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Transitory Shaped Test Signals Synthesis for Leak Locating Algorithms Analyzing

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Abstract –This work presents two methods for generating test signals that encounter a certain degree of transitory amplitude changes similar to those met in real leak signals. A performance index is also developed, based on both the amplitude and the argument of the cross-correlation function, for evaluating the effects of these abrupt changes on different algorithms' estimation results in leak location systems.

Index Terms – Leak detection; Time delay estimation.

I. INTRODUCTION

Early detecting leaks in operating transport pipeline systems represent an important issue in pipeline industry. Leaks can cause serious damage due to wasting precious supplies which are distributed through the pipes. Secondly, the transported material can contaminate the environment and injure the pipe bedding, roads or nearby buildings.

One of the most effective techniques for leak locating is based on the analysis of the acoustic noise generated by the material escaped through the leak. ([5], [6], [7], [8], [9]). The acoustic leak signal can be captured by non intrusive sensing devices placed on the pipeline. The method's principle is based on estimating the Time Difference of Arrival (TDOA) at which the leak signal reaches at two separate sensor locations on the pipe. The mathematical model for this problem is assumed to be:

$$\begin{cases} r_1(t) = s(t) + n_1(t) \\ r_2(t) = s(t\text{-}D) + n_2(t), \end{cases} \qquad (1)$$

where $r_1(t)$, $r_2(t)$ are the received signals, $n_1(t)$, $n_2(t)$ are the disturbing additive noises at the sensor locations, s(t) is the original leak noise and D is the time delay.

The cross-correlation function between the received signals is computed. TDOA is estimated as the argument at which the cross-correlation function maximum occurs. Knowing the distance between the two sensors and the noise propagation velocity along the pipe, the leak can be located ([6], [7], [8], [9]).
This technique is usually applied in the literature for generally locating noise sources and gives good estimation results under some simplifying ideal assumptions. The received signals and the disturbing noises are supposed to be stationary, white and Gaussian while the disturbing noises are assumed not correlated with the primary source and with each other [3], [4].

However, in practice, the received data prove to be contaminated by an additional burst-type noise component which will produce a non stationary, non Gaussian effect on the acquired signals. Fig.1 shows a typical signal pair measured in a real experimental installation. Here, due to the additional burst noise component, the acquired signals perform a number of abrupt amplitude variations occurring at some random time instances. These interferences can be produced internally, from a sudden pressure and flow velocity variation (turbulent flow), or externally, by non-stationary disturbing noises such as traffic, human voice, etc. The internally burst noise induced by the turbulent flow can contain the information regarding the time delay, but on the other hand the non stationary data characteristics can seriously affect the estimation accuracy.

The object of this paper is to propose two models of generating internal burst interferences. The reason for attempting this approach is to develop a practical tool by which real leak signals can be studied. By gradually inducing burst-type noises and comparing the estimation results one can find useful insights on how the estimation performance can be affected.

The first proposed model is based on a "software" method of generating random amplitude exponential

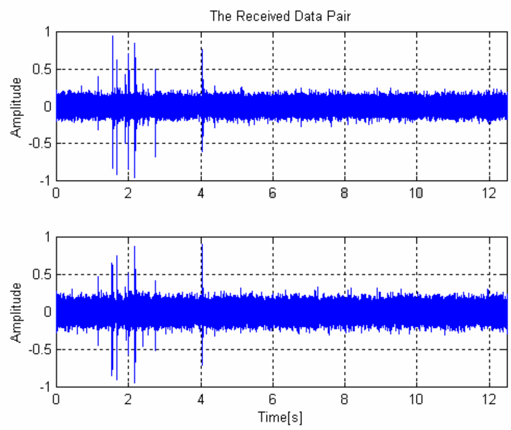

Fig.1 Typical data affected by burst-type noise

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variations. This method is described in section II and some simulation results are discussed in section IV.

The second proposed model is based on a "hardware" technique of generating periodic impulses in an experimental pipe installation for water transportation. The burst noises are induced by a diaphragm pump connected to the installation. This procedure is described in section III, and some experimental results are shown in section V.

In order to compare the degree by which the estimation performance is affected by burst-type noises, a new criterion is proposed. This criterion is based on measuring of how close is the cross-correlation function to the ideal case. Based on the method proposed in [10], this criterion takes into consideration two components instead of one: the amplitude of the cross-correlation function and the estimation error. This criterion is also discussed in section II.

