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MULTIDIMENSIONAL ANALYSIS AND ASSESSMENT OF COMBUSTION ENGINE TECHNICAL STATE BASIS ON SVD METHOD WITH MODERN ENGINEERS SOFTWARE APPLICATION

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Abstract

The changes of vibration estimators as a result of engine maladjustment, waste, damage or failure are the main idea of vibrodiagnostic investigation. Diagnostic investigations that use of vibration to determine the technical state of combustion engines are very difficult. Only a few proposed methods could have a wider technical use in diagnostics. This paper showes the validation of research results of the use of the Singular Value Decomposition (SVD) method.

The research object is combustion engine No. 138C.2.048 with 1.4l. swept capacity, power 55 kW / 75 KM, generally applied to Fiat. It is possible to introduce generated vibration signals as well as the investigation of its adjustment influence on the combustion engine vibration signals change. Thanks to SVD methods, it is possible to decide which symptom given in the observation matrix is the best to recognize the technical state of combustion engines. The results that are introduced in this paper are only the part of realized investigative project and they do not describe wholes of the investigative question, only chosen aspects.

Keywords: *combustion engine, diagnostic inference, damage, symptoms ,SVD*

1. Introduction

The technical state of objects, machine, and vehicles can be described as a set of the all parameters values that define the given object in a given moment of time t. The time sequences of these states could be considered as the time of existence of the device. The use of technical diagnostic methods makes possible the qualification of current technical states of studied objects, machines and vehicles [5, 6].

Diagnostic researches that use vibration to determine the technical state of combustion engines are very difficult to apply and only a few proposed methods could have wider technical use in diagnostics. This paper contains application of SVD methods focused to the identification of the technical state of combustion engines. The SVD method is the appropriate tool for analysing a mapping from one vector space into another vector space, possibly with a different dimension [2,3].

The object of research was a combustion engine No. 138C.2.048 with 1.4l. swept capacity, power 55 kW / 75 KM, generally applied to Fiat. It is possible to introduce generated vibration signals as well as the research of its adjustment influence on the combustion engine vibration signals change [2,3,4]. The necessity of estimating the technical state is conditioned by the possibility of making decisions connected with object exploitation and the procedure methods to diagnose the technical state.

The present development of technical equipment and software creates new possibilities for diagnosing systems and monitoring technical condition of more folded mechanical constructions.[5,6]

2. Model of diagnostics signal generation

The research object was a combustion engine situated in the investigative laboratory of combustion engines in UTP Bydgoszcz. Based on this engine, a model of diagnostic signal generation was created during the investigations [2,3,4,5,6]. The proposed model of combustion engine diagnostic signal generation is shown on Figure 1.

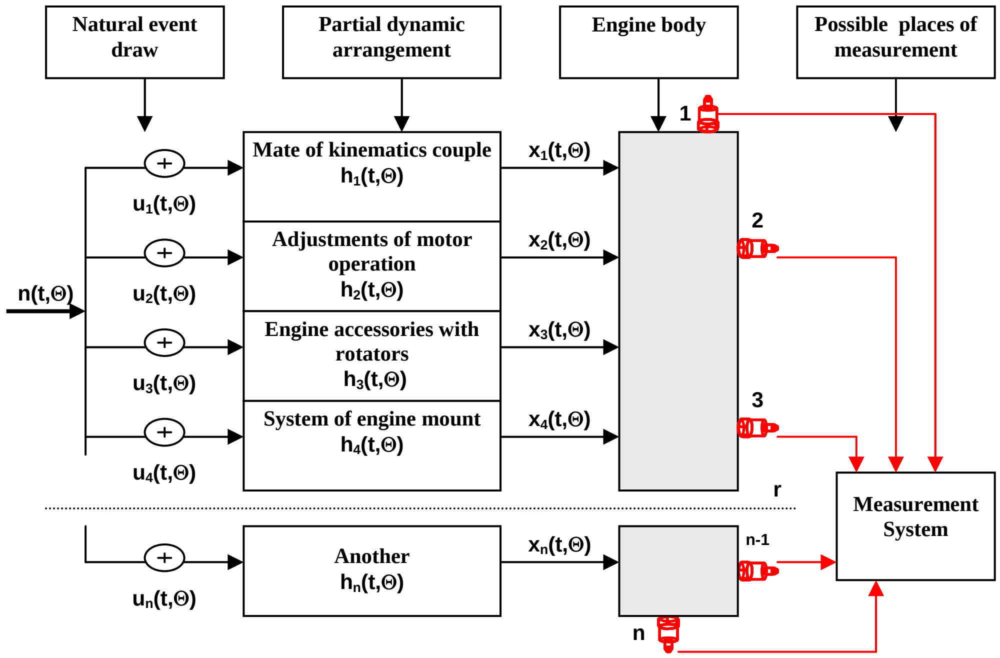

Fig.1. Combustion engine diagnostics signal generation model[4]

The received signals in any point of engine body are the sum of the answer at all elementary events un (t, Θ), outputs in individual partial dynamic arrangements with the pulse function of input hn (t, Θ). These influences after passing by proper dynamic arrangements are summed 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 [2,3,4,5,6].

Based on the Matlab environment the application diagnostics software “DM” was used for vibroacoustics signal analysis, serving to the processing and analysis of the investigative data.

This software enables the obtainment of symptoms from vibration signals and then it makes it possible to describe the technical state of the machine in matrix observation. A model of a machine in good state and another model of the same machine after certain period of usage gives an inference base about the state of the object and vibration predominant sources that allows machine modernization in the next step.

3. Singular value decomposition

The SVD method is the one of the newest diagnostic methods. It is the appropriate tool for analysing a mapping from one vector space into another vector space, possibly with a different dimension [1,6,7]. The SVD method was included in the diagnostics software “DM”, the general programming structure of the Multivariable Diagnosis application developed by the Research Group on Industrial Maintenance (GEMI), Mechanical Engineering Department, Engineering School, EAFIT University and used for result validation. The SVD method algorithm is shown in Figure 2.

