Dynamic Pollutant Sources Identification Based on Multipoint Spectral Analysis

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***Abstract*—**Main objective of this research consisted by identification, evaluation and characterization of a direct linkage between the vibration levels at the intensive pollutant industrial sources and at the proximity areas of these sites or potential sensitive destinations. Based on the virtual instrumentation applications set and using the multipoint spectral analysis method, the authors succeeds to put into the evidence the qualitative effects of a certain vibratory polluntant source on destination points, from the influence area of the respective source. The actual benefit of this global approach in evaluation method helps identification and analysis of this phenomenon of transmisibility. The instrumental tests were performed at the ASTRA Factory, Arad, Romania, on the forges sector, and on proximity zones. This analysis acquires high significance when at the side of the site there are the civil constructions, with preponderant human activities, or habitable areas.

***Keywords*—** vibration, system identification, instrumental tests, multipoint spectral analysis.

I. Introduction

THE vibration pollution becomes a high important environmental factor in our days, because of the high rate of industrial development all over the world. Obvious, this takes different levels as a function of the specific industrial activities. In case of the industrial sectors with intensive dynamic action equipments, (e.g. mould hammers, forge hammers), it is necessary to acquire, monitoring, processing and analysing these actions and theirs main parameters, both at the pollutant source, and at the potential receivers (e.g. civil buildings, private houses, educational places).

In the whole of the technical problems that appears and have to be solved, two of them necessitate more attention: the sinchronization on the signals acquisition procedure and the analysis or evaluation of nonlinear technical systems.

First problem, of sinchronization, appear when the source and the destination are relative secluded, and the acquisition system not furnish wireless or others special capabilities to simultaneous acquire multiple signals.

The second problem is more complicated because of the large variety of the nonlinear mathematical models and the heaviness in modelling and simulation of the technical systems taking into account the nonlinearities of these.

Taking over both kind of problems, another cause consist by the consulting and simulation of the entire set of perturbation factors on the tested system (this have serious influences about the acquire process and about the analysis of nonlinear system behaviour).

According to these potential problems, one of the solutions consists by the global evaluation of the source and the receiver status. Simple and direct computing of Cross-Correlation, Cross Power Spectrum, Frequency Response Function, Transfer Function or Coherence Function is not fully recommanded because of absence of synchronized measurements.

On the other side, the multiple inputs and, in some cases, the multiple outputs, the nonlinearities of different elements, leads to the main idea according to the Point-to-MultiPoint (PMP) topology is more easy to use that mesh topology. A middle way for the complex and fuzzy defined systems could be Multi-Input-Multi-Output (MIMO) methods, but it could be verify that, in many cases, it's very difficult to indicate the real number of the inputs / outputs and to evaluate the expressions of in-out linkages array.

Thus, the isolation and analysis of the short spectral domains, from the interesting areas, could be a valid method for the presented cases of technical systems behaviour evaluation. MultiPoint technique offers the suiting tools for identification and cutting the frequency domains for analysis.

II. Basic Theoretical Formulations

As it was presented in the previous paragraph, the *multipoint spectral isolation method* is a combined method from *multipoint* techniques, *spectral* theory, *isolation* and cutout the interesting areas for a simple analysis.

Briefly, this method is a mixture of procedures, orderly in the next sequence

- *timing acquire* of the acceleration signals at the sources and the receiver;
- *computing* the *spectral composition* of the acquired signals;
- *filtering the signals*, by using the narrow band pass filter, with manual selectable cutoff limits;
- *cutting out* a significant length from the signal (from time-domain evolution), and rigorous processing this;

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- *liken the spectral composition* of the source with that of the receiver, and detect the common parts of these.

Running over the method procedures sequence, it results that this method are based on the Correlated-Spectral-Identification (CSI) technique, completed by classical procedures for spectral functions evaluation. CSI technique means actually the mixed procedure of filtering and cutting of significant parts from the two liken signals.

Spectral composition of the acquired signals was performed using the Auto-Power-Spectrum method

$$S_{XX}(\omega) = F[x(t)] \cdot \overline{F}[x(t)] = \\ = X(\omega) \cdot \overline{X}(\omega) = |X(\omega)|^2 \quad (1)$$

based on the Fourier Transform

$$X(\omega) = F[x(t)] = \int_{-\infty}^{+\infty} x(t) e^{-j\omega t} dt \quad (2)$$

where the $\overline{F}[x(t)]$ denote the complex conjugate of the Fourier Transform.

