Flexible force-sensitive distributed pressure sensing system for soft connection of aircraft Cockpit Cover

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Abstract: With respect to the actual application of the edge bonding of transparent part of the fighter jet cockpit cover by soft connection, the flexible force-sensitive distributed pressure sensor system is developed, which covers the flexible force-sensitive sensor, calibration device, circuit and data analysis software. The pressure distribution during pressurizing of the edge bonding of multidimensional curved surface transparent parts is vividly showcased by 2D and 3D images. A number of people are assigned to carry out operation. Based on the pressure distribution map and data acquisition, it is determined that the existing bonding process has the serious deficiency of uneven pressure distribution that cannot be addressed, and there is huge potential for improvement.

1 Introduction
The fighter jet cockpit cover is mostly connected with the transparent part by soft connection. It’s the most critical step[1][2] of the cockpit cover to transfer load with the jet body by bonding the flexible polyester rubber to the edge of the transparent part. Certain pressure needs to be applied during bonding. The uneven distribution of pressure may cause low local bonding strength and debonding, thereby affecting the system reliability or leading to rework. Therefore, it’s necessary to conduct relevant study on the pressure distribution of flexible connection.

In recent years, the flexible force-sensitive sensing system has been increasingly applied[3]~[8] in the fields of robotics, medical treatment, automobile, ship and wearable devices, such as robotic hand grasp tactile information, dental occlusal apparatus, force-bearing analysis of automobile brake pad and seat human-machine curved surface pose optimization. The most typical example is the U.S. Tekscan[9]~[11] product. Such sensor is very flexible, creating a favorable condition for measuring the pressure of a variety of complex contact surfaces. The domestic research on the flexible force-sensitive sensor began in 1987, and plenty of results have been achieved in this regard. With respect to the manufacturing material of the flexible force-sensitive sensor, domestic researchers improve its performance by changing through research the mix of the conductive material. Along with the ongoing research on the new conductive material of the flexible force-sensitive sensor, a number of reports[12]~[15] have been disclosed and published. However, it's still very deficient in terms of the actual engineering application. There is still a certain gap in terms of the manufacturing technology, compared with foreign research findings.

At present, the sensor manufacturing process based on screen printing is still the mainstream practice at home and abroad. In terms of sensor signal acquisition, it’s mainly to improve the signal acquisition circuit published abroad[16], and there are few self-developed sensor signal acquisition circuits. By now, the application of flexible force-sensitive distributed pressure sensor system in the
aerospace field is relatively rare. Besides, the development of special flexible force-sensitive pressure distributed sensor system according to the actual working conditions is scarcely reported.

2 Development of Flexible Force-sensitive System

2.1 Overall design

The main composition of the whole system is shown in Fig. 1. The hardware part of the system is composed of the sensor needs to be corrected by the calibration system, and the signal is transmitted to the data processing and analysis software by circuit.

![Fig.1 Composition of flexible force-sensitive distributed pressure sensor system](image)

2.2 Design of sensor and circuit

Same as the Tekscan plan for the conventional product, the sensor uses the manufacturing technique based on screen printing. The pressure sensor is composed of 2 very thin polyester films. The inner surface of one film is lined with several rows of ribbon conductors and the inner surface of the other is lined with several rows of column conductors. The outer surface of the conductor is applied with a special pressure-sensitive semiconductor coating. When two thin films are merged, a large number of cross points of transverse and longitudinal conductors form an array of pressure sensing points. When the external force is applied to these sensing points, the resistance of the semiconductor will change proportionately with the external force, thus reflecting the pressure readings of the sensor point. The resistance is highest when the pressure is 0. The bigger the pressure, the smaller the resistance, so that the pressure distribution between two contact surfaces can be fed back.

The width of the sensor conductor and the line spacing are designed according to different measurement requirements. Take the edge of the front glass of the cockpit cover of a certain type of plane as an example. Design parameters are seen in the Table 1. The overall size of the induction area fully matches the size of the soft connection at the edge of the transparent part. There are 225 pressure monitoring points of 45 columns and 5 rows. Then, the amplitude and time characteristics of the surface force can be determined by scanning and measuring the resistance change of each force applying unit by design circuit. The sensor structure is seen in Fig. 2, data acquisition device is seen in Fig. 3.

![Table 1 Sensor specifications](image)

| S/N | Item                              | Parameter         |
|-----|-----------------------------------|-------------------|
| 1   | Design of induction area          | (900×15) mm²      |
| 2   | Size of single point              | (20×3) mm²        |
| 3   | Line spacing of sensor            | 1 mm              |
| 4   | Number of points                  | 225               |
| 5   | Range                             | >5 Mpa            |
6 Encapsulation thickness 0.25 mm
7 Mode of signal lead 52 columns*44 rows

![Fig.2 Sensor design and installation position](image)

(a) data acquisition device (b) Connection to sensor

![Fig.3 data acquisition device and Connection](image)

2.3 Software interface design

In terms of software design, a total of 16 color codes were set, starting from the blue mark, and ending at the red mark. The pressure readings of different color codes up to standards increased successively, and the display area mainly included 2D and 3D display. In addition to the process reading, the static display and dynamic monitoring of pressure distribution were achieved. Different figures of sensitivity represented different initial pressure readings. The lower the sensitivity, the bigger the initial pressure readings. The data display area mainly recorded the total pressure, average pressure, maximum pressure, contact area, etc. The menu bar included functions such as the calibration and data export.

