DIAGNOSTICS IN CAR MAINTENANCE

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Summary

The paper proposes an extension of the currently applied vehicle inspection, based on the OBD II system, and periodical inspection, by vehicle dynamic load testing. The method involves generating faults based on an analytic model of traffic. The method takes into account the static and dynamic properties of a vehicle within the whole range of its operation, taking into account the variable traffic intensity, and enables early detection of defects which accumulate at variable random loads. The highest precision of computation is ensured by traffic models with elastic and damping constraints, with variable rigidity and damping.

Keywords: diagnostics, vehicle maintenance, dynamic load.

DIAGNOSTYKA W UTRZYMANIU POJAZDÓW SAMOCHODOWYCH

Streszczenie

W pracy zaproponowano rozszerzone podejście do obecnie stosowanej kontroli stanu pojazdów, opartej na OBD II i kontroli okresowej, o pomiary obciążeń dynamicznych pojazdu. Zaproponowano metodę generacji niezdatności pojazdu na podstawie modelu analitycznego ruchu drogowego. Metoda ta uwzględnia własności statyczne i dynamiczne pojazdu w całym zakresie jego pracy z uwzględnieniem zmiennej intensywności ruchu i pozwala na wczesne wykrycie rozwoju uszkodzeń kumulujących się przy zmiennych obciążeniach losowych. Największą dokładność obliczeniową mogą zapewnić modele ruchu z więzami sprężystymi i tłumiącymi o zmiennej sztywności i tłumieniu.

Słowa kluczowe: diagnostyka, utrzymanie pojazdu, obciążenie dynamiczne.

1. INTRODUCTION

The basic tasks of technical diagnostics include detection and identification of failures and faults in cars, which – directly or indirectly – result in their unreliability. The elements of faults in which various factors result in disturbing the balance of forces, moments or balance in the continuity of energy and information flow, which may result not only in a vehicle fault, but also in its failure or even a car accident. Another task is the choice and implementation of a strategy of car maintenance, whose aim is to slow down the process of its degradation and to restore its fitness for use [6].

The theoretical foundations for developing various diagnostic methods are algorithms of car inspection on various levels of its complexity (decomposition). The knowledge of the dynamics of a vehicle steering provides more in-depth and comprehensive information about the vehicle condition and static characteristics. The degrading effect of dynamic load on kinematic nodes is greater than that of static load or natural wear. The causes of failures and faults in the system of vehicle operation system are the following [6]:

- dynamic input function in the course of vehicle operation,
- a driver's errors made in the "man – car – road – service" system,
- construction errors made in the process of designing the system of a vehicle operation,
- manufacturing errors, made in the production process,
- maintenance errors, made in the condition inspection and during the process of maintenance.

The problem of diagnosing the condition of a vehicle during its operation can be reduced to checking the correctness of parameter changes in relation to the operation time t and determination of status control cycles as well as locating the faults in a vehicles.

Diagnosing a vehicle may be reduced to comparing actual characteristics u with assumed ones u_o, according to the following relationship:

$$\int_{t_0}^{t_k} \rho(\overline{e})\left[u_0(\overline{e}_0,t)-u(\overline{e},t)\right]^k dt = \min$$

where:
$\rho(\overline{e})$ - function of weight, $\rho \in [0,1]$;
$\overline{e}_0$ and $\overline{e}$ - a set of assumed and actual diagnostic parameters;
t - variable time of vehicle condition inspection;

$k = 1,2$ - exponent of integrand.

The essence of the currently applied diagnostic systems can be reduced to the action of a summing node

$$\sum_i \overline{e}_i - e_{0i} = \Delta\overline{e}_i$$

where the programmed values e_0 are compared with the set $\overline{e}$ which describes the current status, taking into account the defects and faults of a vehicle.

2. STANDARDS OF ON-BOARD DIAGNOSTICS (OBD)

The current standards adopted for the assessment of the technical condition of cars as OBD I in the last decade of the 20th century have a number of restrictions. Since 1996, the OBD II standard has been applied for cars. Technical diagnostics in this approach consists in identification and location of a failure where it originated, usually defects in the power transmission system, assemblies and the vehicle functional systems from the point of view of road safety and environment protection [4].

The principles of on-board diagnostics were determined by SAE (Society of Automobile Engineers) in its standard SAE J 1830, while the requirements of on-board diagnostics by European car manufacturers in the standard ISO 9141-2. These standards constitute a set of technical and legal requirements which define the on-board diagnostic system as diagnostic procedures, installing diagnostic sockets, processing the diagnostic signal, monitoring the basic parameters of the power transmission system, including exhaust emission parameters.

