An Experimental Study of Electrostatic Discharge Immunity Testing for Wearable Devices

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***Abstract*— Wearable electronic devices have proliferated in recent years. Since such devices are used by attaching to a human, every time the human is electrically charged or discharged, the electric potential of such a wearable device abruptly changes. Thus the device is exposed in close proximity to the resultant transient electromagnetic fields, which may cause malfunctions in the device. Electrostatic discharge (ESD) immunity test methods that assume this situation are not yet developed in the present international standards. In this study, to investigate such ESD immunity testing, we considered the worst case as an ESD event which occurs when the body-mounted wearable device approaches a grounded conductor. In lieu of actual devices, we measured discharge currents caused by air discharges from a charged human through a hand-held metal bar or through a semi-sphere metal attached to the head, arm or waist. As a result, we found that at a human charge voltage of 1 kV, the peak current from the semi-sphere metal is large in order of the attachment of the waist (15.4 A), arm (12.8 A) and head (12.2 A), whereas the peak current (10.0 A) from the hand-held metal bar is the smallest. It was also found that the discharge currents from the semi-sphere metal decrease at around 50 ns regardless of the attachment positions, however, the current from the handheld metal bar continues to flow at over 90 ns. This suggests that ESD immunity testing for wearable devices needs different specifications of test equipment and test method from the conventional testing.**

Keywords*— *Wearable device; human attachment; ESD immunity testing; air discharge; discharge current.

I. INTRODUCTION

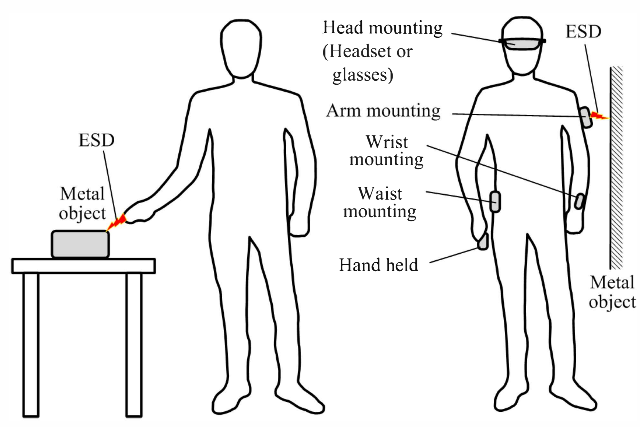
The electrostatic discharge (ESD) immunity testing for electric/electronics equipment or devices is prescribed in the international standard IEC 61000-4-2 [1] , which specifies the detail of test equipment specification and actual test methods. Basically, this testing is based on ESD phenomena caused by the touch action of a charged human. With the popularization of smart phones, on the other hand, wearable devices [2] have proliferated, which allow the users not only to provide information but also to monitor their body conditions or send the collected bio-data by radio to other computers. Since these devices are normally used by attaching to a human, every time the human is charged or discharged, the electric potentials abruptly change. As a result, the devices are frequently exposed in close proximity to the resultant transient electromagnetic fields, which may cause malfunctions in the devices. However, ESD immunity test methods which assume this situation are not yet developed in the international standards at present [1].

In this study, to investigate ESD immunity testing for wearable devices, we consider the worst case as an ESD event that occurs when the body-mounted wearable device approaches a grounded conductor. In lieu of actual devices, using a metal bar and semi-sphere metal, we show measurement results of discharge currents caused by air discharges from a charged human through a hand-held metal bar or through a semi-sphere metal attached to the head, arm or waist.

II. WEARABLE DEVICE AND MEASUREMENT METHOD

A. ESD phenomenon of human with wearable device

Figs. 1(a) and 1(b) show an ESD phenomenon of a device placed on a table due to a charged human and typical position of body-mounted wearable devices along with an example of the ESD phenomenon, respectively. The standard ESD test method for system equipment as table-top is specified on the basis of the situation as shown in Fig. 1(a). In this case, when a charged human hand or hand-held metal approaches a device, a spark happens between the human and the device, so that a discharge current flows from the human to the device. In the



(a) ESD phenomenon of device on a table.

(b) ESD phenomenon of wearable devices.

Fig.1. ESD phenomenon of charged human.

