35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Theoretical Analysis of Body Hair Movement in ELF Electric Field Exposure in Different Environmental Conditions

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***Abstract*— To elucidate the mechanism of the biological effect of ELF (extremely low frequency, 0–300 Hz) electric field and to settle appropriate safety standards, the body hair movement in AC electric field exposure was analyzed. We derived the equation of motion to describe the body hair movement cause by the electric force, and obtained an analytic solution for AC input. We applied this solution to practical conditions and clarified the body hair movement in AC electric field exposure. Using this solution, we analyzed the body hair movement in different humidity and verified the validity of the analysis in experiments.**

I. Introduction

The biological effect of extremely low frequency (ELF, 0–300 Hz) electric field is a familiar issue in the cases of high-voltage power transmission lines and household electrical appliances. There have been reports on the possible relevance to childhood cancers and leukemia. There have been numerous research conducted, but many important points concerning the biological effects remain unknown. Among several possible mechanisms, the stimulation of the body surface has been recognized as a clear biological effect. We perceive the stimulation as a somatic sensation. Thus, the safety standard for the field exposure has been established on the basis of the perception threshold of the electric field in many countries including Japan [1]. However, there are many uncertain points in the field perception and the safety standards are different across different countries.

When relative humidity changes, the dielectric constant of the hair changes and the electric force on the hair changes accordingly [2]. Thus, the electric force on the body hair varies with humidity. This might be one of the reasons why the safety standards are different in different countries. To clarify this phenomenon objectively, we have conducted the study on the field perception in electric field exposure. In this study, we found that the hair movement caused by the electric force was a significant factor for the body surface stimulation [3]. We modeled the body hair in an electric field, and theoretically analyzed the hair movement for DC field exposure.

On the other hand, AC electric field is more common under the high-voltage power transmission lines. Therefore, in the present study we expand the previous study to analyze the body hair movement in AC electric field exposure. In this paper, we present a new formulation and the solution for the AC field exposure. We apply this solution to practical conditions to show the manner of the hair movement in the field exposure. Finally, we clarify the difference in hair movement in the electric field exposure in different humidities around the hair.

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II. Modelling of Body Hair Movement

We modeled the body hair as a dielectric cylinder with a homogeneous diameter that is standing obliquely (with its axis of rotation in a vertical plane) at the angle θ on a horizontal conductor plane. When this cylinder is exposed to an electric field, the electric force is applied at the air-dielectric boundary. We can obtain the total electric force exerted on the hair by the vector integration of this force over the surface of the hair. If we assume the hair as an elastic cylinder, the angle $\theta(t)$ is given as the solution of the following equation [4],

$$\ddot{\theta} + \frac{R}{m_h}\dot{\theta} + \frac{f}{m_h\delta_{\max}}\theta = \frac{3f}{2m_hL}, \tag{1}$$

where R, m_h, f, $\delta_{\max}$, and L are the coefficient of the resistance exerted on the cylinder by viscous fluid [Ns/m^2], the mass per unit length of the hair [kg/m], the electric force per unit length of the hair [N/m], the final deviation of the tip of the hair [m], and the length of the hair [m], respectively.

When a DC electric field is applied to the hair, the f becomes a step function, and the solution is given as,

$$\theta(t) = K\left\{1 - \frac{\alpha+\sqrt{\alpha^2-1}}{2\sqrt{\alpha^2-1}}e^{-(\alpha-\sqrt{\alpha^2-1})\Omega t} + \frac{\alpha-\sqrt{\alpha^2-1}}{2\sqrt{\alpha^2-1}}e^{-(\alpha+\sqrt{\alpha^2-1})\Omega t}\right\}, \tag{2}$$

where $K = \frac{3}{2L}\delta_{\max}, \alpha = \frac{R}{2\Omega m_h}, \Omega = \sqrt{\frac{f}{m_h\delta_{\max}}}$.

