Theoretical derivation and law research on electrostatic charge of human walking

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Abstract. Electrostatic charging and discharging have an important impact on the safety and reliability of electronic products, and human static electricity is one of the important sources of electrostatic hazards in the production and use of electronic products. In order to analyze the electrification law of human walking and explore the electrostatic protection measures of human body, the theoretical model of human walking electrification is further deduced on the basis of previous studies. The electrification law of human walking under typical conditions is analyzed, and the influence of maximum foot lifting height on potential is studied. When the maximum lifting height is small, the potential oscillation approximately conforms to the sine law, and with the increase of the maximum lifting height, the sine law is no longer satisfied. When the maximum foot lifting height is small, the actual peak potential cannot reach the saturation potential. Therefore, on the basis of taking electrostatic protection measures, reducing the foot lifting height when walking is helpful to prevent electrostatic hazards.

1. Introduction

With the continuous improvement of modern industrial level, polymer materials, microelectronic devices and electric explosive devices are widely used in various fields, and the harm caused by static electricity has been paid more and more attention. The most common source of static electricity in actual production, work and life is human static electricity. Due to factors such as self-action and contact separation or induction with other objects, human beings can carry thousands of volts or even tens of thousands of volts of static electricity. When the static electricity is charged to a certain value, electrostatic discharge will occur, resulting in large current and broadband electromagnetic radiation, which will cause interference, failure and even damage of electronic devices or equipment, and may ignite flammable and explosive substances, leading to major safety accidents. Therefore, the law of human static electricity and its discharge characteristics are one of the important research contents of electrostatic protection engineering [1–3].

The study of human electrostatic charging law is the basis for effective prevention of human electrostatic hazards. Academician Liu Shanghe team in China has established a simplified human electrostatic charging model and deduced the human electrostatic charging equation [1]. However, the human capacitance is not constant, and the change of posture and walking will change the human capacitance. Therefore, the model has certain limitations. Ficker of Bournot University of Technology proposed the charged model of human walking considering the change of capacitance when human walking, carried out theoretical derivation and experimental verification [4], and further improved the charged model of human walking. According to the test method of human body walking voltage specified in IEC61340-4-5 standard, Han Yunan Engineer has tested the time domain waveform of
human body walking voltage under different conditions, and proposed the equivalent circuit model of human body walking voltage[5]. The results are consistent with the live laws deduced by T. Ficker. In recent years, Chen Xi’s team of Beijing University of Technology has applied human static electricity to human-computer interaction and gait recognition, and established the charge distribution model of dressed human body[6]. However, the charged situation of human body is complex and there are many influencing factors. The electrostatic charged model of human body still needs further improvement.

Based on previous studies, this paper further deduces the theoretical model of human walking charged, analyzes the model, and discusses the influence of the maximum foot lifting height on the electrostatic potential of human walking.

2. Theoretical model
Walking is one of the important sources of human static electricity. The starting process is as follows: shoes and the ground are contacted and separated, and the sole and the ground will have an equal amount of charge with different signs. Assuming that the sole is positively charged, due to electrostatic induction, the proximal foot will induce negative electricity, and the distal human body will induce positive electricity. At the same time, the charge will dissipate through the resistance to the ground. When walking continuously, the human body continues to charge and discharge until it reaches saturation. The live equivalent circuit of human walking is shown in figure 1, R is the earth resistance of the human body, Q(t) and U(t) are electrostatic charge and potential of human body respectively. i(t) represents the charging rate of human electrostatic electricity, C(t) is human capacitance to the ground, which is related to human body shape, sole material, posture and surrounding objects, etc. When the human body is standing on the ground, there is a dielectric layer between the sole and the earth, that is, the sole of the shoe, When standing on both feet, the body capacitance to the ground is $C_s$, the capacitance formed by a single foot to the ground is $C_s/2$, and when walking, The feet are lifted away from the ground alternately. For the capacitance formed by the lifted foot and the earth, it is equivalent to a capacitance in series on the original capacitance with an area of the sole, an air medium and a distance $d(t)$. That is:

$$C' = \frac{C_s C_d(t)}{C_s + 2C_d(t)}$$

Where $C'$ is the sole area, assume $d_0$ is the maximum foot lifting height when walking, foot lifting height can be approximately expressed as:

$$d(t) = \frac{d_0}{2}(1 - \cos(2\pi ft))$$

Where f is Step frequency for human walking. In addition, the human body to the ground capacitance in addition to the foot to the ground capacitance, there are other parts of the body to the surrounding grounding body capacitance, so the human body real-time capacitance can be expressed as:

$$C(t) = C' + \frac{C_s}{2} + C_r$$

The experimental results show that the foot-to-ground capacitance accounts for about 60% of the earth capacitance of human body, while the capacitance formed in other parts of the body accounts for 40%[7]. From (1), (2) and (3), the capacitance of human body during walking is:
\[ C(t) = \frac{5C_S}{3} \left[ \frac{1}{2} + \frac{C_Sd_0}{2\varepsilon S} \left[ 1 - \cos(2\pi ft) \right] \right] \tag{4} \]

Figure 1. The charged equivalent circuit of human walking

Equations can be listed by Kirchhoff’s law:

\[ \frac{dQ}{dt} + \frac{1}{RC} Q - i = 0 \tag{5} \]

The solution is:

\[ Q(t) = e^{-\frac{1}{RC}} \left[ \int_0^t e^{\frac{u}{RC}} idt + Q_0 \right] \tag{6} \]

Where \( Q_0 \) represents the charge at the initial time, assuming that the electrification starts from zero, that is \( Q_0 = 0 \); Because the earth capacitance in this formula only affects the saturation potential and time constant, and does not affect the analysis of the law, so the assumption does not change for simplified calculation. If walking at a stable speed, the power generation rate is constant, which is set as \( I_0 \). Equation (6) is further simplified as:

\[ Q(t) = I_0 RC(1 - e^{-\frac{t}{RC}}) \tag{7} \]

From (4) and (7), the electrostatic potential of human walking is:

\[ U(t) = \frac{Q(t)}{C(t)} = U_o \left( 1 - e^{-\frac{1}{RC}} \right) \left( 1 - \frac{4}{8 + \frac{C_s}{C_{d_0}} (1 - \cos(2\pi ft))} \right) \tag{8} \]

Where \( U_o \) is the saturated potential of walking, accord with \( U_o = \frac{6 I_0 R C}{5 C_s} \), because \( C_s = 0.6C \), then \( U_o = 2I_o R \); \( C_{d_0} \) is the capacitance corresponding to \( C_d(t) \) at the maximum lifting foot height. From the formula (8), it can be seen that the human body walking potential consists of three parts. The first part represents the saturated potential of electrostatic charge, which is related to the starting rate and the earth resistance. The second term indicates that the human body potential increases exponentially before saturation. The third part reflects the law of potential oscillation during human walking.
3. Analysis and discussion

3.1. typical case
Assuming the feet to ground capacitance $C_S$ is $100 \, \text{pF}$, then the total capacitance of human body is $167 \, \text{pF}$, set the resistance to ground is $6 \times 10^9 \, \Omega$, then the time constant is $1 \, \text{s}$, assuming the charge rate is $8.3 \times 10^{-8} \, \text{A}$, so the saturation potential is $1 \, \text{kV}$. When walking, the maximum foot lifting height is 7.6 cm (3 inches) specified in ANSI/ESD STM97.2 standard, and the sole area of single shoe is 150 square centimeter. The potential curve at this time can be obtained from the above parameters, as shown in figure 2. When walking at zero time, the human potential increases exponentially. In the process of lifting the foot, the human capacitance gradually decreases with the rule of Equation(4), and the potential further increases. When the foot is raised to the highest point, the body capacitance reaches the minimum value, and the potential is the maximum value. With the foot falling, the capacitance increases and the potential decreases gradually until the foot reaches the minimum. In this instant, the other foot rises and the capacitance decreases again. This cycle leads to the periodic oscillation of the potential. After 3s, the electric quantity reaches saturation, and the human potential changes only with the change of capacitance.

