The concept of on-board diagnostic system of working machine hydraulic system

Leszek Surówka
Stanislaw Staszic State School of Higher Vocational Education in Piła, Politechnic Institute
64-920 Piła, ul. Podchorąży 10, e-mail: LeszekSurówka@interia.pl

Key words: machine hydraulic systems and their diagnosing, concept of on-board diagnostic system of working machine hydraulic system

Abstract
In the study a characteristic of working machine hydraulic systems, selected issues of basic methodology of their diagnosing and a concept of an on-board diagnostic system for their condition evaluation were introduced.

Introduction
Diagnosing of working machine hydraulic systems covers their construction, manufacturing quality and exploitation. This activity should be realized according to procedures contained in diagnostic methodology. Taking into account theoretical foundations of technical diagnostics and exploitation pragmatics it can be assumed that diagnosis methodology of hydraulic systems should take into account definition of system states set and diagnosis parameters, as well as parameters dependence on a state, and setting a diagnostic test for state control and defect localization.

Characteristics of working machine hydraulic system
Assuming some simplifications it can define designation of working machines hydraulic systems as:
- driving of parts of working units and subunits;
- controlling and control supporting of machine units and subunits;
- greasing of machine cooperating parts;
- cooling of machine parts;
- cleaning of machine parts from products of machine aging;
- limiting of degrading atmosphere influence (for example oxidation) on machine elements.

In working machine hydraulic systems it can distinguish the following functional subsystem:
- supply;
- control;
- realizing;
- diagnostic equipment.

Considering the above the general schedule of hydraulic system in construction and task concept is shown in figure 1.

Functioning of working machine hydraulic systems consists in cooperation of their blocks, which results in continuous transformation of consumed energy (with disturbances) to assumed effects and associating residual processes. The final effect is movement of machine executive element. The residual processed constitute a set of products generated during exploitation of hydraulic system which are not the goal of their action. The physical and chemical processes happening in hydraulic systems during their exploitation are associated with machine functioning and aging processes of their parts, as well as working liquid.

During many analyses results it can distinguish phenomena being sources of emission of many diagnostic signals. Example diagnostic parameters in hydraulic systems assigned to physical and chemical phenomena are shown in table 1.
Definition of system states set

Assuming that an object technical state depends on its elements state, definition of its technical state is possible when functions realized by these elements and relations between them are known. Then a working machine hydraulic system can be presented as a graph:

$$ G = <X, W, P> $$

where:
- $X$ – set of system functional elements;
- $W$ – set of structural and functional relations between system elements;
- $P$ – predicate expressing interactions between the elements.

The analysis of hydraulic system state choice problem, resulting from analysis of bibliography, as well as from own research results concerning reasons for defectiveness and system diagnostic susceptibility indicates, that among the known methods for state set definition such as: system work safety associated with machine exploitation lifetime, weak link and element defect probability, it is rational to assume the safety method.

The machine work safety method consists in using machine element wear course character in different exploitation periods in which different wearing processes take place. The course of wearing of sets during exploitation depends on which of the wearing processes is dominant. Thus, for all sets of working machine hydraulic system where sliding friction exists, there are usually three periods of wearing (introductory ageing, normal wearing period, accelerated wearing period) affecting machine work safety.

The work safety method associated with machine exploitation phases consists in using machine...
work safety criterion setting apart these machine defects which cause change in work parameters, e.g. lifting capacity, work movement acceleration, work movement delay, influencing machine work safety. Such differentiated states cover defects which do not let use the working machine hydraulic system according to designation, they are danger to work safety for people and environments and should be basis for sending the system to repair. If a working machine system set state \( W(t_n) \) at a time moment \( t_n \) can be characterized with a diagnostics parameter value set \( \{ y_j(t_i); \ j = 1,\ldots,m \} \) then hydraulic system at time \( t_n \) is in ability state \( W^0 \), when the following condition is fulfilled:

\[
W(t_n)=W^0 \iff \forall (j = 1,\ldots,m) \left[ y_{j,d} \leq y_j(t_n) \leq y_{j,g} \right]
\]

where: \( \{ y_{j,d}, \ y_{j,g} \} \) – sets of lower and upper limit values for diagnostic parameters.