III. Solution of Motion Equation

The electric force is proportional to the square of the electric field intensity exposed on the body surface. Thus, in the AC electric field exposure, the third term on the left-hand side of (1) becomes a function of the time t, and the equation seems to be nonlinear. However, the final deviation of the hair tip $\delta_{\max}$ is also proportional to the square of the exposed electric field intensity. So, (1) reduces to the following inhomogeneous linear differential equation with constant coefficients,

$$\ddot{\theta} + a\dot{\theta} + b\theta = c\sin^2\omega t. \tag{3}$$

where $a = R/m_h$, $b = k_1/(m_hk_2)$, $c = 3k_1/(2m_hL)$, $f = k_1\sin 2\omega t$, and $\delta_{\max} = k_2\sin^2\omega t$. k_1 and k_2 are constants, and ω is the angular frequency of the exposed AC electric field. We can solve (3) analytically, and the following solution is obtained as a sum of homogeneous and inhomogeneous solution as,

$$\theta(t) = A_1 \exp\left(\frac{-a+\sqrt{a^2-4b}}{2}t\right) + A_2 \exp\left(\frac{-a-\sqrt{a^2-4b}}{2}t\right) + \frac{c}{2b} - \frac{c}{2}\times\left\{\frac{b-4\omega^2}{\left(b-4\omega^2\right)^2+4a^2\omega^2}\cos 2\omega t + \frac{2a\omega}{\left(b-4\omega^2\right)^2+4a^2\omega^2}\sin 2\omega t\right\}, \quad (4)$$

where A_1 and A_2 are the arbitrary constants of the homogeneous solution.

IV. Body Hair Movement in ELF Electric Field

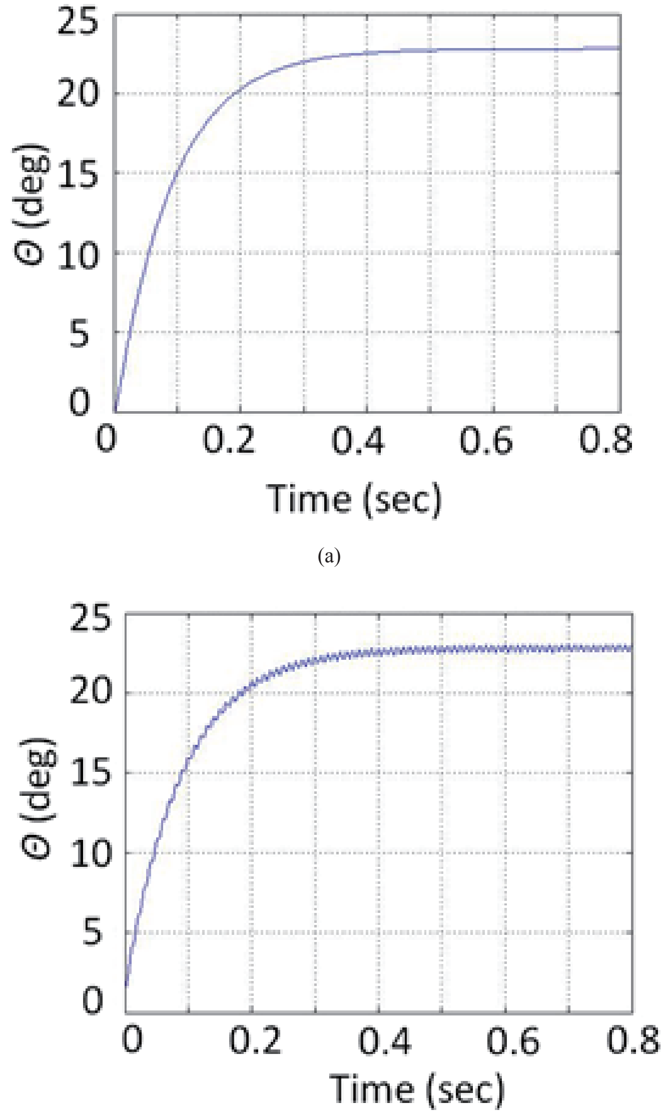
In order to investigate the characteristics of the derived analytical solution, we applied the parameters [4] of the practical condition of the body hair to the solution. Fig. 1(a) shows the temporal change of the hair angle calculated with (2). This is the result when a uniform electric field of 450 kV/m (RMS) is applied to the body hair model with the initial angle of 1 degree. The hair stands up exponentially toward the final angle of 23 degrees. Fig. 1(b) shows the result calculated with (4). The conditions are all the same as the case of Fig. 1(a) except for the applied field that is the sinusoidal 50 Hz AC field. It is apparent that the hair stands up in the same manner as in the DC case but with the vibration of twice as much frequency, or 100 Hz. The characteristics of these results agreed well with the body hair movement observed with the naked eyes. In these analyses, the validity of the derived solution was confirmed.

