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PREDICTION OF PROBABILITY DISTRIBUTION OF ELECTROMAGNETIC WAVE IN VDT ENVIRONMENT BASED ON FUZZY MEASUREMENT DATA UNDER EXISTENCE OF BACKGROUND NOISE

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Abstract—In this paper, based on fuzzy measurement data, a prediction method for probability distribution of electromagnetic wave leaked from electronic information equipment is proposed. More specifically, by applying the well-known probability measure of fuzzy events to the probability distribution in an orthogonal expansion series form reflecting systematically various types of correlation information, a method to estimate precisely the correlation information between the electromagnetic and sound waves from the conditional moment statistics of fuzzy variables is proposed under actual situation in the existence of a background noise. The effectiveness of the proposed theory is experimentally confirmed by applying it to the observation data leaked from VDT in the actual work environment.

1. INTRODUCTION

Some studies on the mutual relationship between electromagnetic and sound waves leaked from electronic equipment in the actual working environment have become important recently because of the increased use of various information and communication system like the personal computer and portable radio transmitters, especially concerning their individual and/or compound effects on a living

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body [1, 2]. Electromagnetic and sound waves especially are often measured in a frequency domain under the standardized measuring situation in a radiofrequency anechoic chamber, reverberation and anechoic rooms. Though these standard methods in a frequency domain are useful for the purpose of analyzing the mechanism of individual phenomena, they seem to be inadequate for evaluating total effects on the compound or the mutual relationship between electromagnetic and sound waves in complicated circumstances, such as the actual working environment. In order to evaluate universally the mutual correlation characteristics and its total image in the actual complex working environment, it is necessary to introduce some signal processing methods, especially in a time domain.

On the other hand, the observed data in the actual electromagnetic and sound environment are inevitably contaminated by the background noise of arbitrary distribution type [3, 4]. Furthermore, the observed data often contain fuzziness due to confidence limitations in sensing devices, permissible errors in the experimental data, and quantizing errors in digital observations [5, 6]. Therefore, in order to evaluate precisely the objective electromagnetic and sound environment, it is desirable to estimate the mutual relationship between electromagnetic and sound waves based on the observation data containing the effects by the background noise and fuzziness.

In this study, a prediction method for probability distribution of elecromagnetic wave leaked from electronic information equipment under actual situation in the existence of a background noise is proposed on the basis of fuzzy measurement data. More specifically, a conditional probability expression for fuzzy variables is first derived by applying the probability measure of fuzzy events [7] to a multi-dimensional joint probability function in a series type expression reflecting information on various correlation relations between the electromagnetic and sound waves. Next, by use of the derived probability expression, a method for estimating precisely the correlation information from various conditional moment statistics based on the observed fuzzy data is theoretically proposed. On the basis of the estimated correlation information, the probability distribution for a specific variable (e.g., electromagnetic wave) based on the observed fuzzy data of the other variable (e.g., sound wave) can be predicted. Finally by applying the proposed methodology to the measured fuzzy data in an actual working environment, the effectiveness of theory is confirmed experimentally.

2. PREDICTION OF PROBABILITY DISTRIBUTION FROM ARBITRARY FUZZY FLUCTUATION FACTOR

2.1. General Theory (Summary [1])

The observed data in the actual electromagnetic and sound environment often contain fuzziness due to several factors such as limitations in the measuring instruments, permissible error tolerances in the measurement, and quantization errors in digitizing the observed data.

In order to evaluate quantitatively the complicated relationship between electromagnetic and sound waves leaked from an identical electromagnetic information equipment, let two kinds of variables (i.e., sound and electromagnetic waves) be x and y, and the observed data based on fuzzy observations be X and Y respectively. There exist the mutual correlation relations between x and y, and also between X and Y. Therefore, by finding the relations between x and X, and also between y and Y, based on the probability measure of fuzzy events [7], it is possible to predict the true value y (or x) form the observed fuzzy data X (or Y). For example, for the prediction of the pdf (probability density function) $P_s(y)$ of y from X, averaging the conditional pdf $P(y|X)$ on the basis of the observed fuzzy data X, $P_s(y)$ can be obtained as $P_s(y) = \langle P(y|X)\rangle_X$, where $\langle\rangle$ is averaging operation with respect to the random variables. The conditional pdf $P(y|X)$ can be expressed under the employment of the well-known Bayes' theorem:

$$P(y|X) = \frac{P(X,y)}{P(X)}. \tag{1}$$

The joint probability distribution $P(X, y)$ is expanded into an orthonormal polynomial series on the basis of the fundamental probability distributions $P_0(X)$ and $P_0(y)$, which can be artificially chosen as the probability functions describing approximately the dominant parts of the actual fluctuation pattern, as follows:

$$\begin{aligned} P(X,y) &= P_0(X)P_0(y)\sum_{m=0}^{\infty}\sum_{n=0}^{\infty} A_{mn}\psi_m^{(1)}(X)\psi_n^{(2)}(y), \\ A_{mn} &\equiv \left\langle \psi_m^{(1)}(X)\psi_n^{(2)}(y)\right\rangle, \end{aligned} \tag{2}$$

where $\psi_m^{(1)}(X)$ and $\psi_n^{(2)}(y)$ are orthonormal polynomials with the weighting functions $P_0(X)$ and $P_0(y)$. The information on the various types of linear and nonlinear correlations between X and y is reflected in each expansion coefficient A_{mn}. Form (2), the probability distribution of X can be expressed as:

$$P(X) = \int P(X,y)dy = P_0(X)\sum_{m=0}^{\infty} A_{m0}\psi_m^{(1)}(X). \quad (3)$$

Thus, by substituting (2) and (3) into (1), the predicted pdf $P_s(y)$ can be expressed in an expansion series form:

$$P_s(y) = P_0(y)\sum_{n=0}^{\infty}\left\langle \frac{\sum_{m=0}^{\infty} A_{mn}\psi_m^{(1)}(X)}{\sum_{m=0}^{\infty} A_{m0}\psi_m^{(1)}(X)}\right\rangle X\psi_n^{(2)}(y). \quad (4)$$

2.2. Expression of Probability Distribution

When X is a fuzzy number expressing an approximated value, it can be treated as a discrete variable with a certain level difference. Therefore, as the fundamental probability function $P_0(X)$, the generalized binomial distribution with a level difference interval h_X can be chosen:

$$P_0(X) = \frac{\left(\frac{N_X - M_X}{h_X}\right)!}{\left(\frac{X - M_X}{h_X}\right)!\left(\frac{N_X - X}{h_X}\right)!} p_X^{\frac{X-M_X}{h_X}} (1-p_X)^{\frac{N_X - X}{h_X}},$$
$$p_X \equiv \frac{\mu_X - M_X}{N_X - M_X},\ \mu_X \equiv \langle X\rangle, \quad (5)$$

where M_X and N_X are the maximum and minimum values of X. Furthermore, in the measurement of electromagnetic and sound environment, the observation data are generally contaminated by a background noise. The power state variables satisfying the additive property of the specific signal and the background noise are considered in this study. A Gamma distribution suitable for random variables fluctuating within only a positive range such as the specific signal in a power scale is adopted as the fundamental pfd $P_0(y)$ of y [8].

$$P_0(y) = \frac{y^{m_y - 1}}{\Gamma(m_y)s_y^{m_y}} e^{-\frac{y}{s_y}},$$
$$m_y \equiv \frac{\mu_y^2}{\sigma_y^2},\ s_y \equiv \frac{\sigma_y^2}{\mu_y},\ \mu_y \equiv \langle y\rangle,\ \sigma_y^2 \equiv \langle (y-\mu_y)^2\rangle, \quad (6)$$

where $\Gamma(\bullet)$ is a Gamma function. The orthonormal polynomials $\psi_m^{(1)}(X)$ and $\psi_n^{(2)}(y)$ can be determined as [1, 8]