The criterion of assessment of whether an assembly and its functional elements work properly is the exceeding of the adopted threshold of 50% of the diagnostic parameter, which is signalled and recorded with relevant error codes [5]. The OBD II system is able to detect faults which are the main elements of a power transmission system, i.e. increased waste emission above the accepted threshold. They are mainly related to signalling of faulty operation of electronic systems, sensors in the engine power supply system, leaks in the fuel system, etc. Ultimately, the existing OBD II will provide a basis for developing a comprehensive diagnostic system for an entire vehicle, with the possibility of connecting to a remote service for locating any defects and failures of the vehicle with the use of the GPS system.

The adopted system has a number of restrictions which are a consequence of reducing the status control only to selected test points and the location of errors at the assembly and test element level. The difficulties encountered here include diagnostic inference, identification of diagnostic relations and locating the types of failures. Therefore, this paper proposes to extend the scope of a vehicle diagnostics by new diagnostic signals, taking into account the intensity of the vehicle work and the dynamic load in the process of its use.

3. IDENTIFICATION OF DYNAMIC LOAD AND VIBRATIONS IN VEHICLE MOTION

A vehicle and its elements are adapted for transferring specific static and dynamic load. The load taken into account in the process of a vehicle design, in terms of the course as well as the values and time, correspond to the average operating conditions. Such conditions can be referred to as the average vehicle load with cargo, good road surface condition, moderate utilisation of engine power and driving speed [2].

The level and nature of the dynamic load originating in a vehicle depends on its structure and technical condition and on the traffic conditions. Dynamic load is a result of vibrations produced by a vehicle motion. The vibration intensity and, consequently, the level of dynamic load increases with:

- increase in the driving speed and vehicle weight;
- increase in the power transmitted by the power transmission system;
- deterioration of the road surface condition;
- driving style, including frequent changes in the engine rotational speed, engaging the clutch and gears;
- increasing clearance in connections, which cause parts to hit one another.

The most dangerous values of high dynamic load and the resulting extreme tensions in the vehicle parts may be caused by:

- driving at high speed on a bumpy road;
- vehicle overloading;
- construction changes which are at variance with the documentation provided by the vehicle manufacturer, e.g. increasing the engine power, wheel track;
- resonance in the power transmission system or suspension.

Additionally, all the rotational elements with clearance in connections, imperfect shape or balance, may result in periodical dynamic interactions. They increase with increasing rotational speed, and the coincidence of the rotational speed with the natural frequency of an element or assembly results in resonance and rapidly increasing dynamic load.

The actual load changes are random. Despite the complex character of load which corresponds to particular stages of a vehicle drive, they can be approximately substituted with blocks of repeatable cycles with predetermined amplitude and frequency. The results of such tests can be shown, e.g. as a Wöhler's diagram. The diagram was used to present the relationship between the variable load σ_A and the number of load cycles N before the vehicle damage (destruction). If, while driving, a vehicle element is subjected to load with an amplitude of σ_{Ai}, it can withstand without defect the number N_i of load change cycle, which may correspond to the number of kilometres of driving (Fig. 1).

Further considerations involved Palmgren-Miner's hypothesis of fatigue life, which describes the process of linear accumulation of fatigue failures of machine elements. The greater the load changes amplitude, the more intensive the microdamage development. If the load cycles are repeated, microdamages accumulate (add up) in the element and the element becomes damaged (e.g. cracks) after a certain number of load cycles.

In order to describe the process of damage accumulation, the coefficient (*D*) is introduced:

$$D_i = \frac{n_i}{N_i}$$

where:

n_i - number of load cycles with the amplitude σ_{Ai};

N_i - the number of load cycles σ_{Ai}, after which the element becomes damaged.

The number n_i is determined from the load change course in the analysed element, and N_i is determined from the Wöhler's diagram. An element damage, i.e. exceeding its durability, takes place after the sum of load cycles is equal to:

$$D = \sum_i D_i = 1$$

These considerations will be used in a computational example. An example changes course of a bearing load is shown in Fig. 2.