II. COMPUTER BURST- NOISE MODELING

The proposed mathematical model which besides the additive disturbing ambient noise includes a burst component is described by equations (1). In this particular case, s(t) is given by:

$$s(t) = b(t) \times x(t) \tag{2}$$

where b(t) is the burst component and x(t) is the original leak signal. We specify that equation (2) refers to the situation in which the burst-type perturbation is produced inside the pipeline system due to some sudden pressure and flow velocity variations with random occurrence, typical of a turbulent flow. In this case the burst perturbation will also include the time delay information D, which is desired to be estimated. On the other hand, the explosive signal variations will affect the estimation performance up to a certain degree.

In this paragraph, a "software" method for generating random burst perturbations is proposed. The block diagram for producing the test signal s(t) in equation (2) is depicted in fig.2. Here, xw(t) is a white Gaussian noise generated using Matlab® environment; x(t) is a test signal obtained by passing xw(t) through a low-pass filter; b(t) is a train of exponential impulses with a random occurrence and s(t) is the resulting test signal. The block diagram by which the signal b(t) is generated is shown in fig.3. In this diagram, $\mathbf{t_0}$ is an exponential distributed random variable denoting the burst series start time. The random variable **p** denotes the number of burst events

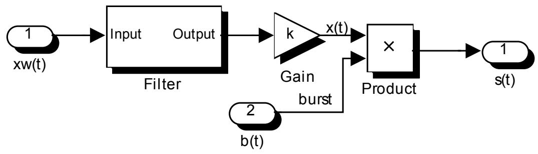

Fig.2 Model's block diagram

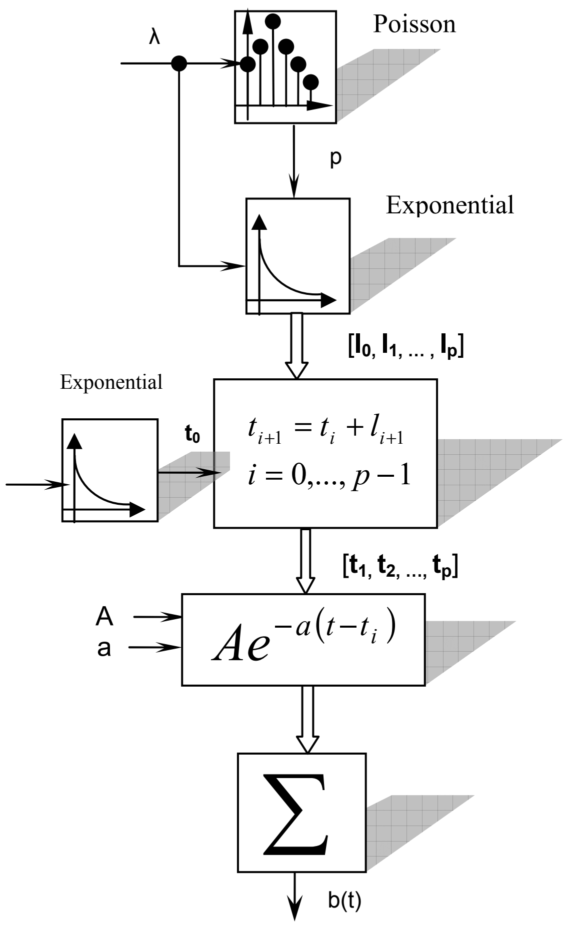

Fig.3 The proposed burst generator

occuring after $\mathbf{t_0}$ beeing described by a Poisson distribution with mean λ [1]. The random vector $[\mathbf{l_0,...l_p}]$ contains the interval lengths between two consecutive burst events, having also an exponential distribution with mean $\mu = 1/\lambda$, [1]. The random vector $[\mathbf{t_1,...t_p}]$ denotes the time moments at which the burst events occur in accordance with:

$$\begin{cases} t_{i+1} = t_i + l_{i+1}, & i = 0,..., p-1, \\ t_p \le (N-1)T_s \end{cases} \tag{3}$$

where N is the number of samples of each signal and T_s is the sampling period. At each moment $\mathbf{t_i}$, i=1,…,p, a spike signal of exponential form is generated:

$$spike(t) = Ae^{-a(t-t_i)} \tag{4}$$

where the variables "A" and "a" denote the amplitude and the time constant of the spike signal, respectively. The burst signal b(t) is then obtained by summing all the generated spike signals. If more "t_0" moments are generated, the burst concentration in the signal increases. An example of a test signal obtained using the algorithm described above is shown in fig.4

