THE MULTIDIMENSIONAL ANALYSIS OF THE COMBUSTION ENGINE INVESTIGATIONS RESULTS WITH SVD METHOD

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Abstract

New approach to investigation of combustion engine technical state is vibroacoustics as a diagnostic tool. The main idea of vibroacoustics investigation is following the changes of vibration estimators as a result of engine maladjustment, waste, damages or its failure. Combustion engines technical state diagnostic investigations with use of vibration are very difficult and only few proposed methods could have wider technical use in diagnostics. The combustion engine No. 138C.2.048 with 1.4l. swept capacity, power 55 kW / 75 KM, generally applied to Fiat and Lancia is the investigation object. The engine is situated in the investigative laboratory of combustion engines in UTP Bydgoszcz. It makes possible to introduce generated vibration signals as well as the investigation of his adjustment influence on the combustion engine vibration signals change. As a validation of investigation results in this paper is shown presentation of Singular Value Decomposition (SVD) method. The SVD method is the appropriate tool for analysing a mapping from one vector space into another vector space, possibly with a different dimension. Thanks to SVD methods we could decide which symptom given in observation matrix is the best to recognize a set of combustion engine technical state. Relationships cause - consecutive expressing quantitative relation between studied variable symptoms results were qualified using the function of the multiple regression. Introduced in this paper results of investigations are only the part of realized investigative project and they do not describe wholes of the investigative question, only chosen aspects.

Keywords: *combustion engines, diagnostic inference, SVD*

1. Introduction

The technical state of object, machine, vehicle can be described as a set of the all parameters values that defining the given object in given moment of time t. The time sequences of this states could be consider as the time of the device existence. He leads inevitably the destructive influences of external extorting and internal factors to the machine condition change. The use of technical diagnostics methods makes possible to qualification of current technical state of studied object, machine and vehicle [5, 6].

Combustion engines technical state diagnostic investigations with use of vibration are very difficult and only few proposed methods could have wider technical use in diagnostics. The paper contains application of SVD methods focused to a combustion engine technical state identification. The combustion engine No. 138C.2.048 with 1.4l. swept capacity, power 55 kW / 75 KM, generally applied to Fiat and Lancia was the investigation object. It makes possible to introduce generated vibration signals as well as the investigation of his adjustment influence on the combustion engine vibration signals change [2-4].

The necessity of the technical state estimation is conditioned by the possibility of making decisions connected with object exploitation and the procedure of next advance with object. The present development of automation and computer science in range of technical equipment and software creates new possibilities of realization of diagnosing systems and monitoring technical condition of more folded mechanical constructions [5, 6].

2. Model of diagnostics signal generation

The investigations object was a combustion engine which was situated in the investigative laboratory of combustion engines in UTP Bydgoszcz. Basis on this engine during investigations was created model of diagnostics signal generation [2, 3, 5, 6]. The proposed model of combustion engine diagnostic signal generation is shown on Fig. 1.

