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Denoising Using Blind Source Separation for Pyroelectric Sensors

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This paper deals with a process of denoising based on a Blind Source Separation (BSS) method. This technique is inserted in an experimental device of nondestructive testing. Its excitation is a laser beam and its detectors are pyroelectric sensors. The latter are sensitive to the temperature. As they are also piezoelectric, they are particularly sensitive to the environmental noise. Therefore, it is necessary to denoise them. With this aim in view, a technique of blind source separation is implemented. One source corresponds to the incidental beam and the other sources are various noise. A judicious experimental device was designed in the laboratory. It fits to the requirements of the BSS technique, and it allows indeed a restoration of the incident signal.

Keywords and phrases: blind source separation, denoising, pyroelectric sensor, multi-sensor, laser beam, humidity profile.

1. INTRODUCTION

This paper describes the measurement of the time-dependent change in a space profile of moisture in a breadboard construction for nondestructive testing. The profile is defined according to the depth of a biopolymer. The change is measured by photothermal methods in which a sample is optically excited by a laser diode and the heat produced is measured. The exciting wavelength was that of an absorption band of the water spectrum.

The intensity of the laser beam is modulated in frequency in order to excite sample zones at various depths. This effect is similar to the skin effect in electromagnetism. The frequencies of modulation were 0.1– 400 Hz, to make the penetration depths compatible with the required resolution ($10\,\mu$m) and the thickness of the sample (1 mm). The pyroelectric sensor placed behind the sample detects thermal waves coming from its surface. No direct contact is required [1, 2]. The sample is analysed by synchronous detection between the modulated control signal sent to the laser diode and the signal from the detector. Each frequency of modulation corresponds to a value of the gain and a value of the phase, to give characteristic gain and phase curves. Both are representative of a moisture space profile. Their use with various physical models allows to go up to this profile [3].

1.1. The problem

Synchronous detection provides dispersed experimental measurements of phase and gain. The main causes are defects in the laser beam and the extreme sensitivity of the sensors.

1.2. The defects in the laser beam

The radiation from the laser beam is a fundamental frequency of modulation that undergoes two types of defects; its amplitude fluctuates in time and interfering signals are added to it.

The nondestructive study of biopolymers requires a very low power excitation so that the space distribution of the humidity profile does not change. In these experimental conditions, variations in the amplitude of the fundamental frequency are perceptible. Similarly, the laser diode power supply produces a parasite in the modulated beam whose principal component is a frequency of 100 Hz. This is due to the rectification of the supply voltage at 50 Hz. The laser diode

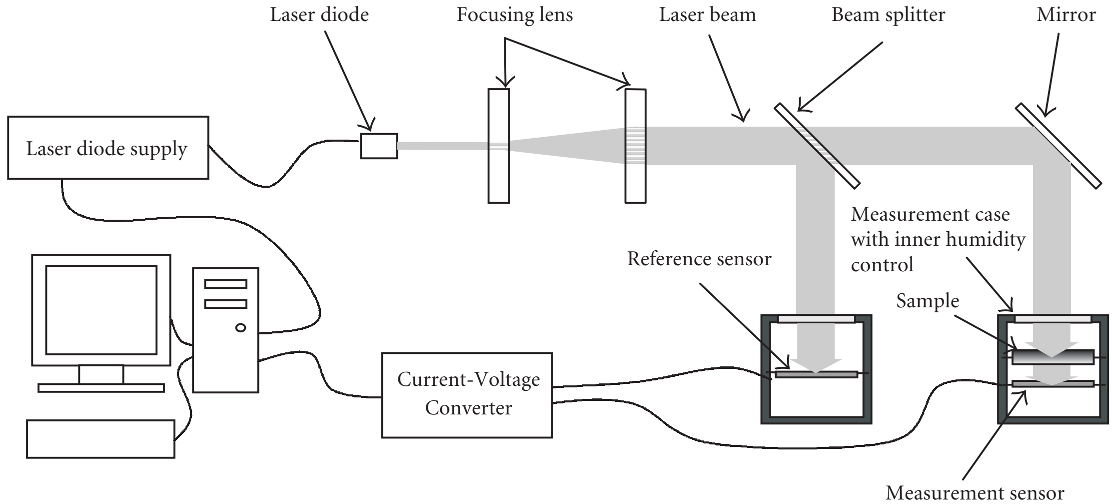

Figure 1: Measurement device.

also produces harmonics of the fundamental modulation frequency in the laser beam depending on the operating point and whose amplitude fluctuates in time. This point corresponds to the nonlinearity of the transfer function between the command signal of the diode and the intensity of the laser beam.

The added signals components (harmonics of the frequency modulation, and the 100 Hz frequency) lie in the useful frequency range. Since they are not stationary, they cannot be eliminated by simple filtering.

We check the stability of the incident beam on the precision of the gain and the phase before trying to remove these disturbances. We simulated a synchronous detection over 20 periods between a sinusoidal signal and the same noisy sinusoid. This signal corresponds to the main frequency modulation. It has a signal to noise ratio (SNR) of 30 dB, similar to the disturbances of the experimental exiting beam (100 Hz + harmonics of the excitation frequency). There were variations in the gain of 1% and in the phase of 2%. Preliminary tests of a moisture space profile determination showed that the resolution was to be approximately 0.1 dB and 0.1° [3]. Thus, it is necessary to take into account the real exiting beam. A second pyroelectric sensor is used as a reference, it receives part of the laser beam due to insertion of a separating blade in the device (Figure 1). As variations are included in the reference signal, they will not distort the results obtained at output of synchronous detection.

The reference sensor also compensates for fluctuations in the amplitude of the fundamental modulation frequency.

1.3. The extreme sensitivity of the sensors

The second cause of dispersions is the extreme sensitivity of the sensors used. They are also piezoelectric and are particularly sensitive to acoustic noises and vibrations. Their position and their keeping in the housing also influence the way in which they perceive noise. The reference and measuring sensors perceive noise differently, the phase and the gain characteristics at the output of synchronous detection are disturbed. It is thus necessary to denoise each sensor separately upstream of the synchronous detection.

1.4. The purpose of noise removal

The technique selected for noise removal was applied to process the response of the reference sensor. This principle is also applicable to the measuring sensor. We first describe the initial system without any noise removal and show that the classical techniques of noise removal are not suitable. We then describe a breadboard that includes the conditions for applying the BSS method using a double sensor. The results were analysed and the concept of using many sensors refined, such as a triple sensor. This will lead to more effective noise removal indeed and as well to a better understanding of the behaviour of the measuring device.

2. EXPERIMENTAL DEVICE

2.1. Construction of the initial reference sensor

This part is dedicated to the description of the experimental system. It consists in the reference sensor and the exciting beam. It is designed to restore the “true” laser beam whose main component is the modulation frequency of the laser beam. The signal contains the fundamental modulation frequency, its harmonics and a 100 Hz component (rectification of the supply voltage). The low power excitation also makes the fluctuations in the amplitude of the exciting frequency perceptible. These various components and fluctuations of the laser beam must be restored with the main component because they damage the precision of the gains and the phases. This partial “a priori” knowledge of the exiting beam (excitation frequency + harmonics + 100 Hz signal) will enable us to check the quality of noise removal.

The pyroelectric sensors perceive various types of noise:

- Thermal: changes in the temperature of the environment of the experimental device.
- Vibratory: starting a motor some distance away, displacement in the room, vibrations inherent in the device.
- Acoustic: somebody speaking in the room.

