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Application of Wigner–Ville Distribution in Electromigration Noise Analysis

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Abstract—Electromigration noise analysis has shown great potential for the nondestructive evaluation of electromigration performance of metal stripe. However, contradictory conclusions have been published from the electromigration noise analysis. These contradictory conclusions mainly stem from the complex dynamics of the atomic movement during electromigration, rendering the electromigration noise as a nonstationary signal, and, hence, the standard Fourier transform is not adequate. Among the various nonstationary signal analysis tools, Wigner–Ville distribution is used for the analysis of electromigration noise data for the first time. It is found that much “hidden” and useful information in the noise data can be revealed by using this distribution. These information will enable us to “see” the dynamic of the atomic movement during electromigration, enhancing our understanding of electromigration processes.

Index Terms—Electromigration, noise analysis, time–frequency analysis, Wigner–Ville distribution.

I. INTRODUCTION

NOISE measurements have been used for the characterization of electromigration in metallic stripes [1]. The first electromigration (EM) noise test result was published by Vossen [2] in 1973. Since then, much work has been carried out on the study of low-frequency EM noise. Cottle *et al.* [3] and Kraayeveld *et al.* [4] showed the validity of the low-frequency noise measurement method by comparing its results with the conventional EM test method. A very highly sensitive measurement system has been developed recently making nondestructive EM test possible with considerably reduction in the stress current, temperature, and time [5], [6]. In most cases, the activation energy for EM can be obtained in just a few hours by using the noise measurement method [1].

The source of EM noise was first proposed to be due to grain-boundary diffusion by Koch *et al.* [7]. Since then, the grain-boundary diffusion path has been commonly assumed as the main source of EM noise [8], [9]. However, different diffusion paths have been found to be possible noise sources in other experiments [9]–[11].

The application of EM noise tests to date can be categorized into the estimation of EM lifetime [12], derivation of EM activation energy [13], prediction of EM dominant mechanism [1], [8]–[11], [13], and, less commonly, as an EM failure criteria

[14]. However, EM noise is a highly sensitive parameter and varies with many factors, including stress condition (temperature and current density) [15], sample microstructure and geometric [16], [17], observation frequency range [1], and the fabrication technique of the sample. As a result, controversial conclusions and experiment observations have been found, especially in EM activation energy measurement and dominant diffusion mechanism predictions.

On the other hand, since noise is such a highly process-sensitive parameter, one can, in principle, use the noise information to examine the dynamics of the diffusion mechanisms during EM. Simulation has shown that grain structure and current density redistribution can affect the EM noise significantly [18], and the noise magnitude is found to be highly current dependent with a current exponent of 2–4 [19]. Vandamme [20] has also shown that the frequency exponent α of the noise spectrum depends on the scattering mechanism of atoms and temperature. Since diffusion closely depends on the scattering mechanism of diffusing atoms and temperature, one could use the α value from the EM noise spectrum to shed some light on the diffusion mechanisms during the EM test. Dattilo *et al.* [21] demonstrated that the α depends on the microstructural characteristics of the metal line. They found that if the initial value of α is significantly lower than two, then the EM damage to the metal line is weak, even after hundreds of hours of stress. Ciofi *et al.* [14] also showed that the noise power, which is closely related to α , can be used as an indicator of the degradation caused by EM. However, this noise power does not have a smooth behavior, making it difficult to use as an indicator.

From the Dutta–Dimon–Horn’s $1/f$ noise model for the EM noise, it has been found that the frequency exponent depends on the activation energy of the noise induction process [22]. Since the noise induction process is closely linked to the diffusion processes, the frequency exponent could be used to uncover the various diffusion processes during EM.

Experimentally, Oates [23] showed that the frequency exponent of EM noise changes with temperature of the metal stripe under the EM test. It is also known that the dominant diffusion mechanisms change at different temperature, hence, there is indeed a link between the diffusion mechanisms and the frequency exponent of the EM noise.

