Temporal Resolution of the Skin Impedance Measurement in Frequency-Domain Method

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***Abstract*—The temporal-resolution of the frequency-domain method for the identification of the impedance locus depends on the basis frequency used in the current waveform construction, i.e., the higher basis frequency provides the better temporal resolution. The impedance locus can be characterized by the impedance parameters Z_0, β, and τ_m. The frequency distribution of limited number of data in the impedance locus would affect the accuracy of the estimated impedance parameters. Therefore, we investigated the relationship between the estimation accuracy of the impedance parameters and the frequency coverage of the impedance locus in relatively low to high impedance conditions (dc impedance $Z_0 = 51$ k$\Omega - 45$ MΩ). As the basis frequency, 100 Hz was enough for the usual impedance with Z_0 less than 203 kΩ. On the other hand, 10 Hz and 1 Hz were required for the medium-level ($Z_0 = 517$ kΩ), and high-level ($Z_0 = 45$ MΩ) impedance, respectively. The required basis frequency, accordingly the temporal resolution, depended much on the central relaxation time τ_m which affects the frequency distribution on the impedance locus. The results of this study are expected to serve as the reference of the frequency selection in the frequency-domain analysis of the skin impedance.**

***Index Terms*—Basis frequency, central relaxation time, frequency-domain method, skin impedance, temporal resolution.**

I. Introduction

The measurement of skin impedance locus [1] with high temporal-resolution is essential for the identification of the phasic change due to electro-dermal activity elicited by stress, emotional activity, sound, etc, since changes in skin impedance or the skin-electrode interface impedance can occur over time scales as short as seconds [2]. The impedance locus can also be used in the localization of low impedance points, e.g., acupuncture points.

Time-domain analysis [3], [4] and frequency-domain analysis [5]–[9] have been used for the measurement of skin impedance locus. Though the time-domain analysis with square-wave current has good temporal resolution [3], it suffers from poor accuracy of the measured impedance at high frequencies. The frequency-domain method has better accuracy at high frequencies and its temporal resolution depends on the used frequencies.

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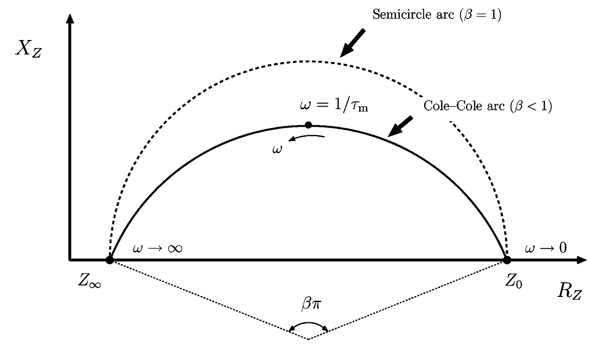


Fig. 1. General impedance locus and corresponding impedance parameters. Note that Z_0, τ_m, β, and Z_∞ indicate the dc resistance, the central relaxation time, the deviation from Debye type $(\beta = 1)$ semicircle, and the impedance at infinite frequency, respectively.

In the frequency-domain analysis, sampling at a limited number of preset frequencies [5], sweeping across a range of frequencies [7], [8], or an application of a digitally constructed current waveform consisting of many preset frequency components [6] have been used. It is noted that the temporal resolution of the frequency-domain method is dominated by the basis frequency i.e., the lowest frequency or the greatest common divisor of all frequencies. Therefore, to improve the temporal resolution, it is desirable to make the basis frequency as high as possible.

Fig. 1 shows general impedance locus called as Cole-Cole's arc [1] and corresponding impedance parameters (Z_0, τ_m, β, and Z_∞). If we can identify the impedance parameters, the impedance value at any frequency on the impedance locus can be determined. Yamamoto *et al.* [5] identified the impedance parameters from three experimental impedance values to achieve 0.2 s temporal resolution. Searl and Kirkup [6], on the other hand, used 30 frequencies evenly distributed in the impedance locus with the basis frequency of 1 Hz to result in 3.25 s temporal resolution. Both above methods were verified for limited range of low impedance i.e., less than 150 kΩ.