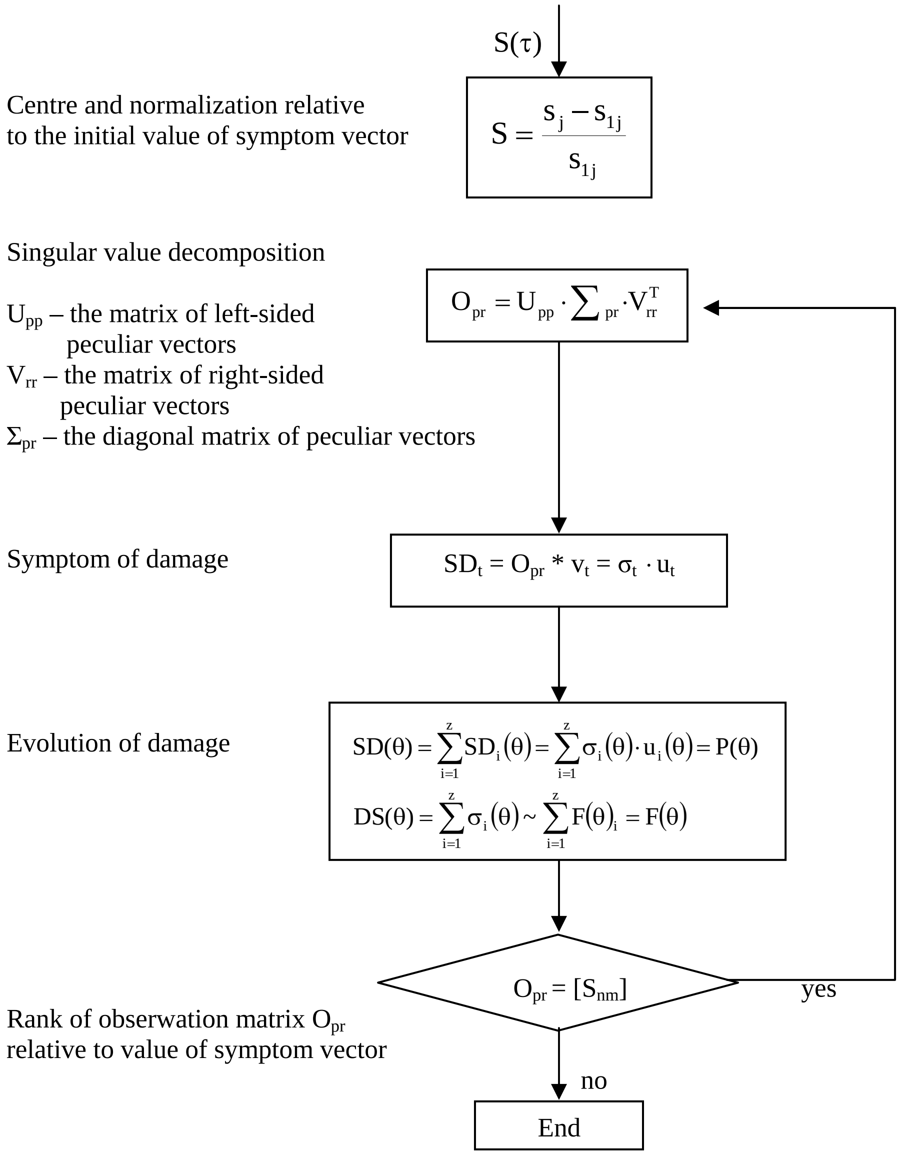

Fig.2. Singular Value Decomposition algorithm [1,6,7]

Figure 3 displays the main window of the SVD module that was used for analysis.

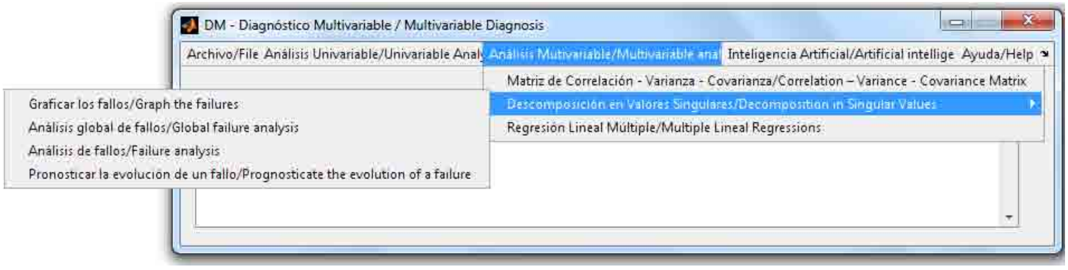

Fig.3. SVD module window

Percentage of damage in the object status description obtained in the "DM" software is shown in Figure 4. The red line marks a value of 50% failure of the principal failure.

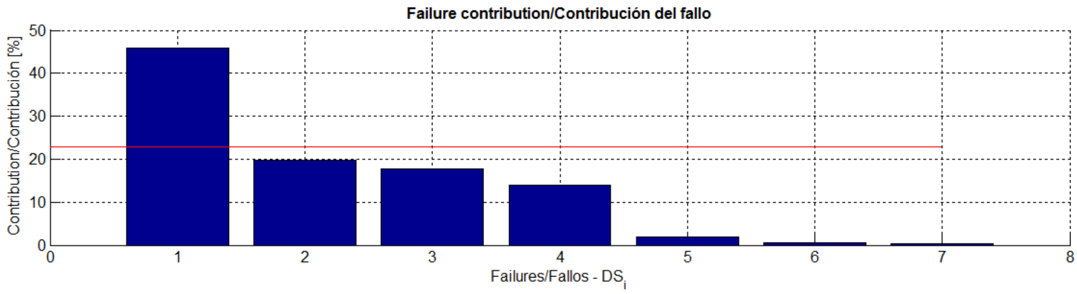

Fig. 4. Graphical interpretation of failures in object

The program allows to present graphical interpretations:

- analysis of the principal failure - Figure 5,
- reliability analysis - Figure 6.

Figure 5 contains two graphs: the first is a graphic interpretation of a generalized state of the object with the specified limit, which is determined based on the configuration parameters. The generalized state of the object is presented using the main damage to its technical state. The second graph relates the analysis of discretion areas by presenting:

- limit,
- probability of success evaluation for a good state,
- probability of unnecessary repairs allowed,
- probability of undetected fault state,
- probability of success in the evaluation of the damage.

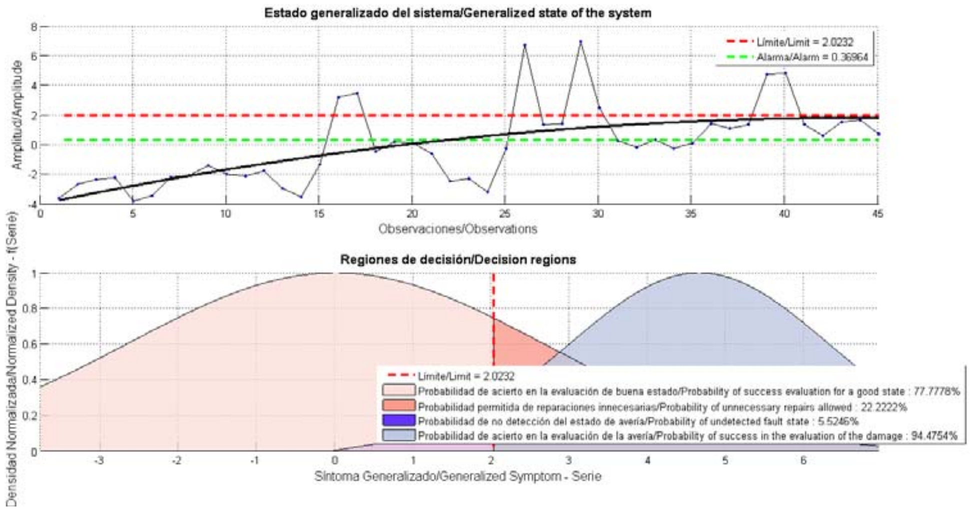

Fig. 5. Graphical interpretation analysis of the principal failure

Figure 6 shows the graphical interpretation of the reliability and damage assessment: speed development risk and its main damage, and speed development of global risk for all damages.

