DIAGNOSTIC OF A TURBOCHARGED DIESEL ENGINE

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Abstract: *The paper deals with non-dismountable diagnostic of the power of a turbocharged Diesel engine. For the purposes of diagnostic the transient operation mode of the engine was described by an extended mathematic model that takes into account the influence of suction volumes and exhaust pipes. The results obtained by this improved model were similar to the values measured by an experiment. This model produces relatively more trustworthy information regarding the influence of some typical defects on the chosen diagnostic parameters. Finally, the improvement makes possible to more accurately identify them, on the basis of changes of selected and measured diagnostic quantities the defect that has caused these changes.*

Keywords: DIAGNOSTIC, TURBOCHARGED DIESEL ENGINE, TRANSIENT OPERATION, MODELING.

1. Introduction

Technical diagnostic forms an important part of comprehensive care about service reliability of engineering. It has been proved that application of diagnostic in the technological procedure of attendance and current repair of tanks and automobiles allows to keep high level of their trouble-free operation and to extend the lifetime of the vehicles parts. For these reasons it is also necessary to pay attention to the diagnostic of their engines and by its help to ensure more economic operation on the whole.

For diagnostic the power of the turbocharged Diesel engines a method of acceleration has been used. It means that the diagnostic parameters are measured during the transition mode of run of the engine and turbocharger, when the engines work under conditions that are close to its full load characteristics.

The decisive element of the correct diagnostics is the choice of suitable diagnostic quantities that have sufficient informative weight. It is suitable to carry out this choice on the basis of knowledge of the results that can be preliminarily obtained by means of a mathematic model of dynamic equilibrium of the engine and the turbocharger, compiled for this purpose. This model is completely general. Its application on to the certain engine can be carried out using data and characteristics of the respective engine and of its turbocharger as well. The characteristics of the engine can be obtained using a suitable mathematic model of the engine cycle, e.g. according to literature [1]. Then the modelling of the most frequently occurring defects can be executed, including the determination of their influence on chosen diagnostic parameters. In this very economical way, it is possible to make the choice of suitable diagnostic parameters, without demanding experimental tests.

In the primary solution we have used simplified assumptions, neglecting the volumes of suction and exhaust pipe of the engine. This simplification resulted into a much faster reaction of the turbocharger within the model than was the reaction of the real engine system (obtained from experiments) which, in its results, lowered the informative value of the diagnostic quantities being studied For this reason the primary and simplified model of dynamic equilibrium of turbocharged Diesel engine was extended and the influence of the volumes of the suction and exhaust pipe was taken into account. The correctness of this theoretical solution was proved experimentally.

2. Methods of diagnostic

For diagnostic of the engine power the method of measuring the functional dependence of the crankshaft acceleration was used. Furthermore, this method was completed by simultaneous measuring of the functional dependence of the turbocharger angular speed, since in the [2] and [3] we have found out that the change of the turbocharger speed is one of the basic diagnostic quantities that reacts very sensitively on most of the modelled defects of the engine.

For numerical modelling of the influence of some typical defects on chosen diagnostic quantities a model based on the dynamic equilibrium of the engine and turbocharger was compiled. The method of mathematic modeling of equilibrium and no equilibrium modes of engine and turbocharger cooperation was used for the solution of the above mentioned problems, including experimental verification.

The following procedure was used to achieve the laid out aims:

1. Creation of the mathematic model of dynamic equilibrium of the engine and turbocharger run, including the influence of the volumes of suction and exhaust piping.
2. Expression of the influence of some typical defects on the chosen diagnostic quantities of the system engine-turbocharger using the model of their dynamic equilibrium. Determination the required characteristic of the model has to be carried out by means of the model of static equilibrium.
3. Experimental verification of the theoretical solutions and results.

With the help of analysis of results of modelling and experiments, the diagnostic quantities of turbocharged Diesel engine were precised.

3. Model of dynamic equilibrium

The turbocharged engine can be assumed, from the point of view of its functioning, to work as a system consisting of two subsystems, i.e. of the engine alone and of its turbocharger, bound together aerodynamically through the mediating gas flow. The block diagram of this engine-turbocharger system is presented in fig. 1.