ESD test, a discharge current is injected to the device by a contact discharge from an ESD generator. Actual ESD phenomena necessarily accompany air discharges [3], [4] or breakdown phenomena in the atmosphere; however the contact discharge is commonly used as the preferable test method due to good test repeatability [4]. As shown in Fig. 1(b), the wearable devices are normally mounted on head as headset or grasses, arm, wrist, and waist with a belt. The ESD phenomena of wearable devices are categorized as the following four scenarios:

1) ESD occurs when picking up the device by hand,
2) ESD occurs when taking off the device from the body and putting it on a grounded conductor,
3) ESD occurs when a human is charged or discharged through a finger,
4) ESD occurs when the body-mounted device or hand-held device directly approaches a grounded conductor.

The above-mentioned scenarios 1) and 2) are the same as touch situations by hand on table top equipment and hand-held equipment, respectively. Those ESD phenomena can be evaluated by the IEC 61000-4-2 standard [1], which uses an ESD generator consisting of an energy charge capacitor of 150 pF as a human body stray capacitance and a discharge resistor of 330 Ω as a hand resistance with a metal piece. The scenarios 3) and 4) are entirely different from the contact discharges by hand. Especially, the scenario 4) is assumed to be the severest since the ESD directly occurs not through hand but from the device itself.

B. Measurement setup and method

We focused on the scenario 4) described above to investigate ESD immunity testing for wearable devices. In lieu of actual devices, semi-sphere metal and metal bar were used. We measured discharge currents for air discharges from a charged human through a body mounted semi-sphere and hand-held metal bar. Fig. 2 shows the measurement setup. Figs. 3(a) and 3(b) show the body-mounted semi-sphere metal and the hand-held metal bar approaching a current target, respectively. The discharge currents were measured through air discharges that occur when a body-mounted semi-sphere

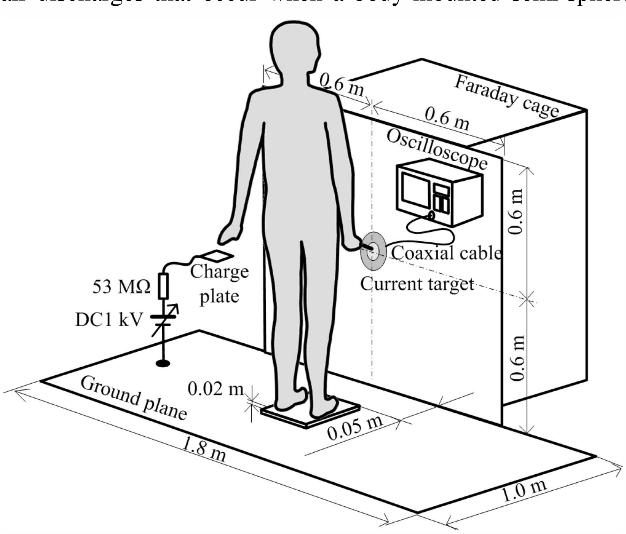
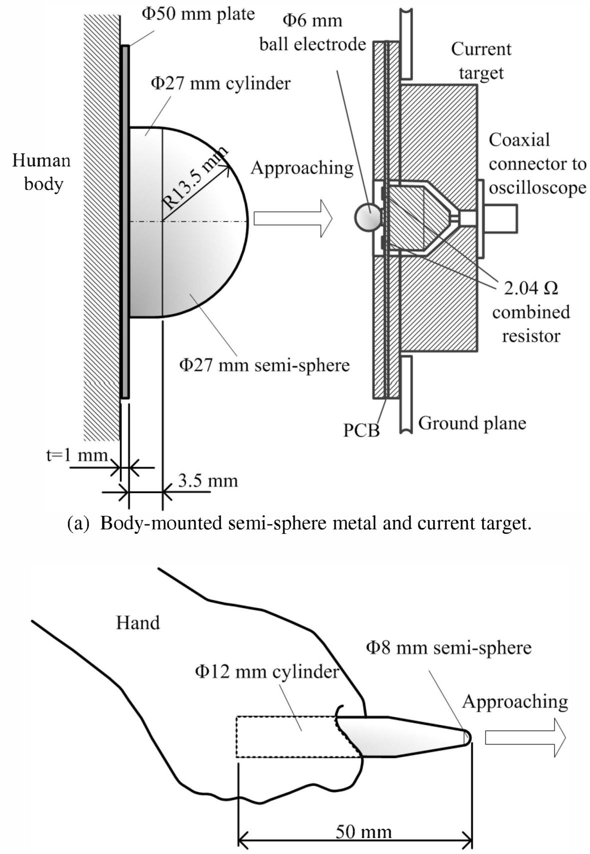


Fig.2. Measurement setup of discharge currents from charged human.