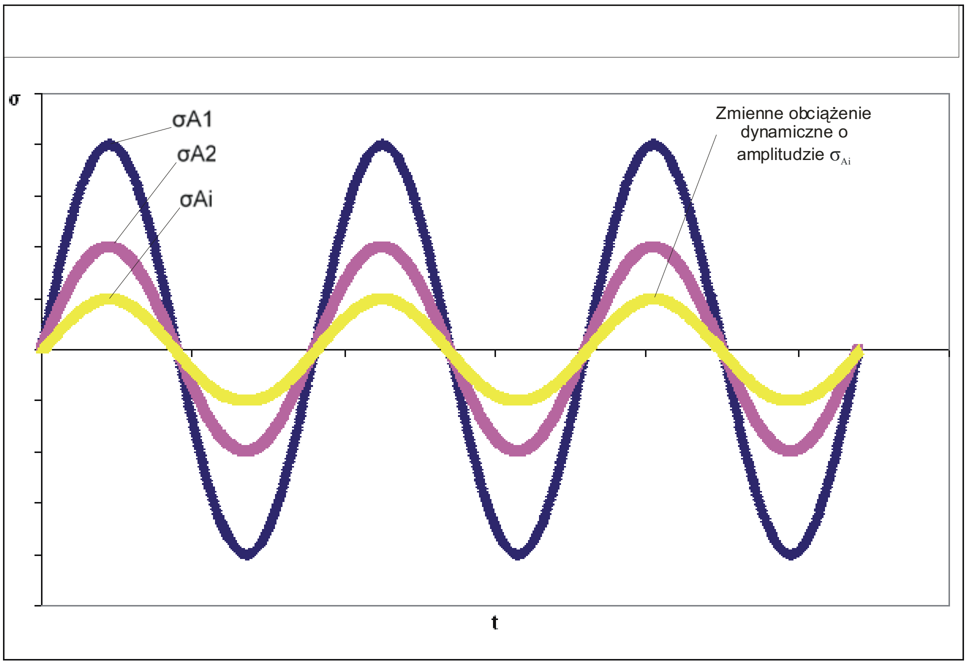

Fig. 1. Idealised load changes during the tests of the elements durability

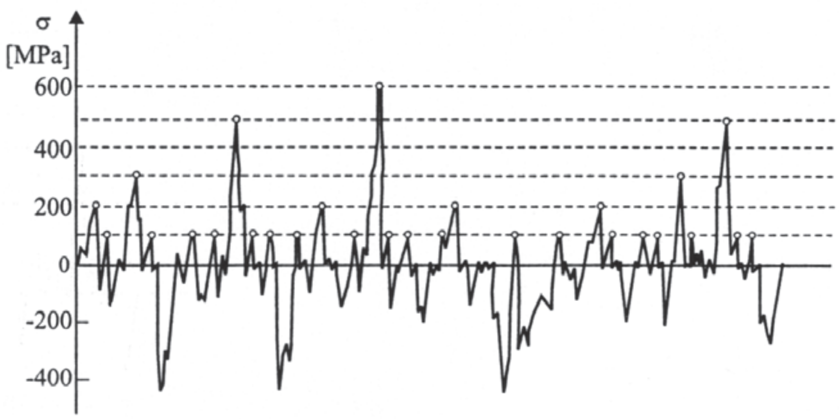

Fig. 2. An example change course of a drive wheel bearing dynamic load

It has been chosen to show the effect of the manner of a vehicle use and the dynamic load which results from it on the vehicle condition. Table 1 shows example results of a bearing fatigue test, performed by the manufacturer. These are the numbers N_i of load cycles with the amplitude of σ_{Ai} until the bearing is destroyed. They were juxtaposed with the results of bearing load test results during the drive over the distance of 10 km. Static load have been omitted in Fig. 2.

The random changes of the operational load was the basis of determination of the load spectrum. To do this, the distribution of peak loads, i.e. local extremes, were found. After the extreme values were counted on particular levels of load, the numbers of cycles n_i of load with amplitude of σ_{Ai} were determined and shown in Table 1.

Adding up the drive wheel bearing load cycles over a distance of 10 km:

$$D=\sum\frac{n_i}{N_i}=\frac{1}{1000}+\frac{2}{10000}+0+\frac{2}{200000}+\frac{4}{500000}+\frac{19}{1000000}$$

$$D=0{,}001237$$

Using the linear hypothesis of damage accumulation, the bearing forecast has been calculated, expressed by the mileage done before a failure (L) for D=1.

$$L_L=\frac{1\cdot 10}{0{,}001237}\cong 8084km$$

Mileage 10 km - failure coefficient D = 0.002476
X km -failure coefficient D = 1.

Therefore, the mileage before the damage calculated for the second case is equal to:

$$L=\frac{1\cdot 10}{0{,}002476}=4039km$$

The computational example clearly confirms that the higher the values of dynamic load during the drive, the shorter the time of the bearing work before a failure. Similar physical phenomena occur with other structural elements of a vehicle. Therefore, assuming a 20% surplus of an element durability, the technical condition of a bearing should be checked in the first case after the mileage of 6,500 km and in the second case – after that of 3,400 km. In the adopted standards of on-board diagnostics, the issues of vehicle dynamics have been practically omitted.