Referring the above expression to machine lifetime curve (Fig. 2) it can formulate a dependence linking a machine lifetime \( t_n \) with its:

- ability state \( W^0 \);
- inability state without threat to machine work safety operation \( W^1 \);
- inability state with threat to machine work safety operation \( W^{11} \).

Then respectively:

For time \( t_1 \):

\[
W(t_1)=W^0 \iff \forall (j = 1,\ldots,m) \left[ y_{j,d} \leq y_j(t_1) \leq y_{j,g} \right]
\]

For time \( t_2 \):

\[
W(t_2)=W^1 \iff \forall (j = 1,\ldots,m) \left[ y_{j,d} \leq y_j(t_2) \leq y_{j,g} \right]
\]

where set \( W^{11} \) can for example contain such states as defect of hydraulic pressing pumps (excessive wear of working area sealing), pressure regulator defect (e.g. spring breaks, defect of valve faying faces, defect of regulating screws), defects of piston rods (significant scratches of outer piston rod surface, shape change, i.e. bucklings).

**Definition of system diagnostic parameters set**

Machine structure parameters \( W \) are variable values changing in time \( W = W(\Theta) \) and in exploitation period they depend on processes forcing the machine ageing. The technical state of a hydraulic system depends on values of structure parameters and its determined by them.

Basing on analyses found in literature and on own research, it was established that diagnostic

---

![Characteristics of a set wear in a working machine hydraulic system](image-url)
parameters reflecting a machine technical state, depend on change of structure parameters and exploitation time of working machine hydraulic system.

\[ Y = f(W(\Theta)) \]  
(6)

\[ Y = g(\Theta) \]  
(7)

Assuming additionally a stationary character of diagnostic parameter values it can, basing on observation of machine parameter diagnostic values in time \( t_i \in T \), conclude about parameter values in the whole time range.

The set of diagnostic parameters \( Y \) differentiates from output parameter set \( Y_{WY} \), which describes the course of output processes (work and associated processes), depending on technical state of the hydraulic system. Mutual relation of structure parameters \( W \) and output parameters \( Y \) from sets \( W \) and \( Y \) respectively as diagnostic parameters and define measurement points in working machine hydraulic system. These conditions are as follow:

Unequivocality condition – each value of structure parameter value \( w_i \in W \) corresponds to only one determined value of output parameter \( y_{wyj} \in Y_{wy} \).

Field width change condition – the biggest relative change of output parameter \( y_{wyj} \in Y_{wy} \) for assumed structure parameter value \( w_i \in W \).

Output parameter measurement availability condition – is characterized by measurement cost indicator \( c_j \) or measurement time \( t_j \), and these indicators have to be minimized.

Fulfilling the above introduced conditions 1 \( \land \) 2 \( \land \) 3 lets us introductory discriminate a set \( Y \) from set \( Y_{wy} \). More precise discrimination of a set \( Y \subset Y_{wy} \) is possible using many methods: minimum diagnosis error, information capacity, correlation with technical condition and preferred method: diagnostic parameter value similarity method.

The diagnostic parameter value similarity method consists in checking of diagnostic parameter assignment correctness to particular classes of hydraulic system states [1, 2]. It uses a relation saying that a matrix of total sum of observation deviation squares from observation weight center \( T \), is a total sum of deviation squares \( W \) from inter-class averages and total sum of inter-class deviation from global average \( B \). The classification algorithm for diagnostic parameter value observation was presented in figure 3.

In this method general or total variance function decrease velocity is examined, calculated basing on

---

Fig. 3. Algorithm for diagnostic parameter value similarity method

\( W \). The end of classification process, i.e. assignment of particular observations to classes follows reaching the minimum value for the global criterion. As a result of method realization we obtain respectively diagnostic parameter sets for state control test \( D_{KS} \) or for defect localization test \( D_{LU} \).
Definition of relation: diagnostics parameter – system technical state

Relations between diagnostic parameters and state features are as a rule stochastic relations. These relation in machine diagnostic practice can be defined by Boolean observation matrix and preferred observation matrix according to relation: diagnostic parameter – working machine exploitation time.

