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A NEW UNIFIED METHOD OF DYNAMICALLY ESTIMATING THE UNKNOWN NOISE SIGNALS CONTAMINATED BY BACKGROUND NOISE AND ITS APPLICATIONS TO ACTUAL NOISE ENVIRONMENT

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INTRODUCTION

Generally speaking, from the engineering viewpoint for evaluating a stochastic environmental phenomena in our daily life, such as residence noise, road traffic noise, machine and structure vibration etc., there is very often a necessity of estimating any of statistical quantities like mean, variance and the other higher order moments, owing to the fact that various evaluation procedures have been proposed from many different viewpoints because of the variety of phenomena and the complexity of human response to them. Furthermore, in the actual situation of measuring the environmental noise level fluctuations, it is very oftem that only the resultant phenomenon can be observed after being contaminated by a background noise of arbitrary distribution type. Then, in order to evaluate the actual environmental noise through the observed noisy data embedded in such undesirable additive noise, some systematic methodology should be definitely necessary for removing the effect of an background noise on the evaluation indexes of the phenomena.

For the purpose of evaluating or controlling more precisely the actual noise environment under an inevitable additive noise, a unified methodology of detecting the unknown noise signal with arbitrary distribution type based on the successive observations contaminated by the background noise is newly proposed in this paper. More concretely, as one of systematic methodologies of treating the above estimation problem on the statistical evaluation quantity of arbitrary type, the so-called Bayesian point of view is firstly employed. After introducing the appropriate probability function describing the essential or fundamental probability characteristics commonlu latent in the random noise phenomena, a new expression of Bayes' theorem is found in the form of orthogonal series expansion, which is suitable for deriving a recurrence algorithm of estimation on statistical quantities of arbitrary type matched to the successive observation of environmental phenomena. It is noticeable that the proposed method corresponds to some generalizations of well-known Kalman's filtering theory. That is, it can treat the general cases when an arbitrarily distributed input noise passes through an arbitrary non-linear dynamical environmental system with possibly time-variant parameters.

Furthermore, apparantly as a part of background noise or substantially as the different additive noise from background noise, the error noise derived from an idealized situation in the case of modelling mathematically the actual environmantal system is newly taken into consideration in the above general estimation method. For instance, in the actual situation of road traffic noise or room acoustic, there are some deviations from an idealized auto-regressive model due to the mathematical modelling or an idealized average-energy concept of Sabine's reverberation equation.

Finally, the validity and the effectiveness of proposed theoretical results are experimentally clarified through the several applications to actually observed data of road traffic noise and of room acoustics in Hiroshima city.

THEORETICAL CONSIDERATIONS

A Unified Estimation Method for the Environmental System Under Background Noise Analyzing the random fluctuations of the physical pnenomenon by applying the systematic procedure in the field of time series analysis, we will model the environmental noise system in terms of the non-linear time-variant dynamical model with a general stationary random input of arbitrary distribution type, U_k, as follows:

$$X_{k+1} = \Phi_k(X_k, U_k), \tag{1}$$

where X_k is the state variable at the k-th time stage. It is usual that the instantaneous observations of the random phenomena in the environmental pollution problems are given in the form of level values with a discrete time, after contaminated by the background noise and/or the measurement error of arbitrary type. Then, in order to derive the unified methodology for estimating the unknown state X_k of stochastic system (1) based on the successive observations contaminated by the undesirable additional noise, we will formulate the physical measurement mechanism by using newly the observation equation expressed as follows:

$$y_k = H_k(X_k, V_k), \tag{2}$$

where y_k denotes the noisy observation of the environmental system (1) contaminated by the observation noise V_k. The statistical information on the input U_k and the background noise V_k is assumed to be a priori given.

Now, let Y_k be the sequence of observations $(y_1, y_2, \cdots, y_k)$. Given a realization of the observed sequence Y_k, the discrete estimation problem consists of finding the estimate of an arbitrary function of X_k

based on Y_k. Then, consider the Bayes' theorem on the conditional probability functions as the fundamental relationship to derive an estimation:

$$P(X_k|Y_k) = P(X_k|Y_{k-1})\cdot P(y_k|X_k, Y_{k-1})/P(y_k|Y_{k-1}). \quad (3)$$

In order to overcome the difficulty of estimating the unknown noise signal X_k owing to an inevitable effect of the nonlinear physical mechanism of environmental noise system and the non-Gaussian property of fluctuation on the evaluation indexes of phenomena, we will evaluate the nonlinearity of systems and the non-Gaussian property of fluctuations with the introduction of unified orthogonal series expansion expression with respect to the Bayes' theorem (3). From an analytical viewpoint of the rapid convergence and the steadiness for the expansion series type expression of Bayes' theorem, the arbitrary probability density function has to be selected as the first term of the series expansion. This artificial probability function had better to be selected to describe the essential or fundamental probability characteristics commonly latent in the random phenomena under consideration. Finally, the following newly-derived expansion expression can be obtained by introducing the artifical probability functions $P_0(X_k|Y_{k-1})$ and $P_0(y_k|Y_{k-1})$ for the series expansion:

$$P(X_k|Y_k) = \sum_{n=0}^{\infty}\sum_{m=0}^{\infty} A_{mn}\,\Psi_m^{(1)}(X_k)\cdot\Psi_n^{(2)}(y_k)\cdot P(X_k|Y_{k-1}), \quad (4)$$

where $\Psi^{(1)}{}_m(X_k)$ and $\Psi^{(2)}{}_n(y_k)$ are orthogonal polynomials of degree m and n, associated with the weighting functions, $P_0(X_k|Y_{k-1})$ and $P_0(y_k|Y_{k-1})$, respectively. Then, based on the unified form of series expanded Bayes' theorem, the estimates of any kind of statistics given by an arbitrary polynomial function form $f_{m'}(X_k)$ with an exponent less than m' of state variable can be recursively obtained in the concrete expression of orthogonal expansion series type, as follows:

$$\hat{f}_{m'}(X_k) \equiv \langle f_{m'}(X_k)|Y_k\rangle = \sum_{m=0}^{m'}\sum_{n=0}^{\infty} A_{mn} C_{m'm}\Psi_n^{(2)}(y_k) \Big/ \sum_{n=0}^{\infty} A_{0n}\Psi_n^{(2)}(y_k), \quad (5)$$

where the coefficient $C_{m'm}$ is determined to express $f_{m'}(\cdot)$ with use of $\{\Psi^{(1)}{}_m(\cdot)\}$. It is noticeable that the above new result include some generalization on the type of estimation processes, viz., it can correspond to general case when an arbitrarily distributed input noise passes through an arbitrary nonlinear (possibly time-variant) system.

A Unified Estimation Method for the Environmental System Under Background Noise and Modelling Error Generally speaking, in the actual situation of evaluating or predicting the random phenomena, it is sometimes inevitable to consider the undesirable modelling error generated from incomplete situation in the actual measurement (i.e., the actual observations in an environmental field are very often given under the unsatisfactory situation without keeping the idealized physical property assumed abstractively in the theoretical research), together with an additional background noise. Apparently as a part of backgorund noise or substantially as the different additive noise from background noise, the error noise derived from an idealized situation in the case of modelling mathematically the actual environmental system should be newly taken into consideration in the proposed methodology. Then, in order to establish the unified methodology, we will formulate the environmental system in terms of the nonlinear dynamical model with a general random input, U_k, of arbitrary distribution type, as follows:

$$y_k = \Phi_k(a_k, U_k) + V_k + \varepsilon_k, \quad a_{k+1} = a_k \ (\triangleq a), \tag{6, 7}$$

where a_k denotes the unknown time-invariant parameter of the stochastic system. In the problem of room acoustics, the unknown state a_k corresponds to a reverberation time.

Considering the modelling error ε_k in Eq.(6) as the biased value of the observation y_k, we can derive the recursive algorithm of estimating a_k, based on the unified algorithm (5). Unfortunately, owing to the existence of modelling error, the estimate cannot be calculated. Now, let us consider the fact in the actual measurement:i) The observed data are given in the averaged form through the averaging indicator of the sound level meter, ii)The evaluation of the phenomena is usually expected to remove the effect of modelling error on the averaged statitics. Thus, after expanding the algorithm (5) into a Taylor's series expansion, the following averaged algorithm:

$$\hat{\hat{f}}_{m'}(a_k) \equiv \langle \hat{f}_{m'}(a_k) \rangle = \sum_{m=0}^{m'} \sum_{n=0}^{\infty} \langle A_{mn} C_{m'm} \Psi_n^{(2)}(y_k) / \sum_{n=0}^{\infty} A_{0n} \Psi_n^{(2)}(y_k) \rangle_{\varepsilon} . \tag{8}$$

Hereupon, the criterion function $\langle \varepsilon_k^{s} \rangle = 0$ $(s>0)$ has been adopted, which is introduced by generalizing the Sabine's concept of averaged energy in an idealized situation when removing the modelling error in a statistical form. Thus we can estimate the unknown state of Eqs.(6) and (7).

EXPERIMENTAL CONFIRMATIONS

We have estimated the reverberation time T of the room, by using Eq.(8). The experimental data are observed in Hiroshima University. One of the typical results is shown in Fig.1.

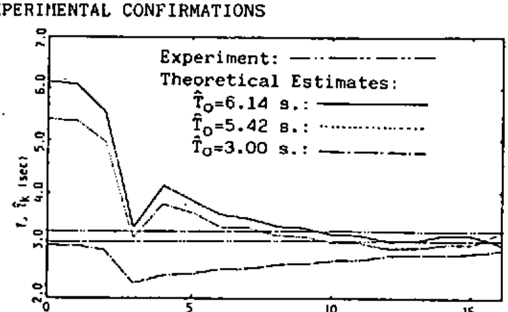

Fig.1 Estimation of reverberation time T.

CONCLUSIONS

The chief purpose of this paper is focused on finding how to extend the wellknown resuls by Kalman by generalizing Bayes' theorem in a new form of unified series expansion, especially in order to be suitable for finding a recurrence algorithm on statistical quantities of arbitrary type.

REFERENCE 1)Kalman,R.E.:Trans.ASME,Series D, Vol.82(1960)p.95.