The Auto-Power-Spectrum could be also evaluate using the Auto-Correlation function, with the expression

$$R_{XX}(t) = F^{-1}\left\{|X(\omega)|^2\right\} = F^{-1}[S_{XX}(\omega)]. \quad (3)$$

In the case of precisely and accurate qualitative and quantitative evaluation of influences between dynamic pollutant sources and sensitive receivers, the comparison between each parts pair of the signals have to be performed by using of classical computational methods.

Thus, the Cross-Power-Spectrum between the two sampled signal parts

$$S_{XY}(\omega) = F[y(t)] \cdot \overline{F}[x(t)] \quad (4)$$

where $F[y(t)]$ is the Fourier Transform of the $y(t)$ signal and $\overline{F}[x(t)]$ denote the complex conjugate of the Fourier Transform of the $x(t)$ signal, indicates the similarities between the spectral components of the involved signals.

The precisely and accurate informations regarding the linkage between the input and the output, the noise existence, the hidden inputs, the system nonlinearities or the existence of other conditionality of the output, it is necessary to use the Coherence function

$$\gamma(\omega) = \frac{|S_{XY}(\omega)|^2}{[S_{XX}(\omega)][S_{YY}(\omega)]} \le 1, \quad (5)$$

where $S_{XX}(\omega)$ and $S_{YY}(\omega)$ denote the Auto-Power-Spectrum of the two involved signals, and the $S_{XY}(\omega)$ is the Cross-Power-Spectrum between them.

On the whole, note, that in this case, the phase information for whatever the estimated parameters (from the previous presented), are not decisive, because of synchronization missing on signals acquire process.

This method are based on the supposition that the noises are additive and the Signal-at-Receiver (*Y*) could be written as

$$Y(i,j) = N_1(i,j) + N_2(i,j) + X(i,j), \quad (6)$$

where $Y(i,j)$ is the signal at the receiver, $X(i,j)$ is the source signal, $N_k(i,j)$, k=1...2, are the noises at the receiver site, i denote the frequency index, and j represents the frame index on Fourier Transform.

On a virtual instrumentation implementation, this method could be recurrently used, in addition with a narrow bandpass filter of high order, thus that the identification and isolation of the signal components will be done until the involved signal become a noise (extracting the whole peaks from the signal spectrum until this remain constant on the analysis frequency domain). This type of implementation assures a high precision in spectral identification procedure.

The previously speculations has to be completed by a briefly presentation of a Multi-Input-Multi-Output method for a linear systems. Tacking into account the supposed class of practical applications, it will be presented that case of a singular output. Thus, this output could be treat as a sum of n outputs $y_i(t)$, with $i=1...n$

$$y(t) = \sum\nolimits_{i=1...n} y_i(t) \quad (7)$$

where $y_i(t)$ is the output part due to the $x_i(t)$ input, when the others inputs was null. Between the partly output $y_i(t)$ and the coressponding input $x_i(t)$ exist a convolution relationship through the ponderal response $h_i(t)$

$$y_i = \int_{-\infty}^{+\infty} h_i(t)\, x_i(t-\tau) d\tau \quad (8)$$

respectively, on frequency domain

$$Y_i(\omega) = H_i(\omega) \cdot X_i(\omega)\,. \quad (9)$$

Using the Power Spectral Density (PSD) functions and supposing that the inputs are not correlated, results

$$G_{yy}(\omega) = \sum\nolimits_{i=1...n} H_i^*(\omega) \cdot H_i(\omega) \cdot G_{ii}(\omega) \quad (10)$$

and

$$G_{iy}(\omega) = H_i^*(\omega) \cdot G_{ii}(\omega)\,. \quad (11)$$

If the inputs are correlated, the previous expressions becomes

$$G_{yy}(\omega) = \sum_{i=1...n} \sum_{k=1...n} H_i^*(\omega) \cdot H_k(\omega) \cdot G_{ik}(\omega) \quad (12)$$

and

$$G_{iy}(\omega) = \sum_{k=1...n} H_k^*(\omega) \cdot G_{ik}(\omega)\,, \quad (13)$$

where

G_{yy} denote the output PSD;
G_{ii} denote the PSDs of the inputs;
G_{iy} denote the Cross-Power Spectral Density functions;
G_{ik} denote the Cross-Power Spectral Density functions of the inputs;
H_k denote the transmisibility function;

H^*_k denote the complex conjugat spectrum of transmisibility function.

Supposing in expression (6) that noises N_k will be affects the system as a singular input signal, and the system have a unique major input that could affect the output, it is obvious that we have to do with a double input system.