It also shows the histogram of the principal failure with: limits, probability of not exceeding the limit value, probability of exceeding the limit value, type of distribution together with the values of distribution parameters. The next stage of analysis is the graphical interpretation of the correlation symptoms with the selected failure as shown in Figure 7. The analysis of correlation symptoms with the selected failure allows to rank the symptoms due to the correlation coefficient value as shown in Figure 7. Figure 8 shows a graphic interpretation of the generalized object state with the specified limit and permissible value for the selected fault.

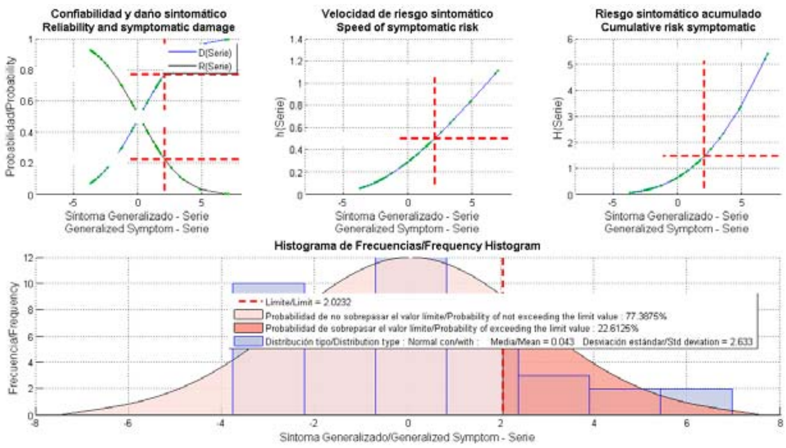

Fig. 6. Graphical interpretation reliability analysis

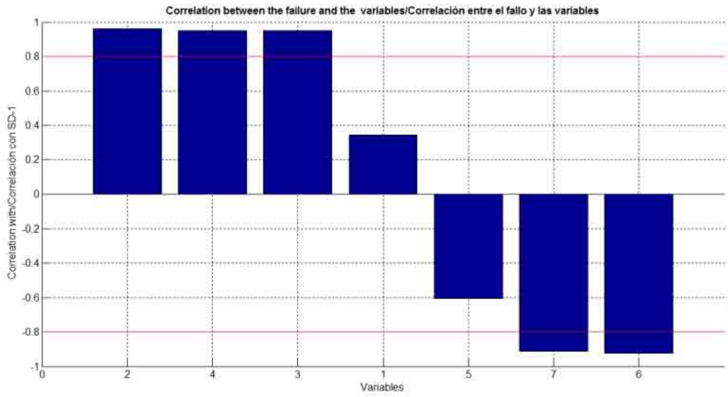

Fig. 7. Graphical interpretation correlation of symptoms with the selected failure

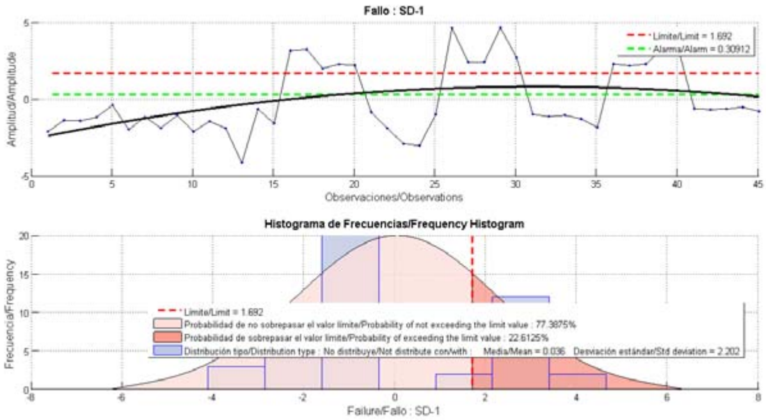

Fig. 8. Graphical interpretation analysis of the selected failure

The generalized state of the object is presented by a selected damage in relation to states of the object. Figure 8 shows the histogram of the selected fault value with:

- limits,
- probability of not exceeding the limit value,
- probability of exceeding the limit value,
- type of distribution together with the values of distribution parameters.

4. The results of research

With the object of research in the laboratory, 33 states were simulated with the damages to the spark plug and injectors on the individual cylinders of the engine and the combination of these damages. Figure 9 shows the failure to the spark plug electrodes modeled by removing the side electrode and the injector damage modeled by the release the signal cable.

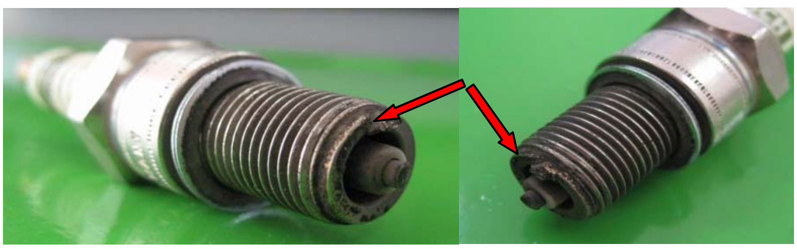

Fig. 9. Failure of removing the spark plug side electrode

During the experimental research uniform conditions in the engine are needed in order to guarantee the success of the analytical process. The research was performed under the following conditions:

- 830 r.p.m was executed measurements for the rotational speed of the engine,
- for neutral gear - temperature of the trunk of the engine carried out 71 degrees,
- the dynamic state of the engine is described 30 measuring files,
- the investigations were executed using two measuring channels for the fulfillment of the state of Fourier transformation.

The measuring track consisted of (Figure. 10) :

- two acceleration sensors ICP Model: 352C68,
- two leads series 002,
- data acquisition module VIBDAQ +.

