Analysis, improvement, and verification of stress in aircraft harness bending

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Abstract. This study proposes innovative wire harness bending manufacturing processes and fatigue test platforms to address the issue of wire breakage caused by bending stress during aircraft wire harness assembly. Through modeling analysis, the impact of wire harness bending length changes on internal wire core stress is clarified, and optimized manufacturing processes are designed to reduce the risk of wire breakage effectively. Simultaneously, the developed fatigue test platform can simulate different bending conditions, verifying the reliability and effectiveness of the new processes. This technology addresses manufacturing challenges under assembly space constraints and bending requirements, improving the flexibility and assembly quality of wire harnesses by reserving process allowance and optimizing bending molds. Experimental results show that the improved wire harnesses exhibit higher fatigue resistance during simulated docking tests, significantly reducing damage and providing a strong guarantee for the safety and reliability of aircraft wire harnesses. This research not only provides new solutions for the field of aircraft wire harness manufacturing and assembly but also has significant implications for improving the overall performance and safety of aircraft.

Keywords: Aircraft wiring harness; Bending length model; Bending manufacturing process; Wiring harness fatigue test platform

1 Introduction

The manufacturing and assembly techniques of aircraft cables stand out as a cardinal phase in aircraft construction, encapsulated with a holistic consideration of structural, electrical, and assembly compatibility attributes. These techniques must satisfy not only functional demands but also performance requisites. Unlike rigid structural elements, cables, on account of their flexibility, pose a considerable challenge to design engineers in controlling their shape and location in the design of wire harness paths [1]. During the product assembly process, handling the assembly of cables alongside rigid structures often involves a crisscross method. The practical assembly skills of the assemblers play a crucial role in determining the assembly quality. While complex to capture, these skills typically resist formulation by mathematical equations [2]. The count of cables also tends to rise in correlation with the complexity of products, stirring up an exponential increase in cable assembly sequence, with a diversified selection for cable assembly paths.

The majority of the planners of aircraft cable assembly technology accomplish the task after rigid structural items are produced, undergoing trial mounting on the actual physical model. Subject to repeated mounts, the process seeks to determine relevant information on flexible cables, hence making it strenuous to accomplish a unified process of cable assembly. As a result, it hardly suffices to maintain the quality, reliability, consistency, and coordination in cable assembly, making precise assembly an utmost priority [3]. Control over bending in cables represents a critical limiting factor in the assembly phase, requiring discrimination based on cable type and outer diameter, among other physical aspects. However, the stringent space constraints often shadow the need for conditions of assembly. Additionally, the conventional method of equal-length flat production cannot support the mounting needs in these confined spots, inevitably leading to frequent open circuits in individual conductors within the cables [4-5].

Cable harness assembly, an indispensable quality control phase in aircraft assembly, involves the strict channeling of various cable harnesses to distinct compartments post-installation. Following their anchorage through clamps post-installation, cable harnesses incur various degrees of bending under the impact of factors such as material attributes, slack in length, and installation methodology [6]. Under different bending states, the harness experiences differing levels of tension. The landscape changes further within the cable core in different areas within the harness [7-8]. If a harnessed cable is subjected to continually increased stress post-bending, it can compromise both the longevity of the harness and the electrical connectors' reliability of contact [9].

Currently, the installation of wiring harnesses on aircraft often primarily draws on empirical knowledge to specify reference ranges for technical requirements such as length and bend degree, owing to the intricacy of onboard installation conditions. However, the internal stress conditions of the wiring harness vary in response to different technical requirements. No definitive data exists to support this. In this paper, we have taken the initiative to model the force situation encountered by the bending harness and have also undertaken a theoretical analysis of the relationship between the bending radius and the occurring stress. Based on this groundwork, we have presented a crafting process for cables with inadequate radii in the design stage, also providing the requisite precautions for harness assembly derived from curved manufacturing processes. Furthermore, a fatigue testing platform for the cable harness has been designed, which can simulate a wide gamut of bending conditions for cable harnesses in an off-aircraft setting. This testing platform substantiates that our approach in bending manufacturing substantially mitigates wire breaks due to over-stress in cable harnesses, thereby improving the quality of cable harness assembly.