In order to use the frequency exponent of the $1/f$ noise to detect the change in diffusion mechanisms during the EM test, one needs to use nonstationary signal processing tools for the analysis of the noise data. This is because electromigration is a highly complex and dynamic failure process. Traditional Fourier transform is inadequate and unsuitable as an analysis tool since it is applicable only to stationary signals. In fact,

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TABLE I
COMPARISON OF THE FULFILLMENT OF THE DESIRABLE PROPERTIES FOR
THREE COMMONLY USED TIME-FREQUENCY DISTRIBUTIONS

	STFT	Wavelet	WVD
<i>Correct Energy</i>	✓	✓	✓
<i>Correct Marginal</i>			✓
<i>Reality</i>	✓	✓	✓
<i>Invertibility</i>			✓
<i>Shift Invariance</i>			✓
<i>Linear Scaling</i>			✓
<i>Moyal's condition</i>			✓
<i>Convolution</i>			✓
<i>Positivity</i>	✓	✓	
<i>Time support</i>			✓
<i>Frequency support</i>			✓

with this understanding, it is not surprising that contradicting conclusions have been drawn from different experimental setups and samples when Fourier transform is used for the noise analysis. Therefore, the time-frequency analysis method is necessary for the noise data collected.

In this paper, Wigner-Ville distribution, a time-frequency analysis distribution, is first proposed for the analysis of EM noise data, and its modification and applications to the analysis will be illustrated.

II. NONSTATIONARY ANALYSIS TOOL FOR ELECTROMIGRATION NOISE DATA

Time-frequency distribution is not a unique distribution, and it depends on the construction operation method adopted. It is always desirable for the loss of information of the original signal to be minimized during the transformation. Table I lists some of the properties that ensure the integrity of the time-frequency analysis [24], [25]. Table I also compares the three most common types of time-frequency distributions, namely, the wavelet, short-time Fourier transform (STFT) and Wigner-Ville distribution (WVD), in terms of these desirable properties. From the comparison, it is clear that WVD is the obvious choice for this work.

The Wigner-Ville distribution was first introduced by Wigner [26], but it was Ville [27] who incorporated it into signal analysis. Wigner-Ville distribution has found its wide applications in the nonstationary signal processing [28]–[31]. This distribution is favorable because of its good time and frequency resolutions. One of the two shortcomings of WVD is its nonpositivity. The negative power value gives rise to an interpretation difficulty. The practical steps to get rid of these negativities are either to exclude them or to take an absolute value of WVD. The latter is done in this paper.

The Wigner-Ville distribution is a distribution directly related to the signal-correlation function [32]. Hence, when, for instance, two frequency components are present, a term that reflects the correlation of the two signal components will exist in the middle of the two components in the time-frequency plane. The amplitude of the cross term can be double that of the original signal [25] and, hence, it will severely distort the interpretation of the original signal. Thus, the WVD does not fulfill the

Fig. 1. Frequency exponent variation with time during different test time intervals. For each test interval, only the first minute of noise signal is shown ($N = 512$, $M = 10$ for SPWD).

frequency/time support property. This is the other shortcoming of the WVD.

Much work has been carried out to overcome this artifact. One of the most direct ways is to convert the real signal into an analytical signal, given as [33]

$$z(t) = s(t) + jH[s(t)] \quad (1)$$

where $s(t)$ is the signal in time domain and $H[s(t)]$ is the Hilbert transform of $s(t)$, given as

$$H[s(t)] = \hat{s}(t) = \frac{1}{\pi} \int \frac{s(t')}{t - t'} dt'. \quad (2)$$

To further reduce the artifact in the WVD due to the multicomponent signal, insertion of a smoothing function is employed [34]. However, the attenuation of the cross-term interference through smoothing may not work if the signal and the cross term are closely spaced. Thus, a proper tradeoff of the interference attenuation versus time-frequency concentration is necessary. In this work, the smoothing is done separately in time and frequency domains. This results in the formulation of smoothed pseudo-WVD (SPWVD).

The pseudo-WVD (PWVD) is a short-time version of the WVD with a running window $h(t)$ [35], known as the frequency-smoothing window, given as

$$\text{PWVD}_s(t, \omega) = \int s\left(t + \frac{\tau}{2}\right) s^*\left(t - \frac{\tau}{2}\right) \left|h\left(\frac{\tau}{2}\right)\right|^2 e^{-j\omega\tau} d\tau. \quad (3)$$

To satisfy the correct total energy property, we need an $h(t)$ with real-valued even-normalized ($h(0) = 1$) and finite length, i.e.,

$$h(t) = 0, \quad \text{if } |t| > T_h/2 \quad (4)$$

where T_h is the window length [35].