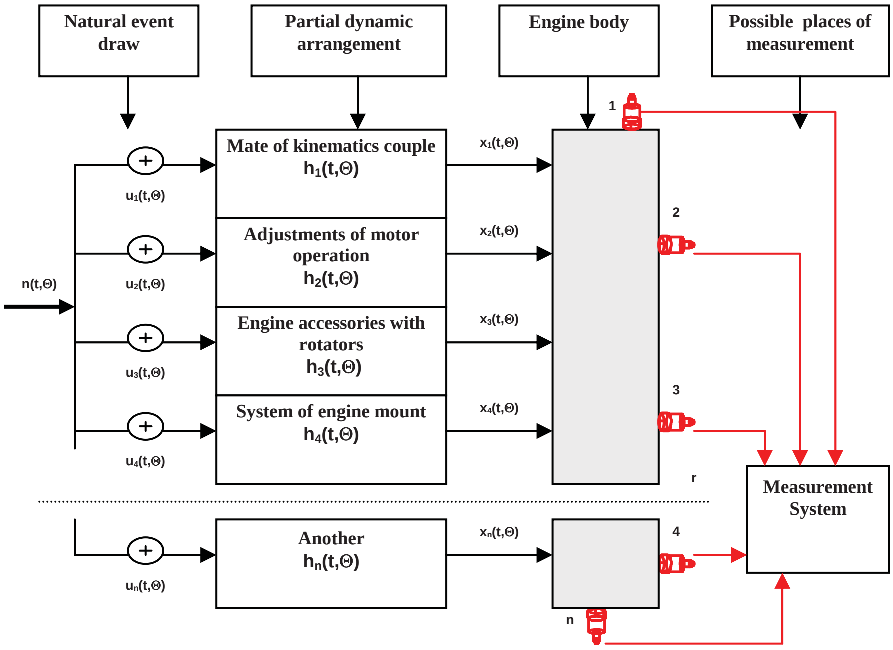

Fig. 1. Combustion engine diagnostics signal generation model [2, 3, 5, 6]

The received signals in the any point of engine body are the sum of the answer at all elementary events u_n (t, Θ), outputs in individual partial dynamic arrangements with the pulse function of input h_n (t, Θ). These influences after passing by proper dynamic arrangements are sum up on the engine body, on chosen points was measured by the vibration transducers. As a result of conducted measurements output signals was used to estimation. By n (t, Θ) was marked accidental influence stepping out from presence of dynamic micro effects such as friction [2-6].

Basis on the Matlab environment the application "Symptoms generation" was used for vibroacoustics signal analysis, serving to processing and analysis of the investigative data. This software enables to estimators obtainment from vibration signal and them it makes possible to technical state description of machine in matrix observation. Model of machine in good condition and model of the same machine after certain period of usage give as an inference base about object waste, vibration predominant sources, that allow in the next steep the machine modernization.

3. Singular Value Decomposition

The SVD method is the one of the newest diagnostic methods. The SVD is the appropriate tool for analysing a mapping from one vector space into another vector space, possibly with a different dimension [1, 6]. The SVD method was included in diagnostics software "SIBI" that was developed at UTP Bydgoszcz and used for result validation. The SVD algorithm is shown on Fig. 2.

Figure 3 display the window with the SVD module that was used for analysis.

The observation matrix of transformation symptoms relative to the initial value example is shown on Fig. 4.

Graphical interpretation of first generalized damage and evolution of damage calculations is given in Fig. 5.