Vibrations during the vehicle work not only create dynamic load of elements and assemblies, contributing to their lower durability, but they also significantly affect the effectiveness and efficiency of the driver's actions and those of people travelling in the vehicle.

4. A FAILURE – DIAGNOSTIC - ORIENTED MODEL OF DYNAMIC LOAD IN A POWER TRANSMISSION SYSTEM

Considerable dynamic load may appear in the power transmission system, due to:

- variable nature of the action of resistance forces while driving;
- uneven work of a combustion engine;
- improper action of the driver on the clutch, brake system and when changing gears;
- lack of balance and kinematic compatibility of the drive shaft and axle-shafts;
- imprecise workmanship, wear and clearance in assemblies of the drive transmission system.

These factors produce primarily torsional vibrations as well as vibrations and noise in the power transmission system.

A vehicle model is a set of interconnected partial models:

- a driver model;
- a steering system model;
- a power transmission system model;
- a model of wheel cooperation with the ground (a wheel model in combination with the ground model);
- a chassis model;
- a work environment model.

The driver model describes the forcing actions performed by the driver (the force on the steering wheel, the position of the clutch and brake levers, batching fuel, etc.). It is related closely to the function of senses, mental processes in the brain, reflexes, the level of manual skills. The steering system model describes the geometrical and dynamic relationships in the steering mechanism. It helps to examine clearances and friction. It helps determine the position of turning wheels and moments on the stub axles depending on the steering wheel position and the force applied to it, as well as the shift of the suspension elements.

The basic tool applied in the process of the vehicle model construction, are automatic system of generating the equations of motion, used to analyse multi body systems (MBS - **M**ulti **B**ody **S**ystem Formalizm), which include: [8]:

* - Failure – loss of a vehicle's ability to perform the required functions.
Critical failure – one which poses a threat to humans, results in considerable material damage or other unacceptable outcome [PN-93/N-50191].

**- Fault – a condition of a vehicle in which it is unable to perform the required functions [PN-93/N-50191].

Table 1. Number of load cycles n_i, isolated from dynamic load changes of a drive wheel bearing, assumed during the drive over the distance of 10 km

Number of load cycles	Amplitudes of load cycles					
	σ_{A1}	σ_{A2}	σ_{A3}	σ_{A4}	σ_{A5}	σ_{A6}
	600MPa	500 MPa	400 MPa	300 MPa	200 MPa	100 MPa
N_i	1000	10 000	50 000	200 000	500 000	1 000 000
Number of load cycles n_i, recorded during the drive in nominal conditions	1	2	0	2	4	19
Number of load cycles during extreme driving	2	3	6	5	10	11

- ADAMS (**A**utomated **D**ynamic **A**nalysis of **M**echanical **S**ystems);
- SIMPACK (**SIM**ulation **PACK**age for multibody systems);
- MEDYNA (**ME**hrkörper DYNAmik);
- DADS (**D**ynamic **A**nalysis and **D**esign **S**ystem);
- SD/FAST (**S**ymbolic **D**ynamics/**FAST**);
- MADYMO (**MA**thematical **DY**namical **MO**del);

According to Schiehlena W., the most common and advanced MBS systems include: ADAMS and DADS.

DADS helps analyse dynamics in the time domain of rigid body systems (the latest version of the program enables analysing pliable bodies). Such bodies may be interconnected by kinematic and pliable nodes.

The model notation and analysis employing it are made possible by the following program blocks:

- DADS Pre-processor – makes it possible to enter model data;
- DADS Analysis – generates motion and node equations which are used to determine: position, speeds, accelerations and reactions.
- DADS Postprocessor – generates computation results in the form of time series;
- DADS Graphic Environment – generates graphic interpretation of computation results (animation).

The DADS environment has been used to generate the equations of motion of a vehicle. A system of difference equations is generated automatically based on Lagrange's equation of the second type in it input form [8]:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} + \frac{\partial E_p}{\partial q_i} = Q_{qi} \ ,$$
$$i = 1,2,\ldots,s \ ;$$

where:
E_k – the system kinetic energy;
E_p – the system potential energy;
q_i – i-th generalised coordinate;
Q_{qi} – generalised force corresponding to the i-th generalised coordinate;
s – the number of the system's degrees of freedom.

