

Three modes of contradiction matrix in vibration condition monitoring of machines

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Summary

Up to now machine condition monitoring has not been seriously approached by TRIZ² practitioners, and the knowledge of TRIZ methodology has not been applied there. However, there is one introductory paper of present author posted on Diagnostic Congress in Cracow [Cempel 12]. But it seems to be a need to make such an approach from different sides in order to see if some new knowledge and technology will emerge. In doing this we need at first to define the ideal final result (**IFR**). As a next we need a set of engineering parameters to describe the problems of vibration condition monitoring (VCM) in terms of TRIZ parameters, and a set of inventive principles possible to apply on the way to IFR. This means we should present the machine VCM problem by means of contradiction matrix of TRIZ. When specifying the problem parameters and inventive principles, one should use analogy and metaphorical thinking, which by definition is not exact but fuzzy, and leads sometimes to unexpected results and outcomes. The paper undertakes this important applicational problem and brings some new insight into system and machine VCM problems. It follows from the paper that one can use one set of inventive principles to solve specified contradiction of VCM problem, and also another set of inventive principles to enhance obtained solution.

Key words, *vibration condition monitoring, TRIZ, ideal final result -IFR, engineering parameters, contradiction matrix, inventive principles.*

1. Introduction

During the machine operation (*life*) its condition deteriorates, what can be observed as evolving faults typical to a given machine type. Condition monitoring of machines (*systems*) is the science and technology for the assessment of condition by means of observation of machine phenomenal field – mostly vibration, where symptom of condition can be captured and measured and condition inferred (*see for example [Collacott 77]*). This means that we are trying to determine the fault space of the machine, its dimensionality and fault advancement, by some observed symptoms of condition, creating in this way machine **observation space**. The primary concept of machine condition, the **fault space** of a system (*machine*) can be defined by some prior knowledge taken from the experience with the other running machines, and the same concerns with symptom observation space.

Fault space of every machine is multidimensional, for example we have usually unbalance, misalignment, bearing faults. The similar multidimensionality is needed in our observation space, and as usually it needs some redundancy too. This is because the symptoms which we measure are usually interdependent, and by means of some symptom processing procedures, we can determine the dimensionality of observation space and so called generalized fault symptoms (*see for example [Tabaszewski, Cempel 10]*). These results enable us to infer on the machine fault space and intensity (*advancement*) of the main faults which evolve during the machine operation in its lifetime θ .

Condition monitoring is mostly applied to critical machinery, where by special monitoring system we can observe thermo and vibroacoustical phenomena carrying needed information on system condition. This means that by some measurements of these phenomena and respective signal processing we can create symptom of condition, like for example the velocity vibration amplitude measured at the bearing pedestal, or some other location of machine casing. What is important here that by means of special signal and symptom processing procedures, one can determine the type of fault, and its advancement. We can calculate also the symptom limit value S_l and symptom reliability $R(S)$, which is analogous to lifetime reliability $R(\theta)$ of the machine [Cempel 91].

In summary, one can say, that having some experience on machine life and running, and a prior knowledge concerning processing of received signals and measured symptoms of condition, we can assess the current machine condition and make forecasting of future condition with a high probability of success. This concerns also the fault type and a date of stopping machine for the

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² TRIZ= Russian acronym for Inventive Problem Solving System, created by G. Altshuller ca 50y ago.

renewal, etc. But up to now machine condition monitoring has not been approached seriously by TRIZ³ practitioners, and the knowledge of TRIZ methodology has not been applied there. Some introductory thinking to connect TRIZ with VCM problems has been already made [Skoryna], [Cempel 12]. And this paper, as a prolongation of previous, deals mainly with determination of a set of contradictions in vibration condition monitoring. These contradictions can be resolved next by set of inventive principles defined by TRIZ, approaching in this way ideal final result - **IFR**. But it seems to that inventive principles can be used also for the enhancement and betterment of obtained solution of VCM problem. Such is the main purpose of the paper.