2 Cable Harness Bend Modeling

2.1 The Cable Harness Bends the Theoretical Length Model

The cable harness bend theoretical length model, employing parameters such as the lengths of cable segments and bending angles, serves to compute the alteration in length experienced by the cable corresponding to any pin location on the terminal face during the course of cable deformation. A graphical representation of this model is shown in Figure 1.

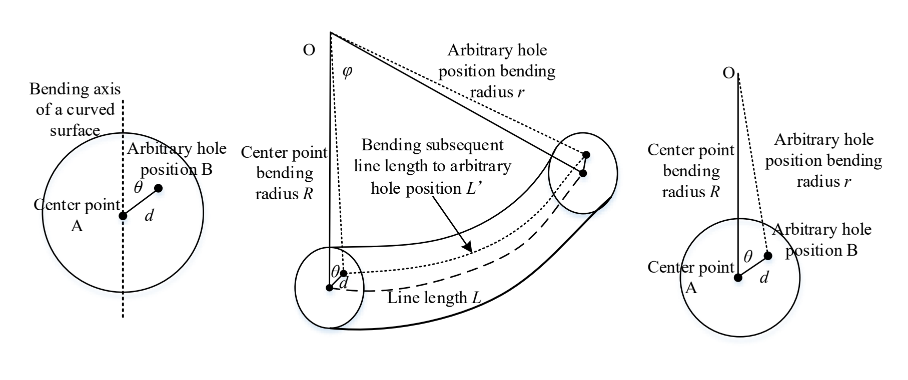


Fig. 1. The cable harness bends the theoretical length model.

Upon the induction of curvature in a segment of the cable harness, the parameter detailing the bending radius specific to the midpoint of said cable segment is defined as:

$$R = \frac{L*360°}{2\pi*\varphi} = \frac{L*180°}{\pi*\varphi} \tag{1}$$

When the cable segment bends, a triangle is formed by the bending radius at the center point R, the bending radius r at any pinhole, and the distance d from the pinhole to the center point on the terminal face of the electrical connector, with an inner angle θ. According to the Cosine Law, the following relationship can be deduced:

$$r = \sqrt{R^2 + d^2 - 2Rd\cos\theta} \tag{2}$$

Therefore, the theoretical length L` of the cable at any pin position after bending can be calculated accordingly.

$$L` = 2\pi r * \frac{\varphi}{360°} \tag{3}$$

Consequently, the length variation of the core wire at any pinhole during the bending process can be formulated as $\Delta L = |L - L`|$, substituting the corresponding parameters we have:

$$\Delta L = \left| L - \frac{2\pi\varphi}{360°}\sqrt{\left[\frac{L^2}{\pi^2} * \left(\frac{180°}{\varphi}\right)^2 + d^2 - \frac{360°}{\varphi} * \frac{L*d*\cos\theta}{\pi}\right]} \right| \tag{4}$$

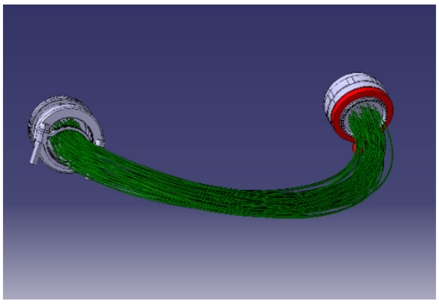
When $0 \leq \theta \leq 90°$, the core wire is situated on the inner side of the bending channel, resulting in wa ire length decrease; when $90° \leq \theta \leq 180°$, the core wire is positioned on the outer side of the bending channel, causing the wire length to increase. Here, 'd' represents the distance from any pinhole to the center of the terminal face; 'L' represents the testing cable length; 'φ' represents the cable bending angle; 'θ' represents the angle between the line connecting a given pinhole on the terminal face to the center point and the plane in which the cable segment bends.