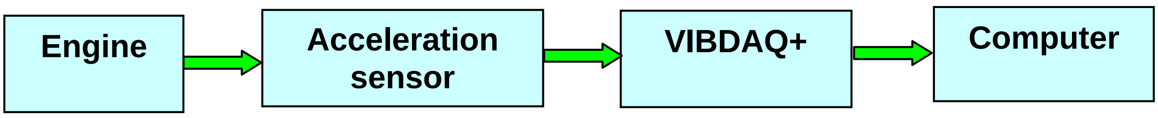

Fig. 10. Block diagram of the measuring system

The research allowed obtaining vibration signals in time response function from selected points on the engine for the simulated research object states.

The results obtained were analyzed in the software "SIBI". SIBI program was developed in the University of Technology and Life Sciences in Bydgoszcz, Faculty of Mechanical Engineering, Department of vehicles and diagnostics, and was used to validate the results of research [7].

The analysis in SIBI program allowed generating eight own measures and eight mutual measures. This measures were analysed by using the SVD method for assessing the diagnostic usefulness of the generated own and mutual measures.

5. The results of validation

Conducted researches on combustion engines depend on the delimitation of vibroacoustics measures of the engine and comparing them with measures appointed for damaged engines (eg. damaged spark plug, injector) to accomplish the assessment through operational vibroacoustic methods of how the received results influence the technical state of an engine.

The observation matrixes have eight own symptoms (χ_{ave} – Average, A_{RMS} – Root Mean Square. P_{MAX} – Pick max., σj – Standard deviation, K – Shape factor, C – Crest factor, I - Impulse factor, R_{xx} – Autocorrelation factor) and eight mutual symptoms γ(f1) – value of coherence for a first characteristic frequency 12,63 [Hz], γ(f2) – value of coherence for a second characteristic frequency 23,27 [Hz], γ(f3) – value of coherence for a third characteristic frequency 46,96 [Hz], γ(Δf) – value of the area under course of the coherence function for the range from the first to the third characteristic frequencies, $R_{xy}(\Delta f)$ – value of the area under course of the crosscorrelation function for the range from the first to the third characteristic frequencies, FFTx(Δf) – value of the area under the course of signal spectrum from the first point between the first and the third characteristic frequencies, FFTy(Δf) – value to the area under the course of signal spectrum from the second point between the first and the third characteristic frequencies $H_{xy}(\Delta f)$ – value of the area under course of the transmittance function for the range from the first to the third characteristic frequencies [2,3]. The final observation matrixes of engine performance given in Table 1 describe 8 own symptom and in the ones in Table 2 describe 8 mutual symptoms.

Table 1. The final observation matrix for own symptoms

Symptom / State	x_{ave}	A_{RMS}	P_{MAX}	σ_j	K	C	I	R_{xx}
damaged spark plug on cylinder 1	0,048	0,057	0,144	0,057	1,197	2,501	2,994	0,043
damaged spark plug on cylinder 2	0,052	0,060	0,152	0,060	1,155	2,535	2,927	0,045
damaged spark plug on cylinder 3	0,060	0,073	0,200	0,073	1,215	2,733	3,321	0,045
damaged spark plug on cylinder 4	0,013	0,014	0,028	0,014	1,131	1,971	2,229	0,043
damaged spark plug on cylinder 1 -2	0,054	0,065	0,191	0,065	1,213	2,936	3,561	0,047
damaged spark plug on cylinder 1 -4	0,076	0,090	0,218	0,090	1,195	2,412	2,882	0,045
damaged spark plug on cylinder 2-3	0,052	0,063	0,166	0,063	1,216	2,649	3,223	0,043
damaged spark plug on cylinder 3 - 4	0,038	0,046	0,107	0,046	1,193	2,342	2,794	0,043
dam. injector on cylinder 1	0,046	0,056	0,151	0,056	1,206	2,698	3,253	0,047
dam. injector on cylinder 2	0,304	0,365	0,815	0,365	1,201	2,235	2,684	0,050
dam. injector on cylinder 3	0,278	0,353	0,871	0,353	1,270	2,469	3,137	0,045
dam. injector on cylinder 4	0,279	0,354	0,912	0,354	1,271	2,575	3,272	0,047
dam. injector on cylinder 1-2	0,353	0,447	1,149	0,447	1,267	2,572	3,259	0,050
dam. injector on cylinder 1-4	0,354	0,424	0,961	0,424	1,198	2,269	2,719	0,045
dam. injector on cylinder 2-3	0,193	0,234	0,625	0,235	1,213	2,665	3,233	0,053
dam. injector on cylinder 3-4	0,235	0,317	1,081	0,318	1,352	3,405	4,605	0,055
dam. injector on cylinder 1 and spark plug on cylinder 2	0,355	0,411	0,868	0,411	1,160	2,111	2,449	0,045
dam. injector on cylinder 1 and spark plug on cylinder 3	0,352	0,403	0,833	0,403	1,146	2,069	2,371	0,047
dam. injector on cylinder 1 and spark plug on cylinder 4	0,376	0,432	0,829	0,433	1,149	1,916	2,201	0,045
dam. injector on cylinder 2 and spark plug on cylinder 1	0,273	0,319	0,700	0,319	1,169	2,193	2,563	0,040
dam. injector on cylinder 2 and spark plug on cylinder 3	0,188	0,215	0,619	0,216	1,144	2,874	3,286	0,050
dam. injector on cylinder 2 and spark plug on cylinder 4	0,272	0,311	0,718	0,311	1,142	2,311	2,639	0,050
damaged injector on cylinder 3 and spark plug on cylinder 1	0,103	0,133	0,431	0,133	1,292	3,234	4,177	0,018
dam. injector on cylinder 3 and spark plug on cylinder 2	0,347	0,398	0,889	0,399	1,146	2,231	2,558	0,047
dam. injector on cylinder 3 and spark plug on cylinder 4	0,188	0,214	0,539	0,214	1,136	2,518	2,861	0,053
dam. injector on cylinder 4 and spark plug on cylinder 1	0,348	0,400	0,827	0,400	1,147	2,069	2,373	0,045
dam. injector on cylinder 4 and spark plug on cylinder 2	0,359	0,413	0,868	0,413	1,152	2,101	2,420	0,045
dam. injector on cylinder 4 and spark plug on cylinder 3	0,223	0,252	0,551	0,252	1,131	2,190	2,477	0,050
dam. injector on cylinder 1 and spark plug on cylinder 1	0,361	0,412	0,851	0,412	1,141	2,067	2,357	0,047
dam. injector on cylinder 2 and spark plug on cylinder 2	0,152	0,182	0,509	0,182	1,197	2,799	3,351	0,047
dam. injector on cylinder 3 and spark plug on cylinder 3	0,082	0,102	0,300	0,102	1,232	2,955	3,639	0,045
dam. injector on cylinder 4 and spark plug on cylinder 4	0,050	0,064	0,220	0,064	1,275	3,448	4,394	0,045

