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ISSN 0543-5846
METABK 53(1) 75-77 (2014)
UDC – UDK 669.18:661.993:66.084=111

UTILIZATION OF SIGNAL SPACES FOR IMPROVEMENT OF EFFICIENCY OF METALLURGICAL PROCESS

Received – Prispjelo: 2013-04-01
Accepted – Prihvaćeno: 2013-06-25
Preliminary Note – Prethodno priopćenje

The contribution deals with some questions associated with utilization of mathematical spaces, especially Hilbert spaces, in the area of process control. The authors of the paper point out the possible method of prediction of undesirable leaks of CO gas in oxygen converter in steel production. This prediction is based upon monitoring concurrent vibrations of the converter that are processed in abstract Hilbert space. To the current state of the process corresponds a point in the space. To the critical state of the process then corresponds a particular point of its trajectory. The structures of abstract space enable to visualize the trajectory of the process in the converter and quantitatively specify the distance of the process from the critical point.

Key words: steel production, oxygen converter, leaks of CO gas, Hilbert space, vibro-signal

INTRODUCTION

The principles of the control of technological processes must be based on the character of the particular process but also on the measurability of the process quantities. In standard methods of control the basis is the mathematical model of the process that can have different form. However, there are technological processes whose character prevents the creation of such mathematical model of the process. The reason can be strong stochastic character of the process, immeasurability of process quantities, strong nonlinearities in the process, complicated relations between key process quantities etc.

In such a case one can consider some nonstandard procedures of controlling the process.

This contribution deals with one such nonstandard procedure [1-4].

There exist many technological processes characterized by their concurrent vibro-acoustic emissions. With a suitable monitoring, e.g. on the device body, an information (process) signal is generated whose character and parameters then correspond to the current state of the process [5-9].

As an example of the process generating vibro-acoustic emissions as a usable process signal is e.g. the process of milling in a mill, the process of steel solidification in an oscillating crystallizer, the process of steel production in an oxygen converter, the operation of a rotary machine, the motion of so-called thin load in a heat aggregate etc. [10-12]. The authors of this contribution direct their scientific research toward utilization of concurrent vibro-acoustic emissions that are generated by the process of rotary drilling, and for efficient control of the rock massif separation mode. The process vibration signal in this case is interpreted as a function – point – vector of abstract mathematical space in the sense of functional analysis. The signal space of Hilbert type becomes here the state space of the process of drilling. Its set, algebraic, topological, and geometric structure enables the solution of some tasks, such as state recognition of the process or the task of monitoring the process dynamics, as geometric problems in the sense of analytical geometry.

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INNER PRODUCT AS KEY ALGEBRAIC OPERATION DEFINED ON SET STRUCTURE OF HILBERT SPACE

The inner product is an algebraic operation that associates a scalar value to a pair of vectors in the space. The particular algebraic form of the inner product depends on the specific class of spaces. Hilbert spaces of class L_2 [0, T] have inner product of pair of vectors x_i, x_j $\in L_2$ [0, T] defined in the form

$$\left\langle x_i, x_j \right\rangle = \int_0^T x_i\,(t), \overline{x_j\,(t)}\,\mathrm{d}\,t. \qquad (1)$$

If we consider Hilbert space as a complex infinite-dimensional space with structure C^∞, then in the sense of functional analysis the inner product is a functional realizing the mapping $C^\infty \times C^\infty \rightarrow C$.

The power of Hilbert space from the application point of view stems just form the inner product. It's because it is the „building block“ of their topological and geometrical structure. In short, it is about these facts:

- Inner product generates the norm

$$\|x\| = \langle x, x \rangle^{1/2}. \tag{2}$$

It is the mapping $C^\infty \to R_0^+$ and it expresses geometrically the length of vector or the distance of the element of the space from the origin of the coordinate system. In the case of the signal space the square of the norm represents the energy signal as an element of the space, so that $E_x = \|x\|^2 = \langle x, x \rangle$.