3 Methods and Effects of Wire Harness Bending in Manufacturing

3.1 Current Methods and Issues in the Production of Planar Equally-Length Wire Harnesses

The current manufacturing processes for aircraft wiring harnesses follow a planar equi-length method, where production units mark and terminate the harnesses to the designed length on a flat workstation. Due to the confined working space in aircraft installations, wire harnesses are typically installed pre-assembly and then interconnected post-installation. During such interconnection, the bending radii of harness ends are often very small, with a differential need for wire lengths on the inside and outside of the curve. The planar equal-length manufacturing method cannot adequately meet the assembly requirements. Moreover, due to insufficient flexibility at the branch ends, external wires can become overstretched and lead to wire breakage upon bending.

A model of theoretical bending length for wiring harnesses provides quantifiable predictions for the lengths of wire after curving, which can be utilized to refine existing manufacturing procedures for harness production. Owing to spatial limitations in certain aircraft compartments, it is imperative to bend wiring harness branches for connection post-production. This necessitates the wires from the outer sides of the connectors to be longer than those from the inner sides; thus, we simulate and model the internal wires of the interconnection wire harnesses, as shown in Figure 2. However, under the traditional planar equal-length manufacturing process, the lengths of wires situated on the inner and outer sides of the harness curvature are identical. As a result, some harnesses with short overall lengths and poor limberness result in the outer wires being stressed upon bending, which may lead to wire fracture and failure.



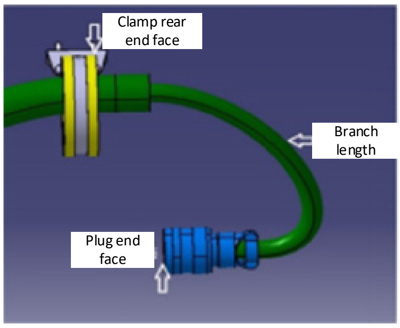
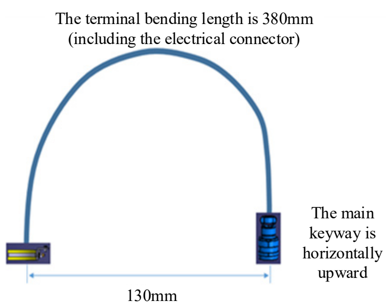


Fig. 2. The required lengths of the inner and outer wires are not consistent when the wiring harness branches bend.

Fig. 3. Wiring harness branching model.

3.2 Wire Harness Bending Manufacturing Process Method

To address the aforementioned issues, we propose an innovative manufacturing technique for wire harness branch end bending. The characteristics of the wire harness branch end (as shown in Figure 3) are extracted, which include three quantifiable features (as shown in Figure 4): the diameter of the wire harness branch end bending, the total length of the wire harness branch end (including the connector) and the relative position of the main keyway of the connector with respect to the direction of wire harness bending. These characteristics are communicated to the wire harness manufacturing units. Subsequently, the units customize the bending manufacturing molds and transfer conformal fixtures based on these feature requirements. This allows for the bending of the wire harness during manufacturing and the conformal transportation of the harnessed wire, as shown in Figure 5.



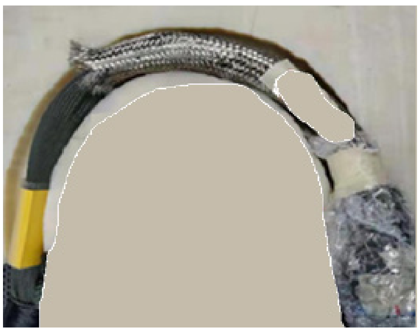


Fig. 4. Description of manufacturing characteristics for wire harness bending.

Fig. 5. Wire harness bending manufacturing mold.

In accordance with specified requirements, the harness manufacturing entity marks out wires with a 40mm technological allowance retained at the terminations. Upon entering the harness bending mold for wire arrangement, a maximum discrepancy of 39mm in length is observed between inner and outer wires at the curvature, as calculated through three-dimensional simulation shown in Figure 2. Adhering to the constraints of the bending mold, the outer wires are allocated a 40mm technological allowance, while the inner wires are only allotted a mere 1mm leeway for manufacturing variability. Wires at the midpoint are assigned a 20mm technological allowance. Following a graduated system, corresponding allowances are systematically allotted to other wires in the harness. The process reaches closure with the termination and assembly of connectors, culminating in the creation of a harnessed branch that meets the requisite criteria for bent manufacturing. This manufacturing methodology is graphically elucidated in Figure 6.