Table 2. The final observation matrix for mutual symptoms

Symptom / State	$\gamma(f_1)$	$\gamma(f_2)$	$\gamma(f_3)$	$\gamma(\Delta f)$	$R_{xy}(\Delta f$	$FFT_x(\Delta f$	$FFT_y(\Delta f$	$H_{xy}(\Delta f)$
damaged spark plug on cylinder 1	0,439	0,982	0,691	7,576	12,402	0,007	0,007	16,680
damaged spark plug on cylinder 2	0,797	0,987	0,308	6,167	18,817	0,006	0,027	23,493
damaged spark plug on cylinder 3	0,893	0,972	0,125	6,573	19,924	0,007	0,008	15,729
damaged spark plug on cylinder 4	0,576	0,906	0,207	5,043	1,495	0,003	0,005	23,397
damaged spark plug on cylinder 1 -2	0,292	0,989	0,339	4,416	7,067	0,035	0,041	22,863
damaged spark plug on cylinder 1 -4	0,335	0,987	0,961	5,784	4,064	0,044	0,047	20,212
damaged spark plug on cylinder 2-3	0,947	0,992	0,852	7,443	5,886	0,060	0,072	21,766
damaged spark plug on cylinder 3 - 4	0,746	0,975	0,328	4,924	6,335	0,044	0,057	20,140
dam. injector on cylinder 1	0,606	0,123	0,058	4,498	0,533	0,012	0,104	16,897
dam. injector on cylinder 2	0,914	0,986	0,143	5,292	0,467	0,013	0,057	15,316
dam. injector on cylinder 3	0,969	0,989	0,905	4,800	0,357	0,011	0,049	13,977
dam. injector on cylinder 4	0,970	0,993	0,711	4,406	0,304	0,010	0,056	23,070
dam. injector on cylinder 1-2	0,813	0,980	0,966	9,941	5,758	0,418	0,132	6,060
dam. injector on cylinder 1-4	0,990	0,998	0,543	10,458	8,054	0,286	0,084	5,796
dam. injector on cylinder 2-3	0,957	0,931	0,513	10,143	10,479	0,265	0,056	4,475
dam. injector on cylinder 3-4	0,998	0,941	0,909	7,798	6,570	0,386	0,101	4,204
dam. injector on cylinder 1 and spark plug on cylinder 2	0,623	0,993	0,497	7,027	9,149	0,273	0,208	21,748
dam. injector on cylinder 1 and spark plug on cylinder 3	0,699	0,990	0,870	3,771	0,940	0,197	0,130	13,359
dam. injector on cylinder 1 and spark plug on cylinder 4	0,773	0,995	0,943	4,130	0,825	0,254	0,139	8,254
dam. injector on cylinder 2 and spark plug on cylinder 1	0,981	0,888	0,851	4,374	0,847	0,253	0,178	13,147

dam. injector on cylinder 2 and spark plug on cylinder 3	**0,929**	**0,707**	**0,819**	**6,516**	**15,671**	**0,203**	**0,165**	**15,254**
dam. injector on cylinder 2 and spark plug on cylinder 4	**0,845**	**0,848**	**0,843**	**5,497**	**15,647**	**0,183**	**0,160**	**14,334**
damaged injector on cylinder 3 and spark plug on cylinder 1	**0,880**	**0,984**	**0,619**	**4,538**	**9,495**	**0,250**	**0,173**	**13,718**
dam. injector on cylinder 3 and spark plug on cylinder 2	**0,754**	**0,985**	**0,347**	**15,695**	**17,729**	**0,189**	**0,192**	**26,972**
dam. injector on cylinder 3 and spark plug on cylinder 4	**0,938**	**0,344**	**0,771**	**7,616**	**14,901**	**0,169**	**0,127**	**15,253**
dam. injector on cylinder 4 and spark plug on cylinder 1	**0,808**	**0,996**	**0,226**	**5,605**	**13,350**	**0,195**	**0,194**	**17,487**
dam. injector on cylinder 4 and spark plug on cylinder 2	**0,859**	**0,997**	**0,487**	**8,947**	**15,324**	**0,210**	**0,193**	**23,706**
dam. injector on cylinder 4 and spark plug on cylinder 3	**0,792**	**0,628**	**0,850**	**7,746**	**8,431**	**0,172**	**0,151**	**17,617**
dam. injector on cylinder 1 and spark plug on cylinder 1	**0,613**	**0,976**	**0,922**	**5,342**	**7,884**	**0,180**	**0,140**	**12,710**
dam. injector on cylinder 2 and spark plug on cylinder 2	**0,964**	**0,918**	**0,533**	**6,337**	**10,451**	**0,096**	**0,061**	**10,632**
dam. injector on cylinder 3 and spark plug on cylinder 3	**0,974**	**0,990**	**0,907**	**5,689**	**4,026**	**0,109**	**0,078**	**9,978**
dam. injector on cylinder 4 and spark plug on cylinder 4	**0,992**	**0,993**	**0,883**	**5,518**	**3,455**	**0,091**	**0,092**	**10,789**

For the purposes of analysis the technical states were classified into 3 groups:

- first group - damage spark plug,
- second group - damage the injector,
- third group - damage the injector and spark plug.

The following illustrations shows the graphical interpretation of own symptoms revealed through the analysis research results with the SVD method (failures in the engine, the histogram of values the principal failure, the correlation between of individual symptoms of root damage). For the first group of states:

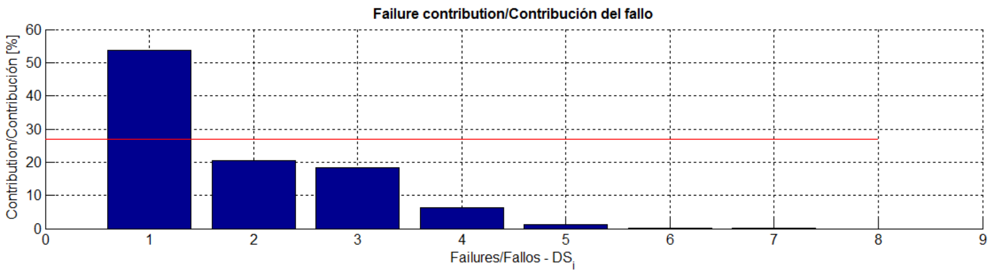

Fig. 11. Graphical interpretation of the failures in objects for the first group of states