However, the frequency distribution on the impedance locus significantly depends on the measured object and the skin-electrode condition, e.g., size, material, paste, and humidity and, therefore, it is important to determine the needed frequency components for the identification of the impedance parameters with acceptable accuracy, e.g., 2% error in various conditions. The motivation of this study is the question "How low frequency components are required, i.e., how high temporal resolution is possible, for the identification of the impedance parameters?" To answer for this question, we investigated the relationship between the estimation error of the impedance parameters and the frequency coverage (dominated by the basis frequency) for wide dc impedance range (51 kΩ–45 MΩ).

II. Methods

A. Impedance Measurement and Parameter Estimation

The current $i(t)$ was constructed as (1) with multiple frequency components with identical intensity $|I|$ and phase θ_{i_n} (set to be zero) for all the frequency components. $|I|$ was adjusted in the range of 1–20 μA_{RMS} to develop the voltage of 1 V_{RMS} to ensure similar signal-to-noise (S/N) ratios for all the experimental conditions. The measured voltage $v(t)$ can be described as (2) with the phase θ_{v_n} determined from the Fourier transform. The experimental impedance is determined by (3), where $I(j\omega_n)$ and $V(j\omega_n)$ are the Fourier-transform of $i(t)$ and $v(t)$, respectively, at ω_n. One important fact is that

TABLE I
TEST *RC* MODELS FOR THE LOW TO MEDIUM LEVEL IMPEDANCE

Model no.	Impedance level	RC model		Reference impedance parameters			Test frequencies
		R[Ω]	C[F]	Z_0 [Ω]	τ_m [ms]	β	
1	Low	51K	22n	51K	1.122	1	10, 20, 30, 40, 50, ..., 90 100, 200, 300,... 1000Hz
2 3	Medium1 Medium2	203 K 517 K	14.9n 89.1n	203K 517K	3.02 46.06	1 1	10, 20, 30, 40, 50, 100, 200, 300, 400, 500Hz
4	High	7-terms distributed network (see table 3)		45M	320.0	0.8	0.1, 0.2, 0.3, 0.5, 1, 2, 3, 5, 10, 20, 40, 100Hz

TABLE II
CORRESPONDENCE OF THE TEST CIRCUIT TO THE ACTUAL SKIN IMPEDANCE CONDITION

Model no.	Material	Size	Humidity	Skin-electrode interface	Electrode attachment site
1	Ag-AgCl	ϕ=10mm	normal (50~60%)	cream-paste	sweated palm/forearm
2	Ag-AgCl	ϕ=10mm	normal (50~60%)	cream-paste	non-sweated palm/forearm
3	Ag-AgCl	ϕ=10mm	normal (50~60%)	Solid-gel	non-sweated palm/forearm
4	Ag	ϕ=2mm	dry (40%)	Solid-gel	non-sweated forearm

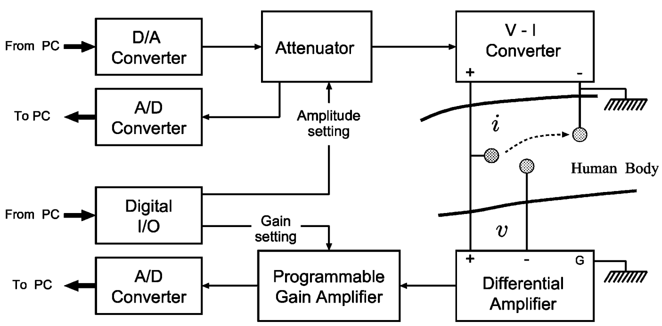


Fig. 2. Experimental setup for the skin-impedance measurement with three-electrode configuration. The current waveform constructed from PC is applied and the developed voltage is measured. Both the current and voltage are sampled with 20 kHz sampling rate.