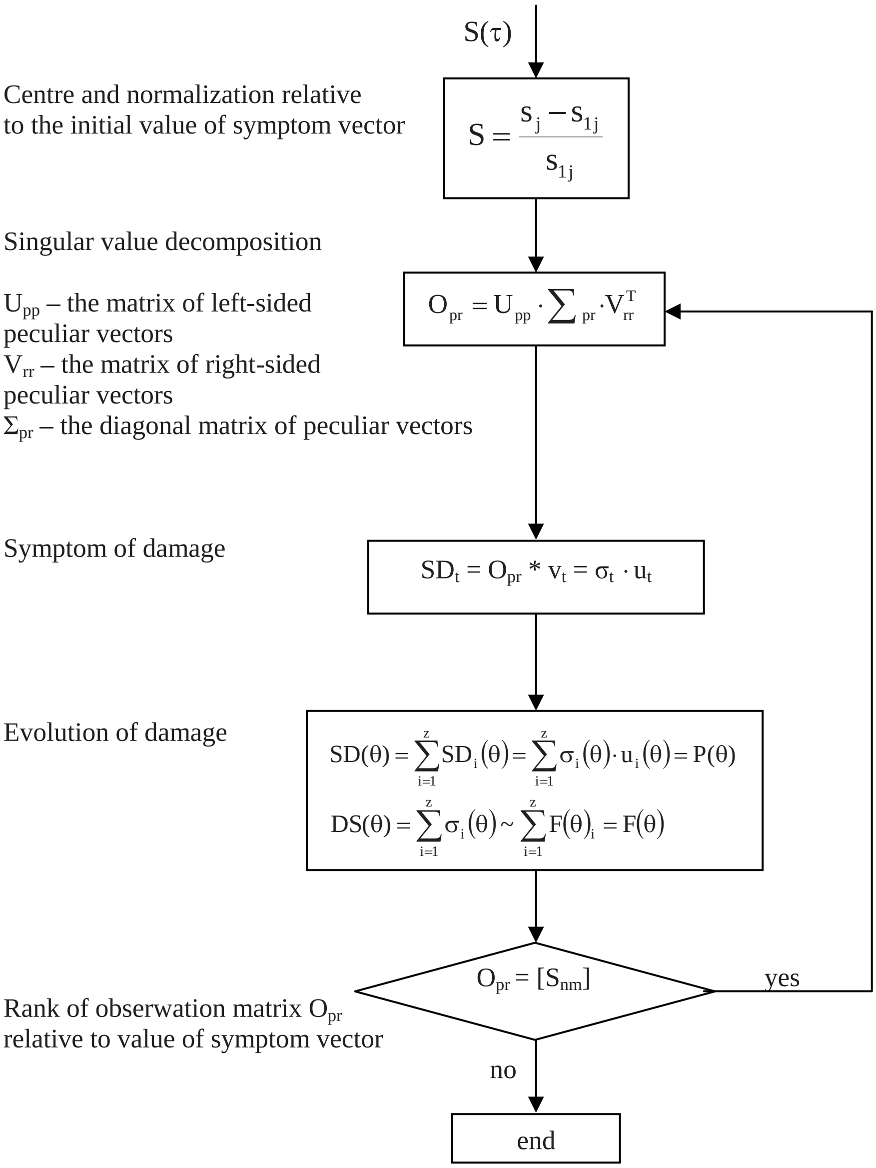

Fig. 2. Singular Value Decomposition algorithm [1, 6]

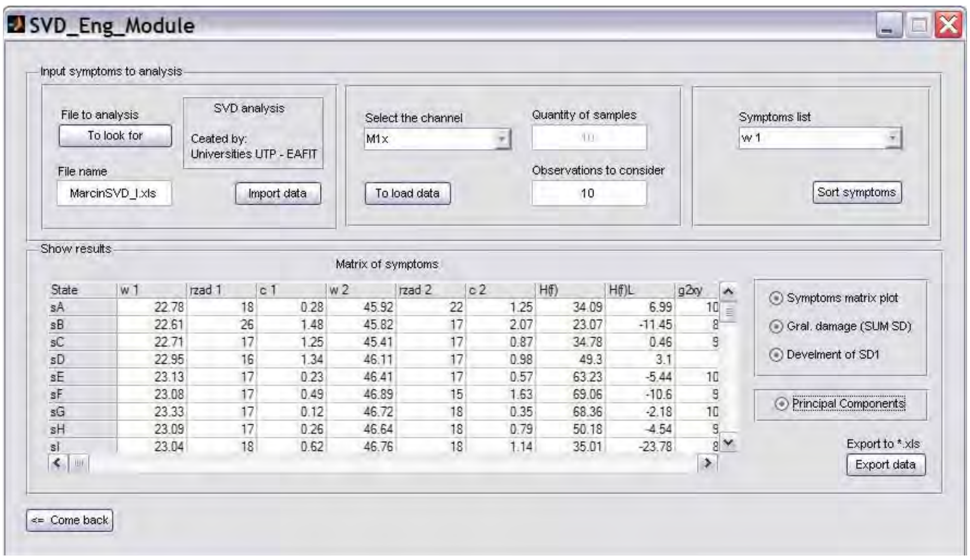

Fig. 3. SVD module window [2-4]