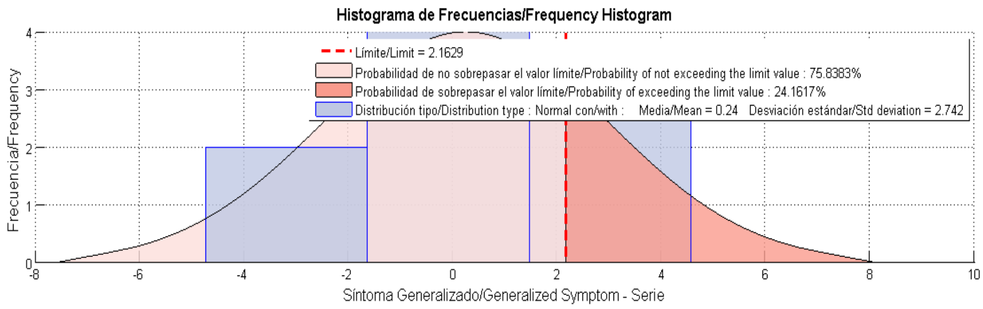

Fig. 12. Graphical interpretation histogram value of the main failure for the first group of states

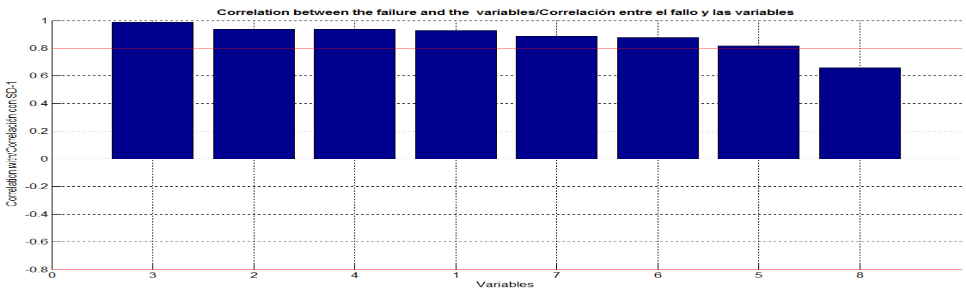

Fig. 13. Graphical interpretation of the correlation of own symptoms with the main failure for the first group of states

For the second group of states:

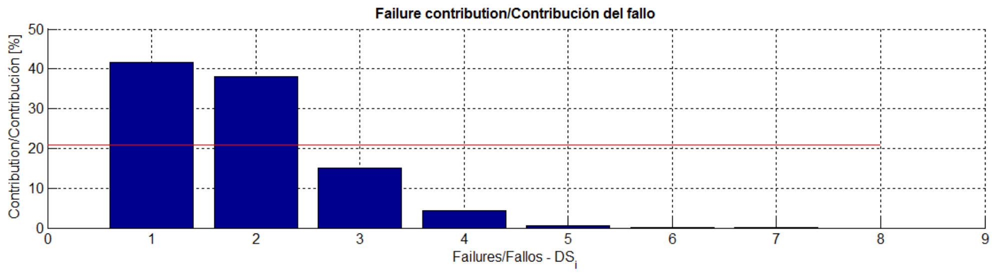

Fig. 14. Graphical interpretation of the failures in objects for the second group of states

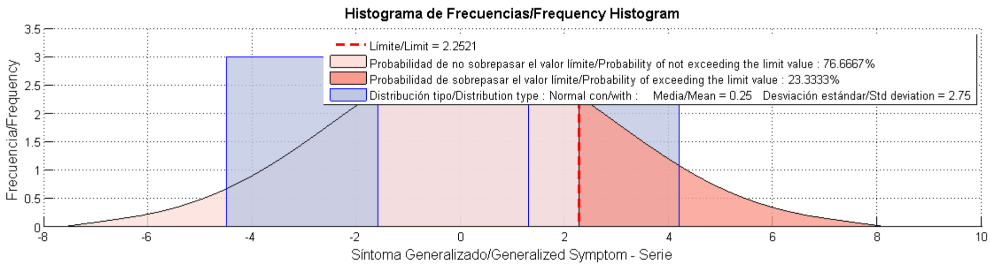

Fig. 15. Graphical interpretation histogram value of main failure for the second group of states

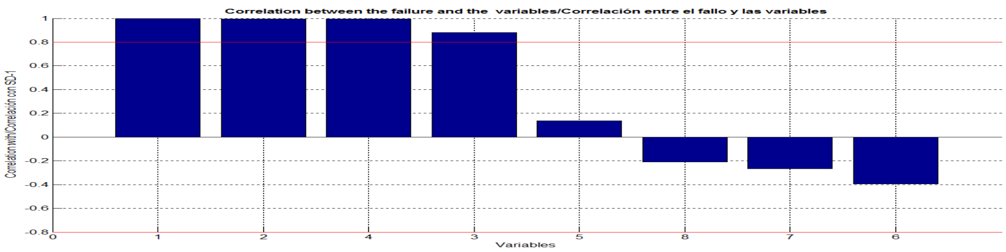

Fig. 16. Graphical interpretation of the correlation of own symptoms with the main failure for the second group of states

For the third group of states:

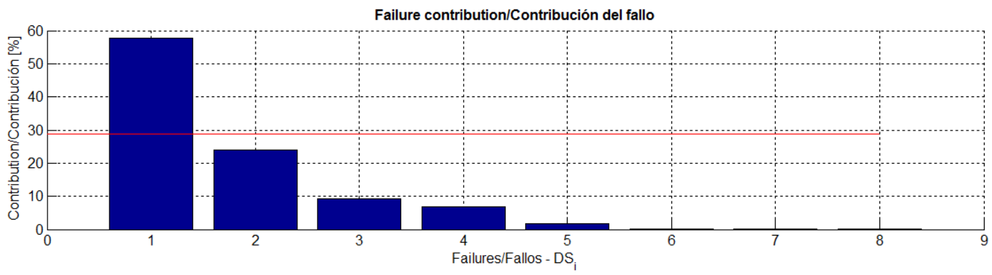

Fig. 17. Graphical interpretation of the failures in object for the third group of states

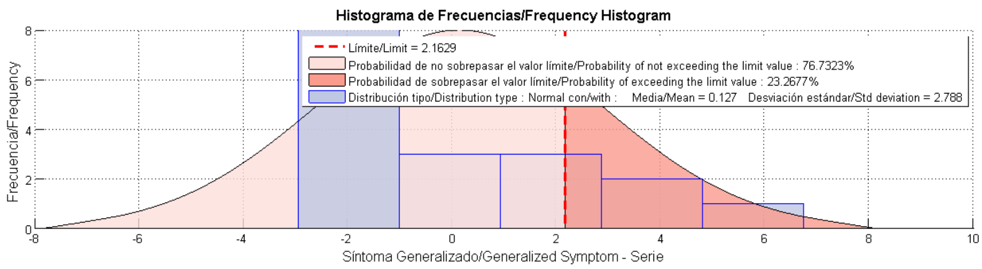

Fig. 18. Graphical interpretation histogram value of main failure for the third group of states

