Electric Performance Model and Finite Element Analysis of Fuzz Button

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Abstract. This article focuses on the electrical properties of the Fuzz buttons, determines the relevant parameters that reflect the electrical properties of the Fuzz buttons at work, and establishes three electrical models of Fuzz buttons based on the actual shape and manufacturing process of the Fuzz buttons. Using HFSS software to analyze the electrical performance of the Fuzz button, various curves of the electrical performance parameters of the Fuzz button following the frequency change are obtained. By comparing with the electrical performance data measured by the Fuzz button laboratory, the accuracy of electrical performance parameters are analyzed under three models, so that providing a basis for the establishment of a more accurate electrical performance model of the Fuzz button.

Keyword: Fuzz buttons; Electrical performance; HFSS.

1. Introduction
With the development tendency of electronic systems being in the direction of integration and intelligence, the system structure becomes more and more complex, and its volume becomes larger. In recent years, the three-dimensional assembly technology has attracted more and more attention because it can greatly increase the system's assembly density and reduce the size of the system, especially the technology which has broad application prospects in the aerospace and military fields [1]. However, the aerospace field places extremely strict requirements on the reliability of electronic systems, and with the development of electronic warfare technology, the performance requirements of electronic equipment for signal transmission have increased significantly. Modern military and civilian electronic equipment, especially radar and communication systems such as airborne and bomb-borne, not only require electronic equipment to become smaller and smaller in size and weight, but also require higher technical indexes and more functionalities. Especially in weapons platforms such as combat aircraft, drones and smart bullets, the requirements for volume and quality are getting smaller and smaller, but the demand for equipment with higher indicators and more functionalities is doubling. Electronic equipment is developing in the direction of miniaturization, light weight, high integration, high operating frequency, multi-function, high reliability and low cost [2], which places higher and higher requirements on assembly and interconnection technologies. The three-dimensional packaging
and assembly technology can greatly reduce the parasitic loss during signal transmission, reduce the power consumption of the system, and achieve high-density packaging [3] at certain level, which therefore makes this technology being particularly important and worthwhile an in-depth study. Vertical interconnection technology is one of the solutions of three-dimensional assembly technology [4]. However, the traditional design methods in today's world cannot meet the above connection requirements, and new design ideas and integrated process methods must be developed.

The use of Fuzz buttons instead of connecting wires [5], and by supporting the auxiliary structure between the boards, can realize the vertical interconnection between the mechanical and electrical aspects of the circuit boards [6]. Fuzz button has good RF and DC transmission performance, and is able to greatly reduce the number of cables used and completes the three-dimensional assembly, thereby reducing the size and quality of the system and facilitating subsequent maintenance and repair. This paper break through the limitation of researching which was solely performed on the application of Fuzz buttons in the past. Taking the constitutive model of Fuzz buttons as the research object, this paper focuses on the electrical performance parameters of Fuzz buttons. As well, by using software, it establishes a micro-model of Fuzz buttons to understand the internal structure of Fuzz buttons in depth. It performs finite element analysis of the electrical performance parameters of Fuzz buttons and increases the experimental group for reference. It aims to provide a true, accurate and reliable Fuzz button model, in order that it provides a basis for in-depth study of the electrical performance model of the Fuzz button.

2. Micro Model of Fuzz Button

The size and specifications of the Fuzz buttons used in the following models are: diameter 2mm, height 7.62mm, metal filling rate 25%, internal wire diameter 50μm. According to the structure, size and processing method of the Fuzz button, the hollow cylindrical wire frame structure and the bent wire micro-element structure were established.

2.1. Hollow Cylindrical Wire Frame Structure

Referring to the internal structure and manufacturing process of metal rubber it is found that they are very similar. The metal rubber is a homogeneous elastic porous material [7], which is made by firstly applying a special processing method to discharge a wire, of a certain quality, stretched, and of spiral-state in an orderly stamping or rolling die, and then finalizing its shape by cold stamping and the necessary heat treatment process. Because it not only has both of the elasticity and the damping properties of rubber materials, but also maintains the appearance of metal, this material is named "metal rubber". Referring to the modelling process of metal rubber, the modelling process of Fuzz buttons is as follows:

1) Create a hollow Archimedean spiral with a maximum diameter of 2 mm on the YOZ plane, as shown in Figure 1.