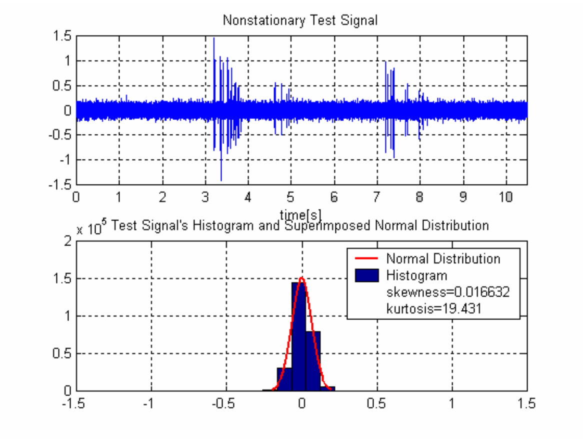

Fig.4 A typical test signal and its histogram

The effect of the burst noise on the test signal's histogram depends on both the amplitude and the concentration of the generated exponentials. The last component depends on the number of the exponential trains generated and can be defined as:

$$c = \left(\sum_{u=1}^{\max u} p \right) \Big/ N \tag{5}$$

On studying the test signals' behavior in section IV, in order to be able to evaluate the effects of the burst noise component on the estimation's accuracy it is important to separate the signal-to-noise ratio factor in two parts: "additive signal-to –noise –ratio", NSNR, and "burst-signal-to-noise-ratio", BSNR, defined by the following equations:

$$\begin{cases} NSNR[dB] = 10 \cdot \lg(P_x / P_n) \\ BSNR[dB] = 10 \cdot \lg(P_x / P_b) \end{cases} \tag{6}$$

where P_x, P_n and P_b denote the power of the original source signal, additive noise and burst-noise signals, respectively. The global signal-to-noise ratio that describes the entire test signal is given by:

$$SNR[dB] = 10 \cdot \lg[P_x / (P_n + P_b)] \tag{7}$$

From this last relationship derives that if any of the signal-to-noise components is much greater than the other, the global SNR will be reduced to the smallest component. If both components are comparable in size, then the global SNR is reduced with approximately 3dB than either of them.

Another important issue in evaluating the burst effects on the estimation results is to find a comparison criterion. Starting from the criterion described in [10], a new criterion is developed in this paper. The proposed criterion defines a performance index for measuring the signals' cross-correlation function degree of approach to the ideal case. This new performance index takes into consideration both the amplitude of the cross-correlation function and the estimation error, and is defined by the following relationship:

$$IDEG = \begin{cases} IDDEG(1-2\varepsilon), for 0 \le \varepsilon \le 0.5 \\ 0, for 0.5 < \varepsilon \le 1 \end{cases} \tag{8}$$

In the above definition, IDDEG denotes the amplitude component of the proposed index. It can be computed as the ratio between the cross-correlation function maximum's power and the total cross-correlation function's power. The other component that describes this index, indicating the estimation error is denoted with ε. It is defined as the ratio between the absolute deviation from the ideal case of the cross-correlation's maximum argument and the maximum delay. The last parameter is supposed to be a-priori known. From these definitions derives that the IDEG index together with its both two parts are positive numbers, smaller than or equal to unity.

Section IV shows some processing results performed on the generated test signals assuming the presented model, and evaluated through the new proposed index.

III. THE EXPERIMENTAL MODEL

The second proposed model for burst-noise generating was implemented by an experimental pipeline installation with configuration depicted in fig.5. The burst-type perturbations were produced by a diaphragm pump, parallel connected at the pipeline's input. The burst noise was generated periodically through the pump control device commanded by an adjustable frequency pulse generator. Fig.6 shows two typical signal pairs captured on this installation at the same locations on the pipe: the left pair was acquired without having the pump working, while the signal pair on the right was captured with the pump functioning at 4 Hz.

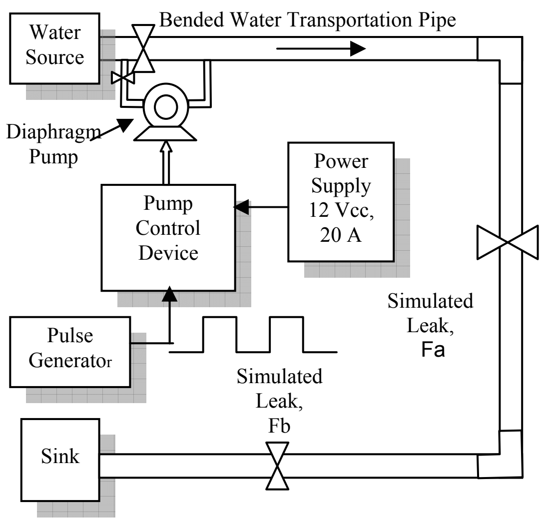

Fig.5 Experimental configuration for generating "hard" burst perturbations.