the spectral leakage in Fourier-transform can be avoided by including only the multiples of the lowest or basis frequency (i.e., $\omega_n = n\omega_0$) in $i(t)$, which improves the accuracy of the measured impedance and dispenses the windowing operation

$$i(t) = \sum_n \sqrt{2}|I|\sin(\omega_n t + \theta_{i_n}) \tag{1}$$

$$v(t) = \sum_n \sqrt{2}|V_n|\sin(\omega_n t + \theta_{v_n}) \tag{2}$$

$$Z(j\omega_n) = \frac{V(j\omega_n)}{I(j\omega_n)} = R_{Z_n} - jX_{Z_n}. \tag{3}$$

The experimental setup for impedance measurement is shown in Fig. 2. The voltage developed by the current as well as the applied current was sampled with 20 kHz. In the actual experiment, test resistance–capacitance (*RC*) circuit models were used instead of the electrode and human skin to secure the reference impedance values, therefore, the voltage measurement was performed at the same leads as were used in the current feeding.

In this study, the impedance at infinite frequency, Z_∞, in (4) is assumed to be zero, because it is usually very small in case of skin impedance measured by 2- or 3-electrodes [3], [5]. Accordingly, the impedance parameters to be determined are Z_0, $\tau_{\rm m}$, and β, which are the dc resistance, the central relaxation time, and the degree of deviation from Debye type ($\beta = 1$) semicircle.

The experimental impedance parameters, which best-fits the experimental impedances, were identified through Levenberg-Marquardt method using (4) as the fitting-function. The accuracy of each identified parameter was evaluated in terms of E_p as defined in (5), where N is the number of measurement (100 times in each test condition), $p_{\rm r}$ is the reference parameter value as listed in Table I, and $p_{\rm e}$ is the estimated parameter value from the measured impedances

$$Z(j\omega) = \frac{Z_0}{1 + (j\omega\tau_{\rm m})^\beta} \tag{4}$$

$$E_p = \frac{1}{N}\sum_i^N \left|\frac{1 - p_{\rm e}}{p_{\rm r}}\right| \times 100[\%]. \tag{5}$$

