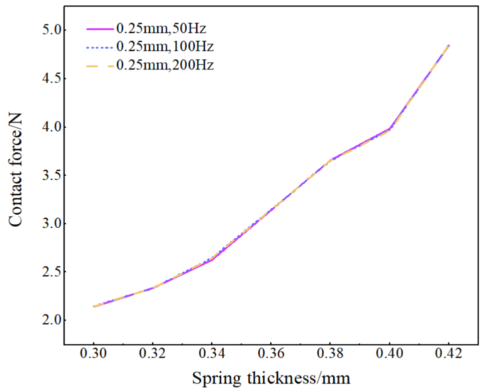
Group	1	2	3	4	5	6
h/mm	0.3	0.32	0.34	0.38	0.4	0.42

To see the stability of the contact force, define the rate of change as:

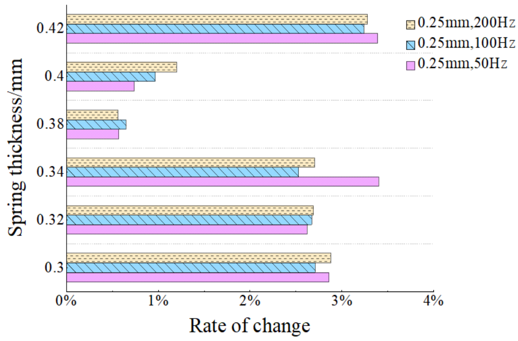
$$\text{Rate of change} = \frac{F_i - F_{min}}{F_i} \tag{3}$$

Where F_i is the initial contact force and F_{min} is the minimum contact force.

As can be seen from Figure 7, when the amplitude is 0.25mm, the minimum contact force value difference under the same spring thickness of different vibration frequencies is very small, and the minimum contact force change rate is not large. The contact force is relatively stable in this condition. With the increase of the thickness, the contact force is basically proportional to the growth.



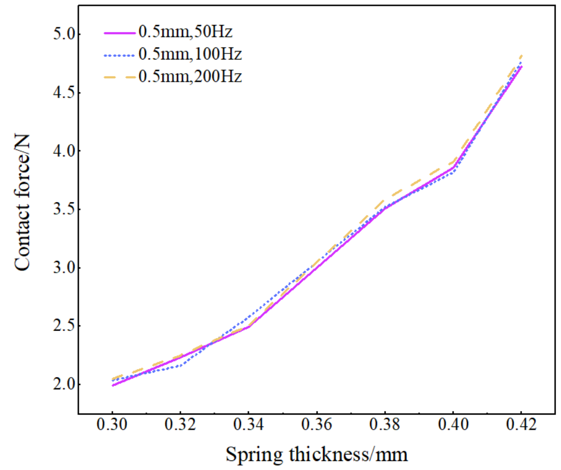
(a):Change in minimum contact force value



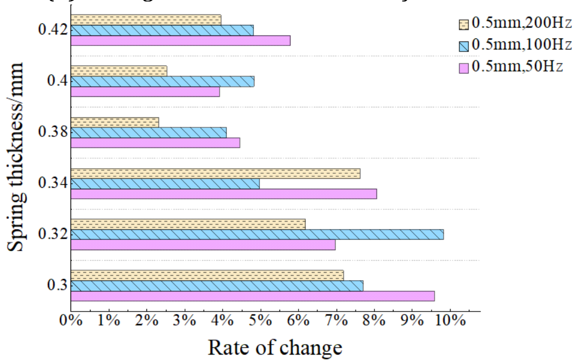
(b):Minimum contact force change rate

Figure 7: Trend of change in minimum contact force (amplitude 0.25mm)

As can be seen from Figure 8, the minimum contact force values for different vibration frequencies with the same spring thickness at 0.5mm amplitude are slightly different, and the minimum contact force for high-frequency vibration is slightly larger than that for low-frequency vibration. In the case of the same vibration frequency, as the spring thickness increases, the rate of change of the minimum contact force decreases.