These various types of noise must all be removed. They can be in the range of the modulation frequencies used for the measurements. They are intrinsically not stationary (e.g., when somebody speaks) and are perceived as a function of the surface area of the sensor [2, 4]. They behave essentially as if they came from a single source and can be regarded as indissociable. Their perception depends on the position of the sensor and the way in which it is kept in place by the sensor housing. This last point concerns especially vibrations.

2.2. Techniques of noise removal

There are two types, single-channel techniques, using only one sensor, and multiple-channel methods.

The single-channel techniques require "a priori" knowledge of the signal to be restored or the noise [5]. The noise is not easy to define in our application, because it is not stationary. And our knowledge of the signal is incomplete. No single-channel method will be able to dissociate fluctuations in the amplitude of the fundamental modulation frequency from noise at the same frequency.

The two-channels technique with noise reference uses two sensors, whose one as noise reference [6, 7]. Their performance is improved when the signal is not present on the reference. But, it is very difficult to obtain a noise reference perfectly representative of the actual perceived noise. Their perception depends on the sensor location, and in the case of the sensor measurement, the small size of the experimental device and the constraints, such as a moisture gradient make it difficult to insert a second sensor. Lastly, the keeping in the sensor housing is specific to each one, the two sensors will not perceive vibration noises identically. These conventional methods of noise removal cannot, therefore, be used. However, the multiple-channel techniques of BSS can be used [8, 9, 10].

2.3. Blind source separation

In the case of two statistically independent sources and two sensors, the first source s_1 will be the incident signal from the laser diode, the second source s_2 will be the main disturbance and others weaker disturbances will be considered as the sensor noise [11]. The BSS techniques suppose that the observed sensor signals must be a linear unknown mixture of unobserved unknown source signals.

Then the unknown source signals are

$$S = [s_1 s_2]^T, \tag{1}$$

and the observed mixed signals perceived by the sensors are

$$X = [x_1 x_2]^T. \tag{2}$$

They fit the linear model given below

$$X = A \cdot S + N, \tag{3}$$

where A is the unknown mixture matrix and N is the additive noise on the sensors. It is always possible to introduce a constant α such that

$$X = \left(\frac{A}{\alpha}\right) \cdot (\alpha \cdot S) + N. \tag{4}$$

This formulation points out the uncertainties in the power of the sources noted S. It is always possible to permute a column of the matrix A and a row in the source vector S, that changes the order of the sources.

The BSS consists of determining a separation matrix $\underline{B}$ such that

$$\underline{B} \cdot A = I. \tag{5}$$

That leads to:

$$\underline{Y} = \underline{B} \cdot X = \underline{B} \cdot A \cdot S + \underline{B} \cdot N. \tag{6}$$

And finally, we obtain

$$\underline{Y} = \Lambda \cdot \Pi \cdot S + \underline{B} \cdot N. \tag{7}$$

The estimated sources named $\underline{Y}$ are equal to the sources S with a permutation matrix Π and a coefficient matrix Λ. The permutation and coefficient matrix come from the estimation of $\underline{B}$.

Additive white sensor noise does not affect the determination of $\underline{B}$. In the following, it will be neglected in the equations, the estimated sources $\underline{Y}$ will be restored with this additive noise.

Most of the time, the first step of BSS algorithms is a singular decomposition value. Orthogonal sources are obtained. The solution is nonunique. It may exist a rotation of the sources which optimises the independence. The matrix $\underline{B}$ is estimated assuming that either the sources are statistically independent, then a criterion of independence is maximised [9, 10, 12, 13], or either they are uncorrelated, then a criterion of noncorrelation [14] is introduced.

An estimation of the mixing matrix can be obtained

$$\underline{A} = \underline{B}^{-1}. \tag{8}$$

In our experimental device, the characteristics of the exciting laser beam and the disturbances are independent. Both are considered to be sources. The construction of a device

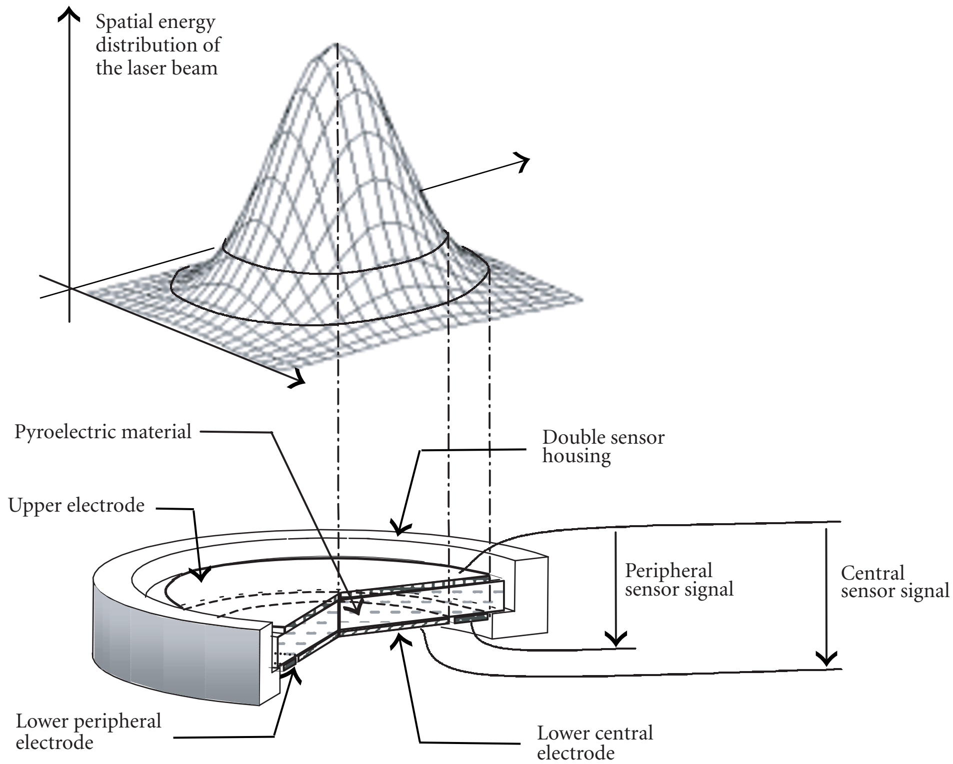

FIGURE 2: The double sensor.

constituted by two sensors collecting a mixture of the two sources could allow to retrieve them by a source separation technique.

2.4. Optimum conditions for using source separation

The pyroelectric sensor consists of a 10 mm diameter, 0.2 mm thick ceramic disc with metal electrodes on both surfaces. The sensor can be modelled as a current generator with a parallel capacitor. We used two characteristics of the breadboard construction for source separation [15]:

- a single pyroelectric sensor can be used as two sensors by cutting an electrode by removing a metal ring,
- the spatial distribution of the laser beam energy is Gaussian.

We made a double sensor by cutting the pyroelectric electrode with a scalpel to give a central disc ($20\ \mathrm{mm}^2$) and a peripheral crown ($34\ \mathrm{mm}^2$) (Figure 2). As the two sensors were on the same substrate, they were located at the same place and the sensor housing influenced them similarly. Thus, noise influenced the response per unit area of the two sensors in the same way. The noise was regarded as a single source, the response was proportional to the area of the sensor, so the central sensor was $0.57(20/34)$ less sensitive than the peripheral one.