In this particular case, the coherence functions (5) could be estimate by

$$\gamma_{iy}^2(\omega) = \frac{\left|H_1(\omega)G_{11}(\omega) + H_2(\omega)G_{12}(\omega)\right|^2}{\left[G_{11}(\omega)\right]\left[G_{yy}(\omega)\right]}, \quad (14)$$

$$\gamma_{2y}^2(\omega) = \frac{\left|H_1(\omega)G_{21}(\omega) + H_2(\omega)G_{22}(\omega)\right|^2}{\left[G_{22}(\omega)\right]\left[G_{yy}(\omega)\right]}. \quad (15)$$

and, based on the (12), result

$$\begin{aligned} G_{yy}(\omega) = {} & \left|H_1(\omega)\right|^2 G_{11}(\omega) + \\ & + H_1^*(\omega)H_2(\omega)G_{12}(\omega) + \\ & + H_2^*(\omega)H_1(\omega)G_{21}(\omega) + \\ & + \left|H_2(\omega)\right|^2 G_{22}(\omega) \end{aligned} \quad (16)$$

III. Instrumental In-Situ Tests

In this paragraph will be briefly presented a real case analysis for a major pollutant shock and vibration source from a factory, to a sensitive receiver situated next to the factory site.

In the Figure 1 is presented the schematic diagram of the measurements sites, relative to the source and the receiver. Such as it was mentioned in the abstract, the instrumental tests were performed as a direct requirement of ASTRA Factory at Arad, Romania.

The first major objective was to provide a serious and decisive proof for the absence of the negative and perturbing effects, due to the forge sector activities, on a private house situated on a side, nearby the factory domain limit. It commes as a direct consequence of the factory requirements, and it was also given a direct responses on these.

The second objective of these instrumental tests comes to furnish a practical example for theoretical aspects presented on the previous paragraph.

On the diagram in Figure 1 it was depicted also the significants points where it was made the instrumental measurements. Both at the source, and at the receiver, it was made a set of tests about adequate settlement of vibration sensors - for better signal acquisition on given situation, especially at the receiver place, where the signal level was very low and the ratio between signal and background noises acquire a high values.

The measurements *in situ* was developed with the approaching of the next hypothesis

- ⇨ the vibration source S1 (mould hammer, of 5 tones) on complete working cycle, moulding a piece from the regular production;
- ⇨ the vibration sources S1 (mould hammer, of 5 tones) and S2 (free forge hammer, of 10 tones) on simultaneous working cycle, processing pieces (one piece for each equipment) from the regular production;
- ⇨ without both the previous S1 and S2 sources, and the others vibration generators sources on the proposed sector (minimum level of vibratory disturbations on forge sector).

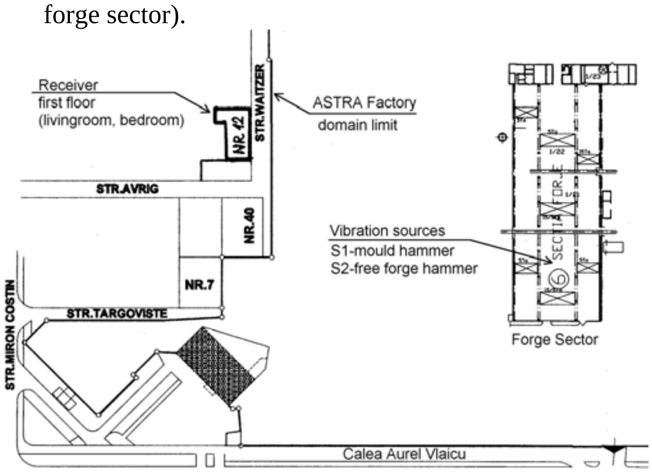


Fig. 1. The schematic diagram of the tests area

The measurement suite framed the Bruel&Kjaer accelerometers, signals conditioners, portable vibro-meter, tunning continuous filter, NI DAQ PC board with LabVIEW™ software package (NI Sound and Vibration Measurement Suite™ included).

The emplacement of the measure points was performed hereby

- ⇨ *at the source* - on the concrete foothold of the forge sector, lined up with the propagation direction, at the 3 m distance from the S1 source, and on the vertical direction;
- ⇨ *at the receiver* - on the first floor of the building, into the livingroom and into the bedroom of the house.

In Figure 2 were depicted major types of vibration sources at the forges sector. These were the significant equipments in the considered factory and the instrumental measurements was developed supposing only the working states of these.

In Figure 3 (top side) was depicted the instrumental tests area at one of the vibration source - presented on the top side in Figure 2. On down side of Figure 3 is presented a detail of the instrumental sensor montage on the solid state metallic block, next to the vibration source (at 3m of this, on the estimated propagation direction of vibrations).