![Figure 2. The charged equivalent circuit of human walking](image)

3.2. Influence of maximum foot lifting height
When the electrostatic charge of human body is saturated, the change of human potential is only related to the capacitance to the ground. From equation(4), it can be seen that the capacitance to the ground of human body is related to the maximum lifting height. Therefore, the study of the influence of the maximum lifting height is helpful to analyze the charging law of human walking.

Assuming the coefficient $C_S/C_{d_0}$ in the third term of Equation(7) is $A$, the maximum foot lifting height affects the variation of potential by influencing $A$. The coefficients corresponding to different maximum foot lifting heights are solved with the parameters in Section 2.1, as shown in table 1.

| $d_0$ (cm) | 0 | 1.5 | 3  | 6  | 7.6 | 9  | 12 |
|------------|---|-----|----|----|-----|----|----|
| $A$        | - | 11.3| 22.6| 45.2| 57.2| 67.8| 90.4|
Thus, the influence of different foot lifting heights on human walking electrostatic potential is obtained, as shown in figure 3.

Comparing figures (a) to (f), it can be seen that the maximum foot-lifting height has an effect on electrostatic potential: ①When the maximum foot-lifting height is small, the oscillation of the potential approximately conforms to the sine law. With the increase of the maximum foot-lifting height, the maximum value of the curve becomes wide and the minimum value becomes sharp. This is because when the walking frequency is constant, the higher the foot-lifting height is, the longer the foot is in the air, and the shorter the time for both feet to stand at the same time. ②When the maximum foot lifting height is small, as shown in (a), even if the saturation potential is 1 kV, the actual maximum potential is less than 900 V.

4. Conclusion
The study of human electrostatic charging law is the basis to effectively prevent the harm of human electrostatic, walking is one of the important sources of human electrostatic, this paper further deduces the theoretical model of human walking charged, and obtains the equation of human walking charged. Through this equation, the typical human walking charged law is analyzed, and the influence of the maximum foot lifting height on the human potential is studied. When the maximum foot lifting height is small, the oscillation of the potential is approximately in line with the sine law, but with the increase of the maximum foot lifting height, it gradually does not meet the sine law. When the maximum foot lifting height is small, the actual peak potential can not reach the saturated potential. Therefore, on the basis of electrostatic protection measures, the staff should try to reduce the height of the foot lifting to prevent electrostatic harm.

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References
[1] Liu Shang-he, Wei Guang-hui, Liu Zhi-cheng, et al. Electrostatic theory and protection[M]. Beijing: Arms Industry Press, 1999.
[2] Wang Jian. Experimental study on influencing factors of ultra-low human electrostatic starting voltage[D]. Nanjing: Nanjing University of Information Engineering, 2020.
[3] Gao Zhi-liang, Song Bo, Wang Ruo-jue, et al. Research on on on-line monitoring technology of human electrostatic potential in anti-static working area[J]. Aerospace measurement technology, 2017, 37(03): 31-35.
[4] Ficker T. Charging by walking[J]. Journal of Physics D: Applied Physics, 2006, 39(2): 410–417.
[5] Han Yu-nan, She Jun-chao, David P, et al. Time domain waveform study of human walking voltage[J]. Journal of radio science, 2015,30(05): 917-921.
[6] Wang Yi-fei, Wang Wei, Tian Shan-shan, et al. Human action recognition based on electrostatic signals[J]. Robots, 2018, 40(04): 423-430.
[7] Yu Jun-fei. Knee joint constrained gait analysis and classification based on human foot electrostatic[D]. Beijing: Beijing University of Technology, 2016.