2. The ideal final result in diagnostics of machinery

This type of thinking, looking explicit for ideal final result (**IFR**) coming from TRIZ methodology is new in machine condition monitoring (MCM). Hence let us imagine, what we really need here? Self repairing machine, like in military aircrafts, it seems to be too early. But if we integrate advanced symptom CM system with the machine and with proper signal and symptom processing, our resultant **IFR** can be as follows.

The machine itself is signaling approaching work stoppage, a type of fault, and a time, when it should be handover for renewal.

In order to do this one can imagine that integrated CM system should contain: thermal, acoustic, and vibration transducers with signal preprocessing, in order to form several symptoms of condition $S_i(\theta)$, $n=1,2,..n$. In this way multidimensional machine observation space is created, which is monitored continuously, and symptom readings are taken with the proper life time distance $\Delta\theta_j$, depending on the machine type and the wearing intensity [Cempel 91]. These successive symptom readings by VCM system, are forming so called symptom observation matrix (SOM), with columns presenting different type of monitored symptoms⁴ and rows giving the values of discrete symptoms readings at θ_j , $j=1,..m$. This rectangular matrix, with the growing number of rows, is the only source of information concerning the overall condition of the machine. One can extract this information applying singular value decomposition (SVD) [Cempel 07], or principal component analysis (PCA) [Tumer 02]. The special processing of SOM can give also symptom **limit value** S_l which may control the stopping of the machine, and also symptom reliability $R(S)$ which assesses the potency of residual running or functional ability of the machine [Cempel91].

Knowing this one can say that by proper SOM processing method, SVD for example, we are **projecting** the observation space on the fault space of the machine. In this way we are gathering wanted information concerning fault evolution, their types and their advancement.

As many symptoms of condition depends on the current machine load, controlled by a production process, special processing of SOM should be elaborated and taken into account [Cempel 11], [Cempel,Tabaszewski 10], which gives the results being almost immune against the load variability and other disturbances as well. When these precaution and preparations are successfully applied into the processing of signals, processing of symptom readings in SOM, the defined above IFR of TRIZ seems to be under the reach of contemporary technology of MCM and signal / symptom processing and computation.

3. The contradiction subset and matrix for machine vibration condition monitoring -VCM

One of the main Altshuller ideas in TRIZ is the **contradiction matrix** enabling to resolve contradictions by means of the use of inventive principles and other TRIZ tools [Savransky 02], [Orlov 06], [Nakagawa 06], [Mann 04]. The space and the dimensionality of contradiction matrix is defined by a specific set of engineering parameters describing every innovative problem in given area of engineering. We will take into account at first 39 engineering parameters used in

⁴ From one broadband vibration signal, received at some location of the machine body, several symptoms of condition can be created and measured during machine operation.

mechanical engineering in its broad meaning, as described in many books and articles concerning TRIZ methodology. Our introductory analysis [Skoryna 10] connected with a broad interpretation convinces us, that out of these 39 parameters the ten or even less engineering parameters will be enough to describe VCM problem properly.

Special comment should be given to choose two newly introduced parameters; the fault space and observation space, the most important entities in VCM. In a normal interpretation of parameters No 3 and 4 of TRIZ, they describe the length of stationary and moving parts of the machine. The length itself is some dimensional coordinate, and when the dimension is taken with plural we can have **fault space** of the machine (*Dimension-I*), the primary entity in condition monitoring with the coordinates being the different faults evolving in a machine during its life θ .

The same reasoning lead us to the second parameter **Dimension-II**, which symbolizes **observation space** of phenomenal field of working machine, with coordinates being the measured symptoms of condition $S_i(\theta)$, $i=1, \dots, n$. The rest of engineering parameters of VCM are as follows; symptom reliability, accuracy in detection measurement and processing, information loss, energy loss, durability or lifetime, ease of use or running, repairability (*maintainability*), and the temperature of machine critical parts and /or casing. Considering the information carried by thermo field of the machine one can notice it is multidimensional spatial information source. While thinking about energy loss as an engineering parameter one can see it is only one dimensional and in many practical cases its dynamics is very low. Hence, we can drop from consideration this engineering parameter and concentrate our diagnostic problem around **9 dimensional** descriptions of many diagnostic problems.