- The norm of the space (2) generates the metric of the space

$$\rho(x_i, x_j) = \|x_i - x_j\| = \langle x_i - x_j, x_i - x_j \rangle^{1/2}. \tag{3}$$

It is the mapping $C^\infty \times C^\infty \to R_0^+$ and it expresses geometrically the distance between two vectors in space.

- Between inner product of two vectors and their norms there is so-called CBS inequality: $|\langle x_i, x_j \rangle| \le \|x_i\| \|x_j\|$ This inequality is geometrically interpreted as a function of the cosine of the angle subtended by two vectors x_i and x_j. So we have:

$$\cos\alpha = \frac{|\langle x_i, x_j \rangle|}{\|x_i\| \|x_j\|} \in [0,1] \Rightarrow \alpha \in [0, +\pi/2]. \tag{4}$$

- The inner product makes it possible to express or test mutual orthogonality of two vectors in space. According to (4) we have: $\langle x_i, x_j \rangle = 0 \Leftrightarrow x_i \perp x_j$.
- In Hilbert space the function $x = (x(t), t{:}0 \mapsto T)$ as a vector can be expanded into Fourier series in complete orthonormal or orthogonal vector base $\{b_k\}_{k=1}^{\infty}$.

In the case of orthonormal base of the space this series has the form

$$x(t) = \sum_{k=1}^{\infty} x_k b_k(t). \tag{5}$$

The coefficients of this series (so-called Fourier coefficients) are given by the inner product:

$$x_k = \langle x, b_k \rangle \in C, k = 1,2,... \tag{6}$$

and represent the coordinates of the vector x in Hilbert space relative to given base $\{b_k\}_{k=1}^{\infty}$.

In Figure 1 is illustrated the geometric structure in signal space, based on the operation of inner product.

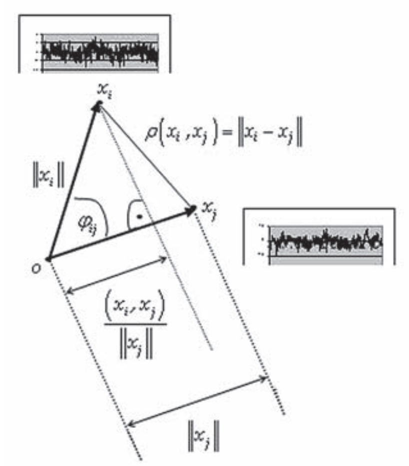

Figure 1 Graphic illustration of mutual geometric relations between pairs of signals as vectors – points in Hilbert space

PREDICTION OF THE LEAK OF CO GAS IN THE PRODUCTION OF STEEL IN OXYGEN CONVERTER

The use of Hilbert space class L_2 [0, T] as a signal space enabled the task of classification of states to be solved as a geometry task. In addition, it was not necessary to extract any attributes from the signal as with standard classifiers. Each of the set of process states was represented in Hilbert space by his/her averaged power spectrum Figure 2 of his/her speech recording with approximate length of 20 second. For the expression of geometric differences of individual states two reference signals were defined as vectors in the space: x_C as the centroid of all states of the process and x_W as white noise.

For the purpose of visual graphic expression of differences between states an algorithm of projection of signal Hilbert space of states into 3-D space was designed. Each set of process states is identified in the space by a triple of real numbers – coordinates: $(\varphi, \vartheta, \|x\|)$ where $\varphi = \sphericalangle(x, x_C)$ and $\vartheta = \sphericalangle(x, x_W)$. Subsequent visualization of the vectors of states into E_3 is realized via polar coordinates into cartesian coordinates. From the above follow the coordinates of points of the space E_3, into which the vectors of individual states from Hilbert space map themselves:

$$\begin{aligned} x &= (y_1, y_2, y_3) \equiv \\ &\equiv (\|x\|\sin(\partial)\cos(\varphi), \|x\|\sin(\partial)\sin(\varphi), \|x\|c\,os(\partial)). \end{aligned} \tag{7}$$

The result of visualization of distinguishability of states is shown in Figure 3.