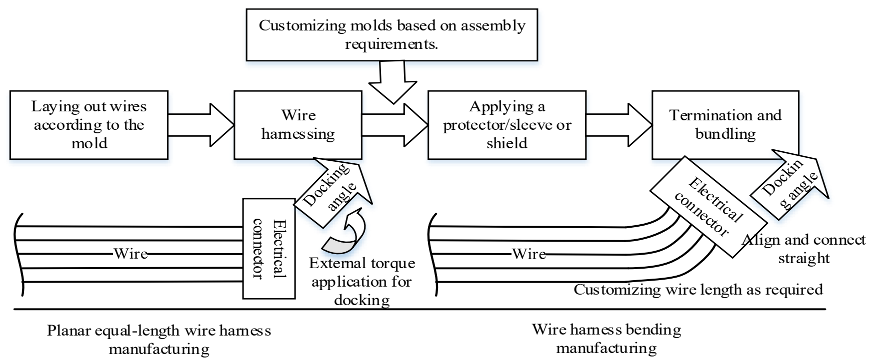


Fig. 6. The cable harness bends the theoretical length model.

3.3 Precautions for the Laying and Installation of Harnesses after Bending Manufacturing

In the process of cable harness installation, the bay where the bending manufacturing branch resides should be selected as the starting bay to avoid deformation of the shaped branch harness during laying. If it cannot be guaranteed that this bay can serve as the initial start point, the cable harness branch's layout path should be specifically defined in the laying Assembly Operation (AO). This ensures that the bending status of the harness does not change due to overframe issues or force deformation during the process of laying. During cable harness installation, when adjustments are being made for bay harness installation, priority should be given to securing the clips at the ends of branches involving bending manufacturing connectors. Before fixing the clips, a simulation of the connector mating status should be undertaken. This guarantees that the harness's bending status is basically consistent with its status after mating with the finished product, therefore ensuring the harness deformation does not compromise the effectiveness of the bending manufacturing process.

3.4 The Outcome of Quality Improvement in the Wire Harness Bending Manufacturing Process

Improvements were made to the wire harness bending manufacturing processes for the two plug ends of the aircraft that undergo bending during mating. This improvement was implemented, and adjustments were made to the laying and installation requirements after the bending manufacturing process. Post implementation, there have been no re-occurrences of wire breakage at the ends of these two plugs, effectively solving the issue of wire disconnection. This suggests that improvements in the bending manufacturing process have been effective.

4 Wire Harness Bending Fatigue Test

4.1 Overall Design of the Wire Harness Fatigue Test Platform

To verify the fatigue resistance of the wire harness after bending manufacturing, we designed a wire harness fatigue test platform, as shown in Figure 7. The structure of the test platform includes:

- A triaxial moving platform.
- A workbench.
- A control cabinet.
- Clamp slider for wire harness.
- Clamp support for wire harness.
- Slider track for wire harness clamps.
- A three-jaw chuck.
- A spherically hinged base.
- Harness clamp.
- Testing wire harness.

The wire harness fatigue test platform is designed to simulate the conditions that a wire harness could encounter over its service life. Its purpose is to repetitively bend the harness until cumulative strain leads to fatigue damage. This method, forcing the harness to repeatedly withstand such stress that it might only experience once or periodically during actual use, tests the product's limits. The aim of this testing is to assess the harness's durability under the stipulated conditions (which are often more severe than typical operational conditions). The objective of testing under more stringent conditions is to ensure the reliability and safety of the wire harness under both standard and extreme conditions, providing detailed insight into the harness's durability and robustness.

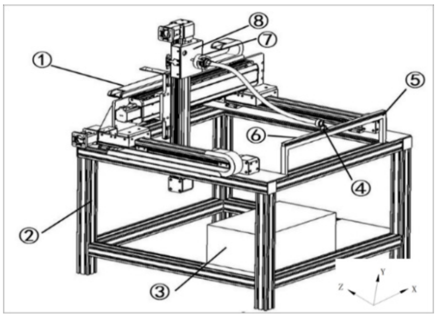


Fig. 7. Wire harness fatigue test platform.