(a) Body-mounted semi-sphere metal and current target.

(b) Hand-held metal bar.

Fig.3. Measurement method of discharge currents through metal object from charged human.

metal or a hand-held metal bar approaches the center-mounted current target (Noiseken 06-00067A), which has an input DC resistance of 2.04 Ω and its frequency flatness response of DC - 1 GHz: ±0.5 dB and 1 GHz - 4 GHz: ±1.2 dB) [4], [5]. These specifications meet requirements specified in the IEC 61000-4-2 [1]. This current target was connected to a 6 GHz bandwidth oscilloscope (LeCroy Wave-Pro-760Zi, sampling frequency: 40 GHz). A volunteer (height: 1.74 m, weight: 72 kg, male) stands on an insulation plate with a thickness of 0.02 m, which was placed on a 1.8 m by 1.0 m ground plane at a distance of approximately 0.05 m away from the front of the Faraday cage, as shown in Fig. 2. The human was charged to 1 kV through a 53 MΩ resistor by an electrode connected to a high voltage power supply.

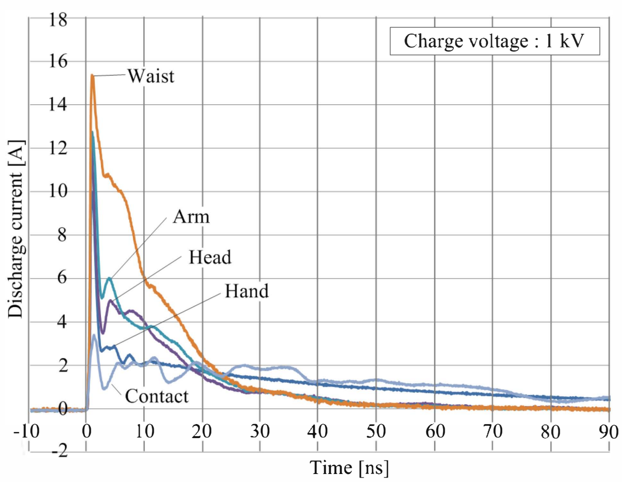
As shown in Fig. 3(a), the semi-sphere metal with a 50 mm diameter metal plate was directly mounted on each part of upper arm, head or waist. The center contact part of the current target was changed to a 6 mm diameter metal ball to stabilize air discharges. The approach speed of the body-mounted metal or hand-held metal bar was approximately 50 mm/s. Body postures were changed so that each part of the metals approaches the current target. For the hand-held metal bar, as shown in Fig. 3(b), the air discharge electrode of an ESD generator (Noiseken ESS-2000AX with TC-815R) as specified in the IEC 61000-4-2 [1] was used.

Measurements were conducted 20 times for each part of the body-mounted semi-sphere metal or hand-held metal bar. The room temperature and relative humidity were 25.1 degrees centigrade and 40 %, respectively.