$$\begin{aligned}
\psi_m^{(1)}(X) &= \left\{\left(\frac{N_X - M_X}{h_X}\right)^{(m)} m!\right\}^{-\frac{1}{2}} \left(\frac{1-p_X}{p_X}\right)^{\frac{m}{2}} \frac{1}{h_X^m} \\
&\cdot \sum_{j=0}^{m} \frac{m!}{(m-j)!j!}(-1)^{m-j}\left(\frac{p_X}{1-p_X}\right)^{m-j} (N_X - X)^{(m-j)} (X - M_X)^{(j)}, \\
&\left(X^{(n)} \equiv X(X-h_X)\ldots(X-(n-1)h_X),\ X^{(0)} \equiv 1\right), \\
\psi_n^{(2)}(y) &= \sqrt{\frac{\Gamma(m_y)\, n!}{\Gamma(m_y+n)}} L_n^{(m_y-1)}\left(\frac{y}{s_y}\right),
\end{aligned} \tag{7}$$

where $L_n^{(m-1)}(\bullet)$ is Laguerre polynomial of n-th order, defined by the following equation:

$$L_n^{(m)}(y) \equiv \frac{e^y y^{-m}}{n!} \frac{d^n}{dy^n}(e^{-y} y^{n+m}). \tag{8}$$

3. ESTIMATION OF CORRELATION INFORMATION BASED ON FUZZY OBSERBATION DATA

The expansion coefficients A_{mn} in (2) have to be estimated on the basis of the fuzzy observation data, when the true value y is unknown. Furthermore, in the measurement of electromagnetic and sound environment, the effects by a background noise are inevitable. Then, based on the additive property of power state variables, the observed electromagnetic or sound power z is expressed as

$$z = y + v, \tag{9}$$

where v is a background noise in a power scale. We assume that the statistics of bapckground noise are known. Therefore, by paying our attention to the available observation data, the joint pdf $P(X, z)$ has to be considered instead of $P(X, y)$ in (2).

$$\begin{aligned}
P(X, z) &= P_0(X)P_0(z) \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} B_{mn}\psi_m^{(1)}(X)\psi_n^{(3)}(z), \\
B_{mn} &\equiv \left\langle \psi_m^{(1)}(X)\psi_n^{(3)}(z)\right\rangle,
\end{aligned} \tag{10}$$

where $P_0(z)$ and $\psi_n^{(3)}(z)$ are the fundamental pdf and the orthonormal polynomial of z, and are expressed in a Gamma distribution and a

Laguerre polynomial as follows:

$$P_0(z) = \frac{z^{m_z-1}}{\Gamma(m_z)s_z^{m_z}} e^{-\frac{z}{s_z}}, \tag{11}$$

$$\psi_n^{(3)}(z) = \sqrt{\frac{\Gamma(m_z)n!}{\Gamma(m_z+n)}} L_n^{(m_z-1)}\left(\frac{z}{s_z}\right) \tag{12}$$

with

$$m_z \equiv \frac{\mu_z^2}{\sigma_z^2},\ s_z \equiv \frac{\sigma_z^2}{\mu_z},\ \mu_z \equiv \langle z \rangle,\ \sigma_z^2 \equiv \left\langle (z-\mu_z)^2 \right\rangle. \tag{13}$$

Let the joint probability distribution of X and fuzzy observation Z for z, be $P(X, Z)$, and the joint pdf of X and z be $P(X, z)$. By applying probability measure of fuzzy events [7] to $P(X, z)$, $P(X, Z)$ can be expressed as:

$$P(X, Z) = \frac{1}{K} \int \mu_Z(z) P(X, z) dz, \tag{14}$$

where K is a constant satisfying the normalized condition:

$$\sum_X \sum_Z P(X, Z) = 1.$$

The fuzziness of Z can be characterized by the membership function $\mu_Z(z)$, and the following function suitable for the Gamma distribution is newly introduced.

$$\mu_Z(z) = (Z^{-\alpha} e^{\alpha}) \exp\left\{-\frac{\alpha}{Z} z\right\}, \tag{15}$$

where α (> 0) is a parameter. Substituting (10), (11) and (15) into (14), the following relationship is derived (cf. Appendix A).