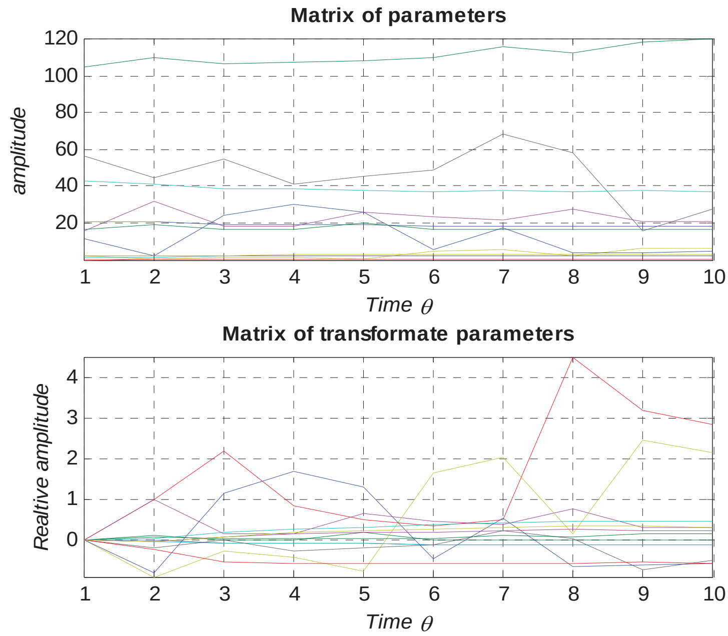

Fig. 4. Matrix of symptoms before and after transformation

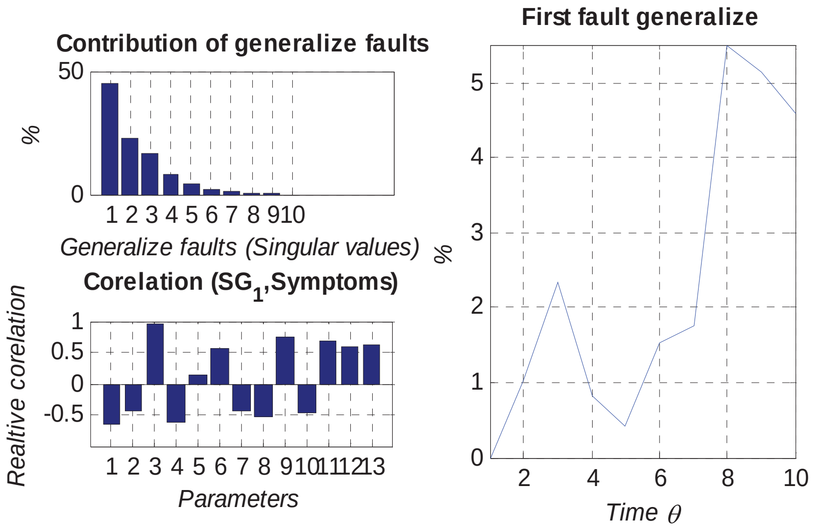

Fig. 5. Graphical interpretation of first generalized damage and evolution of damage

4. Results validation

Conducted investigations of combustion engine depended on delimitations of vibroacoustics measures for fit engine and comparison them with measures appointed for damaged engine (e.g. damaged spark plug, injector) and accomplishment the assessment of received results influence on engine state by operational vibroacoustics methods including modal analysis methods. The final observation matrix of engine performance given in table 1 described 13 symptoms. The matrix have six modal symptoms (ω_1 – first natural frequency, rząd1 – modal order of first natural frequency, ξ_1 – modal damping coefficient of first natural frequency, ω_2 – second natural frequency, rząd2 – modal order of second natural frequency, ξ_2 – modal damping coefficient of second natural frequency) and the last seven symptoms are vibration process (H(f) – real part of transfer function, H(f)L – imagine part of transfer function, γ^2_{xy} – coherence function, $A_{RMS(t)}$ – Root Mean Square in time domain, β_{kurt} – kurtosis, C_s – crest factor, I – impulse factor) [2-4].