However, in some special cases of working machinery, especially with **variable** load and other working conditions, like rotational speed and the like, we must introduce additional descriptive parameter, which can be interpreted like the **speed** of change, variable load, or better the **variability** of working conditions. Narrowly thinking it may be associated with parameter 9 of TRIZ, but it is far more than this, hence we will introduce additional parameter **40, as variability** of working conditions. Hence, in the case of unstable working condition we will have **10** engineering parameters in our VCM problem, and contradiction matrix as well.

Having chosen all important descriptive parameters of machine condition monitoring let us think creatively how to describe inherent contradictions connected with these parameters, which can be encountered in the improvements of machinery diagnostics problems. Some important contradictions are described below in Table 1a.

Table 1a. The list of main contradictions found in VCM problems

1	The variable load of machine influences negatively the accuracy of signal detection, processing and information processing
2	The variable speed and load can increase the information loss in a diagnostic system
3	The variable load and speed are against the ease of use of a machine
4	The high working temperature lowers the durability or residual lifetime of the machine elements
5	The high working temperature is also against accuracy of measurements
6	The high working temperature may induce additional faults and/or increase the intensity of present faults
7	The dimension of the observation space (<i>number of symptoms</i>) makes troubles in calculation of symptom reliability
8	The dimension of the observation space (<i>number of symptoms</i>) is against accuracy of condition estimation
9	The dimension of the fault space (<i>number of faults</i>) is against repairability , it may prolong the downtime of the machine
10	The dimension of the fault space (<i>number of faults</i>) is usually against accuracy of signal detection, information processing, and symptom processing as well
11	The high dimension of the fault space makes trouble in reliability calculation (assessment)
12	The higher the dimension of fault space , more sophisticated observation space should be
13	The loss of information during the machine operation is against its repairability , because we may not know exactly, what is going on in a machine, when to stop it and what to repair
14	Improper choice of observation space can increase information loss

Tab.1b Primary contradiction matrix (see 14 V) of TRIZ for machine vibration condition monitoring (VCM) area

Directions of contrad. summation ↓ →	Fault space (dimens.I)	Observation space (dimens.II)	Reliability (symptom reliability)	Accuracy; (detection / measur./ processing)	Variable working conditions (speed,...)	Informa- tion loss	Durability/ lifetime	Ease of use/ running	Repair- ability, mainten.	Tempe- rature	Sum of contrad-ns
Fault space (dimens.I)	X →	V	V	V					V	V	5
Observation space (dimens.II)		X →	V	V		V					4
Reliability (symptom reliabil.)			X →								2
Accuracy; (detect./measur. /processing)				X →	V					V	4
Variable working conditions (speed,..)					X →	V		V			3
Information loss						X →			V		3
Durability/ lifetime							X →			V	1
Ease of use /running								X →			1
Repairability, maintenance									X →		2
Temperature										X →	3

Tab. 2 Inventive principles (No) able to solve and enhance VCM problems in comparison to primary contradictions (V) of table 1a.

Improving Directions of ↓ contrad. summ. ↓	Fault space (dimens.I)	Observation space (dimens.II)	Reliability (symptom reliability)	Accuracy; (detection /measurement./ processing)	Variable working conditions (speed,...)	Information loss	Durability/ lifetime	Ease of use/ running	Repairability, mainten.	Temperature	No of principles; different/ all
Fault space (dimens.I)	X →	V, 5, 10 ↓	V, 11	V, 1, 2	⁵ ↓		15		V, 26	V, 1	7/ 8
Observation space (dimens.II)		X →	V,1,2,16,19, 20, 23, 26	V, 5, 10, 19,9, 26	↓	V, 1,2,16 19,20			16, 20	26	10/ 22
Reliability (symptom reliabil.)			X →	9, 10, 15, 16	↓	1, 9	11, 16	11, 20	11, 16	3	13/ 21
Accuracy; (detect./measuram./ processing)				X →	V, 16, 19, 26 ↓	9, 15				V, 1	11/17
Variable working conditions (speed,...)					X →	V, 16, 19, 26		V, 16, 19, 26			3/ 9
Information loss						X			V, 10		11/13
Durability/ lifetime							X	34, 35	34, 35	V, 1	6/ 8
Ease of use /running								X		3	8
Repairability, maintenance									X	3	8/9
Temperature										X →	3/ 7

⁵ Reading direction of inventive principles set for a given parameter, an example.

