Shape Optimal Design of Contact Springs of Electronic Connectors

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Introduction

An electronic connector provides a separable interface between two subsystems of an electronic system. The contact spring is probably the most critical component in an electronic connector. Functionally, the contact spring provides the contact normal force, which establishes the contact interface as the connector is mated. However, connector manufacturers have a basic struggle between the need for high normal contact forces and low insertion forces. Designing connectors with large numbers of pins that are used with today’s integrated circuits and printed circuit boards often results in an associated rise in connector insertion force. It is possible to lower the insertion force of a connector by redesigning the geometry of the contact spring, but this also means a decrease in contact normal force. In this paper, structural shape optimization techniques are used to find the optimal shape of the contact springs of an electronic connector. The processes of the insertion of a PCB into the contact springs of a connector are modeled by finite element analysis. The maximum insertion force and the contact normal force are calculated. The effects of several design parameters are discussed. The geometry of the contact springs is then parameterized and optimized. The required insertion force is minimized while the normal contact force and the resulting stress are maintained within specified values.

In our example, the insertion force of the final contact spring design is reduced to 68.3% of that of the original design, while the contact force and the maximum stress are maintained within specified values. [DOI: 10.1115/1.1463730]

Keywords: Connector, Contact Spring, Insertion Force, Shape Optimal Design
Modeling the Contact Springs of a Connector

Figure 1 shows a pair of contact springs of a board-to-board connector made of copper alloy. The springs are fixed in a plastic housing, with pins sticking out of the housing. Note that only a portion of the interface between the springs and the housing is in interference fit. The left and right springs have different shapes. When the gold plate of a PCB is inserted between the springs, the forces applied by the springs are unsymmetrical. However, in a connector, the pairs of springs are arranged in an alternate pattern, i.e., the left and right springs switch positions in the neighboring pair. Therefore force balance is maintained for the whole connector.

Yamada and Ueno presented an analysis of insertion force in elastic/plastic mating. They considered each instance of the insertion process as a static equilibrium of the insertion force and the contact force, including the Coulomb’s friction force. The board inserted between the springs was considered rigid relative to the springs. As shown in Fig. 2, at the contact point, the contact force direction is offset from the normal direction by the friction angle $\alpha$. The insertion process is assumed to be quasi-static. In the example presented in Yamada and Ueno’s work [9], the analytical expression of insertion force versus insertion depth matches well with experimental data, using the static coefficient of friction $\mu = 0.175$.

Under similar assumptions, Ling [10] also presented a useful analysis for mating mechanics and stubbing of separable connectors. Also referring to Fig. 2, there are two force components at the contact point: the normal force $F_n$ and the tangential force $F_t$, and $F_t = \mu F_n$. The projection of the resultant force in the $y$ direction can be expressed as

$$F_y = F_n \sin \phi + F_t \cos \phi$$

(1)

where $F_y$ is also the required insertion force at this contact point. The projection of the resultant force in the $x$ direction $F_x$ is

$$F_x = F_n \cos \phi - F_t \sin \phi$$

(2)

As shown in these equations, the insertion force and normal force depend heavily on the geometry of the springs, and cannot be determined using a simple beam model. A finite element analysis model is built to calculate the insertion force and normal force of the contact springs in Fig. 1. Two-dimensional plane stress elements are used. Contact elements are added at the interface between the PCB and the springs. The amount of the gap and interference is prescribed as designed.

The insertion force and normal force are calculated under similar assumptions discussed in the literature. First, the contact surface of the springs during the insertion process is identified and divided into discrete contact points, as shown in Fig. 3. It is assumed that there is only one contact point at a given position of PCB. The insertion process is assumed to be quasi-static, therefore the static equilibrium equations such as Eqs. (1) and (2) are satisfied at a contact point.

As shown in Fig. 3, to find the value of contact normal force $F_n$ at a contact point $p_i$ when the PCB is inserted, first the amount of deflection of the spring in the $x$ direction $\Delta x_i$ is calculated from the thickness of the PCB and the geometry of the spring. Then a secant-type interpolation procedure is used to find the value of $F_n$ that would cause this deflection $\Delta x_i$ in the $x$ direction. This process continues in an iterative manner until the values of $F_n$ at all discrete contact points are obtained. Figure 4 shows “normal force versus insertion length” for the contact springs in Fig. 1.
The coefficient of friction is assumed to be 0.175 in this figure. Substituting into Eq. (2), Fig. 5 shows “insertion force versus insertion length” during the insertion process.