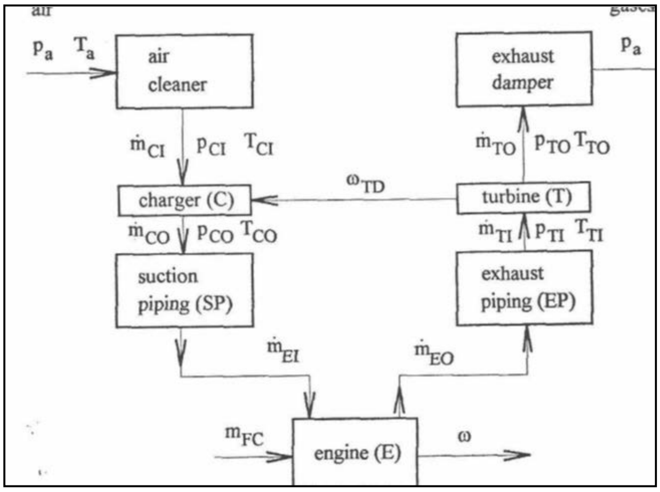


Fig. 1 *Block diagram of the Diesel engine and turbocharger system*

The mathematic description of individual elements of turbocharged Diesel engine is the following:
For the dynamic equilibrium of the engine alone it holds true:

$$J.\frac{d\omega}{dt} = M_E - M_L \tag{1}$$

Where:

J - is the engine inertia moment, i.e. inertia moment of its moving parts reduced into the axis of the crankshaft,
ω - angular speed of the crankshaft,
M_E - engine instantaneous indicated torque,
M_L - instantaneous torque loss of the engine,
$M = M_E - M_L$ - the engine useful torque.

Similarly, for the turbocharger alone, it is valid:

$$J_{TC}.\frac{d\omega_{TC}}{dt} = M_T - M_C \tag{2}$$

Where:

J_{TC} - inertia moment of the turbocharger rotor,
ω_{TC} - angular speed of the turbocharger rotor,
M_T - driving torque of the turbine,
M_C - required torque of the charger.

The torques in the above equations depends on:

- angular speed of the crankshaft (ω),
- fuel injected in the cylinder per a cycle (m_{FC}),
- total feeding pressure of the air behind the charger (p_{CO}),
- total pressure of gases in the exhaust piping (p_π), i.e. in front of the turbine.

The dynamic equilibrium of the change of the air mass in the respective volume of the suction piping can be expressed by the following equation:

$$\frac{dm_{SP}}{dt} = \dot{m}_{CO} - \dot{m}_{EI} \tag{3}$$

Where:

$\dot{m}_{CO}$ - is the air-mass-flow from the charger,
$\dot{m}_{EI}$ - is the air-mass-flow into the engine,
m_{SP} - is the air mass in the suction piping.

Similarly, for the dynamic equilibrium of the change of mass of gases, with the given volume of the exhaust piping, it is possible to write:

$$\frac{dm_{EP}}{dt} = \dot{m}_{EO} - \dot{m}_{TI} \tag{4}$$

Where

$\dot{m}_{EO}$ - mass flow of gases leaving the engine,
$\dot{m}_{TI}$ - mass flow of gases into the turbine,
m_{EP} – mass of the gases in the exhaust pipe.

The last two equations can be rewritten into the following forms. For the suction piping it holds true:

$$\frac{dp_{CO}}{dt} = \frac{n_a . p_{CO}}{V_{SP} . \rho_a} .(\dot{m}_{CO} - \dot{m}_{EI}) \tag{5}$$

and similarly for the exhaust piping:

$$\frac{dp_{TI}}{dt} = \frac{n_g . p_{TI}}{V_{EP} . \rho_g} .(\dot{m}_{EO} - \dot{m}_{TI}) \tag{6}$$

Where:

p_{CO} - is the total pressure of the air behind the charger,
p_{TO} - is the total pressure of the gases in front of the turbine,
ρ_a, ρ_g –are the specific masses of the air and gases,
n_a, n_g, - are the exponents of polytrophic of the air and gases,
V_{SP} - is the volume of the suction piping,
V_{EP} - is the volume of the exhaust piping.