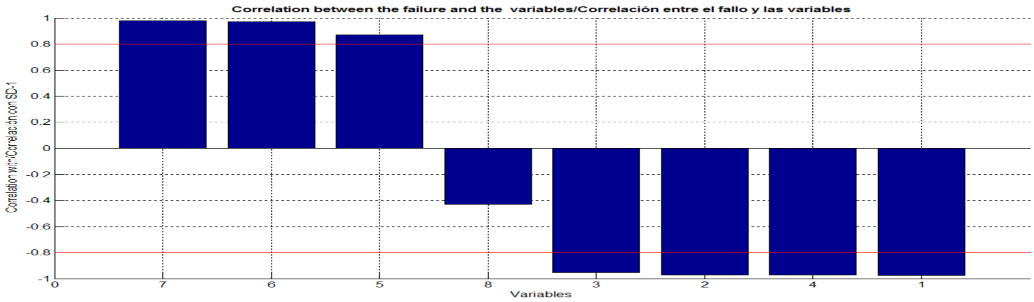

Fig. 19. Graphical interpretation of the correlation of own symptoms with the main failure for the third group of states

The following illustrations shows the graphical interpretation of mutual symptoms revealed through the analysis research results with the SVD method (failures in the engine, the histogram of values the principal failure, the correlation between of individual symptoms of root damage).

For the first group of states:

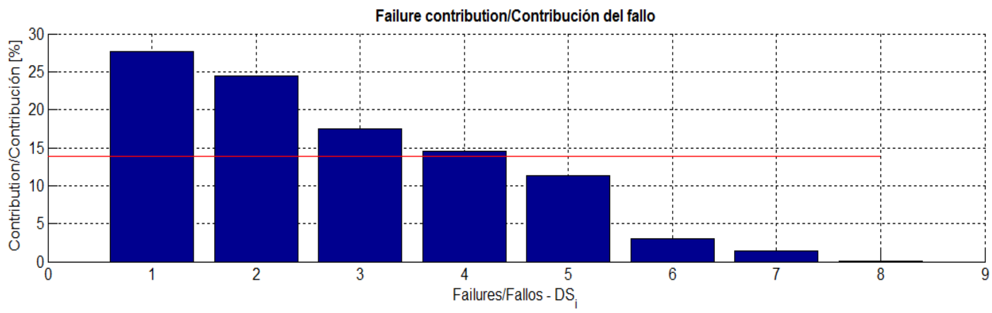

Fig. 20. Graphical interpretation the failures in object for the first group of states

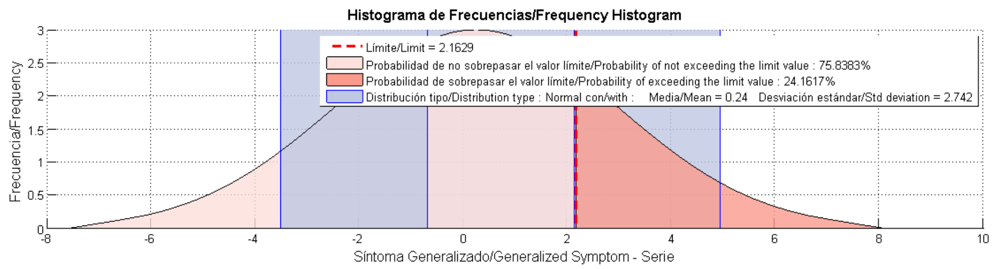

Fig. 21. Graphical interpretation histogram value of main failure for the first group of states

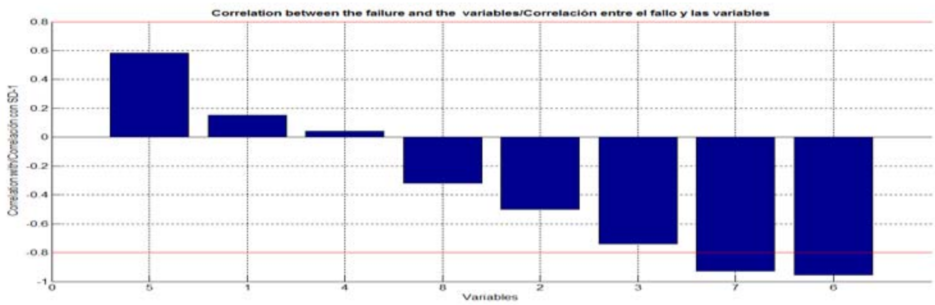

Fig. 22. Graphical interpretation correlation of symptoms with the main failure for the first group of states

For the second group of states:

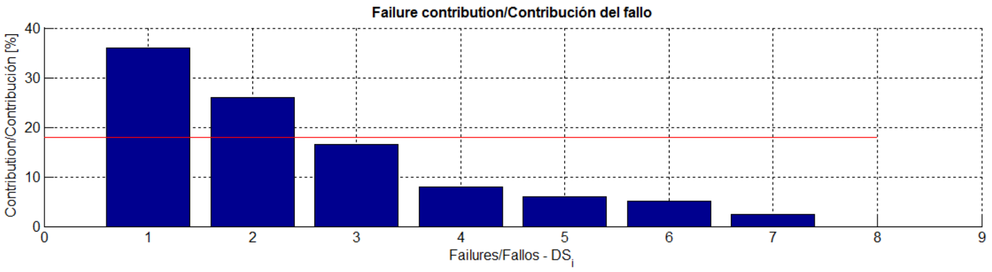

Fig. 23. Graphical interpretation the failures in object for the second group of states

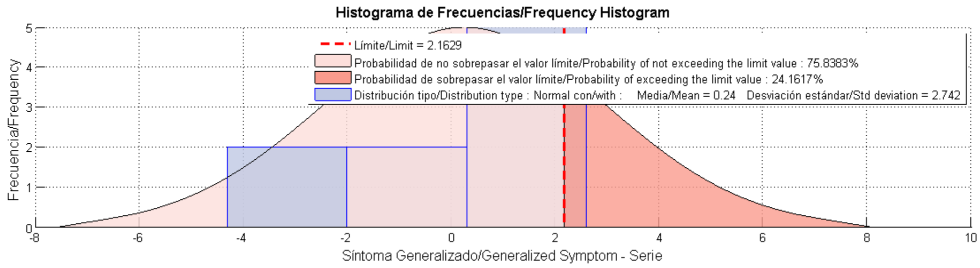

Fig. 24. Graphical interpretation histogram value of main failure for the second group of states