![Figure 1. Hollow Archimedes spiral.](image1.png)

2) Stretching in the X direction. After creating the plane foundation, let it stretch along the X axis, the extension length is according with the length of the Fuzz button model, 7.62mm. We then add a large number of straight lines with a length of 7.62mm as the surface of each layer, forming a grid structure. Create a straight line every 10°, in other word, there are 36 straight lines in a circle, and each adjacent
two spiral lines can be divided into 36 grids, and therefore there are five layers from the outside to the inside, as shown in Figure 2. Only in this way can these spirals become a whole with certain conductivity and testability, and at the same time, they are also the basis of the excellent ductility and stretch ability of metal rubber.

2.2. Micro-element Model of Bent Wire
The structure of the Fuzz button is actually a cylinder formed by randomly arranged metal wires. Therefore, in the modeling process, it is useful to consider in this direction. However, it is difficult to achieve a true disorder through software modeling. We can only start thinking from the most basic model and accomplish it gradually. Figure 3 gives a physical picture of the button for comparative study.

After actually observing the appearance of the Fuzz button, the metal wire inside the Fuzz button can be defined as bending wire, and multiple bending wires are arranged in a cylinder of a certain volume, and there are different positional relationships between them, each bending direction and degree of the wire are also different. Through such simulation, the model can be established to the greatest extent based on the "disorder" criterion. As long as the single bending wire of the bending wire microelement is designed according to certain metal material, the cross-sectional diameter of the metal material is guaranteed, and then each bending wire is elongated to different degrees, and the positional relationship of them is intentionally disturbed, which is made close to Fuzz buttons. In this case, the bent wire microelements are no longer in a non-contact state, but have a combination of mutual contact, as shown in FIG. 4. On the basis of this minimum element, a complete Fuzz button model can be established. It can be divided into ordered bending wire and micro-element model without bending wire.

2.2.1. Ordered Bending Wire Micro-element Model
Ordered bending wire, as the name implies, refers to the orderly arrangement of the wires in the model. Define a certain number of copper wires with a cross-sectional diameter of 50 μm, construct a certain degree of bending and extension, and arrange them inside a cylinder with a length of 7.62 mm to form a Fuzz button model, as shown in Figure 5.
2.2.2. Micro-element Model of Disordered Bending Wire
In order to get closer to the real Fuzz button model and highlight its "disorder" characteristics, the model needs to be further optimized and improved. In the process of modeling, it is necessary to change the cross-sectional direction, bending degree and extension degree of the end surface of the wire inside the Fuzz button and arrange them randomly within the cylinder to reflecting various positional relationships. Build the Fuzz button model base on the above argument, as shown in Figure 6.

Figure 6. Micro-element model of disordered bending wire.
Observing this figure, we can see that the arrangement of the internal wires basically meets our design requirements and guidelines. Except for very few combinations, each wire has only the same cross-sectional area, and the bending extension length and number of turns are almost all different. The preliminary model contains almost all possible spatial position relationships except penetration. For example, on the left side of the cylinder in the figure, there are two parallel relations; on the right side, there are two tangential relations; there is also a wire that obviously runs through the entire cylinder and extends in the X-axis direction. This wire has contact points with a large number of wires. This model is also very similar to the actual model of Fuzz buttons.

3. Analysis of Electrical Performance Parameters of Fuzz Button
In this experiment, we will complete our model establishment and parameter simulation in HFSS software. HFSS – High Frequency Structure Simulator Ansoft's 3D electromagnetic simulation software, which has been acquired by ANSYS company; it is the world's first commercial 3D structure electromagnetic field simulation software, the industry recognized industry standard for 3D electromagnetic field design and analysis. HFSS provides a simple and intuitive user design interface, an accurate adaptive field solver, a powerful post-processor with unprecedented electrical performance analysis capabilities, and being able to calculate S-parameters and full-wave electromagnetic fields of three-dimensional passive structures of arbitrary shapes. HFSS software has powerful antenna design functions, which can calculate antenna parameters such as gain, directivity, far-field pattern profile, far-field 3D graph and 3dB bandwidth. It is able to be used to draw polarization characteristics, including spherical field components and circular polarization field components, Ludwig third definition of field components and axial ratio. Using HFSS, you can calculate: ① basic electromagnetic field numerical solution and open boundary problems, near and far field radiation problems; ② port characteristic impedance and transmission constant; ③ S parameter and normalized S parameter of the corresponding port impedance; ④ eigenvalue of the structure Or resonance solution. Moreover, the Ansoft high-frequency solution composed of Ansoft HFSS and Ansoft Designer is currently the only high-frequency design solution based on physical prototypes, providing fast and accurate design methods from system to circuit to component level, covering All aspects of high frequency design.