Fig. 2. (a) Noise amplitude from 470-h test time interval (first 3 min of the time interval) and the corresponding variation in α . (b) Corresponding variation in the mean value of α .

To complete the smoothing operation, a time-smoothing window function $g(t)$ is inserted. The resultant distribution is the SPWVD. It is defined as [34]

$$\begin{aligned} \text{SPWVD}(t, \omega) &= \int_{t'} g(t - t') \text{PWD}(t', \omega) dt' \\ &= \iint g(t - t') \xi_h(\omega - \omega') \text{WD}(t', \omega') dt' d\omega' \end{aligned} \quad (5)$$

where $g(t)$ serves as a lowpass function.

With these smoothing functions, the time concentration of the signal components can be preserved, and at the same time, the cross-term interference in the frequency domain can be attenuated effectively [36].

In practice, since the noise signal is collected in a discrete format, a corresponding discrete version of the SPWVD is required. Given a discrete function $s(n)$, the discrete WVD (DWVD) is given as [37]

$$\text{DWVD}(n, \omega) = \sum_{m=-\infty}^{\infty} z(n+m) z^*(n-m) \exp(-j2\omega m)$$

Fig. 3. (a) Noise signal of the first 3 min at the 400th test hour. (b) Corresponding IPS contour plot. (Frequency is in hertz, and time is in seconds.)

where $z(n)$ is the analytical signal for $s(n)$, and n is the time index. However, this definition of DWVD suggests a noncausal operation, which requires knowledge of the signal at all times. This can be overcome by introducing a running window function just as in the PWVD, and the discrete version of the PWVD is [38]

$$\begin{aligned} \text{DPWVD}(n, m) &= \frac{1}{2} N \sum_{k=-N+1}^{N-1} |h(k)|^2 \\ &\quad \cdot z(n+k) z^*(n-k) \exp\left(\frac{-j2\pi km}{N}\right) \end{aligned} \quad (7)$$

where

- $h(k)$ frequency-smoothing window with length $2N - 1$;
- m frequency index;
- N time index;
- $z(n)$ analytical signal.

After inserting the time smoothing functions, we have SPWVD in discrete form (DSPWVD) as follows:

$$\begin{aligned} \text{DSPWVD}(n, m) &= \frac{1}{2} N \sum_{k=-N+1}^{N-1} |h(k)|^2 \\ &\quad \cdot \left[\sum_{p=-M+1}^{M-1} g(p) \cdot z(n+p+k) z^*(n+p-k) \right] \\ &\quad \cdot \exp\left(\frac{-j2\pi km}{N}\right) \end{aligned} \quad (8)$$

(6) where $g(p)$ is the time-smoothing window with length $2M - 1$.

Fig. 4. (a) Noise signal of the first 3 min at the 450th test hour. (b) Corresponding IPS contour plot. (Frequency is in hertz, and time is in seconds.)

In this paper, (8) will be applied for the time–frequency analysis of the EM noise.

III. APPLICATION OF DSPWVD TO EM NOISE DATA

The noise data was collected from the test set 1 of the work in [21] with the metal width equal to $0.45 \mu\text{m}$. The measurement lasted for 550 h, and it was terminated without any significant resistance variation observed.

DSPWVD is used to analyze the noise data. However, it is unrealistic to analyze the total 550 h of the noise data as the computation time will be too excessive. Instead, 12 sets of noise data are extracted at the first, 10th, 20th, and 390th–470th hours of the noise data. Each set of data lasts only 1 min.

Fig. 1 shows the variation of the frequency exponent α in different test data sets using $N = 512$ and $M = 10$ for the DSPWVD. The size of N and M are chosen so that the computation results are accurate, and yet, the computation time is not too excessive [36]. One can see that α does not vary much for the first 20 h of the test data, indicating the lack of change in diffusion mechanisms during the period. This could correspond to the incubation time of the metal line before EM takes place. On the other hand, α changes significantly even within 1 min after prolonged testing, especially for some time intervals such as those at the 390th, 420th, and 490th hours. These intervals could correspond to the phenomena where the dominant void dynamic has changed from void nucleation to void growth, and from void growth to void shape change. As the void dynamic

changes, the diffusion paths changes, and current redistribution occurs, causing a change in α .