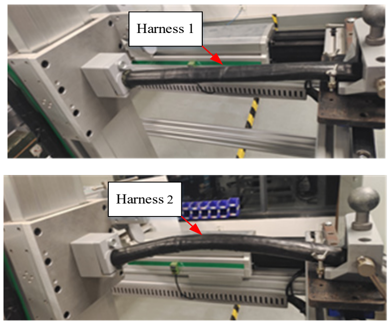


Fig. 8. Wire Harness Fatigue Comparative Test.

4.2 The Design of Wire Harness Fatigue Testing

In order to validate the performance of the wire harness post-bending manufacturing using the test platform, a wire harness fatigue comparative test was designed. Harness 1 is a 99-core planar isometric manufactured cable, with all wire cores having a length of 400mm. Harness 2 is a 99-core bending manufactured wire harness with wire core lengths ranging from 380mm to 420mm. The outer side of the curved harness is 40mm longer than the inner side. The test platform drives the bending motion of the harnesses, simulating the bending and mating process of the harness connectors. Harness 1 and Harness 2 undergo the same test conditions, as shown in Figure 8.

4.3 The Analysis of Wire Harness Fatigue Test Results

The test harness was installed on the fatigue test platform. We simulated the installation and mating process of the harness in the aircraft under the settings on the simulation test platform. The parameters were configured as follows: bending angle of 180° downward, bending movement speed of 0.3m/s, and an ambient temperature of 25°C. We proceeded to simulate the mating process 10, 000 times and 50, 000 times, observing the test results after each simulation. Detailed results are shown in Tables 1 and 2.

Table 1. Results of the bending test after 10, 000 cycles.

	No. of bending cycles	Damage outcome
Harness 1	10, 000 times	Two conductors are broken at the upper edge
Harness 2	10, 000 times	0 conductors broken

Table 2. Results of the bending test after 50, 000 cycles.

	No. of bending cycles	Damage outcome
Harness 1	50, 000 times	Five conductors are broken at the upper edge
Harness 2	50, 000 times	0 conductors broken

The planar equi-length manufactured wire harness exhibited conductor breaks -2 conductors after being subjected to 10, 000 simulated bending cycles, and a further increase to 5 conductors after 50, 000 bending cycles. In contrast, the bending manufactured wire harness did not record any conductor breakage through the entire simulation process (both at 10, 000 and 50, 000 bending cycles). This test result unequivocally suggests that the wire harness produced through the bending manufacturing method can effectively reduce fatigue-induced damage during the bending process when compared to those made with planar isometric manufacturing. As can be seen from the previous theoretical analysis, differences in wire core lengths directly affect the bending performance and internal stress distribution of the harness. In harnesses with equal-length wire cores, stress concentration occurs on the outer wire cores during bending, which can easily lead to wire breakage due to bending. However, in curved harnesses with unequal wire core lengths, the harness is manufactured using molds to achieve the desired curved shape. During bending, there is no stress concentration on the outer side of the harness, thus preventing wire breakage due to bending.

5 Conclusion

This research focuses on the wire breakage issue caused by bending stress during the assembly of aircraft wiring harnesses. Modeling analysis clarifies the impact of changes in harness bending length on internal wire core stress, revealing the differences in the stress conditions of the harness and its internal wire cores under different bending states. This provides a theoretical basis for optimizing the manufacturing process. Based on the results of harness bending stress analysis, an optimized harness bending manufacturing process is designed. By reserving process allowance and optimizing the bending manufacturing mold, the risk of wire breakage caused by excessive bending stress is effectively reduced, improving the flexibility and assembly quality of the harness. A fatigue test platform has been developed to simulate different bending conditions to verify the optimized harness manufacturing process. Experimental results show that the improved harness exhibits higher fatigue resistance and significantly reduces damage in simulated docking tests. Through practical application, the harness bending manufacturing process and fatigue test platform proposed in this research has been verified, solving the harness manufacturing challenges under assembly space limitations and bending requirements and providing strong support for the safety and reliability of aircraft wiring harnesses.

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