As the spatial distribution of the laser beam energy is Gaussian, the central part perceives more than the peripheral part, and the ratio of the sensor responses depended on the focusing of the beam.

Each sensor received a different mixture of signals from one source (the modulated laser beam with its own imperfections) and a second source (environmental noise).

A preliminary statistical study of the noise of unladen sensors in the experimental device revealed that it was white and Gaussian. The intensity was such that it could be regarded as negligible. The thermal diffusion length of pyroelectric material at working frequencies is sufficiently low compared to the width of the metal-free ring for the two parts of the double sensor to be regarded as independent.

2.5. BSS application

The mixture matrix of the previous model given in equation (3) is

$$A = \begin{bmatrix} 1 & a_{1,2} \\ a_{2,1} & 1 \end{bmatrix}. \tag{9}$$

The laser beam is s_1, the noises are s_2, the signal from the central sensor is x_1, and x_2 is the signal from the peripheral sensor. Then the coefficient $a_{1,2}$ is equal to the ratio of the surface areas of the sensors (0.57). The coefficient $a_{2,1}$ corresponds to the ratio of the energy emerging from the laser beam perceived by the peripheral sensor over that perceived by the central sensor. The inversion of the mixture matrix provides the separation matrix

$$\underline{B} = \Lambda \cdot \Pi \cdot \begin{bmatrix} 1 & -a_{1,2} \\ -a_{2,1} & 1 \end{bmatrix}. \tag{10}$$

The estimated sources are

$$\underline{Y} = \underline{B} \cdot X, \tag{11}$$

such that $\underline{y_1}$ is the estimate of the laser beam and $\underline{y_2}$ is the estimate of the disturbances. The estimate of the laser beam $\underline{y_1}$ is proportional to $(x_1 - a_{1,2} \cdot x_2)$, that shows that only the coefficient $a_{1,2}$ contributes to the restoration of $\underline{y_1}$.

The use of source separation would not be justified if the coefficient $a_{1,2}$ were known. However, the hand-made double sensor allows only a rough estimate of this coefficient. Creating several sensors on a single substrate would allow the use of a noise reference technique. But it would be necessary to focus the laser beam so that it would no longer fall on the peripheral sensor.

2.6. Applied algorithms

Source separation techniques are based on the statistical independence of the sources. The decorrelation requires second-order statistics, but the independence requires higher-order statistics than two. As third-order statistics are representative of the dissymmetry of the density of probability, fourth-order statistics are mainly used to determine statistical independence of various sources in practice. If the sources are temporally correlated or, are not white, which is equivalent, second-order statistics of the sources and the time-shifted sources can be used. But higher-order statistics must be used if they are white.

The signal from the laser beam has a strong temporal coherence, so an algorithm based on the second-order statistics which takes into account the correlation between the sources and the time-shifted sources such as SOBI [14, 16] is efficient. SOBI was developed by Belouchrani et al. It consists of a first step of orthogonalization of data, followed by a second step which jointly diagonalized several cross correlation matrices from signal sensors to provide the demixing matrix. It is a block algorithm well adapted for this device because there is no temporal constraint, but online algorithms are used in real time working systems. It can be used directly, it just required the observed mixture signals X, the number of searched sources "n" and the number "p" of delayed cross correlation matrices which take into account the temporal correlation.

Most source separation algorithms use higher-order statistics, we also used other block algorithms based on fourth-order statistics such as the ACI of Comon as defined in [13] and JADE of Cardoso [12] which maximise a contrast function. Both are classical references and are depending on the probability density function. Although they are less robust for these experimental signals, because they cannot take into account the temporal coherence through the temporal correlation. Depending on the experimental noise context, they can fail to retrieve the sources. Nevertheless, they enabled us to confirm the results obtained with SOBI.

We recorded the sensor signals labelled X. We apply a BSS block algorithm which provides estimates of the mixing matrix $\underline{A}$ and the source signals $\underline{Y}$. The estimated laser beam $\underline{y_1}$ is used in the post treatment which is a synchronous detection (lock in detection).

3. DOUBLE SENSOR: EXPERIMENTAL RESULTS

We then checked the effectiveness of the setup. The exiting signal was composed of a fundamental frequency, its harmonics and a 100 Hz component. This was all our "a priori" knowledge of the real exiting beam. It was used to check whether the noise removal resulted in the exact restitution of the signal of the laser beam.

3.1. Double sensor-temporal field

We generated a modulated exiting signal at 10 Hz, sampled at 1 kHz for 10 s and simulated noise by generating disturbances with a vibrating pot (exciting of calibration of 0.7 N) at 5.5 s and 6.5 s of the sampling time. The emerging laser beam had a rather low power ($0.4\,\mathrm{mW_{eff}}$). The SOBI algorithm separated in the signals from the sensors in time with a joint diagonalization of 5 intercovariance matrices [17] (Figure 3). The notations sensor 1 and 2 are the responses of the central and peripheral sensors. The estimated sources 1 and 2 are the estimates of the signals corresponding to the laser beam and the generated noise. The amplitudes of the estimated sources were obtained within a multiplying coefficient and were normalised.

The three disturbances were removed from the estimated source 1, but this signal corresponding to the estimated laser beam was still disturbed (Figure 3). The estimated matrix of separation $\underline{B}$ such that

$$\underline{Y} = \underline{B}X \tag{12}$$

is

$$\underline{B} = \begin{bmatrix} 1 & -0.5 \\ -0.18 & 1 \end{bmatrix}. \tag{13}$$

The coefficient $a_{1,2}$ corresponding to the ratio of surfaces (0.5) was not equal to that expected (0.57). This could be because:

- the hand-made metal removal from electrodes induced an error in the surface areas,
- the double sensor was inserted in a sensor housing, which could modify its response, especially the boundary conditions of the peripheral sensor. As it is at the periphery (Figure 2), a resonance effect (different from

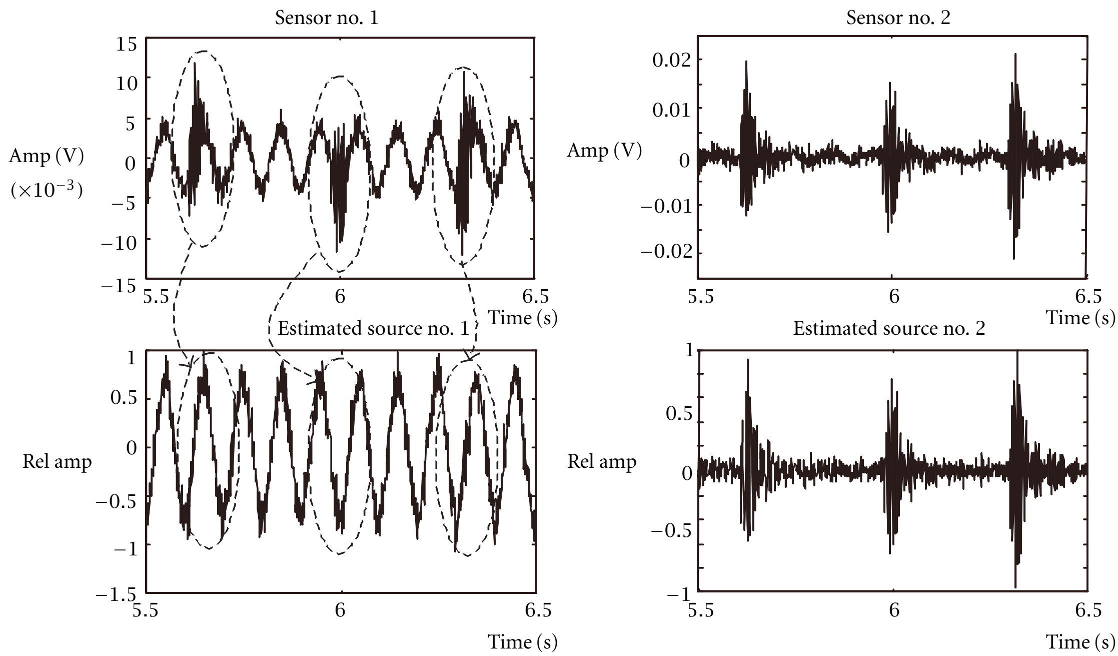

FIGURE 3: Vibratory noise-time domain.

