Reliability Analysis of Structure Strength based on Spacer Installation Robot

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Abstract. During the construction of high-altitude 10kV power lines, manual installation for spacers has considerably numerous limitations and problems, for example, safety issues, efficiency etc. A new-type spacer installation robot has been introduced to assist the worker to install spacer in air. Prior to put it into usage or production, the reliability of structure strength needs to be tested and verified. This paper verifies the reliability through mathematical calculation and Solidworks/Simulation in which generates stress and displacement plots to determine whether the stresses and elongations in the structure are in a reasonably safe range for both under working conditions and without load.

1. Introduction

With the rapid development of technology, automatic robots have been playing an increasingly significant role in people’s daily lives. Due to this EHV transmission technology¹ that is not yet fully matured, there are mainly three ways to install spacers²³ between power lines: 1). The personnel steps on the power line to install the spacer; 2). Use aerial work flyers⁴ for spacer installation. 3). Aircraft-assisted installation⁵. However, the above methods all have their own problems. For instance, the safety of construction personnel is not guaranteed though with protection equipment, and the installation efficiency is low. Secondly, the working flyers are not fully automated that still need assistance from personnel. Hence, cost and efficiency problems are still not improved or addressed. Lastly, the cost of aircraft-assisted installation is considerably high.

In addition, the installation process is extremely dangerous and time-consuming since workers are only protected by one single safety belt at high altitude. Therefore, the spacer installation robot has been innovated to ensure the safety of workers and speed up the installation process. Plenty of experiments have been performed in the laboratory to test and verify its ability of obstacle climbing and the automaticity of repairing and maintaining power transmission and transformation system. Moreover, this spacer installation robot is designed based on the pivotal technology ---- RTK positioning technology⁶⁷.

To be more specific, the purpose of this paper is to examine and determine whether the material, structure and design of this robot is reliable enough to support the personnel working on the power lines in air.
2. The Structure of Spacer Installation Robot and Carrying Capacity Analysis with Simulation

2.1. Design of Spacer Installation Robot
The scheme of the design of spacer installation robot is shown in Figure 1. The design mainly has seven modules controlling the working platform: mounted walking module, working platform module, disassembled toolbox module, spacer mounting module, power module, visualization control module and vision control module. The main structure is made of 6061 aluminum alloy. In consider of cost, machinability, anticorrosion, weight and density, 6061 aluminum alloy has good performance in all these aspects. Therefore, 6061 aluminum alloy is overall the best option for the design.

It is easy to be carried and assembled with bolts and nuts between each module since all modules are assembled in advance. Portability and weight are also important factor for the design.

2.2. Physical Prototype in Real Working Condition
In the real working condition, personnel sit on the working platform with control rocker on the left to move forward and backward in various construction environment. When it arrives at the designated position, take off one spacer hanged on the working platform and install it on the quad split wire. Repeat the previous steps to install more. The simulated working condition for reality is done in the laboratory which only shows the working scheme of the spacer installation robot.

As illustrate in the figure 3, there is not obvious hazard by visual observation. However, it is not yet enough to conclude that it can be put into use. Then, mathematical models and simulations need to be performed to test the reliability of spacer installation robot.

Figure 1: Scheme of the Designed Spacer Installation Robot

Figure 2: Solidworks Model of Spacer Installation Robot

Figure 3: Simulated Working Condition for Reality
2.3. Mathematical Calculation

To verify the reliability of spacer installation robot, the maximum capacity of taking weight and elongation is required to be tested and verified to ensure the safety of workers.

To be specific, the weight of this spacer installation robot can be determined by using:

\[ W = mg \]  \hspace{1cm} (1)

Where \( W \) is weight; \( m \) is mass; \( g \) is gravitational acceleration.

Then, by checking its tensile stress inside these four beams, to make sure that the maximum tensile stress is not exceeding its yield strength using:

\[ \sigma_t = \frac{P}{A} \]  \hspace{1cm} (2)

Where \( \sigma_t \) is tensile stress; \( P \) is tensile force acting on the beam; \( A \) is cross sectional area of the beam.