Observation method for relation: parameter – exploitation time consists in defining of observation matrix for different values of time \( t_n \) at which defects of hydraulic system occur (referring to selected levels of system decomposition) changing diagnostic parameter values which affect machine work safety. Such defined observation matrix can be a base to designate a test of state control and defect localization, definition of hydraulic system defect intensity and designation of time for machine exploitation deadline. Limiting values of diagnostic parameters are established for machine state fulfilling producer’s demands and they have their relation to the time of machine fitness for use.

\[
M^S_B = \begin{bmatrix}
t_1 \rightarrow s^9 \\
t_2 \rightarrow s^1 \\
\vdots \\
t_3 \rightarrow s^{11}
\end{bmatrix}
\]

Such shape of observation matrix seems to be especially useful in research of relation state – diagnostic parameter in case of a passive experiment event, which often takes place in case of working machines.

Designation of diagnostic test for state control and system defect localization

Basing on analyses of research possibility for diagnostic parameter relation to hydraulic system state it is believed, that for designation methods the most interesting are methods of designation of state control tests and for defect localization which use Boolean observation matrix and parameter – working machine exploitation time observation matrix. One of them is a method of state classification.

Hydraulic system state classification method consists in principle that as a result of determination of diagnostic parameter set with diagnostic parameter – exploitation time relation observation method we obtain relation pairs: diagnostic parameter set \( \{ y_j \} \) – suitability set \( S^0 \), diagnostic parameter set \( \{ y_i \} \) – inability states \( S_i \), \( j = 1, m \), \( i = 1, k \), which let us use the diagnostic parameter set \( \{ y_j \} \) (in special event it is single element set) for designation of test \( D_{KS} \):

\[
D_{KS} = \{ y_j \} \quad (9)
\]

\[
D_{KS} = \{ d_j \} \quad (10)
\]

where: \( d_j \) – checking of parameter \( y_j \) value.

In case of determining of tests \( D_{LU} \) elements as a result of state classification method realization (state pair subsets \( S_l \), \( S_i \); \( l = 1, k \); \( i = 1, l \) \( i \neq l \) we obtain a diagnostic parameter set \( \{ y_j \} \) for determination of test \( D_{LU} \). Then test \( D_{LU} \) takes the following shape:

\[
D_{LU} = \{ y_j \} \quad (11)
\]

\[
D_{LU} = \{ d_j \} \quad (12)
\]

The alternative to these procedures for determination of state control and defect location test is using a check vector, defined from Boolean matrix \( Y = \{ y_n \} \); \( n = 1, N \). Then, e.g. test \( D_{LU} \), will take shape:

\[
D_{LU} = \{ y_1, \ldots, y_n \} = \{ 1, \ldots, 0 \} \text{ – state } S_i \text{ – defect of set } i \text{ of this working machine hydraulic system set}
\]

Recapitulating the presented considerations referring to methods of determining diagnostic tests there is need to say that on account on preference in diagnostic method choice of similarity method and the way of examination for diagnostic parameter – state relation, the state classification method is optimal.

The concept of on-board diagnostic system

The researches of working machine hydraulic system state performed by the author using the above described research methodology showed, that it is possible to use the worked out diagnose procedures in the on-board diagnostic system of working machine system. The analysis showed that in the concept of on-board diagnostic system it must be taken in consideration a system description of hardware and software and showing possibility to use the concept in design, production and exploitation of working machine hydraulic system.

Resulting from performed work it was assumed that the concept of on-board hydraulics diagnosing system should cover issues from areas of design,
production and exploitation of hydraulic systems of working machines. They are for example: functional and construction features of machine hydraulic system, exploitation and service conditions, service back-up potential, economic calculation.

Concerning the results of tests performed it was stated that:

- construction of on-board working machine hydraulic system should use the analysis of pressure change of working liquid in the area of defined working movements;
- a complement of this should be parameters concerning: working liquid amount, working liquid temperature, pollution of working liquid filters, rotational speed of pump system driving shaft, moment of tilt of excavator chassis, tilt angle of the body.

It was assumed, that the on-board diagnostic system of working machine hydraulic system should ensure the control of condition and localisation of its defects.