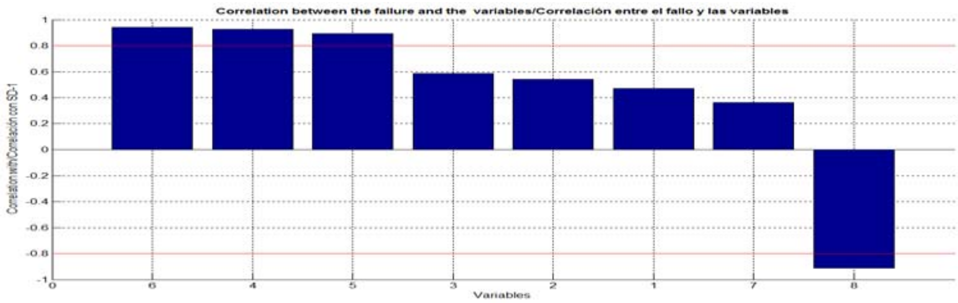

Fig. 25. Graphical interpretation correlation of own symptoms with the main failure for the second group of state

For the third group of states:

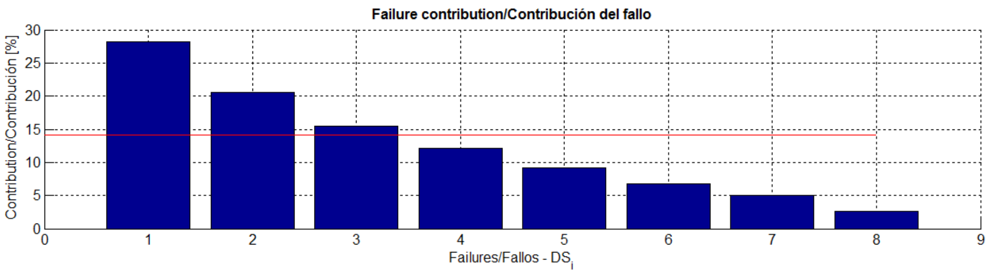

Fig. 26. Graphical interpretation the failures in object for the third group of states

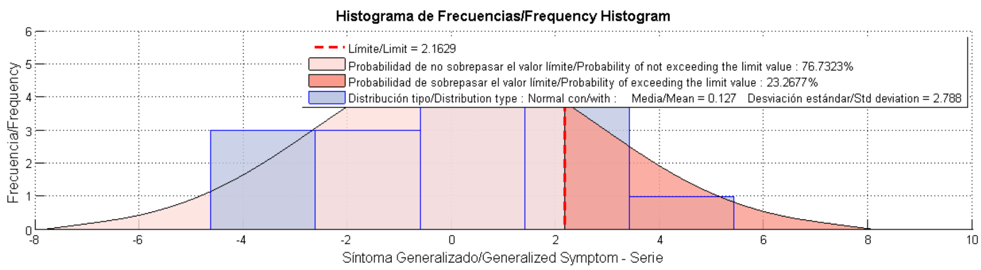

Fig. 27. Graphical interpretation histogram value of main failure for the third group of state

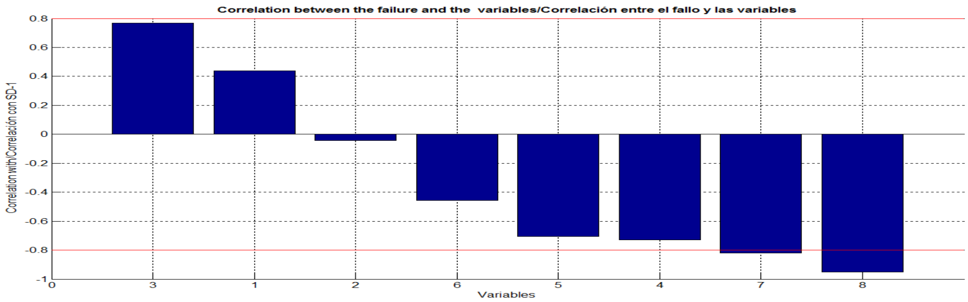

Fig. 28. Graphical interpretation correlation of own symptoms with the main failure for the third group of state

The result of the analysis with SVD method obtained five own and five mutual symptoms that best describe the states of the internal combustion engine. The summary of selected symptoms are presented in Table 3.

Table 3. Results of SVD method with five own and mutual symptoms that best describe the states of the internal combustion engine

GROUP STATE	OWN SYMPTOMS				
First group	P_{MAX}	A_{RMS}	σ_j	x_{ave}	I
Second group	x_{ave}	A_{RMS}	σ_j	P_{MAX}	K
Third group	I	C	K	A_{RMS}	P_{MAX}
GROUP STATE	MUTUAL SYMPTOMS				
First group	$R_{xy}(\Delta f)$	$\gamma(f_1)$	$\gamma(\Delta f)$	$FFT_x(\Delta f)$	$\gamma(f_2)$
Second group	$FFT_x(\Delta f)$	$\gamma(\Delta f)$	$R_{xy}(\Delta f)$	$\gamma(f_3)$	$\gamma(f_2)$
Third group	$\gamma(f_3)$	$\gamma(f_1)$	$\gamma(f_2)$	$FFT_x(\Delta f)$	$R_{xy}(\Delta f)$

The analysis indicates the need to assess the technical state of using mutual symptoms. The SVD method indicated that mutual symptoms have greater stability to describe the technical state of the engine. Own symptoms play an advisory role, based on which it is not possible to make a clear description of mutual symptoms.

The next step of the quantitative and qualitative analysis description of participation symptoms in the assessment of technical state is modelling engine cause - effect relationships using multiple regression [7]. Modelling makes it possible to identify the relationship between symptoms.

SVD method allows the selection symptoms for modelling because it is multidimensionality.

5. Conclusion

In modern technical systems, taking into account technological progress and the great opportunities available for acquisition and signal processing makes it possible to obtain a lot of information from the signals recorded in different parts of the machine. This information must be processed and interpreted in most cases by staff to determine the status of the machine. In the practice of diagnostic investigations, the utilization of vibrations allows describing the dynamic condition of the machine by set of estimators from various vibration symptoms. Received symptoms in the vibroacoustics signal experiment unambiguously show the different technical state of the combustion engine. The diagnosis of complex systems based on a multidimensional analysis, gives the opportunity to evaluate the relationship between symptoms whose values have changed as a result of damage. SVD methods marked the most important symptoms for describing the technical state of engines- the best symptoms are: γ(f1) – value of coherence for a first characteristic frequency 12,63 [Hz], γ(f2) – value of coherence for a second characteristic frequency 23,27 [Hz], γ(f3) – value of coherence for a third characteristic frequency 46,96 [Hz], γ(Δf) – value of the area under course of the coherence function for the range from the first to the third characteristic frequencies). Among the possible techniques that use the relationship between symptoms is the SVD method. SVD method can be used to eliminate symptoms that do not provide important information about the state of the machine that is being tested. This method allows to generate a new set of independent symptoms that may be useful for the diagnosis of technical systems. This is why the SVD method is useful in many applications, such as statistics, control theory, compression, processing a lot of information and evaluation of technical state of complex objects. This paper is a part of investigative project **WND-POIG.01.03.01-00-212/09**

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