the intrinsic resonance of pyroelectric material) could occur where the signal from the central sensor was amplified, while that from the peripheral sensor was attenuated. This reasoning is valid for vibrations because of their transmission, but is not applicable to acoustic or thermal noise.

3.2. Double sensor-frequency field

We visualize these same signals in the frequency domain through a Hamming type window (Figure 4). The spectral power of the source was set at 1. The "very high" energy of the main frequency (10 Hz) compared to the other components, imposes to magnify the curves for the signal received by sensor 1 and the restored source 1 signals by an identical ratio.

Figure 4 shows the signal received on sensor 1. The frequency of the noise is mainly between 100 and 150 Hz, and the harmonics of the modulation frequency and the 100 Hz component are embedded in the noise. The estimated source 1 signal is the estimate of the laser beam. The frequency components of the noise were removed and the harmonics of the main frequency and the 100 Hz signal remained, the third harmonic at 30 Hz is particularly visible. The noise removal was therefore particularly effective. Nevertheless, there remains a frequency of 400–500 Hz which was allotted to no source. These frequencies corresponded to a signal in the two sensors whose coefficients of the mixture matrix were different from those given previously. That comes from the principle of the source separation algorithms, which consists of, taking into account two sources, the two independent signals of the higher energy. Other signals will be restored in the two estimated sources considered and will be distorted through the separation matrix B.

3.3. Test with greater power

A complementary test was carried out using a laser beam working point of about 20 mW$_{\text{eff}}$. Stronger vibrations were generated to get similar magnitudes in the different signals. The noise removal remained very effective. The coefficient $a_{1,2}$ for separation was 0.9. This abnormal value may have two probable origins:

- the piezoelectric coefficients are defined as the electric load collected on the electrodes of the sensor in response to a mechanical, acoustic or vibratory stimulus. These coefficients depend on the operating temperature. The new working point implied a different increase. The average temperature of the central sensor is higher than that of the peripheral sensor and especially different from the previous test.
- the vibratory noise was particular (possible resonance), and acted on the sensors with a different ratio, depending on the power.

3.4. Discussion

The first test revealed the need for blind source separation to determine the exact values of the coefficients $a_{1,2}$ and $a_{2,1}$ for the separation matrix. The knowledge of $a_{1,2}$ allows to remove noise from the signal by simple subtraction

$$s_1 = x_1 - a_{1,2} \cdot x_2. \tag{14}$$

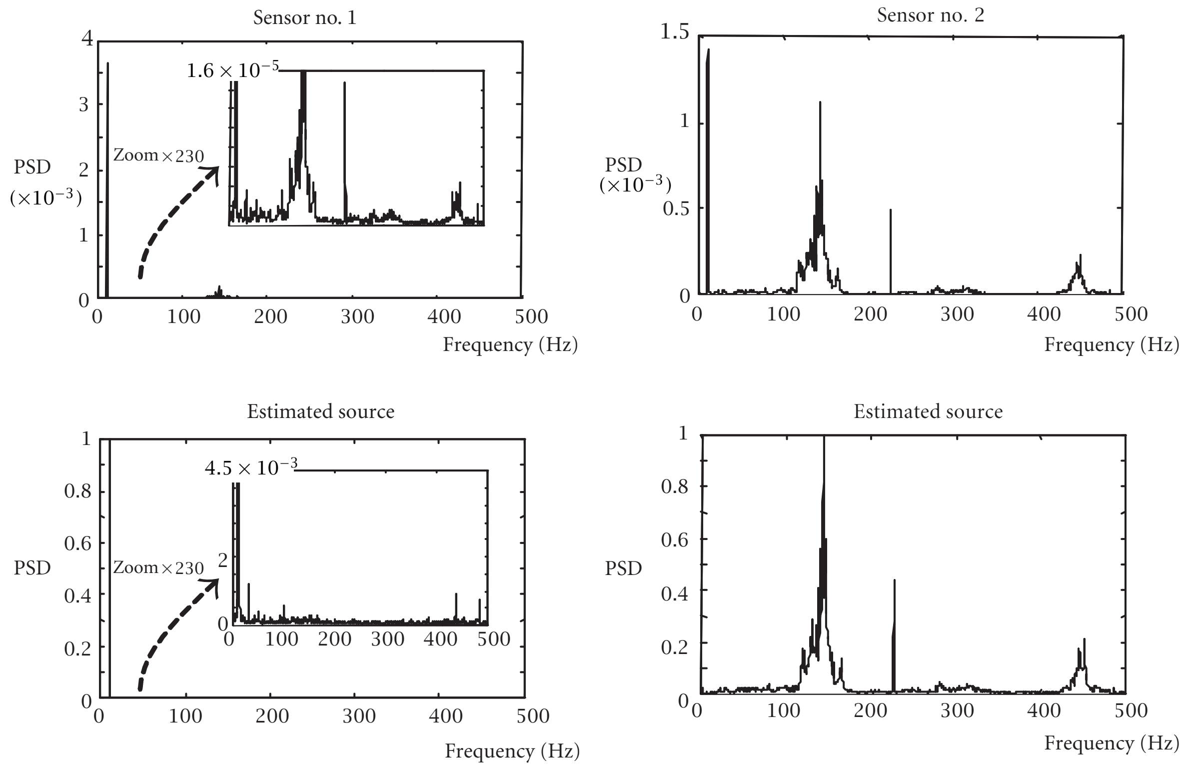

Figure 4: Vibratory noise-frequency domain.

The second test, carried out at a different operating point and a higher power, provided another value of $a_{1,2}$. These values of the mixture matrix coefficients are linked to the type of test (power, type of noise).

BSS methods are needed to determine the coefficients exactly, which then leads to noise removal. We therefore undertook a thorough study of the sensors by considering more sources and increasing the number of sensors. Vibratory noise was closely linked to sensor anchoring (boundary conditions), while accoustic noise influenced the output signal proportionally to the volume of the sensor.

4. TRIPLE SENSOR: EXPERIMENTAL RESULTS

We made a triple sensor, consisting of a central sensor (sensor 1), an inner peripheral crown (sensor 2), and an external peripheral crown (sensor 3), the areas of these three sensors were different. We standardised the areas to that of sensor 2 to simplify comparison of the ratios. The standardised ratios of areas of sensors 1, 2, and 3 were 0.11, 1, and 0.3. The acoustic and thermal noises infuence these sensors as a function of their area (the thickness of the disc being constant). But the effect of vibratory noise is certainly influenced by the sensor housing and the shape of the sensor. As the triple sensor was made from one disc, the central part could be more influenced by vibrations than the peripheral parts. The different areas and the shapes and locations of the three sensors allowed the three sources to be dissociated, particularly acoustic or thermal noise from vibratory noise.