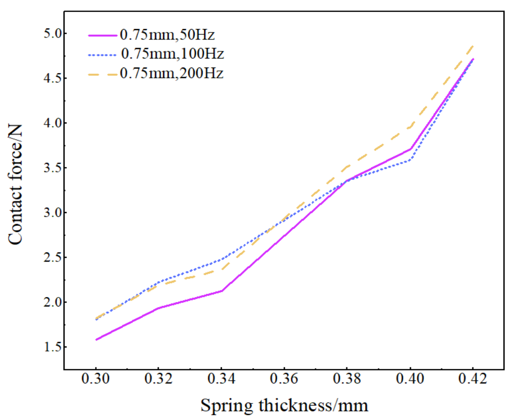


(a):Change in minimum contact force value

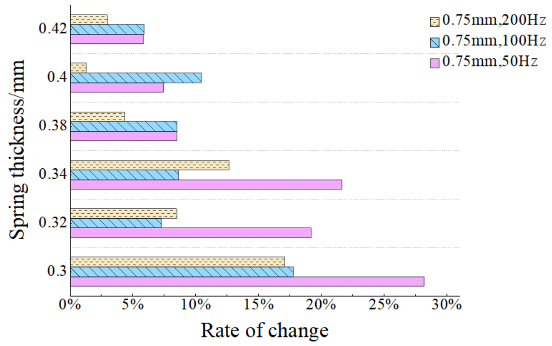


(b):Minimum contact force change rate
Figure 8: Trend of change in minimum contact force (amplitude 0.5mm)

As shown in Figure 9, when the amplitude is 0.75mm, the minimum contact force value difference under the same spring thickness of different vibration frequencies is large, and high-frequency vibration conditions under the stability of the contact force are better than the low-frequency vibration. When the frequency is the same, the minimum contact force change rate decreases more significantly with the increase of the spring thickness. In this case, especially in low-frequency vibration conditions, the spring thickness should be increased to ensure the stability of contact force.



(a):Change in minimum contact force value



(b): Minimum contact force change rate
Figure 9: Trend of change in minimum contact force (amplitude 0.75mm)

Through the above results, it can be found that the spring thickness and the contact force between the terminals are approximately proportional to each other. When the vibration amplitude is large, the stability of the contact force between the terminals is better as the increase of spring thickness. When the vibration amplitude is small, the change in spring thickness does not have a significant effect on the stability of the contact force between the terminals. Figure 10 shows the three-dimensional mapping of all the analysis results. The magnitude of the contact force is represented by different colors, and the relationship between the minimum contact force and the amplitude, frequency, and spring thickness can be seen more clearly.

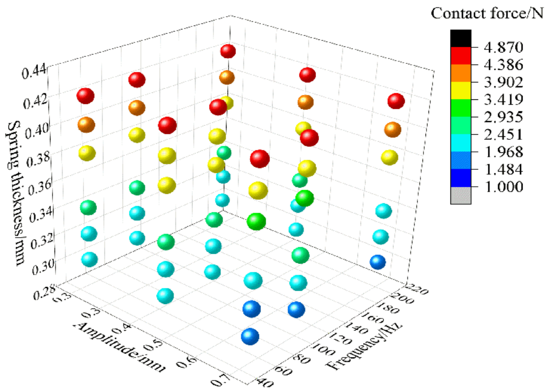


Figure 10: Minimum contact force for different spring thicknesses under different vibration conditions

4. Contact Force Modeling

4.1 Data Fitting

The obtained simulation data were fitted and analyzed. The independent variable is X= [x_1 vibration amplitude, x_2 vibration frequency, x_3 spring thickness], and the dependent variable is Y=minimum contact force. The relationship between Y and X can be obtained as follows.

$$Y = 2.9232 - 0.2599X_1 - 0.2298X_1^2 + 0.0006X_2 - 59.1292X_3^2 + 167.0344X_3^3 \quad (4)$$

The fitting results are shown in Fig. 11, with a mean square error MSE = 0.0145, and the overall fitting is good.

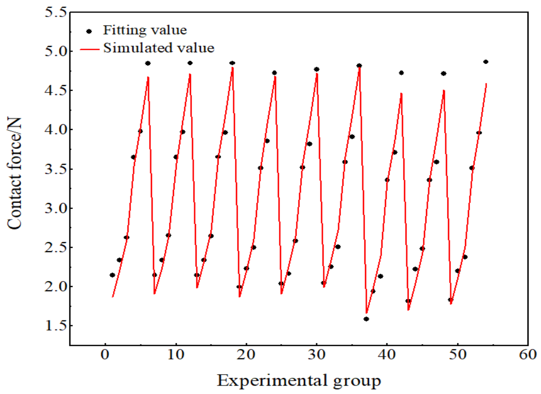


Figure 11: Fitting of minimum contact force for different spring thicknes

4.2 Model Analysis

If one of x_1 and x_2 is a non-zero constant, equations (5) and (6) are obtained. Eq. (5) represents the relationship between Y and x_2, x_3 when x_1 is 0.25 mm, and Eq. (6) represents the relationship between Y and x_1, x_3 when x_2 is 200 Hz. The final fitting effect is shown in Fig. 12, With the increase of the spring thickness, the contact force tends to increase, but when the spring thickness is small, with the increase of the amplitude, the contact force decreases more obviously. while the increase of frequencies leads to a relatively small change in the contact force. This difference also becomes progressively smaller when the spring thickness increases to 0.34 mm.