The receiver point was placed at a first floor at a private residence, on a livingroom. From closeness deems, it was not depicted the whole images of receiver place. However, in Figure 4 is shown only the measurement area at this place.

Fig. 2. Vibration sources in forges sector at ASTRA Factory, Arad, Romania

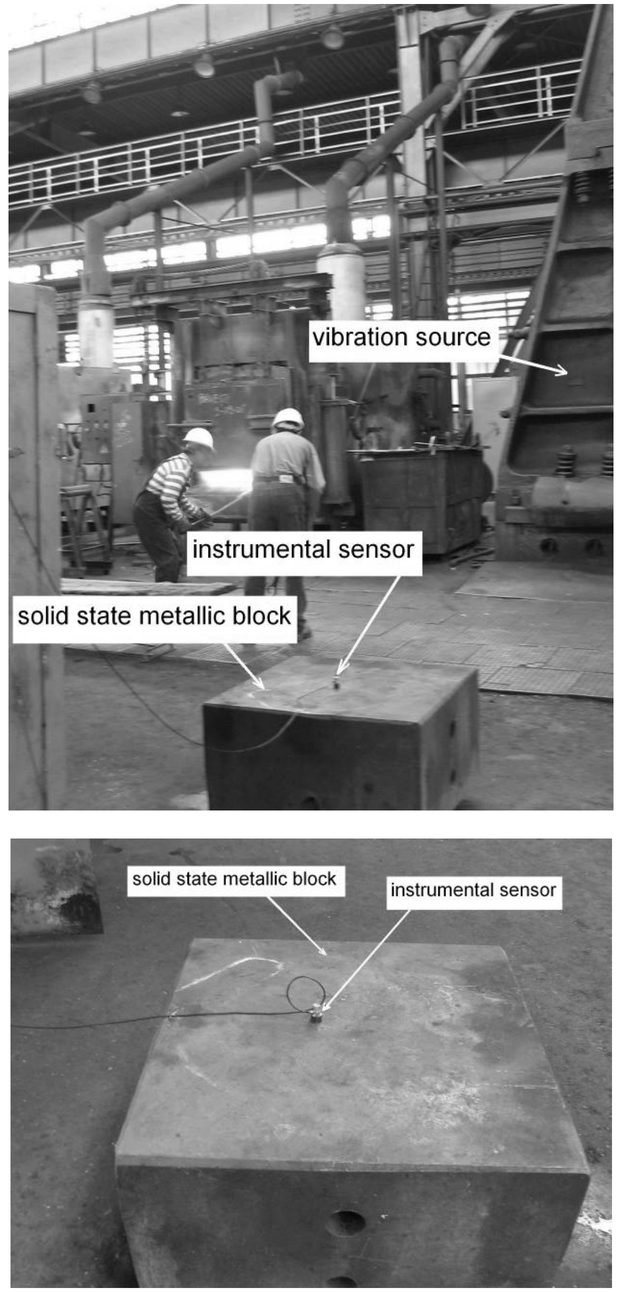


Fig. 3. The instrumental tests area at vibration sources

In the next paragraphs it will be briefly looking over the standards and normatives stipulations about the vibration admissible levels on this case.

According to the ISO 4866-1990 "*Mechanical Vibrations and Shocks - Vibrations of buildings - Guidelines for the measurement of vibrations and evaluation of their effects on buildings*", the regular parameters based on it was made the vibration effects evaluation about the constructions, was the kinematics parameters that could characterize the movement - acceleration, velocity or displacement - correlated on a maximum 1000 Hz frequency domain.

The kinematics parameters were associated with the strictness levels of the shocks and vibrations, through theirs RMS, Peak Levels, or Max. Levels, evaluated for a denoted time length, or through values of derived parameters that could significant characterize the vibration strictness.

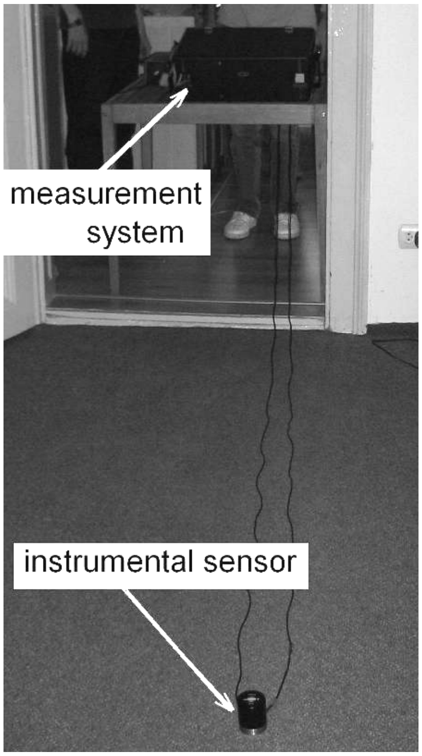


Fig. 4. The instrumental tests area at receiver (detail)

From the point of view of these quantified effects that was framed on the insecure classes (defined such as less and upper limits of each class), ISO 4866-1990 direct to the specific national laws and stipulations.