Figure 5 also shows the effect of the unsymmetrical shapes of the left and right springs. There are two peaks in the curve of total insertion force. In this case, the maximum insertion force 59.8 g occurs at the first peak. Because of the unsymmetrical shapes, the left spring comes into contact first and the peak insertion force of the left spring occurs earlier than that of the right spring. At this contact point, the insertion force of the right spring is still low. Therefore when the insertion force contributed by the left and right springs are added together, the total peak insertion force is only slightly higher than that of the left spring. If the shapes of both springs were identical, the peak insertion force would be twice the peak insertion force of a single spring.

Figure 6 shows the stress distribution of the left and right springs calculated by the elastic finite element model. The maximum stresses, 582 MPa for the left spring and 752 MPa for the right spring, occur at the root of the springs. The yield stress of copper alloy is 635 MPa. The right spring is over stressed at the root of the spring.

The Effect of the Coefficient of Friction

Figure 7 shows insertion force versus insertion length for $\mu = 0.150, 0.225, 0.300$. The maximum insertion force increases from 56.0 g ($\mu = 0.150$) to 90.7 g ($\mu = 0.300$), or almost 60%. Also note that when $\mu = 0.225$, the location of the maximum insertion force switches to the peak of the right spring. In the mean time, the maximum normal force does not change significantly as the coefficient of friction increases.

The important role of the coefficient of friction was noticed and utilized in designing connectors for reducing the insertion force without sacrificing the contact normal force. For example, Kartlucke et al. [11] suggested the application of thiol-based coatings to silver surfaces to provide good corrosion protection and a reduction of the insertion and extraction forces required for electrical connectors.

The insertion forces obtained from our analysis were compared to experimental data. Three samples of the connector were measured experimentally. The insertion force of each sample was measured 30 times. In the 90 measurements, the insertion forces of the connector samples ranged from 59.5 g–69.4 g per pin, and average insertion force was 62.6 g per pin. Comparing with Fig. 5 and Fig. 7, the coefficient of friction of our contact springs is estimated to be 0.18–0.21.
In the mechanical specifications of the connector, the maximum insertion force is 95 g per pin, and the minimum normal force is 60 g per pin. From our analysis, normal force at the final contact point is 118 g for the left spring and 148 g for the right spring for $\mu = 0.2$. The maximum insertion force during the insertion process is 61.8 g. Both contact force and insertion force satisfy the specifications. The maximum stress at the root of the right spring is 708.2 MPa, which is higher than the yield strength of the copper alloy (635 MPa). The size of the spring is very small (the width of the spring is about 0.5 mm). Therefore plastic deformation resulted from the high stress was not visually observable in the experiments.

Another design parameter we explored was the amount of interference at the interface between the spring roots and the housing (as shown in Fig. 1), which might affect the stiffness of the springs. However, we found that varying the length and depth of interference does not have significant effect on the contact normal force and insertion force of the contact springs.

Constructing the Optimization Model

In the current design, the normal contact forces of both left and right springs are much higher than that required by the specifications. In the mean time, the stress of the right spring is too high. We can optimize the geometry of the contact springs to further reduce the maximum insertion force, while the normal force and the maximum stress are kept within specified values. The shape optimization problem of the contact spring can be described as follows:

**minimize**
the maximum insertion force

**subject to**
the normal force has to be higher than a specified value
the maximum stress has to be lower than the strength of material

where $d_0$ is the vector of design variables $d_i$, $i = 1, \ldots, 48$. $N$ is the specified minimum normal force, and $S$ is the allowable stress of the material of the spring. In our example, $N = 100$ g and $S = 600$ MPa. Note that we demand less contact force than in original design. Function $F_{\text{insertion}}(d)$ is the total insertion force. Functions $F_{\text{normal}}(d)$ and $F_{\text{max}}(d)$ are the normal contact forces of the left and right springs. These functions and the maximum stress of the springs $S_{\text{left}}(d)$ and $S_{\text{right}}(d)$ are evaluated by finite element analysis, as described in the previous sections.