![Fig.4 Software interface](image)
2.4 Design of calibration system

2.4.1 Design of calibration device
In order to guarantee the accuracy of the measurement data, it is necessary to calibrate the sensor before use. The precision of calibration is of utmost importance to the ultimate measurement accuracy achieved by the system. There are some domestic and foreign researches on the calibration of tekscan flexible array force-sensitive sensor\cite{17}\cite{18}. The single sensitive point of the sensor array was calibrated by the "balloon pressure method" and a kind of "pin method". The advantages and disadvantages of the two methods were analyzed and compared. The balloon pressure could quickly calibrate the regional sensitive points of the sensor array. By testing the accuracy of flexible force-sensitive sensor, a few foreign researchers have come to the conclusion that the precision of sensor with rigid planar calibration has great defects in practical application. Therefore, the balloon calibration was also used herein. However, relative to the regular sensors on the market, such sensor has greater dimensional difference, and the overall length of the sensor is over 1m. A special pressure calibration device must be developed according to the shape and loading range of the sensor.

The pneumatic calibration device mainly includes three parts of precision pressure regulating device, balloon and the balloon-carrying chamber. The precision pressure regulating device is a common industrial item, which will not be described here in detail. During research and development, it has been found that the shape of the inner tube of the bicycle is highly consistent with the shape of the sensor, which is completely suitable for serving as the balloon. One special chamber was designed based on the balloon, which was divided into the upper part and lower part. The upper part was the balloon installation area while the lower area was the base. Both parts were connected by the quick-release pin and industrial hinge, forming an open/close layout. To guarantee the device's loading capacity, based on the finite element analysis, the number and specifications of the quick-release pin and hinge were determined. At the same time, the stiffener was added inside the chamber to ensure uniform internal force and minimize the overall deformation of the device during pressurizing (Fig. 5).
The upper and lower chambers are machined with 7075 aviation aluminum alloy. By test, the maximum pressure range of the entire calibration device can reach over 1 Mpa.

Fig. 6 Use of pneumatic calibration device

2.4.2 Analysis of calibration data

By collecting and analyzing the pressure calibration data, the sensor calibration data is optimized by threshold method. After determining the calibration line range of the sensor, the calibration data is divided into different calibration lines (Fig.7, Fig.8), thus identifying the calibration line for the sensor array's sensitive points. Such practice can achieve the precise collection of pressure data of 225 points. The system measurement precision after calibration is ~5%, similar to its foreign counterpart tekscan product.

Fig. 7 The relationship between the force value and pressure
3 Image and data analysis of pressure distribution

3.1 Image of pressure distribution
Domestic aviation manufacturing and repair enterprises generally use the anchor spring clip together with the metal plate for bonding and curing. The clamping strength of the single spring clip is about (35~40)kg. When the clamps are arranged at a certain spacing, it can be deemed that under the ideal condition, the pressure distribution is uniform. By pressure calibration, (0.2~0.3)Mpa is set to the color code 5 (light blue), and the system is connected to the clamp. The distribution of color code is seen in Fig.9. First, there are plenty of blank spaces, which can be deemed as the force-free area. Second, the color code spans 16 dimensions, indicating that the pressure distribution is obviously uneven in the force-loading area.

3.2 Analysis of pressure distribution data
Several operators were selected to apply pressure repeatedly, and different pressure distribution results were produced. Five groups of data were randomly selected, and the statistical results of pressure data at 225 points were seen in Table 2. The analysis results are as follows:
  ● The pressure distribution difference is produce in case of a different operator and clamp installation sequence, as well as the slight change of clamp installation position.
  ● The uniformity of pressure distribution can be expressed by the dispersion degree of data, namely the coefficient of variation, which is generally over 40%, and even close to 70% in the pressure out-of-tolerance area.
Due to the equipment deficiency, the pressure out of tolerance cannot be eliminated no matter how to adjust the clamp position.

### Table 2 Pressure distribution data

| Number | Mean (MPa) | MIN (MPa) | MAX (Mpa) | Coefficient of variation |
|--------|------------|-----------|-----------|--------------------------|
| 1      | 0.27       | 0         | 0.83      | 42.6%                    |
| 2      | 0.25       | 0         | 1.06      | 43.7%                    |
| 3      | 0.26       | 0         | 0.78      | 38.6%                    |
| 4      | 0.26       | 0         | 0.86      | 40.2%                    |
| 5      | 0.22       | 0         | 1.16      | 48.1%                    |

### 4 Conclusion

With response to the working condition of soft connection of the fighter jet cockpit cover, the special flexible force-sensitive pressure distributed sensor system was developed, achieving the closed-loop design and manufacturing of sensor, acquisition circuit, calibration and software. The pneumatic calibration guarantees the system precision up to 5%, similar to the foreign counterpart, and successively achieving industrial application. The pressure distribution of soft connection of cockpit cover was presented and analyzed for the first time. It has determined that there is certain quality hazard because the existing process has the serious issue of uneven pressure distribution. The system research and development may provide a forceful support for the successive optimization of soft connection process.

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