$$P(X, Z) = \frac{1}{K} P_0(X) \sum_{m=0}^{\infty} \sum_{n=0}^{\infty} B_{mn} a_n(Z) \psi_m^{(1)}(X), \tag{16}$$

$$a_n(Z) = \frac{Z^{-\alpha} e^{\alpha}}{\Gamma(m_z)s_z^{m_z}} \Gamma(M) D^M \sqrt{\frac{\Gamma(m_z)n!}{\Gamma(m_z+n)}} g_{n0}, \tag{17}$$

with

$$M = m_z + \alpha,\ D = \frac{s_z Z}{\alpha s_z + Z}, \tag{18}$$

where a few concrete expressions of g_{n0} in (17) can be expressed as follows:

$$\begin{aligned}
g_{00} =&1,\ g_{10} = m_z - M\frac{D}{s_z},\\
g_{20} =&\frac{1}{2}(m_z+1)m_z - (m_z+1)M\frac{D}{s_z} + \frac{1}{2}(1+M)M\left(\frac{D}{s_z}\right)^2,\\
g_{30} =&\frac{1}{6}(m_z+2)(m_z+1)m_z - \frac{1}{2}(m_z+2)(m_z+1)M\frac{D}{s_z}\\
&+\frac{1}{2}(m_z+2)(1+M)M\left(\frac{D}{s_z}\right)^2 - \frac{1}{6}(2+M)(1+M)M\left(\frac{D}{s_z}\right)^3.
\end{aligned} \tag{19}$$

The conditional Nth order moment of the fuzzy variable X is given from (16) as

$$\begin{aligned}
\langle X^N|Z\rangle =& \sum_X X^N P(X|Z) = \sum_X X^N P(X,Z)/P(Z)\\
=& \sum_X X^N P_0(X) \sum_{m=0}^{\infty}\sum_{n=0}^{\infty} B_{mn} a_n(Z)\psi_m^{(1)}(X) / \sum_{n=0}^{\infty} B_{0n} a_n(Z).
\end{aligned} \tag{20}$$

After expanding X^N in an orthogonal series expression, by considering the orthonormal relationship of $\psi_m^{(1)}(X)$, (20) is expressed explicitly as

$$\langle X^N|Z\rangle = \sum_{m=0}^{N}\sum_{n=0}^{\infty} d_m^N B_{mn} a_n(Z) / \sum_{n=0}^{\infty} B_{0n} a_n(Z), \tag{21}$$

where d_m^N is an appropriate constant satisfying the following relationship:

$$X^N \equiv \sum_{i=0}^{N} d_i^N \psi_i^{(1)}(X). \tag{22}$$

The right side of (21) can be evaluated numerically from the fuzzy observation data. Accordingly, by regarding the expansion coefficients B_{mn} as unknown parameters, a set of simultaneous equations in the same form as in (21) can be obtained by selecting a set of N and/or Z values equal to the number of unknown parameters. By solving the simultaneous equations, the expansion coefficients B_{mn} can be estimated.

In order to predict the pdf $P_s(y)$ by using (4), the expansion coefficients A_{mn} have to be estimated on the basis of the expansion coefficients B_{mn}. After using the definition of Laguerre polynomial:

$$L_n^{(m)}(z) \equiv \frac{e^z z^{-m}}{n!}\frac{d^n}{dz^n}\left(e^{-z} z^{n+m}\right) = \sum_{r=0}^{n}(-1)^r {}_nC_r \frac{1}{n!}\frac{\Gamma(m+n)}{\Gamma(m+r)} z^r, \tag{23}$$

substituting (9) and (23) into (10), the expansion coefficient B_{mn} can be expressed as

$$B_{mn}=\frac{\Gamma(m_z)n!}{\Gamma(m_z+n)}\sum_{r=0}^{n}(-1)^r{}_nC_r\frac{1}{n!}\frac{\Gamma(m_z+n)}{\Gamma\,(m_z+r)}\left\langle\psi_m^{(1)}(X)\left(\frac{y+v}{s_z}\right)^r\right\rangle. \quad (24)$$