This means we will take into consideration 10 by 10 contradiction matrix, but if needed in some special cases, this dimensionality can be extended easily or diminished a little (*i.e. temperature, or load variability*). Table 1a shows the one sided contradiction matrix of VCM with marks **V** displaying contradictions between particular engineering parameters. One can see there, that almost every parameter possess at least one contradiction, and some of them have 5 like **fault space**, and 4 like **accuracy** of detection measurement and processing (*see the last column*).

It is well known in methodology of invention, and TRIZ as well, that the change of one engineering parameter in the direction of improvement may be the source of worsening of another one, and the only way outside of this loop is to apply some of **40 inventive principles**. Which one to use is usually the matter of careful analogy thinking, and the prior knowledge in the given area of science and engineering.

To solve 14 contradictions shown above and in table 1a and 1b, we will use inventive principles of Altshuller, giving them the meaning taken with mechanical engineering area and extended with the knowledge of metrology and the diagnostic signal / symptom processing. The numbering of inventive principles shown in Tab.2 is in accordance with that given in TRIZ references, and its diagnostic meaning and prescribed actions are given below.

1. **Segmentation** – segmentation of the frequency spectrum of vibration /acoustic process, band analysis and /or Fourier spectral analysis, also cepstral analysis for gearboxes, and also thermal **separation** of machine elements.
2. **Extraction, rejection** – rejection filters for cutting of unwanted signal interferences, like rotational frequency f_0 or the mains frequency 50Hz in Europe.
3. **Local quality** – the use of thermal or acoustic barrier, ear mufflers, the hardening of the shaft ends, etc.
5. **Integration, merging** – the vibration transducers with preamplifier, signal preprocessing, wireless transmission, integrated with a machine at specially chosen points and directions.
9. **Prior counter-action** – the forecast of signal distortion and compensation before transmission and processing.
10. **Prior action** – introductory analysis of a fault space (*dimension I*), and symptom observation space (*dimension II*) of the machine, in order to chose probable machine faults, and respective observed processes and a location/ direction of vibration transducers, on the machine body.
11. **Prior cushioning** – safe shut down procedure in rotating machinery diagnostic systems.
15. **Dynamics** – elastic mounts or spacers, in order to diminish or filter vibration transmission inside machine body.
16. **Partial or excessive action** – use of SVD / PCA⁶ analysis of SOM to filter noise and obtain singular components /values, also signal demodulation for detection of diagnostic information, and symptom value forecast.
19. **Periodic action** – synchronic averaging of signal, signal sampling with preprocessing, over- sampling of vibration process to detect periodicity and reduce noise.
20. **Continuity of useful action** – constant load of a machine in a production process, constant use of condition monitoring subsystem.
23. **Feedback** – monitoring of diagnostic oriented residual processes of phenomenal field of the machine for the assessment of the machine condition and the increase of its reliability.
26. **Copying, model** – infrared picture of the machine and / or acoustic map of its surrounding, to reduce preheated / prestressed areas of a machine, symbolic or mathematical model of the machine symptoms evolution, to elaborate its condition recognition and a forecast.
34. **Discarding and recovering** – self balancing systems in rotating machinery, small regulations and repair during the running of a machine.
35. **Parameters change** – change of mass, stiffness and damping (*passive or active*) in order to reduce excessive and harmful vibration and noise, at some parts of a machine.

⁶ SVD=singular value decomposition, PCA= principal component analysis; for SOM orthogonal decomposition.

One can notice from the above that for the solution of 10 by 10 contradiction matrix in machine condition monitoring, we may use 15 inventive principles interpreted in terms of machine use and signal / symptom processing knowledge and technology. They can be used altogether for the best (*see table 2*), or some of them can be omitted due to lack of knowledge (*see principle 9*), technology (*see principle 5*), or lack of need (*see principle 15*).