$$Y = 2.8439 + 0.0006X_2 - 59.1292X^3 + 167.0344X_3^3 \quad (5)$$

$$Y = 3.0432 - 0.2599X_1 0.2298X_1^2 - 59.1292X_3^2 + 167.0344X_3^3 \quad (6)$$

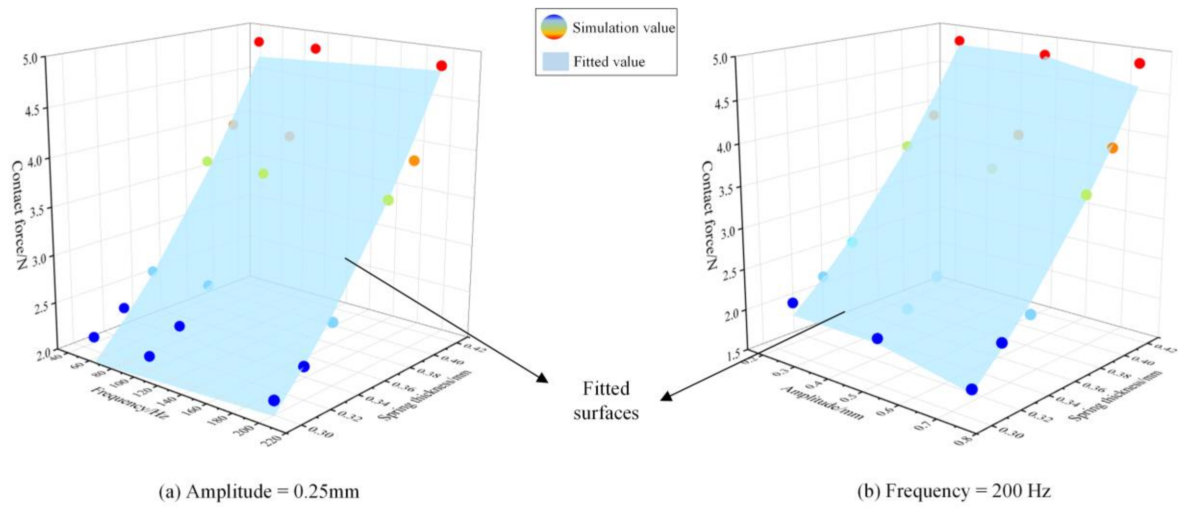


Figure 12: Minimum contact force fitting with constant amplitude/frequency

If Y is 0 and the minimum contact force is zero then it means that the unilateral spring is disengaged and Eq. (4) can be rewritten as:

$$0.2298{x_1}^2 + 0.2599x_1 = 2.9232 + 0.0006x_2 - 59.1292{x_3}^2 + 167.0344{x_3}^3 \quad (7)$$

Where x_2 and x_3 to indicate x_1, the vibration amplitude can be found corresponding to each vibration frequency, and spring thickness given in Figure 13, the amplitude is the maximum amplitude under these conditions to ensure that do not disengage. When the vibration amplitude in the surface below the minimum contact force can be derived from Eq. (4), if more than the range, Eq. (4) will no longer apply.

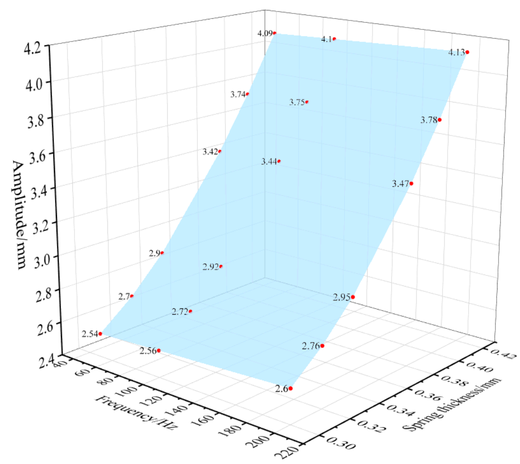


Figure 13 Maximum amplitude of the spring without disengaging under determining vibration conditions