Shape Optimization Result of the Contact Springs

Sequential linear programming (SLP) (Vanderplatts, [12]) is used to find the solution of Eq. (3). In this optimization algorithm, the optimization model in Eq. (3) is linearized at the initial design point $d_0$ to form the following linear programming subproblem:

**min.** $F_{\text{max, insertion}}(d)_{\text{max}}$ $F_{\text{max, insertion}}(d)_{\text{max}}$

**subject to** $F_{\text{normal}}(d)_{\text{max}}$ $F_{\text{normal}}(d)_{\text{max}}$

$S_{\text{left}}(d)_{\text{max}}$ $S_{\text{left}}(d)_{\text{max}}$

$S_{\text{right}}(d)_{\text{max}}$ $S_{\text{right}}(d)_{\text{max}}$

$d_i \leq d_{\text{u}}, \quad i = 1, \ldots, 48$

The sensitivities (the first derivatives) of functions $F_{\text{insertion}}(d)$, $F_{\text{normal}}(d)$, $F_{\text{max}}(d)$, and $S_{\text{max}}(d)$ required in Eq. (4) are calculated by finite differences. This linear programming sub-problem is solved to obtain a new design point. The insertion force, normal
force, and the maximum stress of new design point are calculated to see whether this new design point satisfies the termination conditions. If not, the optimization model in Eq. (4) is linearized again on this new design point. This process continues in an iterative manner until the termination conditions are satisfied.

The last constraint in Eq. (4) imposes “move limits” on the design variables. This is because the linear programming subproblem (Eq. (4)) is a good approximation to the original nonlinear optimization model (Eq. (3)) only in the neighborhood of the current design point. In our example, the move limit is 0.02 mm initially, and is reduced to half if the new design point obtained from the linear programming subproblem becomes highly infeasible.

The SLP algorithm terminates after 5 iterations. Table 1 shows the iteration history. The insertion force of the final contact spring design is reduced to 42.2 g, 68.3% of that of the original design (61.8 g). The maximum stress of the right spring drops from 708 MPa to 564 MPa. The contact normal forces of the final design are 100 g for the left spring, and 113 g for the right spring. The SLP algorithm terminates because the design obtained in the 5th iteration satisfies all constraints, and the improvement in objective function is less than 1% comparing with the objective value of the 4th iteration.

Figure 9 shows the final designs of the contact springs. The shapes of the springs do not have drastic change, the maximum movement of the control points being less than 9% of the width of the spring, though the performance of the springs has been significantly improved. Since the change is so small that it is difficult to see the difference if the new geometry is superimposed on the original geometry, the small arrows in the figure are used to indicate the directions of movement of the control points.

### Conclusions and Discussions

This paper describes how the insertion of a PCB into the contact springs of an electronic connector is modeled by finite element analysis. The insertion force, normal force, and maximum stress of the contact springs can be calculated, and the analysis result matches well with experimental data.

Some design guidelines can be concluded from this analysis:

1. The unsymmetrical shapes of the left and right springs effectively reduce the peak insertion force.
2. The coefficient of friction between the PCB and the contact springs has significant effect on the insertion force. Reducing the coefficient of friction can reduce the insertion force without sacrificing the contact normal force.
3. The amount of interference at the interface between the spring roots and the housing does not have significant effect on the contact normal force and insertion force of the contact springs.

Connector manufacturers have a basic struggle between the need for high normal contact forces and low insertion forces; both are very sensitive to the geometry of the contact springs. In this paper, the analysis procedure is further combined with structural shape optimization techniques to carefully design the shape of the contact springs. The insertion force of the connector can be further reduced while the normal contact force and the maximum stress are maintained within specified values. In our example, after shape optimization, the shapes of the springs do not have drastic change, though the performance of the springs has been significantly improved.

### Acknowledgment

This research is partially supported by National Science Council, Taiwan, ROC, grant number NSC-89-2212-E-155-004. This support is gratefully acknowledged. The authors also thank Nextronics Engineering Corporation, Taiwan, especially Ms. Angela Liu, for providing valuable technical data and professional experience for this research.

### References