Thus, the ISO 4866-1990 direct to the DIN 4150/1 "*Vibrations in building; principles, predetermination and measurement of the amplitude of oscillations*", which offers a method for the effects evaluation based on the peak value of the vibration velocity.

It have to be mentioned the National Standards STAS 12025/1 - 81 and SR 12025/2 - 94, concerning the "*The effects of the vibrations on the buildings or parts of buildings*" and which indicates "*The measuring methods*" and "*The admissible limits*" regarding the distortions of the building structure or elements, and regarding the comfort state assurance on the buildings.

Table 1. Admissible limit values for vibration level (according to the SR 12025/2 - 94)

Admissible values of the vibration equivalent level. Estimation criterion	*Value*
Vibration acceleration criterion - A^{z}_{v}	80 [dB]
Vibration intensity criterion - C^{z}_{v}	+1 [vibrar]
Combined criterion (transversal and longitudinal accel.) - A^{C}_{v}	77 [dB]

In Table 1 are the limit values of the vibration level and the estimation criterion.

According to the general requirements of the proposed method, in the next figures it will be depicted the time-domain evolution and the Power-Spectral-Density function for the initial acquired and filtered acceleration signals on vertical direction.

In Figure 5 it is depicted the source signal, measured at 3 m from the shock and vibration generator (mould hammer pathway), on a grounded solid state metal block (see Fig. 3).

Analysing these diagrams, it could be observed that area of interest is toggled between 20 and 40 Hz, with some relative irelevant peaks up to 80 Hz.

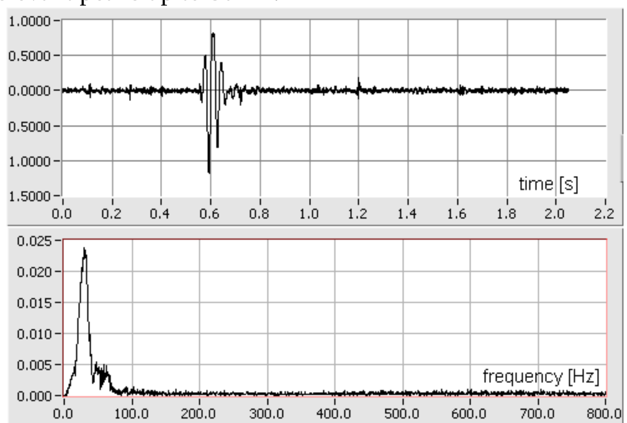


Fig. 5. The signal of the source; at 3 m next to the mould pathway; top: time-domain; bottom: PSD.

In Figure 6 it is depicted the background noise measured at the receiver, in the absence of the tested sources. There is evident on the diagrams that the 0...100 Hz is the area of interest in this case.

Some irelevant peaks covers the area from 150 to 180 Hz, but the relative magnitudes of these indicates a slightly influence on global perception.

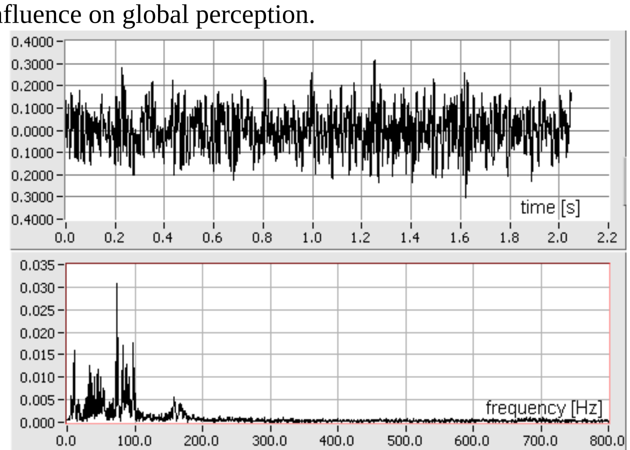


Fig. 6. The signal of the background noise; at the receiver; top: time-domain; bottom: PSD.

In Figure 7 it is depicted the signal measured at the receiver, with normal working state for the tested sources (see fig. 2). As it was mentioned in the previous paragraph, this measurement was performed at the first floor of a building, in a livingroom of a residence.