3.1. Parameter Selection
Resistance: Impedance is a physical quantity that represents the performance of a component or the electrical performance of a circuit. In a circuit with resistance, inductance, and capacitance, the impediment to the current in the circuit is called impedance. As mentioned earlier, the Fuzz button acts as a "wire" in the vertical interconnection technology. The impedance is an important parameter to measure the transmission of electrical signals. The smaller the impedance, the smaller the Fuzz button's restriction on the current transmission, and the transmission performance will be stronger.
Insertion loss: Insertion loss mostly refers to power loss. Attenuation means that the amplitude of the
signal voltage is smaller than the original signal amplitude, reflecting the transmission effect of the signal power before and after using a certain transmission element. The smaller the insertion loss, the smaller the signal attenuation, the better the signal transmission effect. The insertion loss is an important indicator to measure the electrical performance of the Fuzz button. The simulation will also study the change of the insertion loss of the particular Fuzz button under the working state of signal input at different frequencies.

Return loss: The return loss represents a parameter of the signal reflection performance. On the one hand, it reflects the transmission capacity of the Fuzz button, on the other hand, it also reflects whether the Fuzz button is qualified or not. Return loss means that part of the incident power is reflected back to the signal source, combining the effects of both reflections, including deviations from the nominal impedance and structural effects, to characterize the performance of the link or channel. It is caused by the non-uniformity of the characteristic impedance on the Fuzz button. In the final analysis, it is caused by the reflection of the signal at different locations in the Fuzz buttons, the signal arriving at the receiving end is equivalent to the multipath effect in the propagation of the wireless channel, resulting in time spreading and frequency selective fading of the signal. Time spreading causes pulse broadening, which causes the receiving end Signal pulses overlap and cannot be judged.

3.2. Simulation Results
In this experiment, we set the solution frequency to 10GHz to improve simulation accuracy. At the same time, based on the actual measured data table 1 of the Fuzz button, it is compared with the data simulated by the software to analyze the accuracy of the model.

Table 1. Actual measurable data.

| Technical Specifications                                      |
|-------------------------------------------------------------|
| Applications       | LGA, BGA, PGA, CGA, QFN                               |
| Contact Pitch      | 4mm and Above                                         |
| Current Capability | 5 Amps Continuous                                     |
| Operating Temperature | -60°C to 150°C                                |
| Typical Matting Cycles | Fuzz Buttons alone up to 5000 cycles/ with Hardhats up to 500,000 cycles |
| Frequency Capability | to 40 GHz in natural state, to 100 GHz with design optimization |
| Ctrex Talle/Randwidth | 20dB@10GHz                                  |
| Insertion Loss S21 | -1dB@26GHz                                             |
| Return Loss S11    | -20dB@10GHz                                           |
| Inductance         | 0.19nH Self / 0.03nH Mutual                          |
| Capacitance        | 0.16pF Ground / 0.008pF Mutual                        |
| Resistance         | <10mΩ                                                   |
| Rise/Fall Time     | 50ps / 50ps                                           |

Note: Representative values above are for 0.20” diameter/1mm Pitch, see Technical Data page for more information on other configurations.

3.2.1. Hollow Cylindrical Wire Frame Structure
The return loss of the hollow-cylindrical wire-frame model at an incident signal of 10 GHz is -13.3 dB, which is less than -20 dB given in Table 1. However, as can be seen from the figure 7, as the frequency of the incident signal increases, the return loss of the model increases, which is in contradiction with the feature that the Fuzz button model should be able to have a stronger transmission capability under high-frequency conditions.
The hollow cylindrical wire rack structure is a relatively ordered structure, so it can show good electrical performance at low frequencies or static, but as the frequency increases, the reflected structure of the ordered structure is not as good as the disordered metal in the Fuzz button. The change in the wavelength of the silk structure causes the loss to increase, and the Fuzz button can effectively change this phenomenon. If we expand the frequency sweep range to around 15GHz, we will find that the callback loss of this model will increase dramatically. The higher the frequency, the greater the loss and the higher the rate of loss growth, which could even be reaching nearly 60%.