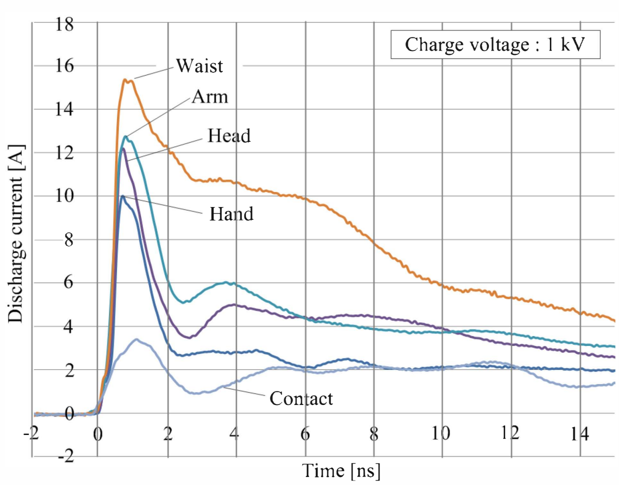
III. Result and Discussions

A. Discharge current waveforms

Figs. 4(a) and 4(b) show the whole range discharge current waveforms and their enlargements around the peaks, respectively. These waveforms are shown with averages of 20 waveforms of discharge currents measured through hand, arm, head and waist of a 1 kV charged human, respectively. Also shown in Fig. 4 are the contact discharge currents from an ESD generator with a charge voltage of 1 kV. As can be seen in Fig. 4, the ESD from the waist causes the largest current peak and a rise time of approximately 0.6 ns which is a little faster than that specified for the contact discharge (rise time: 0.8 ns). It is also found that the discharge currents through the hand-held metal bar or the contact discharge current from an ESD generator did not sufficiently decrease even at 90 ns, while the discharge currents through the body-mounted semi-sphere metal almost decreased to zero at 50 ns regardless of the attachment positions. This implies that the body-mounted semi-sphere metal has a low resistance compared to the hand-held metal bar and the contact discharge from the ESD generator.



(a) Discharge current waveforms from -10 ns to 90 ns.



(b) Discharge current waveforms from -2 ns to 15 ns.

Fig.4. Measured waveforms of discharge currents through hand-held metal bar and body-mounted semi-sphere metal.

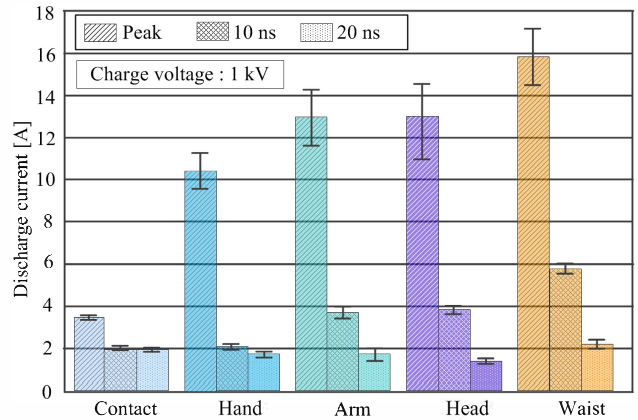


Fig.5. Comparison of current peaks and current values at 10 ns and 20 ns through hand-held metal bar and body-mounted semi-sphere metal.

Fig. 5 shows current peaks along with current values at 10 ns and 20 ns with their averages and standard deviations. It is found that the ESDs from the body-mounted semi-sphere metal and hand-held metal bar cause the peak three to four times as large as the contact discharge. Note that the peak from the semi-sphere metal is large in order of the attachment of the waist (15.4 A), arm (12.8 A) and head (12.2 A), whereas the peak current (10.0 A) from the hand-held metal bar is the smallest.

B. Waveform energy

To investigate the characteristics of discharge current waveforms, we calculated energy E [J] of the discharge current $i(t)$. It can be expressed from Parseval's theorem as

$$E = \int_{-\infty}^{+\infty} \left| I(j\omega) \right|^2 df = \int_{-\infty}^{+\infty} i^2(t)\, dt = \int_T i^2(t)\, dt, \qquad (1)$$

where $I(j\omega)$ is the Fourier transform of $i(t)$ and T is the waveform duration.

Fig. 6 shows energy consumption of the current target load R of 2.04 Ω, which is calculated from (1) with T=90 ns. It was found that the energy of the discharge current waveform from the waist-mounted metal is the largest and is approximately five times larger in comparison with the hand-held metal bar and the contact discharge. This means that the semi-sphere metal attached to the waist has the largest energy storage capacitance. Note that the energy of the discharge current waveforms from the head and arm is less than 40 % compared to the waist.

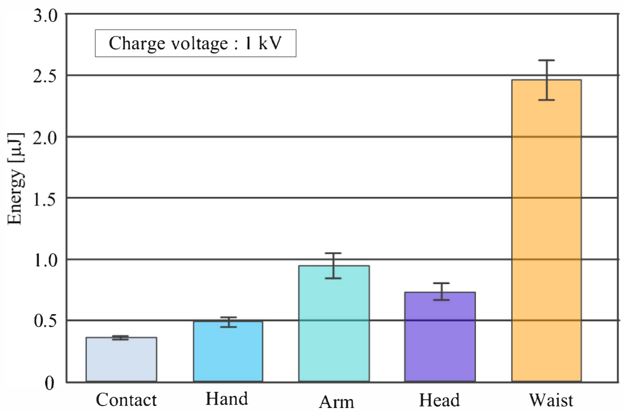


Fig.6. Comparison of energy consumption of current target.