The idea of work of diagnostic system consists in inference about the status a hydraulic system basing on relations between measured values of pressure and reference values of logical structure (set of 0 and 1) of hydraulic system diagnostic matrix. For execution of basic functions of the system procedures of object programming are used.

The basic module of on-board diagnostic system is a knowledge base:

\[
\text{OBJECT, ATTRIBUTE (state feature) \rightarrow VALUE}
\]

The on-board diagnostic system of a working machine hydraulic system should include the following variants of its work:

- usable – refers supervision of hydraulic system during its use;
- diagnostic and maintenance – covers diagnosing of hydraulic system blocks and realizing of its service according to designated service lives and system state;
- informative – refers creation of data base for exploitation history of hydraulic system ensuring:
  - defining the defect types related to exploitation time (performed work – defined for example by amount of energy consumed by supply unit);
  - setting exploitation alert times referred to exploitation safety (first of all people and environment);
  - informing the exploiter about reaching alert time of exploitation by hydraulic system (and state of direct threat for people and environment safety);
  - setting dates for next maintenance.

As a result of the above the on-board diagnostic system of a hydraulic system in particular variants of work should provide:

- continuous control of designated diagnostic parameters of hydraulic system blocks;

---

**Fig. 4. Diagram of configuration and operation of on-board diagnostic system of working machine hydraulic system**
• processing and showing of effects of processed parameters on control panel of working machine (monitor, acoustic signal);
• detailed picturing of incidents when permissible values of parameters were exceeded;
• setting ways of proceeding for operator in certain exploitation situations (maintenance, operation stop, system work stop etc.);
• cooperation with other external diagnostic equipment.

Taking above into account and basing on analysis it was assumed that the on-board diagnostic system of working machine hydraulic system should fulfil the following functions:

• informative – refers information including elements of on-board diagnostic system and working machine on following aspects:
  – usage;
  – maintenance;
  – technical and exploitation parameters (adjustment data);
  – and also (depending on needs) storing of selected measurement results, referring especially exceeded alert and limit values of diagnostic parameters and related messages generated by subsystem of diagnostic visualisation (including technical maintenance of hydraulic system);
• diagnostic – refers examining and evaluation of hydraulic system condition, and also self-diagnostic function of the on-board system;
• control – refers choosing optimal work conditions and way of usage of hydraulic system basing on the knowledge base containing basic regulation parameters of particular units and subunits of the hydraulic system: blocks of supply, control and executive (pressure regulators, amount and temperature of working liquid in the system, cleanliness of working liquid filters, rotational speed of driving shaft of pump system, speed of work movements, tilt moment and tilt of machine body etc);
• efficiency evaluation of hydraulic system work – refers for example: fuel consumption per time unit by combustion engine driving the pump unit of supply block during work of machine in particular working conditions (parameter defined by machine producer), amount and quality of work done by the machine in particular conditions (parameter defined by machine producer);
• working safety – refers supervision of proper function of units and subunits of hydraulic systems, in particular quality of work of devices protecting from:
  – overload;
  – deflection of working tools outside the area defined by the operator (suitability of working tool brakes);
  – machine operation (hydraulic system) in time when the system has not reached required parameters for example: amount and temperature of working liquid, pressure of working liquid in supply block – indirectly it refers to parameters of work of the engine driving pump unit (temperature of cooling liquid, oil pressure, exploitation rotations of engine crank shaft).

Considering the above remarks and settlements it is believed that the concept of architecture of on-board diagnostic system of working machine should ensure:

• supervising the work of hydraulic system units during machine use;
• setting dates for technical maintenance according to programmed time of use and amount of work done;
• generating information for new designed expert systems including use and operation of the system;
• during each start of the working machine, realizing the self-control function of diagnostic system covering:
  – power supply of diagnostic system;
  – signal converters;
  – condition of the central unit of a diagnostic system;
• current pre-definition of designated diagnostic parameter values (only for certain personnel of system operation);
• in certain range be compatible with other diagnostic equipment, for example E-OBD mode;
• visual and acoustic signalling of exceeding accessible values of measured diagnostic parameters (including alert values);
• generating the procedures of behaviour for an operator in dangerous situations (for example working tool halt, engine stop, fire-protection system alarm).