Figure 8 proves this, and also shows that there is a certain difference between the model and the actual structure of the Fuzz button.

As can be seen from Fig. 9, the error of insertion loss is larger. At 26GHz, the insertion loss of this model reaches -23dB, and it shows a fluctuation trend, which obviously does not meet the characteristics of Fuzz buttons. Analysis of the structure of the model shows that the hollow cylindrical wire frame structure is very similar to the grid structure, so there is a gap between each layer of grid, there is no conductor in this gap, so when the frequency of the incident signal changes, the wavelength. With this change, then at some specific wavelengths, it is likely that the signal wave is transmitted directly to the outside of the conductor without being reflected to the axial direction, but not transmitted to the other end of the conductor, causing a large insertion loss; meanwhile, there are also It may be incident on the metal wire, resulting in a very small insertion loss. This feature will make the model very unstable when transmitting electrical signals. This phenomenon will cause great problems, especially when applied in some high-precision fields. So from the perspective of insertion loss analysis, such a structure also has a gap with the actual situation of Fuzz buttons, which could be even unexpectedly large.
Figure 10. Self-impedance changes with frequency.

It can also be seen from the impedance change in Figure 10: at 0GHz, the self-impedance of the model port 1 is 1\(\Omega\), which is in line with the official data. As with the bent wire micro-element model, as the frequency increases, the self-impedance of port 1 also increases. When the frequency is increased to 10 GHz, the impedance is approximately 40 \(\Omega\), which is still maintained at the milliohm level.

3.2.2. Micro-element model of ordered bending wire

It can be seen from Figure 11: when the frequency of the input signal is 10 GHz, the return loss of this model is -20.3 dB, which is very close to the real data.

From Figure 12, it is found that the insertion loss under the ordered bent wire micro-element model is far from the experimental value. It shows that the loss of signal power in this structure is very large, but as the frequency of the incident signal increases, the insertion loss decreases, which confirms the Fuzz button.

Figure 11. Return loss changes with frequency.

Figure 12. Insertion loss varies with frequency.

From the static state in Figure 13, the port impedance of the model is 5\(\Omega\), which is consistent with the experimental data.

3.2.3 Micro-element model of disordered bending wire

It is found from Figure 14 that the value at 10 GHz is -20.10 dB, and it can be said that the measured data is very close to the theoretical one. Moreover, we found that as the frequency increases, the return loss is getting smaller and smaller, that is, the power of the incident signal reflected back is reduced, and the power of successful transmission is increased, which confirms that the Fuzz button has more Features of good transmission performance. In summary, the simulation of return loss was successful.
Figure 14. Return loss changes with frequency. Figure 15. Insertion loss as a function of frequency. For the convenience of observation, the upper frequency limit increased to around 40 GHz. It can be seen from Figure 15, the insertion loss at the frequency of 40 GHz and the measured data at 26 GHz are the same at -1 dB. It shows, with the increasing of the input signal frequency, the transmission efficiency of the Fuzz button is also significantly improved, and the most suitable range is 40GHz, where the insertion loss is suddenly reduced.

At 0GHz, the self-impedance of port 1 of the model is 1mΩ, which meets the data requirements, and as the frequency of the incident signal increases, the impedance of port 1 increases, and by 10GHz, it increases to 35mΩ. Although the growth rate is relatively large, the magnitude of the impedance is known to be maintained at the milliohm level, indicating that the impedance parameters of the disordered bending wire model are very consistent with the experimental data.

Figure 16. Relationship between self-impedance and frequency.

4. Conclusion
By comparing the simulation results of the three models, it can be found that although hollow cylindrical wire frame model of the metal rubber is similar in structure to the Fuzz button, the electrical performance is very different, which does not meet the working characteristics of the Fuzz button. The electrical performance characteristics of Fuzz button is analyzed by HFSS. The data acquired is testified by experiments done in our lab. In the future, more samples of fuzz buttons should be used to further verify the accuracy of the model.

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