Assuming the forces of gravity, elasticity and attenuation as external forces, the equation has the following form:

$$\frac{d}{dt}\left(\frac{\partial E_k}{\partial \dot{q}_i}\right) - \frac{\partial E_k}{\partial q_i} = Q_{qi} \ , \ i = 1,2,\ldots,s \ .$$

An attempt to link dynamic stresses (σ_d) (load) of any vibrating element in a vehicle with the speed of its vibration can be presented as:

$$\sigma_d = V_p \cdot \rho \cdot c \cdot k_d \quad \text{for } \sigma_m = 0$$

where:
σ_d – dynamic stress;
V_p – peak amplitude of vibration speed, measured at the site of maximal dynamic deformations;
ρ – density of the material mass;
c – velocity of speed propagation in the material;
k_d – the dynamic coefficient depending on the energy concentration;
σ_m – working stress.

These equations can be used to identify failures in specific functional circuits of a vehicle. Diagnostic inference employs models of R relationship definite on the cartesian product of the sets of a vehicle failures and faults

$$F = \left\{ f_i ; i = \overline{1, I} \right\}$$

and diagnostic signals (vibrations, power, moment, efficiency, clearances, etc.)

$$S = \left\{ s_j ; j = \overline{1, I} \right\}: \ R_{F/S} \subset F \times S$$

The expression $f_i R_{sj}$ means that the diagnostic signal s_j identifies the fault f_i. For example, the occurrence of the failure f_i (clutch clearance) results in power drop and is a diagnostic signal with the value of *1*. Then the matrix of relationships $R_{F/S}$ can be shown as a binary diagnostic matrix, defined as follows:

$$r(f_i, S_j) = \begin{cases} 0 \Leftrightarrow \left\langle f_i, S_j \right\rangle \notin R_{F/S} \\ 1 \Leftrightarrow \left\langle f_i, S_j \right\rangle \in R_{F/S} \end{cases}$$

The relationships $R_{F/S}$ may be defined by assigning to each diagnostic signal a subset of failures $F(s_j)$, detected by such a signal:

$$F(s_j) = \left\{ f_i \in F : f_i R s_j \right\}$$

Binary diagnostic matrices can be determined by conducting simulation tests on a physical model of
a vehicle or station tests with programmed dynamic loads, and based on expert knowledge.

5. SUMMARY

With the development of car constructions, the dynamics of their work increase, which creates the demand for new diagnostic models based on failure-oriented physical models of vehicle motion. Such diagnostic models help improve the effectiveness of vehicle maintenance by adapting the vehicle inspections to operational input functions. Thanks to early detection of a fault in a vehicle it is possible to prevent a failure and to improve traffic safety.

This paper proposes an extended approach to the currently applied vehicle condition inspection, based on OBD II, and periodical inspection, by a vehicle dynamic load measurement. It proposes a method of generating a vehicle fault based on an analytic model of traffic. The method takes into account the static and dynamic properties of a vehicle throughout the period of its operation, with variable motion intensity, and enables early detection of failures which accumulate at variable random loads. The highest precision of computation is ensured by traffic models with elastic and damping constraints, with variable rigidity and damping.

However, there are some obstacles in this approach which are related to the structure of the diagnostic matrix, the absence of clear diagnostic relations, the effect of non-linearity of models which determine the failure development. As a consequence, it may result in missing the failures to which the adopted diagnostic signals are sensitive.

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Prof. dr hab. inż. **Ryszard MICHALSKI** jest kierownikiem Katedry Budowy, Eksploatacji Pojazdów i Maszyn na Wydziale Nauk Technicznych UWM w Olsztynie.

W działalności naukowej zajmuje się diagnostyką techniczną, niezawodnością, technologią napraw i analizą systemową eksploatacji pojazdów i maszyn roboczych. Posiada w swoim dorobku naukowym ponad 260 publikacji naukowych i naukowo-technicznych oraz 6 patentów. Jest autorem lub współautorem opracowań zwartych w tym: Pokładowe systemy nadzoru maszyn ze sztuczną inteligencją (1997), Metody oceny stanu technicznego, wyceny pojazdów i maszyn (1999), Diagnostyka obiektów technicznych (2002), Diagnostyka maszyn roboczych (2004), Utrzymanie pojazdów i maszyn (2007). Jest członkiem Zarządu Głównego Polskiego Towarzystwa Diagnostyki Technicznej, Redaktorem Naczelnym czasopisma „Diagnostyka", członkiem zarządu Polskiego Naukowo-Technicznego Towarzystwa Eksploatacyjnego, członkiem zespołu środowiskowego Podstaw Eksploatacji Komitetu Budowy Maszyn Polskiej Akademii Nauk, Komitetu Motoryzacji i Energetyki Rolnictwa PAN Oddział w Lublinie.