Furthermore, by expanding $(y+v)^r$ and using the dual relationship for (23):

$$z^n=\sum_{r=0}^{n}(-1)^r{}_nC_r\frac{1}{r!}\frac{\Gamma(m+n)}{\Gamma(m+r)}L_r^{(m-1)}(z), \quad (25)$$

and by introducing two arbitrary parameters m_y and s_y, the following relationship of B_{mn} can be derived.

$$B_{mn}=\Gamma(m_z)n!\sum_{r=0}^{n}(-1)^r{}_nC_r\frac{1}{n!}\frac{1}{\Gamma(m_z+r)}\frac{1}{s_z}\sum_{i=0}^{r}{}_nC_i s_y^i \sum_{j=0}^{i}(-1)^j{}_iC_j\frac{1}{j!}\frac{\Gamma(m_y+i)}{\Gamma(m_y+j)}\left\langle\psi_m^{(1)}(X)L_j^{(m_y-1)}\left(\frac{y}{s_y}\right)\right\rangle\left\langle v^{(r-i)}\right\rangle. \quad (26)$$

The correlation $\langle\psi_m^{(1)}(X)L_j^{(m_y-1)}(y/s_y)\rangle$ in (26) can be expressed by using the expansion coefficient A_{mj} defined by (2) as:

$$\left\langle\psi_m^{(1)}(X)L_j^{(m_y-1)}\left(\frac{y}{s_y}\right)\right\rangle=\sqrt{\frac{\Gamma(m_y+i)}{\Gamma(m_y)j!}}A_{mj}. \quad (27)$$

Therefore, by solving (26) inversely, the expansion coefficients $A_{mj}(j=0,1,2,\ldots)$ can be obtained recursively form $B_{mj}(j=0,1,2,\ldots)$. Furthermore, by using the property of statistical independence between y and v, two parameters m_y and s_y in (27) can be obtained as

$$m_y\equiv\frac{\mu_y^2}{\sigma_y^2},\ s_y\equiv\frac{\sigma_y^2}{\mu_y},\ \mu_y=\mu_z-\langle v\rangle,\ \sigma_y^2=\sigma_z^2-\left\langle(v-\langle v\rangle)^2\right\rangle. \quad (28)$$

4. APPLICATION TO ACTUAL VDT ENVIRONMENT UNDER EXISTENCE OF BACKGROUND NOISE

By adopting a personal computer in the actual working environment as specific information equipment, the proposed method is applied to investigate the mutual relationship between electromagnetic and sound waves leaked from a VDT under the situation of playing a computer game. Some studies on the fluctuation of electromagnetic wave leaked from electronic equipment in the actual working environment have become important recently because of the increased use of various information and communication systems like the personal computer and portable radio transmitters, especially concerning the individual and compound effects on a living body. It is well-known that there are too many unsolved questions on VDT symptom groups to study, such as the complaint of general malaise, the effect on a pineal body, an allergic or stress reaction, any relationship to cataract formation or leukaemia and so on (for example, see reference [9]). In the investigation, one of the first important problem generally pointed out is to find any quantitative evaluation method. The proposed method in this paper is fundamental study to evaluate quantitatively the specific signal on electromagnetic wave.

More specifically, in the actual office environment of using four computers as shown in Figure 1, the electric field strength R leaked from a specific computer denoted by 1 is predicted on the basis of the observation data of sound by regarding the electric field from other three computers as background noise n. Two variables R and n have relationships: $y = R^2$ and $v = n^2$ with the power variables y and v in (9). The proposed method can apply to arbitrary actual background noise without any restrictions for the power spectrum like white and pink noises. The statistics of the specific signal R and the background noise n are shown in Table 1. The RMS value [v/m] of the electric field

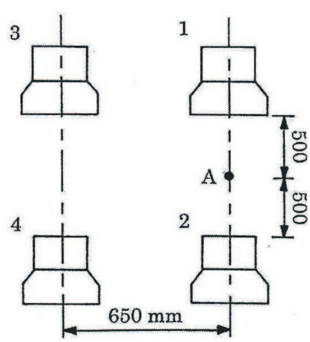

Figure 1. A schematic drawing of the experiment.