TABLE III
7-TERM DISTRIBUTED *RC* NETWORK FOR HIGH LEVEL IMPEDANCE MODEL

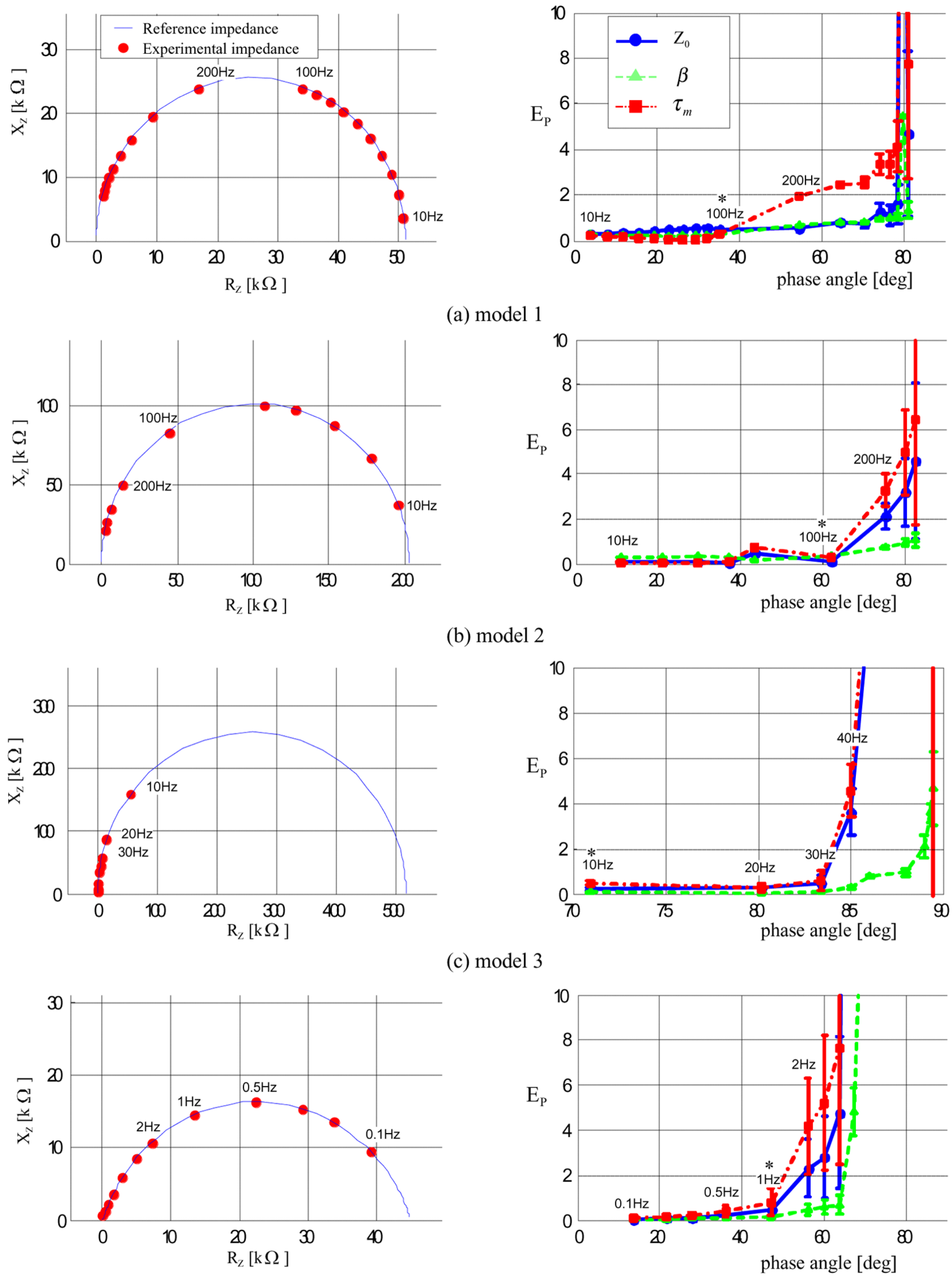
i	1	2	3	4	5	6	7
R_i[MΩ]	11.97	10.76	10.76	4.50	4.50	1.26	1.26
C_i [μF]	0.027	0.057	0.016	0.431	0.012	11.37	0.006

B. Test Conditions

Skin impedance was often modeled as the parallel circuit of 45–55 kΩ resistance and 20–25 nF capacitance [3], [5], [6]. As far as the electrode-skin interface is included in the measured impedance as in the 2- or 3-terminal method, the impedance depends fairly on the electrode type, the electrode attachment site, the electrode-skin interface and the environmental condition. In fact, in case of small searching electrode, the dc impedance becomes as high as 45 $\mathrm{M\Omega}$ [10]. Therefore, the relationship between the accuracy of impedance parameters estimation and the frequency coverage should be investigated in the wide range of impedance. In this study, we designed four impedance conditions for the evaluation of the above relationship. The test *RC* values, the reference impedance parameters, and the test frequencies are specified in Table I. Correspondence of the test circuit model to the actual skin impedance measurement condition is shown in Table II.

The low-level impedance was designed as a parallel circuit of $R = 51\ \mathrm{k\Omega}$ and $C = 22\ \mathrm{nF}$ which had often been used in the previous reports [3], [5], [6]. As for the medium-level impedance to be evaluated, we designed parallel *RC* circuits of $R = 203\text{–}517\ \mathrm{k\Omega}$ and $C = 14\text{–}90\ \mathrm{nF}$. The reference impedance parameters for these models were derived as $Z_0 = R$, $\beta = 1.0$, and $\tau_{\rm m} = R * C$.

As for the high-level impedance, it was difficult to implement accurate *R* and *C* values in electrical circuit, because great R inevitably includes capacitance in itself. Therefore, the parameter estimation error



(a) model 1

(b) model 2

(c) model 3

(d) model 4

Fig. 3. Test results of the low- to high-level impedance. Left: Impedance locus, right: Parameter estimation error where the basis frequency as high as possible is indicated by *. See text for the details.

was investigated with a simulation model under 30–60 dB S/N conditions. The actual simulation model was designed as having reference impedance parameters of $Z_0 = 45\ \mathrm{M}\Omega$, $\beta = 0.8$ and $\tau_{\mathrm{m}} = 320$ ms [10] and represented by a distributed-*RC* network of order 7 [11] to reflect β smaller than 1, where the *RC* values in the network were determined as in Table III [10].