4. Modelling of defects and verification of diagnostic quantities

On the basis of the analyses that were carried out in [2], some suitable quantities have been chosen that react sensitively enough on most of the typical defects that can appear during the engine service and the change of whose reflect trustworthily enough the instantaneous technical state of the engine. These quantities are the following:

- Total temperature in front of the turbine (T_{TI}),
- rpm (n) and angular acceleration (ε) of the crankshaft (expressed indirectly in the form of useful torque M of the engine),
- rpm of the turbocharger (n_{TC}),
- temperature of the cooling liquid (T_W).

The basis for this choice were obtained thanks to the previous modeling and experiments. The influence of typical defects on the chosen diagnostic quantities was stated by means of mathematic models and the obtained results were verified by experiments.

5. Experimental equipment

The theoretical assumptions were verified on the automobile engine SKODA LIAZ M 637 of Czech make. It is a row, six cylinder, water-cooled and turbocharged Diesel engine. The angular position of the crankshaft was measured by the Vibro-Meter KW-T pick up. The second derivation of this quantity has provided the required angular acceleration of the crankshaft. The total pressure of the working fluid behind the charger and in front of the turbine were measured by the help of the Vibro-Meter pick up PR-5K. The total temperature, in front of the turbine, was measured by the thermocouple based on NiCr-Ni alloys. The angular speed of the turbocharger was measured by the optical pick up PU 420. The above mentioned diagnostic quantities were taken by measuring device MC-32, having sampling frequency of 1 MHz.

6. Verification of the theoretical assumptions

By means of the above described mathematic model the calculation of the engine transition process from its equilibrium state at n = 1000 rpm was executed up to the instant of reaching its maximum speed at n = 2000 rpm. During this acceleration the maximum dose of fuel was adjusted.

On the basis of experience from the previous studies [2], [3] there were stated only the values of the following chosen diagnostic quantities:

- speed (rpm) of the turbocharger (n_{TC}) ,
- engine toque (M),
- total temperature of gases in front of the turbine (T_{TI}).

For the possible comparison of these diagnostic quantities we have expressed their dependences on the engine speed.

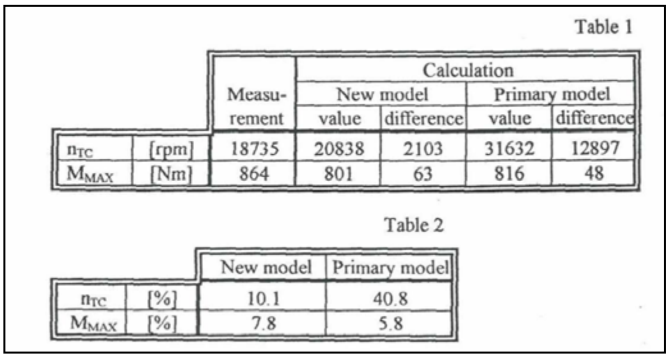


Table 1

		Measu-rement	Calculation			
			New model		Primary model	
			value	difference	value	difference
n_{TC}	[rpm]	18735	20838	2103	31632	12897
M_{MAX}	[Nm]	864	801	63	816	48

Table 2

		New model	Primary model
n_{TC}	[%]	10.1	40.8
M_{MAX}	[%]	7.8	5.8

From the measured and calculated results it is clear that the use of the improved (new) mathematic model of common run of the engine and turbocharger, which respects the volumes of suction and exhaust piping, gives substantionally more precise results, especially in determining the dependence of the turbocharger speed during acceleration. It is possible to demonstrate it on the following results. In the case of the primary mathematic model (without taking into account the influence of volumes of suction and exhaust piping), at the end of the acceleration (i.e. at the engine speed of n = 2000 rpm), the calculated speed of the turbocharger was n_{TC}= 31632 rpm. This value exceeded the measured one by 40,8 %. In the case of the improved mathematic model we have obtained the respective turbocharger speed n_{TC}= 20838 rpm, which is only 10,1% above the measured value.