If x_1 and x_2 are constants, then the relationship between Y and x_3 is a cubic function. In particular, when x_1 and x_2 are both zero, the relationship between contact force and spring thickness at rest is expressed as:

$$Y = 2.9232 - 59.1292X_3^2 + 167.0344X_3^3 \tag{8}$$

Simplifying the jack spring as a cantilever beam, the relationship between the load and the thickness of the beam can be deduced from the deflection formula for the free end of a cantilever beam in the mechanics of materials as:

$$F = \frac{\delta_{max} E b}{4 l^3} h^3 \tag{9}$$

Where F is the load, N; l is the length of the beam, m; δ_{max} is the maximum deflection of the beam free end, m; E is the modulus of elasticity of the material, Pa; b is the width of the beam, m, and h is the thickness of the beam, m. Both Eq. (8) and Eq. (9) are one-dimensional cubic equations, which also verify the reasonableness of Eq. (8) on a theoretical level. However, there is an error in simplifying the female terminal spring to a cantilever beam itself, and if only the cubic term is designed in accordance with Eq. (9) during the fitting process, a larger error is obtained, as shown in error 1 in Fig. 12. Therefore, in order to compensate for the error, the secondary term and the constant term are added on the basis of the original cubic term to improve the fitting accuracy, and the fitting effect after the increase is shown in Fig. 14. The fitting errors are all below 5%, which indicates that Eq. (8) can better represent the relationship between the spring thickness and the contact force.

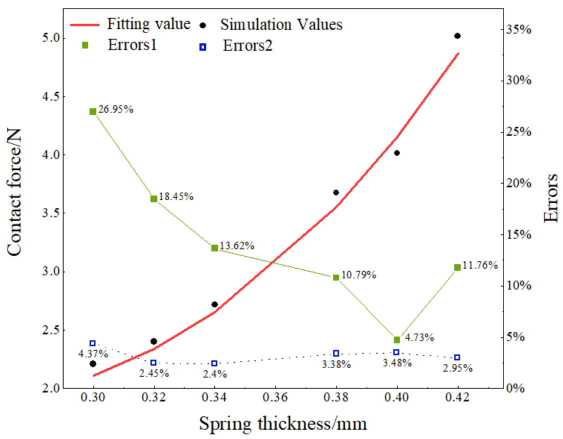


Figure 14: Fitting of contact force at rest

4.3 Model Validation

All of the above was done by fitting the existing data and then analyzing the error situation. In order to verify the accuracy of the model, four groups of comparative tests were designed with reference to the selection range of the previous experimental data (amplitude of 0.25~0.75mm, frequency of 50~200Hz, thickness of 0.3~0.42mm), as shown in Table 3. Among them, the values of the three influencing factors in groups 1~3 were selected within the range of the previous data, and the fourth group was selected outside the range. From Table 4, it can be seen that the errors ε of simulated data *F1* and fitted data *F2* of the 4 groups of tests are less than 5%, indicating that the model predicts well.

Table 4. Validation of model prediction effect

Group	A/mm	ω/Hz	h/mm	F_1/N	F_2/N	ε
1	0.5	100	0.36	2.9559	2.9258	1.02%
2	0.6	200	0.36	3.0766	2.9345	4.62%
3	0.6	160	0.36	3.0461	2.9105	4.45%
4	0.8	250	0.44	5.6280	5.4995	2.28%

5. Conclusions

In this paper, from the perspective of the electrical connector contact force, the influence of the spring thickness on the stability of the electrical connector contacts force and its minimum contact force under the vibration environment is investigated. The following conclusions are obtained:

(1) First of all, the finite element analysis method is used to compare the changes of contact force under different spring thicknesses and vibration conditions, and then the model is established and verified. The model has a high accuracy with less than 5% error. It provides a reference value for the prediction of the minimum contact force in engineering design for the three influencing factors of amplitude, frequency, and spring thickness.

(2) When the vibration amplitude is small, the spring thickness has less influence on the stability of the electrical connector contact force. In the amplitude of 0.25mm, the rate of contact force change is below 3.5%. Therefore, in the design of the working environment for low-amplitude electrical connectors can choose to reduce the spring thickness to streamline the structure and reduce costs.

(3) Low-frequency vibration stability compared to high-frequency worse. When the amplitude is 0.75mm and the frequency is 50Hz, the maximum rate of contact force changes close to 30%. Therefore, when designing the electrical connector for a working environment with high amplitude and low frequency, the spring thickness needs to be increased appropriately to improve the reliability of the electrical connector.

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