The entire set of instrumental tests was made only with the supposition that the two presented equipments were working - simultaneous, in sequence or separately (of course, on the tested area; the rest of the equipments were treated as a pollutant vibration sources).

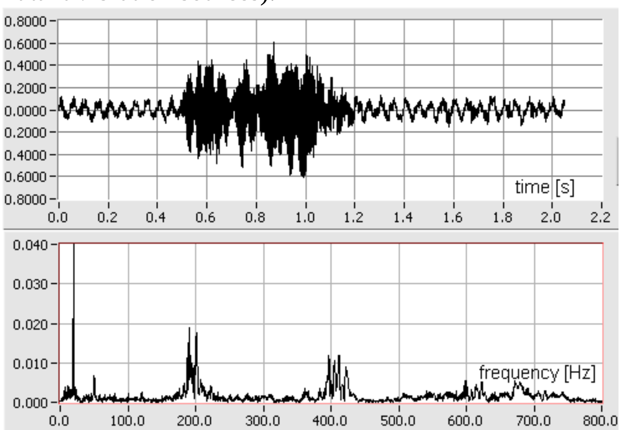


Fig. 7. The signal at the receiver - case I;
livingroom; first floor of building;
top: time-domain; bottom: PSD.

Generally, it was considered both equipments working, the signals was handled in common, as a single unit source. It was supposed that this is a most difficult case of vibratory pollution (after the final processing of experimental data, it was proved that this supposition was right).

In the Figure 8 it is present four diagrams set, issued by filtering the initial signal acquired at receiver (see Fig. 7).

The virtual instrument that was used for this application has a Butterworth bandpass filter of second order implementation, with characteristics given by next expression

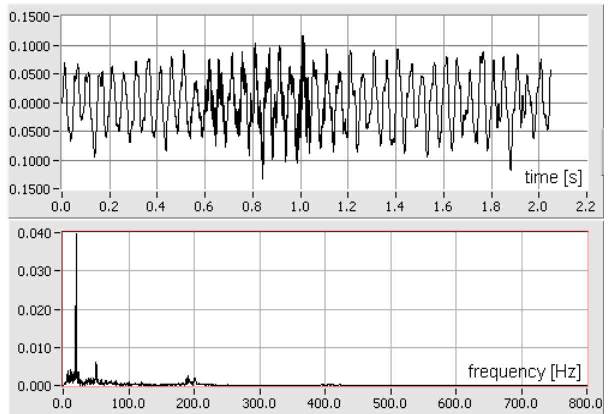
$$A\left(\omega^2\right) = H(s)H(-s)\Big|_{s=j\omega} = \\ = \frac{1}{1+F\left(\omega^2\right)}\Bigg|_{general} = \frac{1}{1+\omega^{2n}}\Bigg|_{Butterworth} \qquad (17)$$

and depicted in diagram from Figure 9.

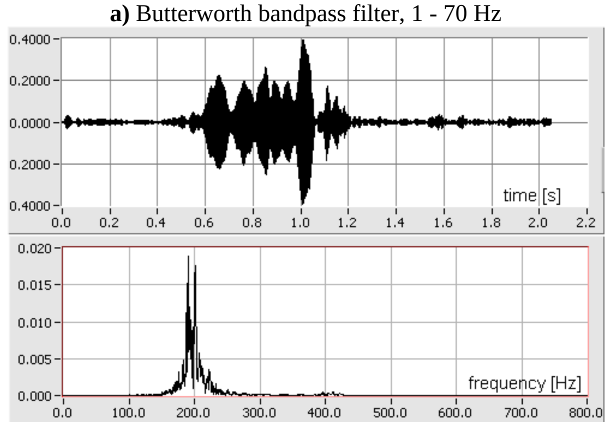
The three graphs in Figure 9 represents filter gain evolutions versus the relative frequency of analysed signal, for second, fifth and, respectively, 20th orders of the filter. Clearly shown in these diagrams that high orders provide accurate residual signals cut off.

The application described in this paper used a second order filter, because the ratio between the results accuracy and the required computing resources has an optimum value.