Tab. 1. The final observation matrix for engine performance

Technical state	ω_1	row 1	ξ_1	ω_2	row 2	ξ_2	H(f)	H(f)L	γ^2_{xy}	$A_{RMS(t)}$	β_{kurt}	C_s	I
1	23.27	18	0.67	46.96	17	1.34	68.56	-2.18	108.18	0.2177	1.5567	1.7239	1.9268
2	21.82	19	0.68	38.09	20	4.33	47.08	30.59	100.22	0.1392	1.8989	2.1204	2.4456
3	22.57	17	1.47	39.74	18	2.00	36.42	8.84	104.40	0.2040	1.7532	1.8656	2.1198
4	22.13	18	3.11	38.59	17	4.09	31.34	-15.28	91.11	0.1769	1.9245	2.0762	2.3992
5	22.82	19	1.18	40.03	27	3.21	46.16	-75.94	101.15	0.2312	1.7148	2.0982	2.3673
6	20.13	18	1.93	39.08	23	6.98	42.24	-8.50	83.73	0.1702	2.5205	2.8157	3.3986
7	20.70	17	2.48	41.43	27	4.61	38.76	22.77	82.34	0.1363	2.2943	2.2926	2.7564
8	21.89	18	1.28	46.34	20	1.78	40.51	-19.29	83.29	0.1726	1.7401	2.0176	2.2929
9	23.58	17	0.71	45.93	18	1.27	19.45	-23.34	99.63	0.1904	1.6144	1.8260	2.0527
10	22.13	20	0.59	38.91	20	2.10	63.23	1.53	98.62	0.2102	1.7096	1.8155	2.0549
11	24.42	17	0.96	42.97	25	5.04	49.50	17.22	110.45	0.1612	1.8583	2.1784	2.5053
12	21.76	19	0.65	37.60	21	4.48	24.62	12.30	92.69	0.1677	1.9735	2.3503	2.7162
13	22.78	18	1.56	39.22	22	7.23	19.85	-19.31	115.62	0.2148	1.8285	2.0563	2.3483

The graphical results of SVD for put engine technical states are given in Fig. 6-9.