V. Effect of Force Change in Motion

As discussed in Chap. III, the motion equation of the hair angle $\theta(t)$ is give as a second-order linear ordinary differential equation with the electric force on the hair as the input, or the inhomogeneous term. In the above analysis, we assumed the amplitude k_1 of the AC electric force ($f = k_1\sin^2\omega t$) constant with respect to time, or time-invariant. However, strictly speaking, the amplitude k_1, changes with the hair angle θ. In this case, the coefficient c in (3) becomes the function of the hair angle $\theta(t)$, and it becomes difficult to solve the differential equation analytically.

To investigate how much this effect is reflected in the result, (3) was solved numerically with the k_1 changed according to the hair angle. Fig. 2 shows the results of the calculation with the constant and varying amplitude k_1 of the AC electric force. The larger the hair angle is, the smaller is the difference in the field intensity between the top and the bottom surfaces of the hair. Since the electric force is proportional to the difference of the squared field intensity, the force becomes smaller as the hair angle increases. Therefore, the final hair angle and the vibration amplitude become smaller if we take the electric force change with angle into account. However, the difference from the case with constant electric force was within 4% and was not notable.

Through these analyses, we confirmed that the analytical solution (4) can represent the hair motion well even with the assumption of the constant electric force.



(a)

(b)

Figure 1. Solutions of motion equation: (a) DC electric field (Eq. (2)), (b) AC electric field (Eq. (4)).

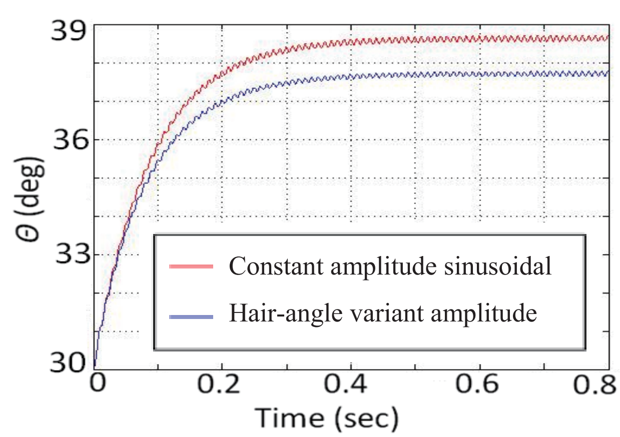


Figure 2. Effect of force change with hair angle in AC field exposure.

VI. Dependence on Humidity Around Hair

A. Theoretical Analysis

It has been reported that the perception threshold of electric field exposure significantly changes with the change in relative humidity [2]. Since the electrical permittivity increases with the increase in humidity, the electric force on the hair increases. This seems to result in the change in the hair movement in field exposure. To examine this possibility, we applied the analytical solution (4) to the hair with different permittivity. Fig. 3 shows the result. The hair relative permittivity 10 and 80 corresponds to those in relative humidity of 50% and 90%, respectively [2]. It is clear that both the final angle and the vibration amplitude increase in high humidity. Particularly, the vibration amplitude increases almost twice as much.