By comparing calculated stress and tensile yield strength, the maximum stress that each beam is taking without personnel is less than 0.1% of the tensile yield strength 6061 aluminium alloy but less than 0.2% with personnel working on it. Therefore, the beam is able to safely support the robot and worker.

Moreover, calculate bending stress of the working platform by using:

\[ \sigma_b = \frac{Mc}{I_z} \]  \hspace{1cm} (3)

Where \( \sigma_b \) is bending stress; \( M \) is moment about z-axis; \( c \) is distance to neutral axis; \( I_z \) is moment of inertia about z-axis.

To obtain \( I_z \), the value of it depends on the shape and position of each segment to the neutral axis. By using the equation (4) below, the moment inertia about z-axis of each segment can be calculated. Then, the total moment of inertia about z-axis of the working platform is simply the sum of each segment.

\[ I_z = \frac{1}{12}bh^3 + Ad^2 \]  \hspace{1cm} (4)

Where \( I_z \) is moment of inertia about z-axis; \( b \) is width of each segment; \( h \) is height of each segment; \( A \) is area of each segment; \( d \) is distance to neutral axis.

Eventually, the calculated maximum bending stress of the working platform is within an acceptable range.

3. Verification of Solidworks/Simulation

The stress distribution and elongation on the spacer installation robot is significantly vital for the designed structure. Hence, a verification of structure reliability is necessary to be performed by using Solidworks/simulation.

A model of simplified spacer installation robot is created for better stress and displacement analysis by using the same parameters with the original design as shown in figure 4. For this simulation, the mounted walking module on power lines is assumed to be fixed. The mounted walking module and spacer mounting module are connected to working platform module via bolts. The bolt connection is set up to be rigid. There are two loads acting on the machine: gravitational force of spacers and weight of a 60-kg worker as demonstrated in table 1.

![Figure 4: Simplified Model of Robot](image-url)
Table 1: Loads Acting on the Robot

| Load Name                        | Load Image                                                                 |
|----------------------------------|----------------------------------------------------------------------------|
| Gravitational Force of Spacer    | ![Image of Gravitational Force of Spacer]                                  |
| Weight of a 60-kg Worker         | ![Image of Weight of a 60-kg Worker]                                       |

Figure 5 and 6 demonstrates the stress distribution that the structure is taking and to what degree it needs to be modified to be able to take more stress. In figure 5, based on calculations, the simulation of stress distribution verifies that the beams are under reasonable stress and are all in good conditions without loading. However, the working platform module is under stress up to 0.1359 MPa. Compared to its maximum allowable stress, it is less than 0.3% to its yield strength.

Figure 5: Stress Plot without Loading

Figure 6: Stress Plot with Loading
Moreover, simulation with assumption of a normal 60kg person working on the spacer installation robot is performed with six spacers hanging on each handle. Each spacer weighs 8kg. As illustrated in figure 6, under simulated working situation, maximum stress of the working platform taken is 1.436MPa which is 2.5% to its yield strength. Overall, all beams perform strong capacity of taking downward force in both cases.

Furthermore, displacement plots have been generated either with or without loading for spacer installation robot to analyse reliability of the structure strength shown in figure 7 and 8. It is clearly shown that tiny to no elongations occurred for these four beams in both cases and there is mainly no displacement of middle of the working platform when not loading. However, as shown in figure 8, displacement occurs within 0.0154mm under 60kg working condition since it is carrying a battery cell.
4. Conclusion
In a view of the reliability of spacer installation robot, specific research is performed to verify its reliability and safety issues. In accordance with all the calculations and experiments performed, strength of the structure of spacer installation robot is satisfied with daily working conditions. Based on the mathematical calculation, beams take stresses up to 0.1% and 0.2% to its tensile yield strength in either with or without workers on it, respectively. The simulation shows there is mainly no change of beams in both cases. Nonetheless, the working platform module is the most important object of analysis. The working platform has tiny to no displacement when it is not loaded. However, small displacement occurs on the platform when loaded with 60kg having maximum deflection of 0.0154mm.

Overall, the design of structure strength of spacer installation robot has been verified and the safety issue of workers is ensured during constructions. Hence, the spacer installation robot has come to an anticipant result.

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