Looking once more for the inventive principles allocated in the contradiction matrix (*Tab. 2*), and described broadly in above listing, one can say, they present contemporary knowledge and technology of VCM. This includes the broad meaning of the inventing principle No 26, where **copy** may mean also the **model** of the symptoms evolution during the machine lifetime, to make condition assessment and forecast. It can be simple regressive model or much sophisticated with artificial intelligence and model updating [Tabaszewski 10].

What is important here, that it was possible to describe VCM problem by means of minimal number of engineering parameters, and to notice importance of two abstract entities; the **fault space** and **observation space**. We should notice also their common definition and influence on symptom reliability, the ease of running and repairability (*maintainability*) of the machine.

Concerning the problem of minimal dimensionality of engineering parameter set to describe MCM problem, it seems to that minimal dimension of engineering parameter set, can be reduced to a number of **nine** or **ten** parameters only, if needed. Also it is possible to extend this number by other engineering parameters; like accuracy of production (*manufacturability-32*), productivity (39), or harmful side effects (31), in some special cases of machine or engine diagnostics.

Applying TRIZ to MCM area it is also interesting to know which engineering parameters are the most important to define, and solve the contradictions on the way to IFR? To answer this question a special column was appended (*yellow numbers*) to contradiction matrix, which enumerate the number of contradiction to solve on the way to IFR. As we can see (*table 1b*), there are three engineering parameters; the **fault space** and **observation space** of the machine and also the **accuracy** of detection, measurement and processing. They include respectively **5** and **4** contradictions to solve on the way to ideal final result – IFR of vibration condition monitoring - VCM.

The similar question should be passed when we look for set of inventive principles solving these contradictions. Table 2 shows the numbers of these inventive principles, and some numbers are in shadowed area, when they solve contradictions of table 1b. Also there are some additional numbers of inventive principles, which can help and ease our way to IFR in VCM. What is more to see in a table 2, some principles are encountered a few times. This means they can be applied to enhance our quality of VCM problems solution, and even more some inventive principles, if applied, can solve or enhance not one contradiction only. For example, principles number; 16, 19, 26 (*see table 2*), can solve contradiction **1** of increasing accuracy of signal and symptom processing, contradiction **2** of reducing information loss, and also the contradiction **3** in extending the ease of use and running of the machine.

One can see also from the table 2, that we have some inventive principle numbers without contradiction sign (**V**), like in case of reliability parameter. There is no direct contradiction found here, but **8** different inventive principles namely **1, 3, 9, 10, 11, 15, 16, 20** can be used for the enhancement or betterment of the VCM problem. In summary one can see from table 2, that in 14 cases we use some inventive principles to solve some contradictions, and also we have 14 cases of using them without direct contradiction presence. This seems to be good side of the TRIZ in VCM, that we can find inventive principles to solve contradictions, and also to use them for the enhancement or betterment of VCM solved problem.

4. Conclusions

As it follows from the above it was possible to transfer creatively the current science and technology of machine vibration condition monitoring into the formal TRIZ tools that means to the

ideal final result (**IFR**), contradiction matrix, and inventive principles. Due to that, the relative importance of the definition of machine fault space and observation space has been elucidated, and taken into account. Also it has been proposed that the minimal number of engineering parameters for VCM problem description and solution can be taken as ten parameters, including the most important observation space and the reliability of the machine.

The number of engineering parameters depends on the type of machinery, when the operating conditions are mostly stable, like in turbosets, we can use 9 description parameters, but having a machine with variable operating conditions we should use 10 engineering parameters and respective contradiction matrix. In order to solve contradictions present in MCM problem one can use altogether 15 inventive principles with the 14 mostly used. And when using proper dimensionality of observation space and software for SOM processing and decomposition we can make machine condition assessment and forecasting with a reasonable accuracy.

The paper reveals one more feature of TRIZ important to VCM, mainly one can use a set of inventive principles to solve contradictions, and also another set of inventive principles for the betterment of obtained solution.

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