B. Experimental Setup

To examine the validity of the theoretical analysis, we conducted experimental verification. Fig. 4 shows the outline of the experimental setup. We simulate the body surface by standing a human hair on the sponge soaked with saline solution. We applied AC high voltage of 9 kV to a set of plane parallel electrodes (110×110 mm^2, 20 mm apart) and generated the vertical AC electric field of 450 kV/m. There was a circular hole with 30 mm diameter in the center of the lower electrode, and the vertical electric field could be exposed to the sponge surface. The electrodes and the model of the body surface were placed in a transparent closed box. The relative humidity inside the box was maintained in either 50% or 90%. The hair movement was recorded from outside the box using a high-speed video camera at the speed of 600 fps.

C. Experimental Verification

Figs. 5 and 6 show the result of the experiment. These figures are the superposition of the images when the hair was in initial position and the positions of the minimum and the maximum deviations. When the relative humidity was 50%, the vibration in the range of 30–50 degrees was observed for initial angle of 30 degrees. On the other hand, when the humidity was 90%, the vibration in the range of 40–70 degrees was observed for the same initial angle.

In comparison with the results of the theoretical analysis, the amplitude of the vibration was larger. However, the qualitative agreement was excellent. The hair angle increased exponentially with the vibration of 100 Hz. The final angle and the vibration amplitude were significantly larger in the high relative humidity. This result suggests that the hair movement becomes larger in high humidity and stimulates the sensory nerves at hair root more strongly. This mechanism explains the following phenomenon well. In the environment with high humidity, the perception threshold becomes significantly low and we can sense the electric field at the body surface easier than in low humidity.

The following causes are the candidates for the quantitative disagreement between the theoretical and

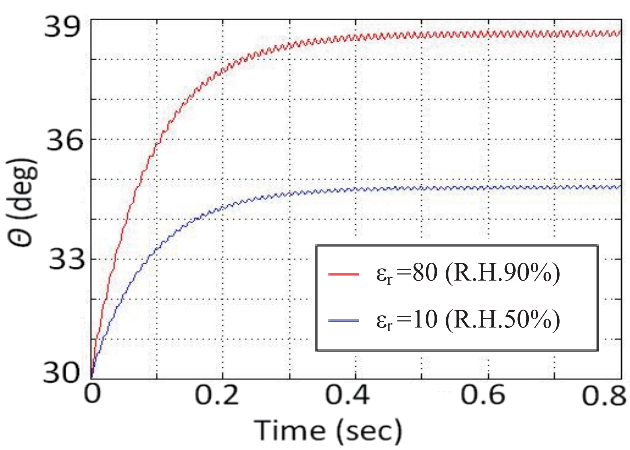


Figure 3. Dependence of hair motion on humidity difference.

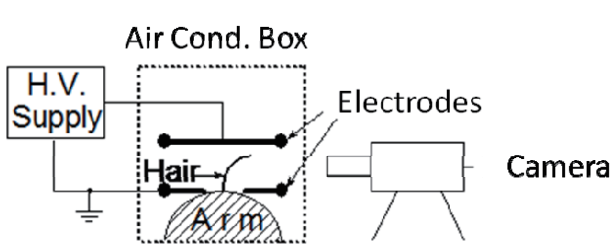


Figure 4. Measurement of hair movement.