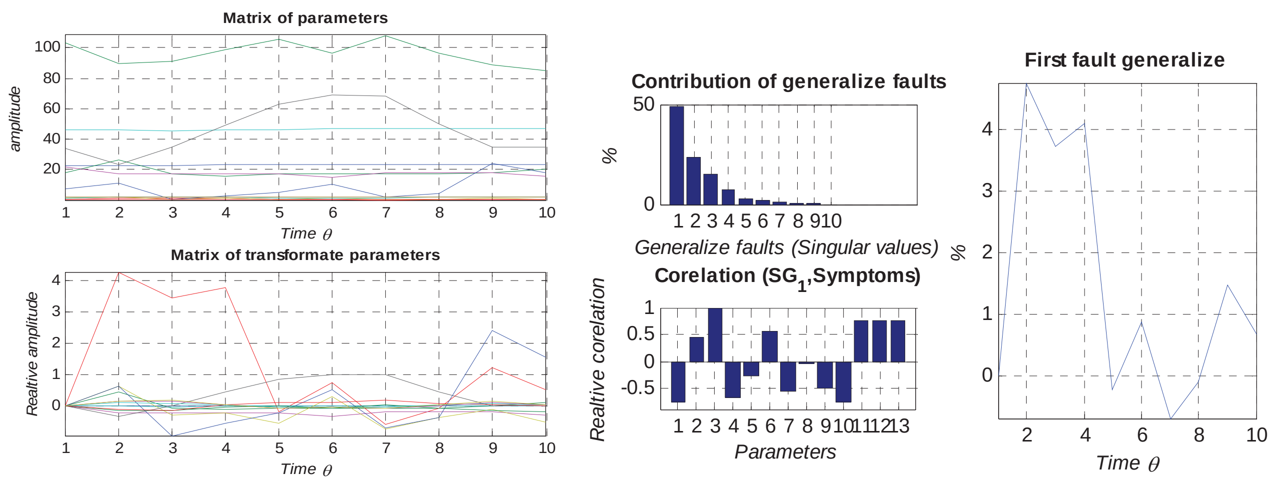

Fig. 6. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for fit engine

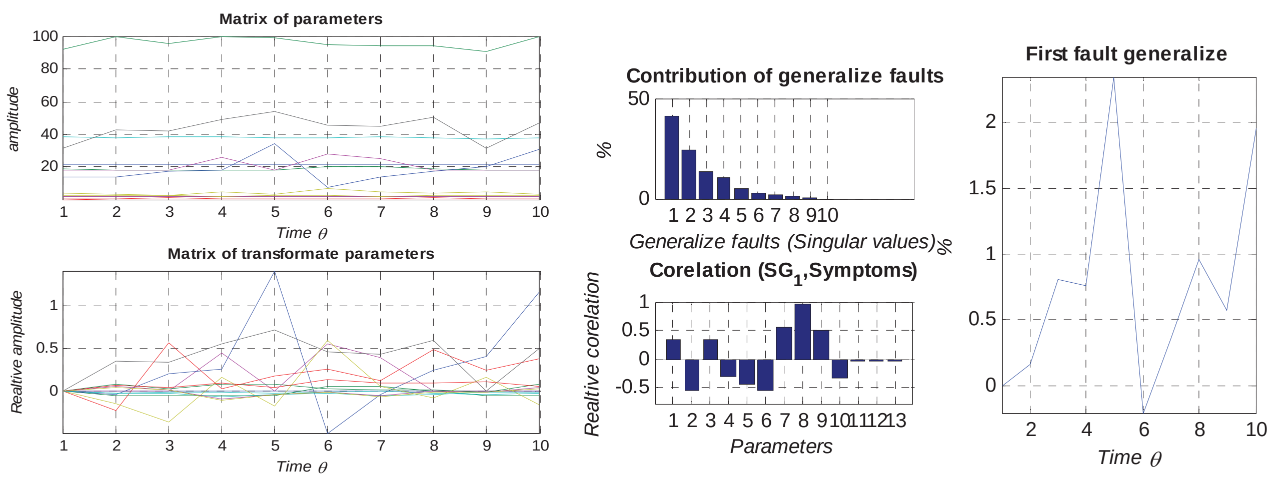

Fig. 7. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for engine with damaged injector on 4th cylinder

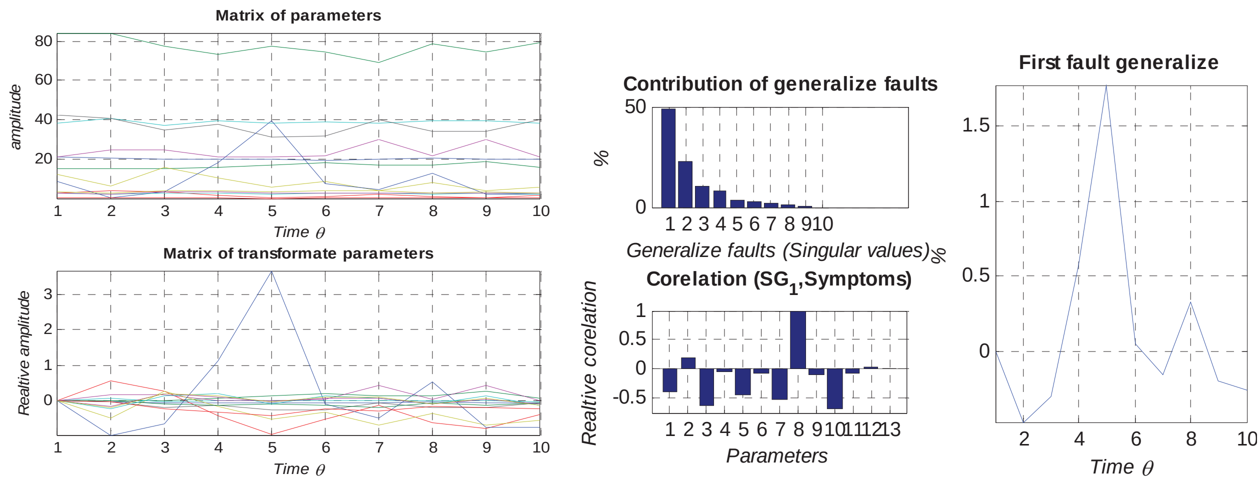

Fig. 8. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for engine with damaged spark plug on 4th cylinder