As it is evident from Table 1 and Table 2, the improvement of the mathematic model has no substantial influence on the calculated value of the engine torque. In both cases of calculations the difference between calculations and experiments is under 8 %.

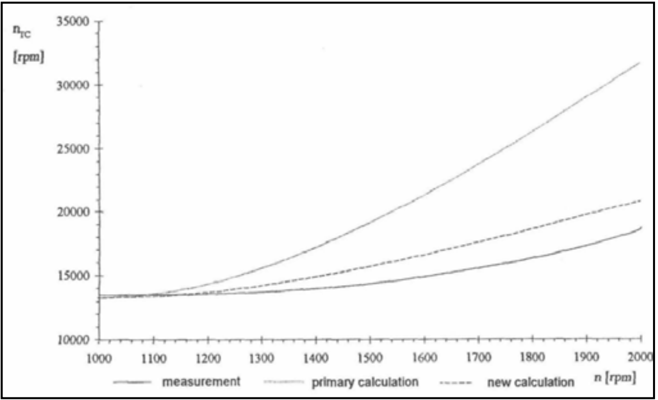


Fig. 2 The turbocharger speed (n_{TC}) dependence on the engine speed (n).

So, the modeling of the engine and turbocharger non-equilibrium run that takes into account the volumes of suction and exhaust piping gives results that differ less from those obtained by experimental measurements. As it can be seen from fig. 2, substantial improvement is reached especially in the case of the turbocharger speed which is one of the most important diagnostic quantities of the engine system.

From the above illustrated facts it follows that the improved mathematic model can give more trustworthy results.

7. Results

The relative changes of the diagnostic quantities to those that correspond to the correct technical state of the engine, which were obtained by using the improved model, are presented in Table 3.

These values were determined for the instant of reaching the engine maximum speed of

n = 2000 rpm. The numbers of corresponding defects taken into account in the Table 3 are the following:

№ 1 : reduction of the fuel dose through 15 %,

№ 2: decreasing the geometric beginning of the fuel injection by changing the crankshaft angle by 6 degree,

№ 3: increasing of the flow resistance in the air cleaner (expressed by the drop of the total pressure in front of the charger) by 10 % at the engine speed of n = 1000 rpm (which is the starting speed of the transition mode of acceleration),

№ 4 : untightness of the cylinder packing, corresponding to 9 % of the engine useful power drop,

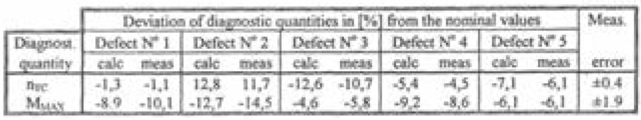
№ 5: increased flow resistance at the engine outlet, expressed by 10 % of pressure rise behind the turbine (at the engine speed of n = 1000 rpm).

Abbreviations used in Table 3 :

calc - values determined by the help of calculation

meas - values obtained by the experimental measurements.

Table 3



	Deviation of diagnostic quantities in [%] from the nominal values										Meas.
Diagnost. quantity	Defect N° 1		Defect N° 2		Defect N° 3		Defect N° 4		Defect N° 5		
	calc	meas	calc	meas	calc	meas	calc	meas	calc	meas	error
n_{TC}	-1,3	-1,1	12,8	11,7	-12,6	-10,7	-5,4	-4,5	-7,1	-6,1	±0.4
M_{MAX}	-8.9	-10,1	-12,7	-14,5	-4,6	-5,8	-9,2	-8,6	-6,1	-6,1	±1.9

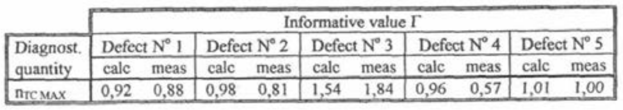
Another criterion, i.e. the informative value of the diagnostic quantities was taken in account and evaluated. Its definition is:

$$\Gamma = \frac{\partial X}{\partial P} \tag{7}$$

Where:

∂X - is the relative change of the respective quantity X and ∂P - is the relative change of the engine useful power P. This informative value Γ, being for a respective diagnostic quantity smaller than 0,8, was taken as a non-governing one. The results of the calculation of Γ for the case of turbocharger speed n_{TC} (which is one of the most important selected diagnostic quantities) are presented in Table 4.