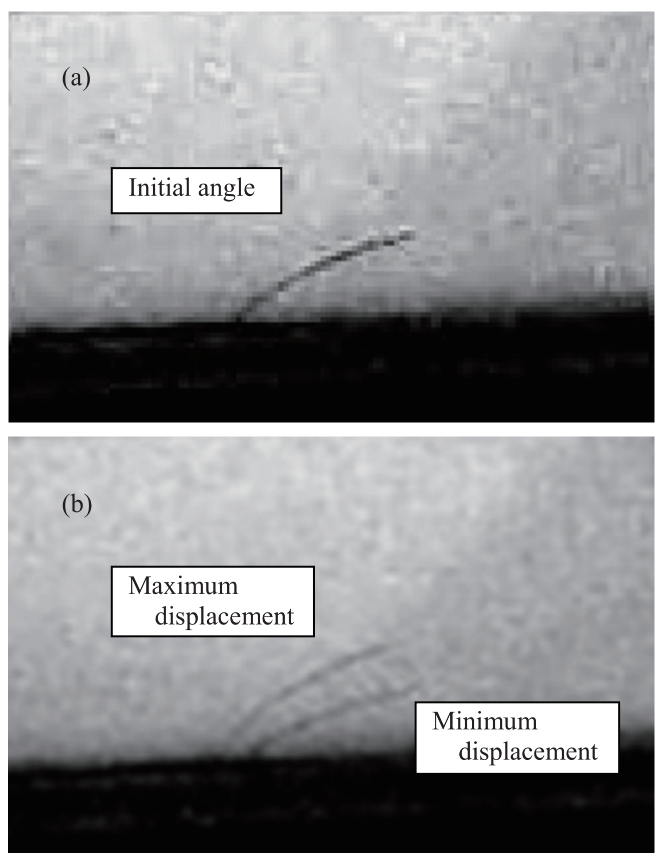
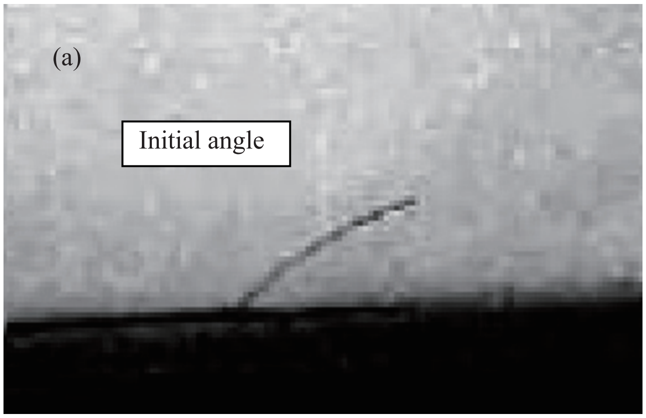


Figure 5. Vibration of hair in 50% humidity: (a) initial angle, (b) maximum and minimum displacement.



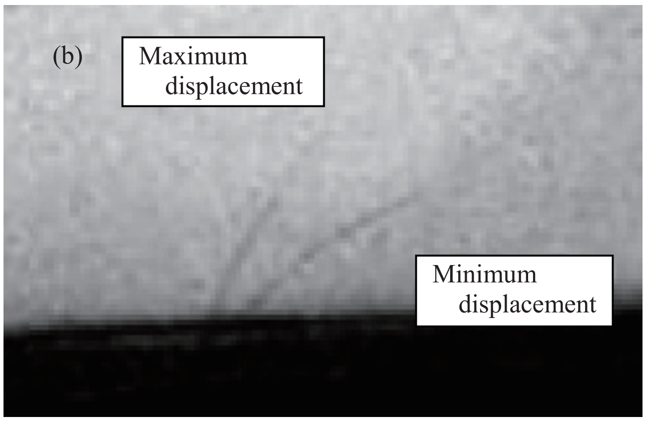


Figure 6. Vibration of hair in 90% humidity: (a) initial angle, (b) maximum and minimum displacement.

experimental analyses.

・The shape of the theoretical model is the right cylinder with the constant diameter from the root to the tip of the hair. Real hair becomes thinner toward the tip.

・The elasticity of the hair was assumed to be homogeneous in the model hair. In reality, the elasticity of the hair seemed to be different from the root to the tip.

・In the model, we assumed the center of rotation of the hair at the body surface. In reality, there is some subcutaneous movement of the hair root.

VII. Conclusion

Among the conceivable mechanisms of the biological effect of ELF electric field, the body hair movement is one of the main mechanisms for the body surface stimulation. Theoretical and experimental analyses were conducted on the body hair movement in AC electric field exposure. The analytical solution for the motion equation was newly derived for the AC field exposure from that of the DC case. The validity of the solution was confirmed with the parameters of practical cases. Using the solution, the hair movement in different humidities was analyzed. Through the theoretical and the experimental analyses, it was verified that the hair moves more in higher humidities. This result suggests that we need to take the effect of humidity in establishing the safety standard for field exposure based on the perception threshold.

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