To go into further detail, the duration of the data set at the 470th hour is expanded to 3 min. Fig. 2 shows the noise amplitude and frequency exponent for such an expanded spectrum. The mean value of α is also shown in Fig. 2(b). One can see two abrupt changes in the value of α . One is at around 38 s and the other is at around 105 s. These two abrupt changes mark the occurrence of changes in the diffusion mechanisms. In between 40 and 100 s, the noise signal increases steadily, however, after the abrupt changes at 105 s, the signal starts to fluctuate, which could represent some kind of atomic dynamics in the metal lines.

However, if Fourier transform is utilized to analyze the same set of data, these abrupt changes will be masked out by a flat value of $\alpha = -1.18$, as shown in Fig. 2. Hence, one can see the advantage of using DSPWVD in the study of the nonstationary processes of electromigration.

The WVD also enables us to determine the instantaneous power spectrum (IPS) of the noise signal. An example of the usefulness of the IPS is shown in Fig. 3, where the signal of the first 3 min of the 400th test hour is analyzed. One can see a significant jump in the noise amplitude at 40 s [Fig. 3(a)]. However, nothing conclusive can be made with simply the observation of step increment in noise amplitude. By constructing the contour plot of the IPS of the spectrum, as shown in Fig. 3(b), interesting results can be seen. In the first 40 s, there are at least three observable frequency trends: ~ 0.7 , 1, and 1.5 Hz. These frequency trends vanish right at 40 s where the step increment in noise is

Fig. 5. (a) Noise signal of the first 3 min at the 420th test hour. (b) Corresponding IF contour plot. (Frequency is in hertz, and time is in seconds.)

found. The vanishing of the frequency trends could indicate the termination of one or more EM related processes, and further investigation is necessary.

Another example to illustrate the usefulness of DSPWVD in providing IPS is shown in Fig. 4. The 450th-hour data set is used, and Fig. 4(a) shows the noise signal for the first 3 min. The corresponding IPS contour plot is shown in Fig. 4(b). From Fig. 4(a), a V shape is observed in the duration of the 50th–60th-s interval. In the corresponding IPS contour plot, two frequency trends (~ 0.3 and 0.6 Hz) are found to vanish in that duration. The 0.3 -Hz frequency component is observable again in the IPS contour plot after the 60th second.

The two examples have demonstrated that variation in the frequency trend observed in IPS plotting is accompanied by changes in the signal. Hence, IPS is a better tool for finding the effect of physical processes on the noise spectrum, because it contains the power (strength) for each observation frequency component.

Another application of DSPWVD to EM noise data analysis is the calculation of the instantaneous frequency (IF). The concept of IF had been developed from the FM modulation to the common nonstationary signal processing. An example of the usefulness of IF is shown in Fig. 5. Fig. 5(a) shows the noise signal of the first 3 min of the 420th-test-hour data set. By applying the DSPWVD, one can obtain the IF of the signal as shown in Fig. 5(b). From Fig. 5(b), a peak in the frequency domain is observed at the 150th s of the test interval. This peak is not surprising as there are abrupt changes observed in the signal amplitude between 140–150-s duration. The peak could represent some kind of change in the dominant EM processes, and again, further investigation is necessary.

From these examples and discussions, we see that DSPWVD enables “hidden” information contained in the noise data to be revealed. This “hidden” information is related to the EM processes. If one can relate this information to various EM processes, a much better understanding of the EM phenomena can be obtained.

IV. CONCLUSION

The shortcoming of using standard Fourier transform is demonstrated. The other type of time–frequency analysis tools are compared, and it is found that Wigner–Ville distribution preserves best the integrity of the noise signal, making the analysis accurate.

The use of WVD for the EM noise data is introduced for the first time. It provides a time monitoring of the EM noise power spectrum and the corresponding frequency exponent. Much “hidden” and useful information can be revealed by using this distribution. By establishing the correlation between the “hidden” information and the dynamics of EM, our understanding of the failure physics of electromigration process can be obtained.

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