Table 4



	Informative value Γ									
Diagnost. quantity	Defect N° 1		Defect N° 2		Defect N° 3		Defect N° 4		Defect N° 5	
	calc	meas	calc	meas	calc	meas	calc	meas	calc	meas
$n_{TC\,MAX}$	0,92	0,88	0,98	0,81	1,54	1,84	0,96	0,57	1,01	1,00

From comparison with the results in Table 3 it is obvious that good agreement between the results of calculation and measurements is in the case of both the chosen diagnostic quantities, i.e. in the case of the turbocharger speed (n_{TC}) and of the angular speed of the crankshaft (presented here by the engine torque M). Also their informative value Γ is high enough and so it is possible to take both these diagnostic quantities as governing ones. For the illustration the effect of the chosen defects on the both mentioned diagnostic quantities is presented in Fig. 3 and Fig. 4.

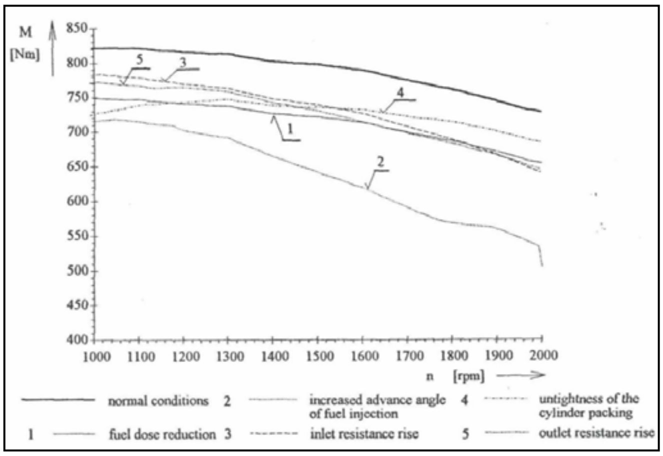


Fig.3 Dependence of the engine torque (M) on the engine speed (n) at difference chosen defects.

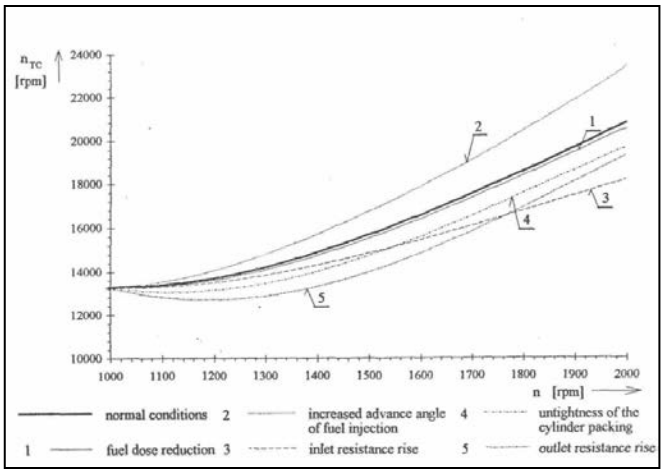


Fig.4 Dependence of the turbocharger speed (n_{TC}) on the engine speed (n) at different chosen defects

7. Conclusions

Ensuring the economic and reliable service of the turbocharged Diesel engines requires diagnostic of their actual technical state. This diagnostics should be simple enough and accurate simultaneously. It should be based on trustworthy information's that reliably correspond to the engine's real technical state. For the prediction of the effect of possible defects on these quantities, it is useful to use a reliable mathematic model which is able to give acceptable results that are close enough to the reality. Starting with the choice of suitable diagnostic quantities, it is then necessary further to precise the model. For the case of the turbocharged Diesel engine it is especially important to precise the two above mentioned diagnostic quantities, i.e. the angular acceleration of the crankshaft and the turbocharger speed.

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