Preliminary tests without a laser beam were used to determine the influence of the various types of noise on the sensors. We recorded the amplitudes of the signals received by the three sensors corresponding to acoustic, thermal, and vibratory signals. Then, we deduced the standardised ratios (with respect to sensor 2). There is no mixing matrix if the ratios for the three noises are identical, thus they cannot be separated. But if the ratios are sufficiently different, they can be separated.

We carried out ten tests on each type of noise at various power inputs. We generated various frequencies for the acoustic and thermal signals. The standardised ratios were 0.13, 1, and 0.32 (standard deviation, $\sigma = 0.01$), for the acoustic and thermal signals, and 0.2, 1, and 0.37 ($\sigma = 0.01$), for the vibratory signals. They depended greatly on the power of the resulting shock. They can be compared with those obtained previously. The acoustic and thermal signal ratios were very close to the surface area ratios, while the ratios of vibratory signals were different, which makes it possible to separate them from the others. Then, BSS tests were carried out. A visible signal from the laser diode is sent, while successively one by one a sound effect, a vibratory signal and a thermal signal was generated. The modulation frequency of the laser beam was of the same order of magnitude as the frequencies of the simulated noise, considered as signals for each test. As

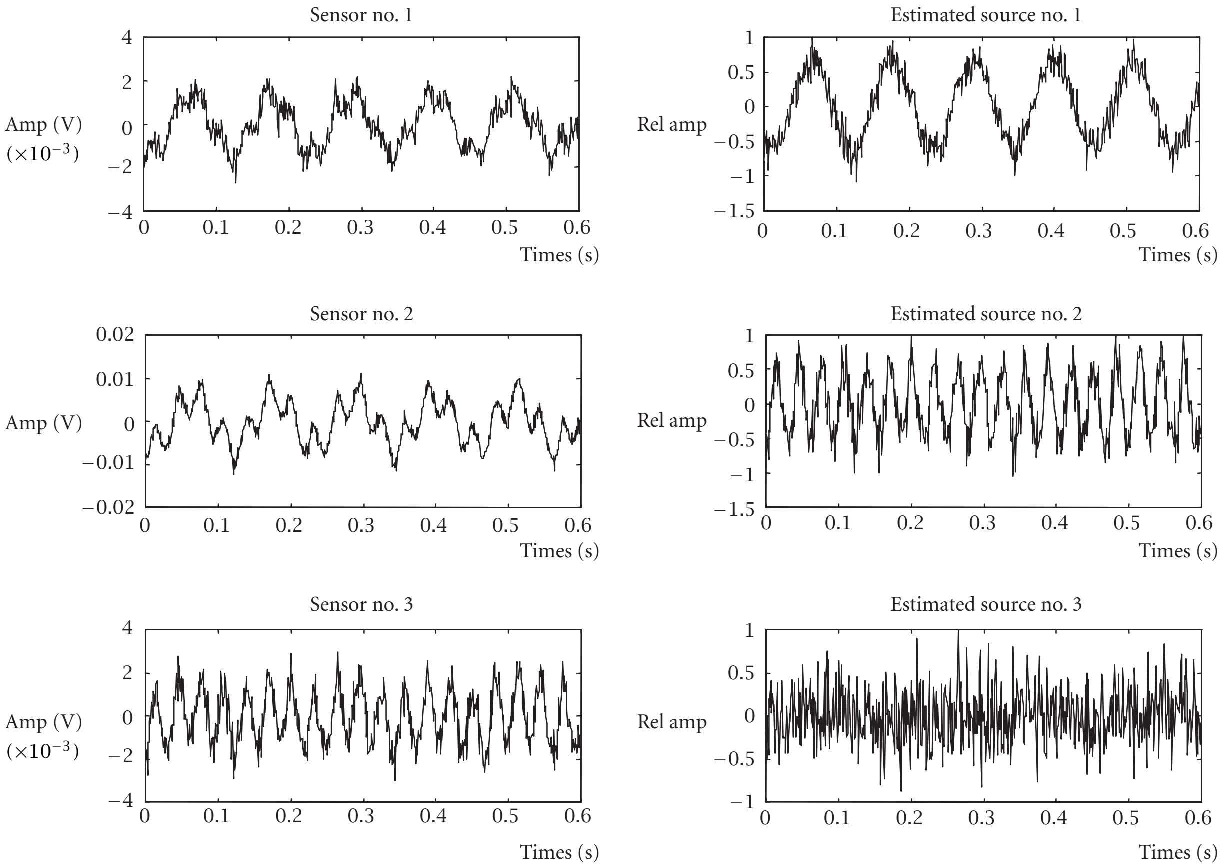

FIGURE 5: Acoustic noise-time domain.

the goal of this work was to show the contribution of source separation techniques to this type of device, the experimental differences between the various tests were of no importance.

4.1. The acoustic signal

The signal from the laser diode is a sine wave of frequency 9 Hz and of power 4 $\mathrm{mW_{eff}}$, the sound effect is a sine wave of frequency 32 Hz. This signal was generated via a low power loudspeaker. The two signals were obviously deformed by the breadboard construction, mainly by the power supply for the laser diode and the loudspeaker for the sound effect. The estimated sources 1, 2 corresponded to the estimated laser beam and acoustic signal (Figure 5).

Three sources were restored although only two sources were present and the sensor noises were white, then the third estimated source should be a white noise which is a linear combination of the three sensor noises. The third source has a temporal coherence when there are really three sources or when the mixture of signals is nonlinear. This third source can be confirmed by the signal analysis in the frequency domain (Figure 6).

The signals from the laser diode (presence of 100 Hz contribution) and the acoustic noise were perfectly restored. The estimated source 3 was not white, but made up of a main frequency at 172 Hz and it was received on sensors 1, 2, and 3 in the ratios 0.4, 1, and 0.6, these were relatively close to the ratios obtained with a vibratory signal 0.2, 1, 0.37, $\sigma = 0.15$. We assumed that this is a particular resonance of the triple sensor. Complementary tests, including frequency analyses with a simple sensor and a double sensor, did not highlight this frequency. It probably was due to the construction of this triple sensor (manual metal removal of two crowns) which weakened it. The estimated sources 1 and 2 always contained the 172 Hz frequency produced by the nonlinearity of the mixing model for this source.