From analysis of action requirements, configuration aspect and needs generated for the concept of on-board diagnostic system result that the architecture of the system should ensure:

• system configuration within previously defined requirements, including introduction of amount, limit and alert values including enter of quantity, limit and alert diagnostic values, system work time;}
• measurement and recording of measured diagnostic signals according to designated condition (measurement start and stop, which values and when recorded);
• diagnostic inference basing on analysis of relations between measured values and observation matrix values;
• visualisation of machine hydraulic condition, including generation of exploitation decisions (suitable or unsuitable, fault localisation, others).

Application of the above concept of the on-board diagnostic system for hydraulics (Fig. 5) will provide execution of the following tasks:
• continuous supervision of diagnostic parameters representative for certain blocks of hydraulic system;
• recording and storing of diagnostic parameters;
• processing of collected data into decisions ensuring effective functioning of a hydraulic system, for example date of change of working liquid;
• actual information about technical condition (and action processes) of a hydraulic system and alarms for fault states concerning for example: stop of excavator spoon in case of excess tilt of the excavator;
• supporting of decision making process in exploitation decisions, concerning for example changing of working liquid filters, working liquid, cleaning of magnetic filters of working liquid etc.

Conferring rules were developed basing on diagnostic matrix analysis and procedures of KS and LU test determination with a checking vector. For particular blocks of hydraulic system of working machine they are as follows:

1. For supply block:
\[ D_{LU} = (y_1, y_2, y_3, y_4) = (1 0 0 0) \] – state \( S_{112} \) – defective connector of a pressure regulator of a servo-motor supply block.

2. For control block:
\[ D_{LU} = (y_1, y_2, y_3, y_4) = (0 1 0 1) \] – state \( S_{623} \) – defective hydraulic separator.

3. For execution block
\[ D_{LU} = (y_1, y_2, y_3, y_4) = (0 0 1 0) \] – state \( S_{232} \) – wear of outer layer of elastic cables for servo-motor supply of cylinder channel.

Interpretation of conferring rules in this concept is as follows:

a) If a logical value of checking vector of a diagnostic parameter assumes value “1” – parameter value is outside the limit value;

b) If a logical value of checking vector of a diagnostic parameter assumes value “0” – parameter value is within the acceptable value range.

Transfer of the generated diagnostic information through the on-board diagnostic system to the operator should be executed on two levels:
• for working machine operator,
• for technical service personnel.
It was accepted that monitor and audio information to operator about condition of machine hydraulic system should have character shown in figure 6, keeping strict rules while additional text in a particular field can inform about a defective state.

Conclusions

Solution of problems of supporting exploitation processes of working machine with tools which optimize their use according to their assigned usage features while ensure required safety conditions for people and environment is still an important matter. One of these problems is evaluation of technical condition of hydraulic systems. Actually, and probably in the distant future, the problem of hydraulic system diagnosing will constitute a very important issue in the aspect of decision making about essential exploitation tasks. It results from improper technical state of most parts of exploited working machines, and also their hydraulic systems. This situation can be avoided by application of the above shown methodology of diagnosing of hydraulic systems and the concept of their application in form of principles for acquisition of diagnostic parameters and their conferring rules. Because of different needs in this respect it is advisable, that possibilities of proposed on-board diagnostic system should be based on its modular construction. This will ensure possibility for system configuration responding to buyer (or may be already an owner of a working machine) needs and possibilities. A solution for such a system will be creation of service units providing:

- specialist consulting in the range of requirements covering application on-board diagnosis systems for particular systems;
- configuration according to above set PSD elements from produced PSD modular sets;
- assembling of chosen and configured PSD in a particular hydraulic system with its software;
- service of PSD installed as above.

The solution introduced here creates possibility of its application in a hydraulic system of a working machine at each stage of its life. The best solution would be implementation of the presented PSD already at design, construction and production stages of a working machine.

Additionally, taking into account possibility of application of the concept of on-board diagnostic system for working machine hydraulic system in its exploitation, it must be kept in mind that it refers to needs of working machine users.

References

Others