The errors in the experimental impedance parameters as in (5) were investigated for various frequency coverage, i.e., all the instances as we exclude one impedance value at a time, to determine the basis frequency. The exclusion started from the impedance of the lower frequencies because the lowest (basis) frequency included in the parameters estimation determines the temporal-resolution.

III. Results

The experimental results are shown in Fig. 3. In the left figures, the experimental impedance values at all the pre-specified frequencies are compared with the reference impedance values calculated from the reference impedance parameters of Table I, according to (4). The parameter identification error E_p for all the instances as we exclude one impedance value at a time is shown in the right figures of Fig. 3. In the figures, the phase angle indicates the counterclockwise angle of the impedance (from the origin on the left impedance plot) at the lowest frequency included in parameter identification, so that the higher phase angle indicates that the less region of the semicircle arc is included. The basis frequency, which is the greatest common divisor of all included frequencies and guarantees E_p less than 2%, is indicated by asterisk $(^*)$ mark.

Fig. 3(a) shows the test result for the circuit model 1. Error less than 2% is confirmed if the included frequencies are multiples of 100 Hz, in which case the temporal-resolution is 0.01 s. Fig. 3(b) and (c) shows the test results with the circuit model 2 and 3, respectively. As is obvious from the electronics, the circuit model 2 with smaller *RC* values had wider distribution of impedance values with high frequencies. In circuit model 2, error less than 2% is confirmed if the included frequencies are multiples of 100 Hz (temporal-resolution of 0.01 s). In circuit model 3, error less than 2% is confirmed if the included frequencies are multiples of 10 Hz (temporal-resolution of 0.1 s).

Fig. 3(d) shows the test result with the circuit model 4 under a very tough condition of $\mathrm{S/N} = 30\ \mathrm{dB}$. The S/N ratio in the range of 30–60 dB did not influence much on the parameter estimation error, i.e., error less than 2% is confirmed for all the parameters if the included frequencies are multiples of 1 Hz, in which case the temporal-resolution is 1 s.

IV. Discussion

The performance of impedance parameters estimation is supposed to depend mainly on the data distribution in the impedance plane. The longer central relaxation time τ_{m} represents the lower medium frequency, and requires the lower basis frequency for wide distribution on the impedance plane. This was confirmed in this study that the lower basis frequency is required to identify the impedance parameters in case of higher-level impedance.

The results also indicates that identification of the impedance parameters with acceptable accuracy (less than 2%) is achieved when the impedance data points covering about the half of the semicircle (phase angle 45 deg–90 deg) is included in the identification process, irrespective of the impedance level. The contribution of this study is the investigation of the identification accuracy depending on the frequency coverage for wide impedance range. The best temporal resolution varied among 0.01 s–1 s depending on the skin-electrode condition.

V. Conclusion

The relationship between the impedance parameter estimation error and the frequency coverage was investigated. It was shown that the impedance parameters could be fairly well estimated with relatively high basis frequency (100 Hz, 0.01 s temporal-resolution) in case of relatively low impedance (under 203 $\mathrm{k}\Omega$) with small τ_{m} less than or equal to 3.02 ms. It was also shown that relatively low basis frequency (1 Hz, 1 s temporal-resolution) is required in case of high-level impedance (45 $\mathrm{M}\Omega$) with greater τ_{m} of 320 ms.

Therefore, the impedance level, accordingly the central relaxation time, of the measured object must be fully considered when increasing the basis frequency to increase the temporal resolution. However, in most cases with general electrodes, inclusion of relatively high frequencies (over 10 Hz, 0.1 s temporal resolution) is enough for accurate (under 2% error) estimation of the impedance parameters. The results of this study are expected to serve as the reference of the frequency selection in the frequency-domain analysis of the skin impedance.

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