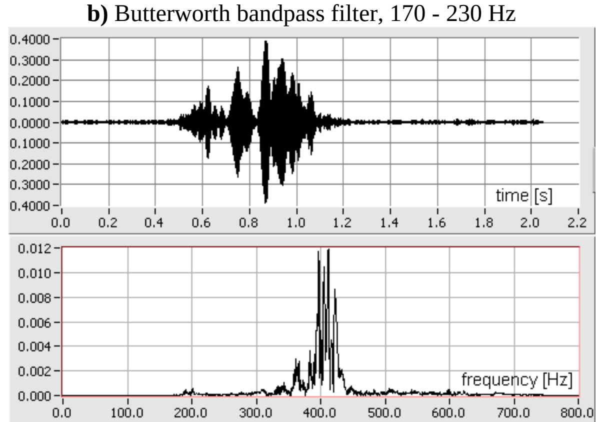
This filtering of a signal is equivalent with a spectral windowing. Theoretical speaking, this operation have to suspend all the spectral components unless those in the filter bandpass. Practical, as a function of filter type, this rejection could be more or less serviceable (see Figure 9).



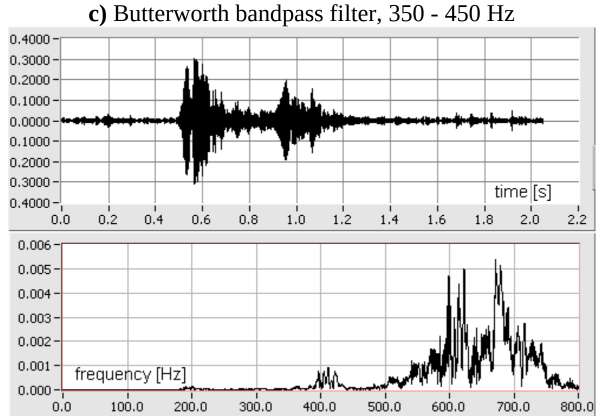
a) Butterworth bandpass filter, 1 - 70 Hz



b) Butterworth bandpass filter, 170 - 230 Hz



c) Butterworth bandpass filter, 350 - 450 Hz



d) Butterworth bandpass filter, 580 - 750 Hz

Fig. 8. The filtered signal of receiver - case I;
top: time-domain; bottom: PSD.

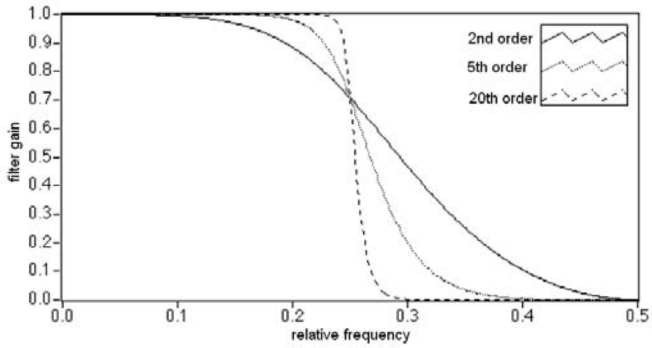


Fig. 9. The Butterworth bandpass filter characteristics

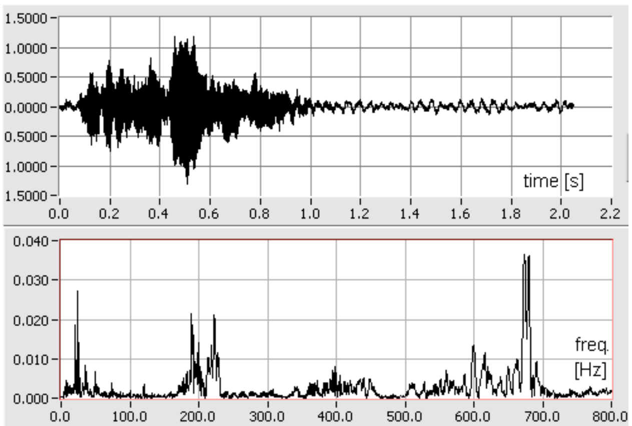
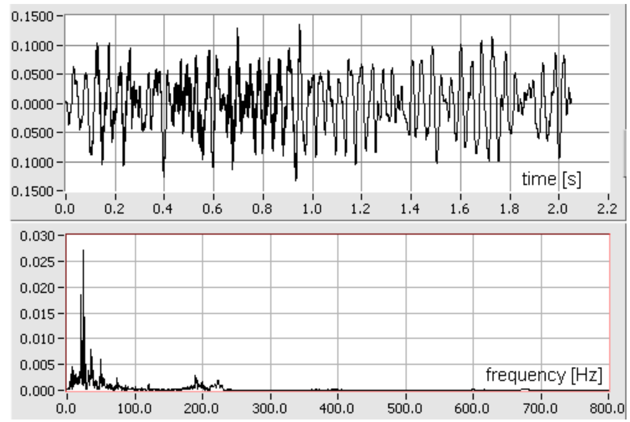
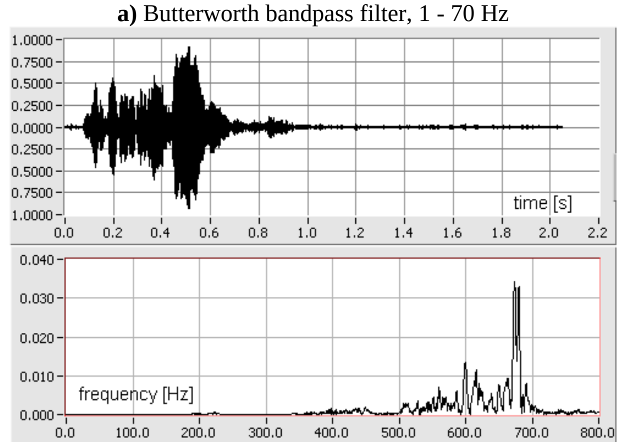