To confirm the above finding, we measured the impedance seen from each body part using a vector network analyzer (VNA). Fig. 7 shows the measurement setup, which indicates a method for measuring the impedance seen through the hand-held metal bar in contact with the SMA connector pin. The resistance and reactance of the impedance were measured in the frequency range from 2 MHz to 8.5 GHz, which are shown in Fig. 8. Also shown is the frequency dependence of the reactance (=$1/\omega C$) of 150 pF capacitor C for reference. Here, R and X are the resistance and reactance, respectively. It was found that the hand resistance is the largest but is smaller than 300 Ω at frequencies over 2 MHz, and the waist resistance is the smallest but is less than half of the head and arm, and is one-third as small as the hand resistance at frequencies below 10 MHz. Although the reactance of head, arm, waist and hand is around the one of 150 pF at frequencies below 10 MHz, the waist reactance is the smallest, which corresponds to the largest energy storage capacitance. These results can explain the characteristics of the discharge current waveforms and their energy.

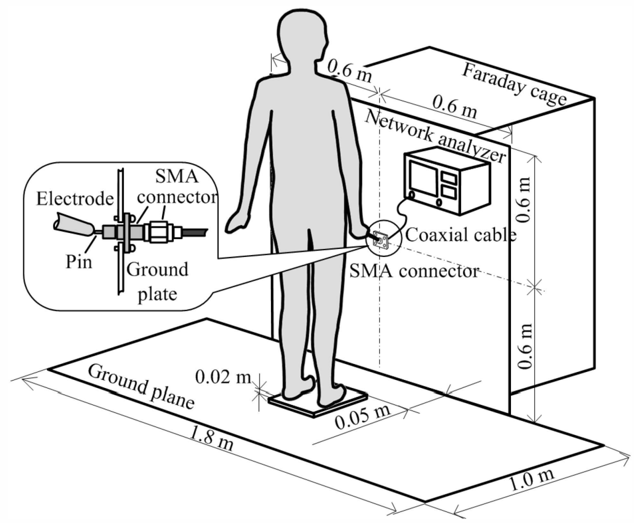


Fig.7. Measurement setup of human body impedance.

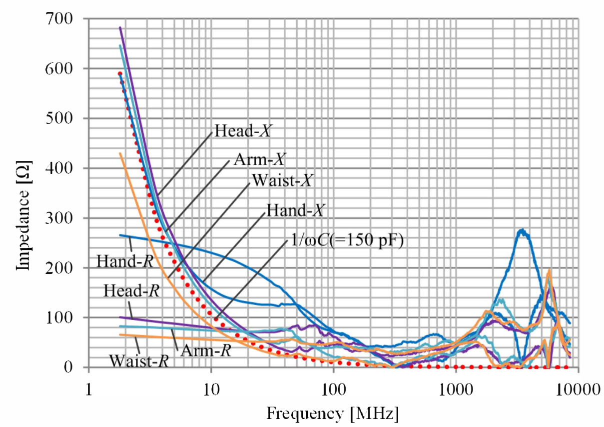


Fig.8. Frequency dependence of human body impedance.

IV. CONCLUSUON

On the assumption that the severest scenario for ESD immunity testing for wearable devices is the case where these devices attached to a charged human approach a grounded conductor, we measured discharge currents for air discharges from a charged human through a hand-held metal bar or through a semi-sphere metal attached to the head, arm and waist in lieu of actual devices. As a result, we found that at a human charge voltage of 1 kV, the peak current from the semi-sphere metal is large in order of the attachment of the waist, arm and head, whereas the peak current from the hand-held metal bar is the smallest. It was also found that the discharge currents from the semi-sphere metal decrease at around 50 ns regardless of the attachment positions, however, the current from the hand-held metal bar continues to flow at over 90 ns. This suggests that ESD immunity testing for wearable devices needs quite different specifications in test equipment and test methods from the conventional ESD immunity testing.

Future tasks are to measure discharge currents from body-mounted metals having various shapes modelled as wearable devices with different charge voltages and different approach speeds.

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