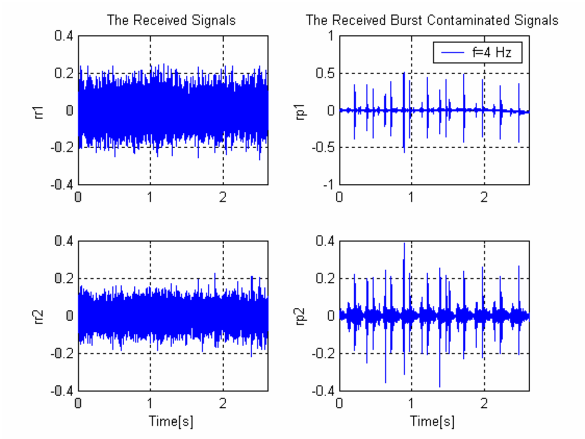

Fig.6 Two real signal pairs with and without induced burst perturbations, respectively.

In this experiment, three different working modalities were chosen for the study. The first one was performed with the mainstream cut off and only with the pump working. The second one was done with both full mainstream and the pump working in parallel, while the third one was made with half mainstream and the pump. Some processing results on the real signals obtained through this method are described in section V.

IV. SIMULATION RESULTS

Based on the algorithm described in section II, three different types of simulation were performed on computer generated test signals. The purpose was to evaluate the estimation performance by comparing the performance index IDEG in three different cases with the ideal one. The considered cases were denoted with BCCF, CCF, WCCF and ICCF. The meaning of these abbreviations indicate that the performance index, IDEG, computed from the cross-correlation function (CCF), was compared in the following cases: test signals with bursts (BCCF), test signals without bursts (CCF), test signals without bursts, whitened (WCCF). All these first three cases denote signals including a certain degree of additive noise. In the last chosen case, the ideal one, (ICCF), the test signals were free of additive noise. The parameters involved in the performed simulations on the test signals were: the burst generation amplitude A –from (4); the burst concentration, c – from (5); the additive signal-to-noise ratio and NSNR –from (6). The simulations were performed by varying each parameter while keeping constant the other two. During each simulation ten trials of test signals generation were performed and the mean of the performance index was taken. The simulation results are shown in fig.7a, 7b and 7c. Fig.7a and 7c also display the performance index as a function of the resulting burst-signal-to-noise ratio computed from (6).

From these simulation results some significant insights on working with burst signals can be accomplished. At relative high additive SNRs and

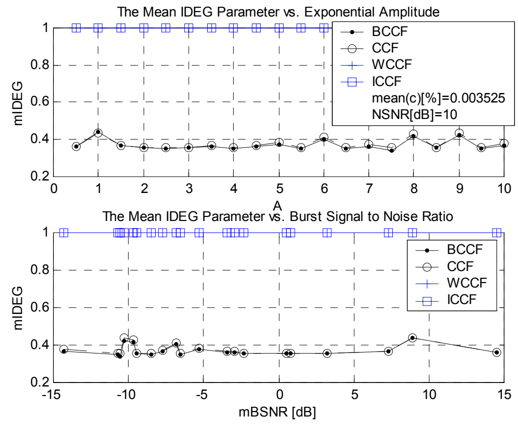

Fig.7a Comparative results of the performance index for burst amplitude variation

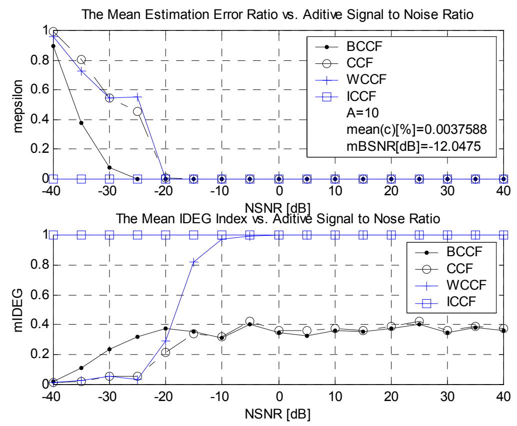

Fig.7b Comparative results of the performance index for additive signal–to-noise ratio variation