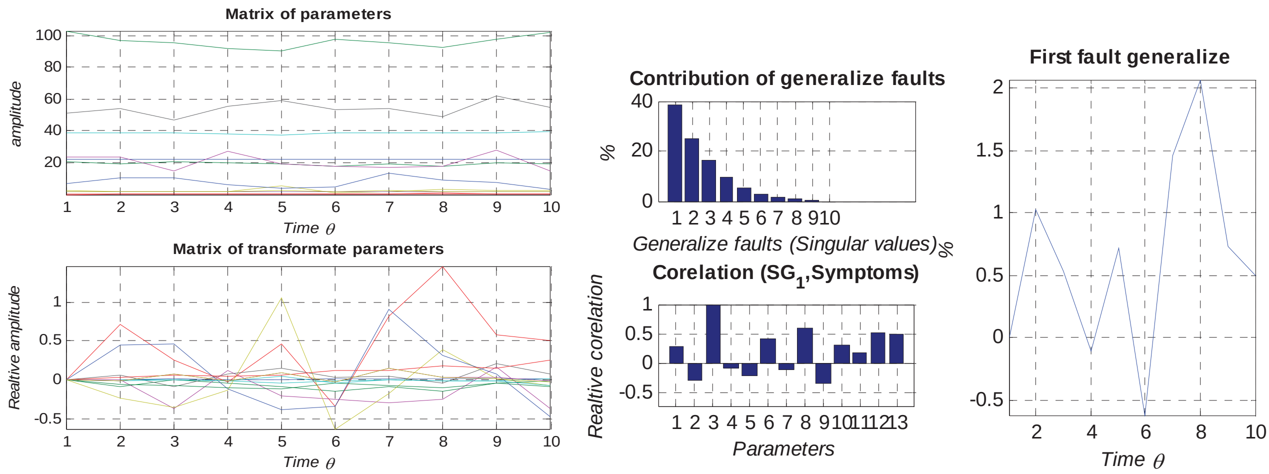

Fig. 9. Matrix of symptoms before and after transformation and graphical interpretation of first generalized damage and evolution of damage for engine with out of action 4th cylinder

In SVD procedure as a result in this paper we got a line-up of five best symptoms given in Tab. 2 that are most important in description of set technical state of combustion engine.

Tab. 2. Results of SVD method with five best symptoms for set of engine technical state

Technical state	1 symptom	2 symptom	3 symptom	4 symptom	5 symptom
1 - fit engine	ξ_1	ω_1	$A_{RMS(t)}$	β_{kurt}	C_s
2 - damaged injector on cylinder 4	H(f)L	row 1	ξ_2	H(f)	γ^2_{xy}
3 - damaged injector on cylinder 3	ξ_1	H(f)L	row 1	ω_1	H(f)
4 - damaged injector on cylinder 2	row 2	H(f)L	ω_2	ξ_2	ξ_1
5 - damaged injector on cylinder 1	ξ_1	row 1	β_{kurt}	$A_{RMS(t)}$	γ^2_{xy}
6 - damaged spark plug on cylinder 4	H(f)L	ξ_1	$A_{RMS(t)}$	H(f)	row 2
7 - damaged spark plug on cylinder 3	ξ_1	C_s	I	rząd 1	γ^2_{xy}
8 - damaged spark plug on cylinder 2	H(f)L	ξ_1	ξ_2	γ^2_{xy}	ω_1
9 - damaged spark plug on cylinder 1	H(f)L	ξ_1	β_{kurt}	C_s	I
10 - out of action cylinder 4	ξ_1	H(f)L	C_s	I	ξ_2
11 - out of action cylinder 3	ξ_2	$A_{RMS(t)}$	ω_1	H(f)L	γ^2_{xy}
12 - out of action cylinder 2	H(f)L	C_s	I	β_{kurt}	$A_{RMS(t)}$
13 - out of action cylinder 1	ξ_1	row 1	ω_1	row 2	ξ_2

Making data analysis in SVD method as a result we got the line-up of symptoms together with the proportional description of given individual symptom of combustion engine technical state. At the end of SVD procedure at figure 10 is displayed the contribution of the third Principal Components (PC_*). The PC_1 is the first principal component of analysed data, it described the direction of fault in the system and it takes 56.44 % of importance degree of the symptoms. Thanks to SVD methods we could decide which symptom given in observation matrix is the best to recognize a set of combustion engine technical state [1].