4.2. Vibratory signal

A vibrating pot (0.7 N) was applied to the frame of the device to generate vibrations. Their frequencies were representative of the physical characteristics of the whole assembly and their amplitudes depended on the magnitude of the shock produced. The resulting signal from the laser diode was a sine wave of frequency 47 Hz and its power received on the triple sensor of about 3 $\mathrm{mW_{eff}}$. The frequency results (Figure 7) are shown as they are more explicit than the time results. The magnified figures of sensor 1 and the estimated source 1 were carried out in the same ratio. There was noise removal, the vibratory signal occupied the same frequency range as

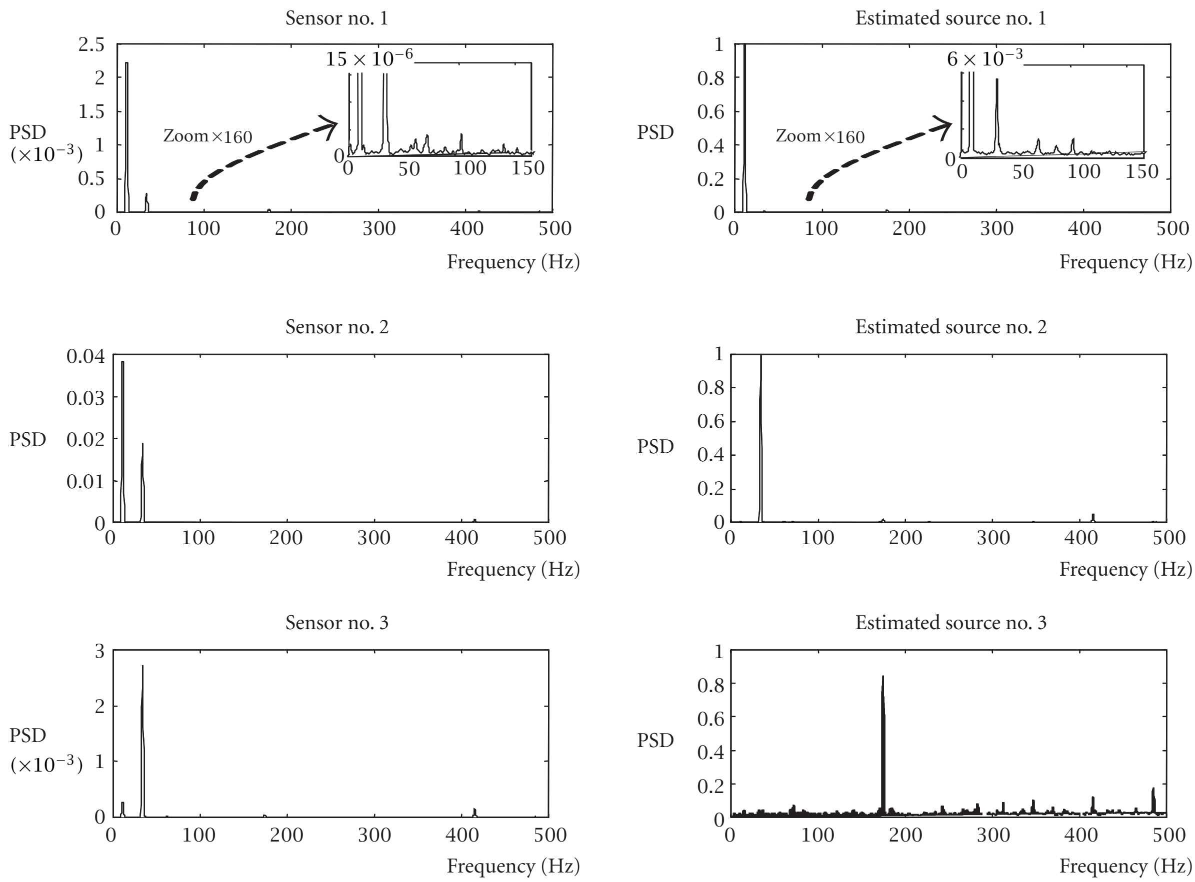

Figure 6: Acoustic noise-frequency domain.

the laser beam. This is particularly visible on the magnified figures of the sensor and estimated source 1 signals. The 172 Hz signal was always in the signals from the sensors, but it was restored with the vibratory signal (estimated source 2). This confirms the assumption that it was of vibratory origin.

The third estimated source corresponded to a stronger signal on the signal sensors, having different coefficients of the mixture matrix from those of the other two estimated sources. This particular result was due to the principle of operation of the algorithms of source separation. These generally operate in two stages, first whitening and then separation. The initial whitening consists of determining the eigenvalues of the intercovariance matrix of the signals from the sensors. For experimental signals where there are more sensors than sources, the sensor noise involves the presence of eigenvalues associated with these noises. When this noise is not white, or when the sensors signals are disturbed by interferences during measurement, the eigenvalues of intercovariance-whitened matrix lead to nonwhite sources that have no real significance. Those do not respect the hypothesis of a linear mixture required for the separation of sources. This introduces this nonreal source in all the estimated sources. Thus, we see a 370 Hz signal in the three figures of the estimated sources.

4.3. *Thermal signal*

The signal from the laser diode was a sine wave of frequency 9 Hz and 3 mW_{eff}. The generated temperature variations were small and of very low frequency (0.4 Hz). The signal separation was quite good (Figure 8). The thermal signal did not intervene in the same ratio as the vibratory signals, the third estimated source was the 172 Hz signal.

4.4. *Analysis*

The three previous tests showed that it was possible to dissociate the laser excitation signal from the acoustic, thermal and vibratory noises. The particular design of the multiple sensor (concentric rings) allowed separation of the vibratory noise from the acoustic and thermal noise. These latter influencing the output signals of the sensors in the same amplitude ratios, and so cannot be separated by this method. The mixture of acoustic and thermal noise was rather difficult to generate because they have a common mode of transmission by the displacement of air molecules.

4.5. *Usefulness of triple sensor*

We measure the advantage of using a triple sensor for acoustic noise [18]. We used only one set of signals from the triple sensor. The double sensor consisted of the central part and the

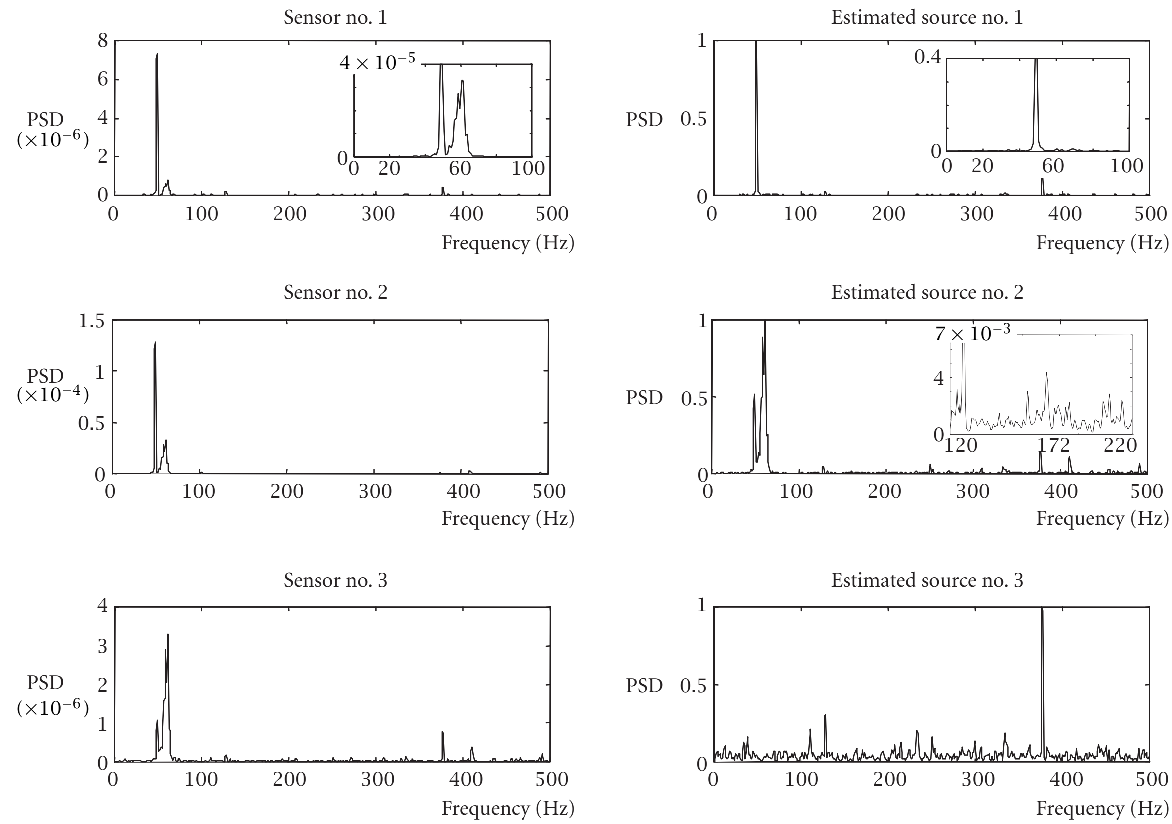

Figure 7: Vibratory noise-frequency domain.