Table 1. Statistics of the specific signal and the background noise.

Statistics of specific signal		Statistics of background noise	
Mean [v/m]	Standard Deviation [v/m]	Mean [v/m]	Standard Deviation [v/m]
2.77	0.0952	0.815	0.245

radiated from the VDT and the sound intensity level [dB] emitted from a speaker of the personal computer are simultaneously measured. The data of electric field strength and sound intensity level are measured by use of an electromagnetic field survey mater and a sound level meter respectively. In order to utilize the additive property of (9), the RMS value of electric field strength R is transformed to the power variable $y\,(=R^2)$. The slowly changing nonstationary 600 data for each variable are sampled with a sampling interval of 1 [s]. Two kinds of fuzzy data with the quantized level widths of 1.0 [(v/m)^2] for electric field strength and 5.0 [dB] for sound intensity level are obtained. Based on the 400 data points, the expansion coefficients A_{mn} (i.e., A_{11}, A_{12}, A_{21} and A_{22}) are first estimated by use of (21), (26) and (27). Next, the 200 sampled data within the different time interval which are nonstationary different form data used for the estimation of the expansion coefficients are adopted for predicting the probability distribution of the electric field based on the sound. Membership function of the electric field is shown in Figure 2. The parameter α is decided so as to express the distribution of data as precisely as possible. The membership functions of triangular shape and/or trapezoid type are usually used from the experimental viewpoint for the simplification of numerical calculation. We adopt a new type of membership function in (15) from the viewpoint of mathematial analysis.

The experimental results for the prediction in the power value y of electric field strength are shown in Figure 3 (in the case when $Z = 17, 22$ [(v/m)^2] and $N = 1, 2$ in (21)) and Figure 4 (in the case when $Z = 21, 22$ [(v/m)^2] and $N = 1, 2$ in (21)) respectively in a form

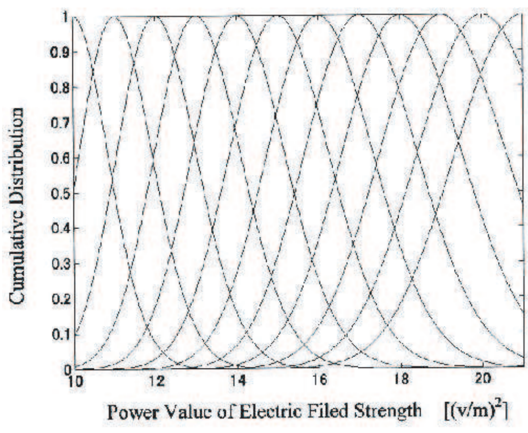

Figure 2. Membership function of electric field.

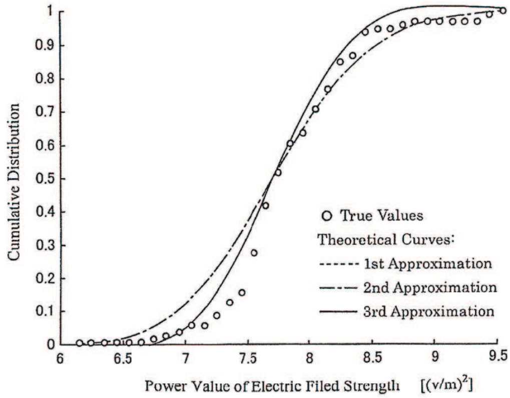

Figure 3. Prediction of the cumulative distribution for the power value of electric field strength based on the fuzzy observation of sound (in the case when $Z = 17, 22\,[(\mathrm{v/m})^2]$ and $N = 1, 2$ in (21)).