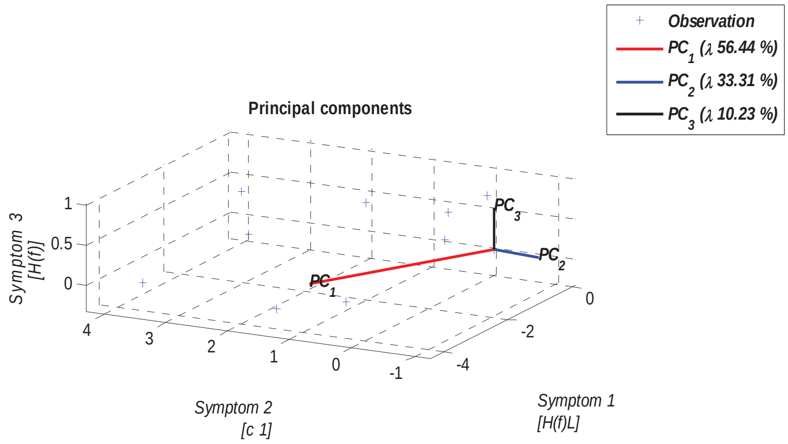

Fig. 10. Example draw of the Contribution of the Principal Components

Relationships cause - consecutive expressing quantitative relation between studied variable symptoms results in this work were qualified using the function of the multiple regression. Basis on SVD results as best symptoms in multiple regressions were given: H(f)L – imagine part of transfer function, ξ_1 – modal damping coefficient of first natural frequency, rząd1 – modal order of first natural frequency, ω_1 – first natural frequency, C_s – crest factor. The equation of multiple regression is obtained in the form:

$$y = 0.0042H(f)L - 0.4933\xi_1 + 0.5069\ \text{row1} + 1.5553\omega_1 + 6.8516\ C_s - 50.5369 \qquad (1)$$

As an example the graphical interpretation of this calculations for dependent variable ω_1 is given in Fig. 11. The red line present real data received during investigations, the blue line – estimated model for dependent variable ω_1.

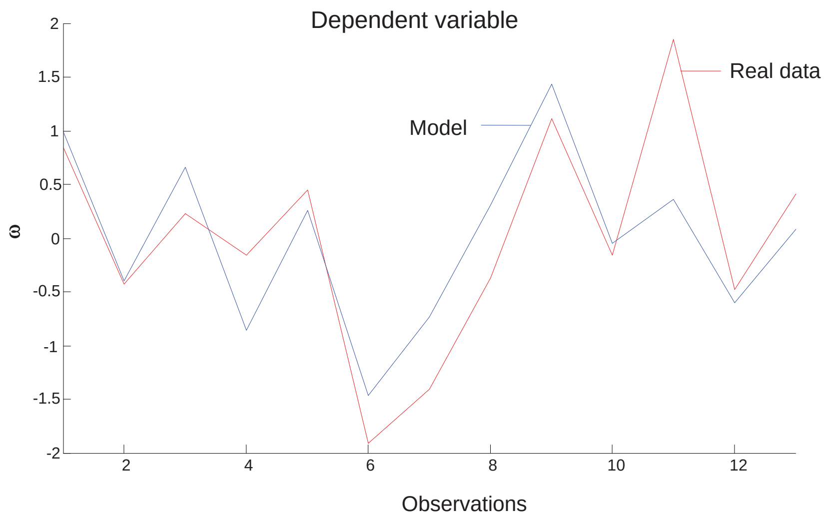

Fig. 11. The example graphical interpretation of multiple regression for dependent variable ω_1

6. Conclusion

Vibrations draw ahead in every mechanical object. Vibrations could be essential just after the crossing certain threshold marked by amplitude and the frequency of the phenomenon. They can be harmful for the object after crossing of this threshold of the vibration, or for his surroundings (e.g.: decrease of the durability of the material).

In the practice of diagnostic investigations, the utilization of vibrations makes possible the description of machine dynamic condition by set of estimators from various vibration symptoms.

Received in the experiment modal parameters and numerical estimators of vibroacoustics signal unambiguously show that the previously assumed conditions of the combustion engine's state reflect themselves in modal as well as other parameters characterising the vibrations and they are possible to be identified.

SVD methods marked most important symptom in description of engine technical state - the best symptoms were given in order: H(f)L – imagine part of transfer function, ξ_1 – modal damping coefficient of first natural frequency, rząd1 – modal order of first natural frequency, ω_1 – first natural frequency, C_s – crest factor. At the end of SVD procedure we got contribution of the third Principal Components (PC_*).

Relationships cause - consecutive expressing quantitative relation between studied variable symptoms results were qualified using the function of the multiple regression.

The introduced in this paper results of investigations are only the part of realized investigative project and they do not describe wholes of the investigative question, only chosen aspects.

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