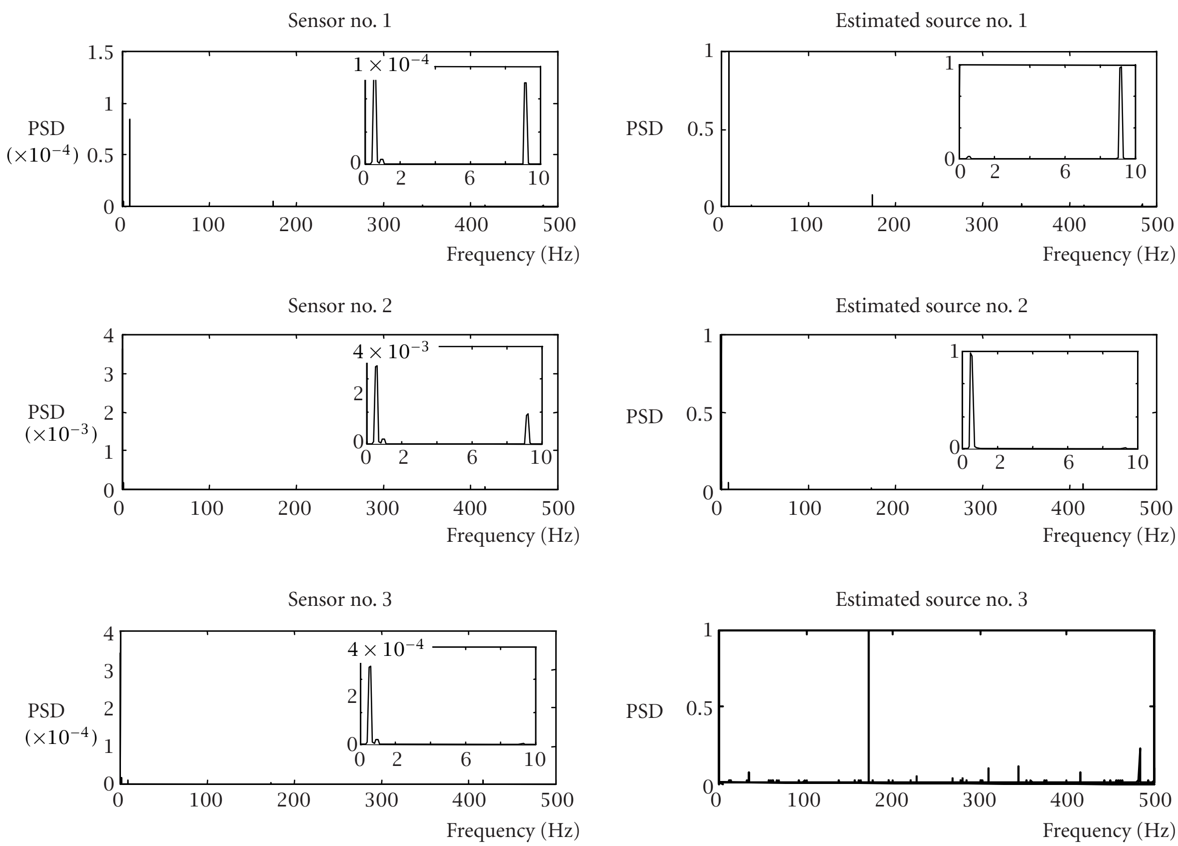

Figure 8: Thermal noise-frequency domain.

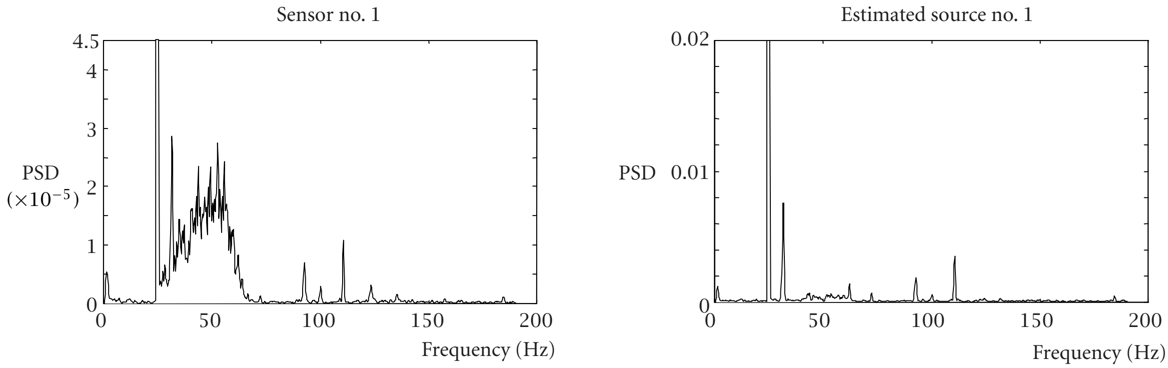

FIGURE 9: Acoustic noise-enlargement-frequency domain.

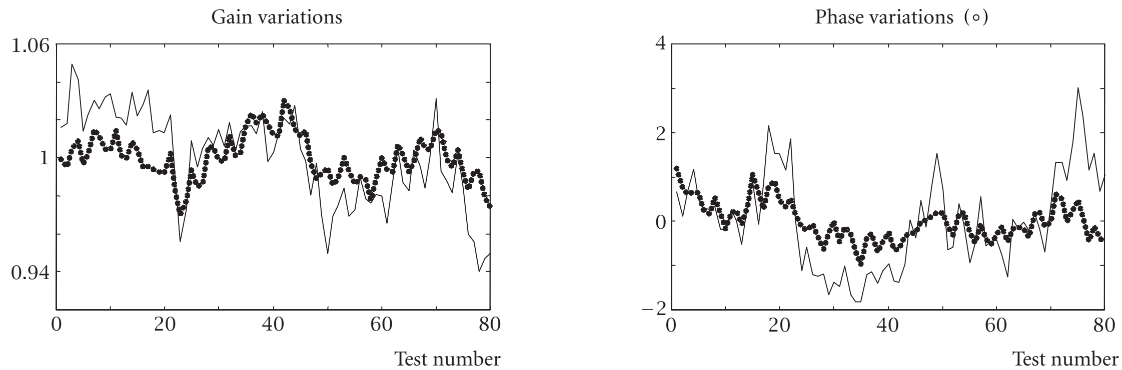

FIGURE 10: Gain and phase of the digital synchronous filter output (20 periods).

adjacent part from the triple sensor. We used the estimates of the signal from the laser beam for both the double and triple sensors. These signals should be pure sine waves corresponding to the frequency modulation. We removed a sine wave signal of the frequency of modulation from the two estimated signals. Effective noise removal should give residues tending towards a white Gaussian sensor noise whose variance must tend towards a significant minimum.