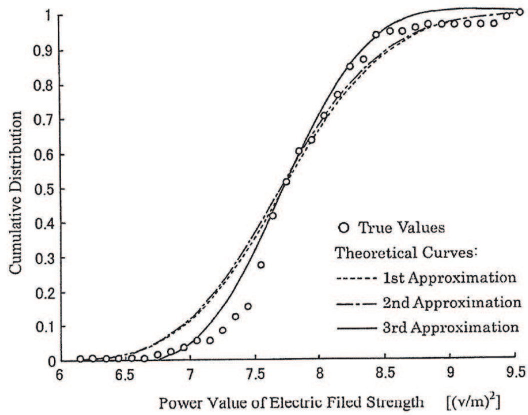

Figure 4. Prediction of the cumulative distribution for the power value of electric field strength based on the fuzzy observation of sound (in the case when $Z = 21, 22\,[(\mathrm{v/m})^2]$ and $N = 1, 2$ in (21)).

of cumulative distribution. In these figures, the predicted results by considering the expansion terms up to $n = 0, 1, 2$ in (4) are shown as the 1st, 2nd and 3rd approximations. Furthermore, the probability distribution in the RMS value R of electric field strength can be obtained by use of the measure preserving transformation, as follows:

$$P_s(R) = P_s(y)\left|\frac{dy}{dR}\right|\Bigg|_{y=R^2} = \frac{2R^{2m_y-1}}{\Gamma(m_y)s_y^{m_y}}e^{-\frac{R^2}{s_y}}$$

$$\sum_{n=0}^{\infty}\left\langle\frac{\sum_{m=0}^{\infty}A_{mn}\psi_m^{(1)}(X)}{\sum_{m=0}^{\infty}A_{m0}\psi_m^{(1)}(X)}\right\rangle_X\sqrt{\frac{\Gamma(m_y)n!}{\Gamma(m_y+n)}}L_n^{(m_y-1)}\left(\frac{R^2}{s_y}\right). \quad (29)$$

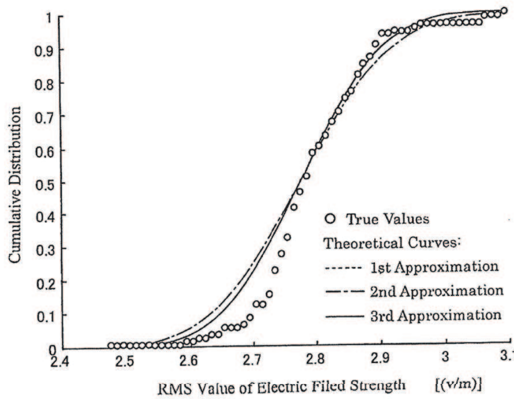

Figure 5. Prediction of the cumulative distribution for the RMS value of electric field strength based on the fuzzy observation of sound (in the case when $Z = 17, 22\,[(\text{v/m})^2]$ and $N = 1, 2$ in (21)).

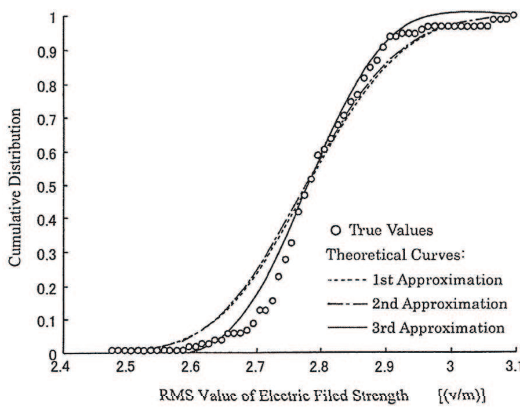

Figure 6. Prediction of the cumulative distribution for the RMS value of electric field strength based on the fuzzy observation of sound (in the case when $Z = 21, 22\,[(\text{v/m})^2]$ and $N = 1, 2$ in (21)).

The comparisons between the theoretically predicted curves and true values are shown in Figures 5 and 6. (The "1st Approximation" denoted by the dashed lines in Figures 3 and 5 coincides with the dash-and-dot lines expressing the "2nd Approximation".) From there figures, it can be found that the theoretically predicted curves show good agreements with the true values by considering the expansion coefficients with several higher orders. The effectiveness of a method based on fuzzy probability has been confirmed in our previously reported study [1] in the ideal situation without background noise, as compared with the generalized regression analysis method [10]. In this study, we extend the previous study in a form applicable to the actual situation with the existence of background noise.