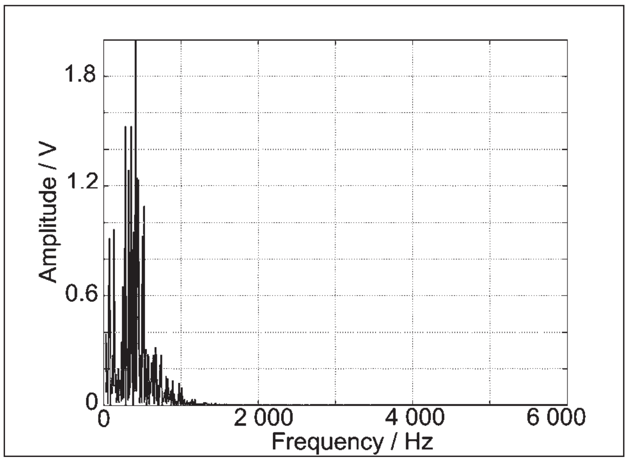

Figure 2 Averaged power spectrum of converter signal as vector in Hilbert space

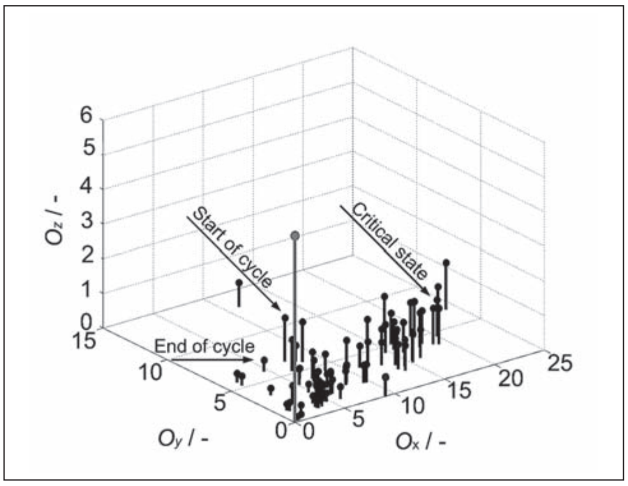

Figure 3 Set of states of the converter in one technological cycle

The signal space of Hilbert type but also the Euclidean space, denoted as E_3, are metric spaces. That enables visualized mutual distances – quantification of the differentiation of signals.

However, the properties of the state space defined here as a normed algebraic linear space make it possible to more simply solve the prediction of undesirable state of the process when the leak of CO gas occurs. By experimental identification of the process during a sufficient number of cycles it would be possible to identify the critical state $|X|^2_{\mathrm{CO}}$ of the process that closely precedes the undesirable phenomenon. Then it suffices for the automated system, working on this principle, to notify the operator of the converter at the instant when the trajectory of the process, or the current state $|X|^2_t$ reaches the ε - neighborhood of the critical state - see Figure 3. By using the metric of the space this situation can be expressed with the inequality:

$$\rho\left(|X|^2_t, |X|^2_{\mathrm{CO}}\right) = \left(|X|^2_t, |X|^2_{\mathrm{CO}}\right)^{1/2} \leq \varepsilon. \qquad (8)$$

CONCLUSION

In this contribution a possibility is shown of using abstract mathematical spaces of Hilbert type as signal spaces with some tasks in the area of signal processing. This approach makes it possible to solve some practical tasks in technical and natural sciences as geometry problems. The authors show the basics of such approach and give some aspects connected with practical solution. Also given is the original method of visualization of geometric layout of signals in Hilbert space, corresponding to mutual differences in these signals. This contribution illustrates the possibilities of applying the method also in complex metallurgical processes generating concurrent vibro-acoustic emissions.

Acknowledgements

This article was created with the support of the OP Research and Development for the project: ITMS 2620220031, co-funded by European Regional Development Fund.

This work was supported by the Slovak Research and Development Agency under the grants VEGA No. 1/2578/12, VEGA No. 1/0746/11, VEGA No. 1/0729/12.

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Note: The responsible translator for English language is Ladislav Pivka, Košice, Slovakia