Fig. 10. The signal at the receiver - case II;
livingroom, first floor of building;
top: time-domain; bottom: PSD.



a) Butterworth bandpass filter, 1 - 70 Hz



b) Butterworth bandpass filter, 500 - 720 Hz

Fig. 11. The filtered signal of receiver - case II;
top: time-domain; bottom: PSD.

From the Figure 8 diagrams results that in spectral composition of the signal at receiver, the influences due to the tested sources are very low. Even the frequency of the peaks in Figure 8.a seems to be the same with the Figure 5, the spectral cross-correlation between them, show the powerless linkage. The rest of the spectral components have nothing or too less in common with the tested source spectrum - see Figure 8.b-d. Too less means under the error level of the procedure and of the measuring instruments, thus that is was uncertain to classify the source.

In the Figure 10 it is presents another set of measurements at the receiver, on the same place as the previous case, and with approximate the same conditions at the sources. In this case, in the Figure 11, it was depicted only two filtered diagrams sets because the others spectral zones has not the significant modification comparative with the case I.

Liken the first set of diagrams, from Figure 8 and from Figure 11, results a good similarity of the two behaviours. Such as the case I, the spectral cross-correlation shows the powerless identification of the source spectral components in the received signal spectrum.

Also, both in the Figure 8, and in the Figure 11 diagrams, it could be observed that spectral components under 100 Hz provides only the background support, the bearer, for the rest of the signal that could be assimilate as an amplitude modulation result.

In the Figure 11.b, both at time evolution, and at spectral composition, it is evident the great percentage of high frequencies participation, thus these have others causes then the tested sources.

IV. Concluding Remarks

Analysing in the whole the diagrams depicted in the Figures 5...8 results two main concluding remarks, such as

- ☑ *first*, regarding the concrete presented case, show there is no evident linkage between the source and the receiver signals, which leads to nullify of the consideration of tested source as a generator of the vibrations measured at the receiver; also, it was observed that frequency zones with major values of acceleration magnitude, from the background noise spectrum, with absence of the tested sources, it was recovered on the receiver signal spectrum, with comparable and closed values.
- ☑ *second*, regarding the multipoint spectral analysis method - based on correlated spectral identification

technique, show there is evident that this simple method is a real choice for dynamic technical systems identification and evaluation, especially in absence of enough and adequate data for usual analysis. This method could be also used, as in the presented case, when the instrumental tests were not providing a synchro and parallel acquisition procedure. Other cases of serviceable using of this method are when the experimental data derived as a result of a statistical procedure applied on sets of measurements in the same testing condition, or derived from a temporal or spatial averanging procedures applied on multivariable functions.

Based on the instrumental "*in situ*" tests, and on the simulations with the numerical models, it could be formulate another conclusion, such as: strong nonlinearities from the tested systems blocked the utilization of the coherence function - the function deviation from unitary value was preponderant due to the nonlinear behaviour. In this case, the cross-correlation power spectrum was furnished the best identification method.

This method could be used as an estimative tool for simple and speedy estimation of source-destination correlation, but it could be also used - and it is recommended - for precisely and accurate qualitative and quantitative evaluation of linkage between dynamic pollutant source and sensitive receivers. This last kind of applications needs virtual instrumentation implementations to increase the accuracy and reducing the processing time. And, at present computing systems have enough power to provide a doable and proper activities of acquire, processing, analyse and manage the sizable volume of experimental data. Thus that it is relative easily to suit and to use a serviceable implementation of multipoint spectral isolation and identification procedures.

The multipoint spectral analysis method was started from an empirical technique and it has been used succesfully, for different behavioural analysis and evaluations of technical systems dynamics.

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