The estimate provided by triple sensor gave a gain of 9 dB on the value of the variance of the residues compared to the estimate obtained by the double sensor. This improvement was mainly due to the fact of taking into account a third source (vibration particular to 172 Hz).

5. APPLICATION TO THE EXPERIMENTAL SETUP

5.1. Acoustic perturbation

This section describes results obtained from the output of the synchronous detection when a signal from a sensor is disturbed by an acoustic noise with a signal to noise ratio (SNR) of 90 dB in a frequency range close to the frequency modulation of the laser beam. The result is compared with that provided by this same signal with the noise removed by sources separation.

The output from the laser beam was 34 Hz and 3 mW_{eff}, the frequency of the acoustic signal was 25–60 Hz (Figure 9). Noise was removed with the JADE algorithm. As the spectral density of the noise was relatively weak compared to that of the exciting signal, we made a proportional magnifying compared to the principal frequency modulation of the two signals.

Then we carried out a synchronous detection between a sine wave of 34 Hz and the signal from sensor 1 (raw signal). We did the same with a 34 Hz sine wave and the estimated source 1 (noise-free signal). The synchronous detection made over 20 periods is sufficient, the record being longer the algorithm is slid (80 successive trials) to give several solutions. This gave the change in the gain and phase at the synchronous detection output. For a pure sine wave, the gain must be 1 and the phase 0 degree. The results are described in Figure 10, the solid line corresponds to the raw signal and the dotted line to the noise-free signal.

There was an improvement of the restitution of the gain and the phase. The standard deviation of the gain was halved and that of the phase was 2.5 times smaller than with the configuration without noise reduction. This improvement was due to the fact that the frequency of analysis was in the frequency range of the noise.

5.2. Discussion

This technique of noise removal was used in an experimental setup for nondestructive testing. We showed that the use of a bad reference in an analysis by synchronous detection disperses the measurements. We reduced this dispersion by designing the experimental device around two pyroelectric sensors (reference and measurement). As the signals from the sensors were disturbed, we used source separation to remove noise.

The online BSS techniques are required for two reasons:

(1) A variation in the beam focusing, or/and in the location sensor imply a change of the mixing matrix coefficients. This drawback may be corrected by using a suitable BSS method at the beginning of the experience to find the new mixing matrix. This correction is similar to a calibration.

(2) During the experience, different types of noise like acoustic or vibratory can operate on the sensors with different coefficients. Then, it is necessary to revalue them. It is an online correction.

We applied these techniques to the reference sensor during an analysis by synchronous detection with acoustic noise. A 2-fold reduction in the standard deviation of the gain and phase was obtained. For similar signals (noise frequency close to signal frequency), a pre-treatment of the signals upstream of synchronous detection improved the precision of the resulting measurements.

6. CONCLUSION

We have developed a technique for removing noise from a signal from a pyroelectric sensor. It is based on the spatial nonuniformity of the signal and the possibility of creating several sensors on a single substrate. The source separation obtained with a double sensor gave precisely the coefficients of the separation matrix needed for noise removal. But unforeseen coefficients led to the production of a triple sensor. This separated three signals, the emerging laser beam signal, vibratory noises and the other noises (acoustic and thermal). Taking into account the three signals improved the restitution of the emerging laser beam signal and provided more information on the device, revealing a resonance frequency in the sensor.

Analysis by synchronous detection effectively rejects noise whose frequencies are far from the frequency of analysis. The removal of noise from the signals is interesting only when the analysed frequency is in the frequency range of the noise or very close to it. The contribution of these techniques to the nondestructive inspecting device described in this paper makes possible to obtain very precise measurements in difficult zones (50 Hz, frequency range of vibrations of the device, …), where analysis by synchronous detection without noise removal would fail.

REFERENCES

[1] J. S. Antoniow, "A photopyroelectric method with air as the thermal coupling fluid," *J. Phys. D: Appl. Phys.*, vol. 30, pp. 1934–1944, 1997.
[2] R. W. Whatmore, "Pyroelectric devices and materials," *Rep. Prog. Phys.*, vol. 49, pp. 1335–1386, 1986.
[3] D. Paris, *Etude de la migration d'humidité dans des biopolymères à base d'amidon par méthode photopyroélectrique*, Thése de doctorat, Université de Reims Champagne-Ardenne, France, 1998.
[4] G. Asch, *Les Capteurs en Instrumentation Industrielle*, Dunod, France, 1987.
[5] L. Ljung, *System Identification*, Prentice Hall, London, 1987.
[6] N. Wiener, *Extrapolation, Interpolation and Smoothing of Stationary Time Series, with Engineering Applications*, Wiley, New York, 1949.
[7] B. Widrow, "Adaptative noise cancelling: Principles and applications," *Proc. IEEE*, vol. 63, no. 12, pp. 1692–1715, 1975.
[8] L. Cai and R. Anin, "La séparation de sources appliquée au denoising en CND par courants de foucault," *Compte rendus du quinzième colloque GRETSI*, pp. 109–112, 1995.
[9] J. F. Cardoso, "Source separation using higher order moments," *Icassp'89*, pp. 2109–2112, 1989.
[10] P. Comon, "Separation of sources using higher order cumulants," *SPIE Conference on Advanced Algorithms and Architectures for Signal Processing*, vol. Real Time Signal Processing 12, pp. 170–181, 1989.
[11] J. L. Lacoume, P. O. Amblard, and P. Comon, *Statistiques d'ordre Supérieur pour le Traitement du Signal*, Masson, France, 1997.
[12] J. F. Cardoso, "Blind beamforming for non-Gaussian signals," *IEE Proceedings F*, vol. 140, no. 6, pp. 362–370, 1993.
[13] P. Common, "Independant component analysis, a new concept," *Signal Processing*, pp. 287–314, 1994.
[14] A. Belouchrani, *Séparation Autodidacte de Sources: Algorithmes, Performances et Application à des Signaux Expérimentaux*, Thèse de l'ENST, France, 1995.
[15] R. Huez, D. Nuzillard, and A. Billat, "Détermination d'un profil de température dans des matériaux biopolymères par une méthode de séparation de sources," in *Compte Rendus du Seizième Colloque GRETSI*, France, 1997, pp. 223–226.
[16] A. Belouchrani, K. Abed Meraim, J. F. Cardoso, and E. Moulines, "A blind source separation technique using the second order statistics," *IEEE Transactions on Signal Processing*, vol. 45, no. 2, pp. 434–443, 1997.
[17] R. Huez, D. Nuzillard, and A. Billat, "De-noising of experimentals signals from pyroelectric sensors by a source separation method," in *Proceedings of the Eusipco'98 Conference,* Rhodes, vol. 4, pp. 2073–2076, 1998.
[18] R. Huez, D. Nuzillard, and A. Billat, "Bss analysis of an experimental setup based on pyroelectric ceramics," in *First International Workshop on Independent Component Analysis and Source Separation ICA'99*, pp. 435–440. Aussois, France, 1999.

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