5. CONCLUSION

In this paper, by extending our previously reported paper [1] in a form applicable to the actual situation in the presence of a background noise, a prediction method for probability distribution of electromagnetic wave leaked from electronic information equipment has been proposed. More specifically, power state variables have been first considered in order to utilize the additive property of the specific signal and background noise. Next, by introducing an expansion series expression of the probability distribution based on Gamma distribution suitable for the power variables, a method to estimate not only the linear correlation of lower order but also the nonlinear correlation of higher order between electromagnetic and sound waves has been derived. By newly introducing a membership function of Gamma distribution type and considering probability measure of fuzzy events, a prediction method of the probability density function of electromagnetic wave based on the fuzzy measurement data has been proposed. The validity and effectiveness of the proposed method have been confirmed experimentally by applying it to the observation data radiated from a personal computer in an actual working environment under the existence of a background noise.

The proposed approach is obviously quite different from the ordinary approach, and it is still at an early stage of study. Thus there are a number of problems to be investigated in the future, building on the results of the basic study in this paper. Some of the problems are shown in the following. (i) The proposed method should be applied to other actual data of electromagnetic and sound environment, and the practical usefulness should be verified in these situations. (ii) The proposed theory should be extended further to more complicated situations involving multi-signal sources. (iii) In order to predict more precisely the probability distribution of the specific signal, it is essential to consider the higher order correlation information in the probability expression of (4). From a theoretical viewpoint, the proposed method can be constructed with higher precision, by employing many of the correlation functions of higher order. From a practical viewpoint, however, reliability tends to be lower for the higher order statistics. It is necessary then to investigate up to what order the correlation functions can be reasonably determined, based on the non-Gaussian property of the phenomena.

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APPENDIX A. DERIVATION OF (16) AND (17)

Substituting (10), (11) and (15) into (14), the joint probability distribution $P(X, Z)$ is expressed as (16). The function $a_n(Z)$ in (16) can be calculated as follows:

$$\begin{aligned} a_n(Z) &= \frac{Z^{-\alpha} e^{\alpha}}{\Gamma(m_z) s_z^{m_z}} \int_0^{\infty} z^{m_z+\alpha-1} e^{-\left(\frac{\alpha}{Z}+\frac{1}{s_z}\right) z} \sqrt{\frac{\Gamma(m_z) n!}{\Gamma(m_z+n)}} L_n^{(m_z-1)}\left(\frac{z}{s_z}\right) dz \\ &= \frac{Z^{-\alpha} e^{\alpha}}{\Gamma(m_z) s_z^{m_z}} \Gamma(M) D^M \int_0^{\infty} \frac{z^{M-1}}{\Gamma(M) D^M} e^{-\frac{z}{D}} \sqrt{\frac{\Gamma(m_z) n!}{\Gamma(m_z+n)}} \\ &\quad \sum_{r=0}^{n} g_{nr} L_r^{(M-1)}\left(\frac{z}{D}\right) dz, \end{aligned} \tag{A1}$$

where two parameters M and D are defined by (18). The fuzzy data Z are reflected in D. Furthermore, g_{nr} $(r = 0, 1, 2, \ldots, n)$ are the expansion coefficients in the equality:

$$L_n^{m_z-1}\left(\frac{z}{s_z}\right) = \sum_{r=0}^{n} g_{nr} L_r^{(M-1)}\left(\frac{z}{D}\right). \tag{A2}$$

By considering the orthonormal relationship of Laguerre polynomial:

$$\begin{aligned} &\int_0^{\infty} \frac{z^{M-1}}{\Gamma(M) D^M} e^{-\frac{z}{D}} \sqrt{\frac{\Gamma(M) n!}{\Gamma(M+n)}} L_n^{(M-1)}\left(\frac{z}{D}\right) \\ &\sqrt{\frac{\Gamma(M) r!}{\Gamma(M+r)}} L_r^{(M-1)}\left(\frac{z}{D}\right) dz = \delta_{nr}, \end{aligned} \tag{A3}$$

(17) can be derived.

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