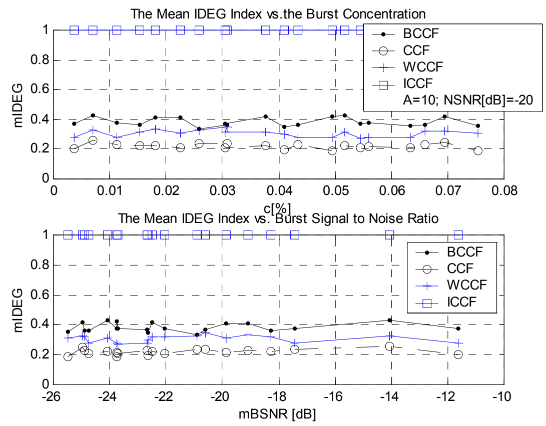

Fig.7c Comparative results of the performance index for burst concentration variation

small burst concentrations –situation often encountered in a water transportation pipeline- the performance index of the signals affected by bursts is close to the one of the signals without bursts (fig.7a). An interesting observation is that at small additive signal-to-noise ratio the burst case (BCCF) index surpasses the other two corresponding indexes for additive noise contaminated signal cases, (CCF and WCCF) (fig 7b). This applies if the burst perturbation is internally produced and thus carries on the information about the time delay –as it might be in the case of turbulent flows. In addition, from fig. 9c can be observed that in the given range, the burst concentration contained in the signal practically doesn't affect the performance index . Finally, as a generally remark, from these results can be seen that the best performance index between the considered cases corresponds in a large range of the NSNR component to stationary, whitened signals.

V. EXPERIMENTAL RESULTS

The performance index, IDEG, defined in section II was also evaluated using real signals captured in the experimental system described in section III. The signal pairs were acquired at the same locations on the pipe with and without the diaphragm pump functioning, respectively. Within each case, the cross-correlation function of the acquired signal pair and of the same whitened signal pair was computed and then the performance index was evaluated from (8). With respect to the mainstream flow, three different system work modalities were assumed: cut mainstream, full mainstream and half mainstream.

The bended pipe installation system having a total length of 12.82 m was implemented from metal pipes of 2.54 cm diameter each. The acquisition system was composed of a pair of non-intrusive vibration sensors KD -Radebeul, two amplifiers M60T with adjustable amplification between 40 and 60 dB, anti-aliasing low-pass filters and a dSPACE DS1102 board connected to a PC [15],[16],[17],[18]. The sampling frequency was set to 25 KHz.

Some comparative experimental results of the performance index are displayed in fig.8. The pump's control frequency was increased in each considered case. The abbreviations used here have the same meaning as in section IV. In addition, BWCCF stands for the case of whitened burst signals. These results show that the performance index of the burst signal pair is lower than the one corresponding to the non-burst signal pair, especially for those operating modes that involve a smaller burst-signal to-noise ratio component (cut mainstream and half mainstream). However, the second diagram in fig.8 shows that using the whitening processing technique [2], the performance index of the burst signals increases for all operating modes surpassing the non-burst signal case, CCF. On the contrary, in this last situation the best results correspond to the cut and half mainstream working modalities.

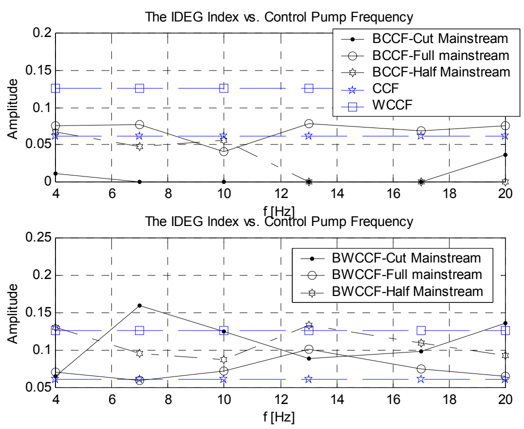

Fig.8 Comparative results of the performance index for real acquired signals

IV. CONCLUSIONS

In a pipeline transport system, the leak locating problem is an important issue. Besides the additive ambient disturbing nose, real leak signals prove to be also affected by burst-type interferences. These perturbations determine signals' distributions deviations from the Gaussian type, up to a certain degree, causing malfunctions of the locating algorithms described in the literature. Dealing with this kind of difficulties assumes avoiding or confronting them, the last alternative being this paper's main idea. This work attempts to develop a practical tool by which one can evaluate in what degree the estimation performance can be affected by these particular kind of perturbations. As a result, two methods of generating burst-type interferences were proposed. In addition, for comparison purposes, an evaluation index based both on the amplitude and the argument of the cross-correlation's function maximum was developed in this paper. The simulation and experimental results bring some useful insights for understanding the real leak signals.

Future work will extend this study to more cases like: wider parameters' varying ranges, other estimation algorithms than the simple cross-correlation function included, or an external burst component superposed in the disturbing ambient noise.

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