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APPLICATION OF OPTIMISATION FOR DETERMINING THE EXTERNAL CHARACTERISTICS OF A TRACTION DIESEL ENGINE WITH SEQUENTIAL TURBOCHARGING

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Summary. The way has been shown how to shape the characteristics of a diesel engine with sequential turbocharging through a rational selection of turbochargers and the course of the speed characteristics of the maximum delivery of the injection pump, taking into account the imposed restrictions. The quality coefficients for the selection of the optimised parameters have been proposed according to the dynamic criterion, comprising the shape of the curve of the maximum torque. In order to determine the value of these coefficients, in the next steps of the optimisation procedure the gradientless Hooke-Jeeves method has been used.

Key words: combustion engine, turbocharging, optimisation

INTRODUCTION

The sequential turbocharging is based on the application of two turbochargers, most often of different sizes, working in various ranges of the engine speed and load [Borila 1986 a, b, c, Wisłocki K. 1991]. In recent years, there has been a significant increase in interest in its further development potential. This has been shown by the research and the most modern designs of e.g. BMW, Opel and others [Doll G. *et al.* 2005, Jungmann T. 2005, Kołodziejczyk A. 2008, Łęgowicz J. 2005, Pflüger, F. 1998, Saulnier S. 2004, Steinparzer F. *et al.* 2005]. An important problem in the turbocharged engines is the selection of a supercharging device and ensuring adequate conditions for its cooperation with the combustion engine [Syomin D. *et al.* 2010]. In case of the sequential turbocharging, this problem is magnified due to the necessity to choose two supercharging devices, and – additionally – due to the need to ensure adequate conditions for cooperation between them. The results of the previous research by the author indicate diverse, often contradictory effects of various factors affecting the quality of the selection of turbochargers and, consequently, on the course of the engine characteristics. Thus, considering the issue of a proper match of the characteristics of different size turbochargers, it becomes obvious that the selection of their design parameters should take place with application of optimisation methods. It is therefore essential to select a criterion for optimal proceeding (quality coefficients) that takes into account the expected effects. This in particular applies to the proper shaping of the torque curve in the conditions of the external characteristics

[Kowalczyk M. *et al.* 1990]. Ensuring proper co-operation conditions is essential in the phase of switching of operation modes between the turbochargers, and thus it requires including the control issues in the optimisation task. Full use of the air being at disposal and of the whole design also requires an appropriate adjustment of the fuel delivery while ensuring sustainable and safe operation of the engine. In case of shaping of the external characteristics of the engine with sequential turbocharging, a complete solution to the problem of optimisation therefore consists of solving the following partial tasks:

- selection of completion of turbochargers
- determination of the operational characteristics of the switching system,
- determination of the speed characteristics of the delivery of the injection pump in the position of the maximum delivery for the determined conditions of the engine supply.

The quality coefficient values in particular steps of the selection of the optimised parameters, on which appropriate constraints have been imposed, defining the area of feasible solutions, have been determined during numerical tests.

CHARACTERISTICS OF THE NUMERICAL PROGRAM

The values of the coefficient of quality of selection of turbochargers have been determined by including the simulation program developed by the author into the optimisation procedure that enables numerical determination of the engine operating parameters in conditions of the external characteristics for various completions of turbochargers at a given fuel dose course or the excess air coefficient. The simulation program has been based on mathematical models of particular system components: diesel engine, radial compressor, radial turbine [Danilecki K. 2007, Danilecki K. 2008].

A simplified model of the combustion engine, limited to the calculation of the average cycle parameters has been presented in the form of functions describing the values of selected parameters depending on the engine operating conditions. These dependencies have been determined through the identification of the engine, by the approximating with the polynomial functions of the second-degree the sets of discrete values of these parameters obtained under steady conditions in the engine test bed.

The compressor model has been presented in the form of second-degree polynomials, developed on the basis of characteristics provided by the manufacturer, describing the dependence of isentropic compression efficiency and the compression in the function of the air expenditure and the speed of the turbocharger.

For the calculation of parameters of the turbine one has used a generalised description in the form of polynomial functions of dimensionless characteristics obtained experimentally. Functional dependencies obtained in this way allow for the determination of the flow parameter value and the adiabatic efficiency for the given values of the rotor diameter and the flow cross-section of the turbine inlet box.

OPTIMAL SELECTION CRITERION

Bearing in mind the fact that the principal purpose of the application of the sequential turbocharging is to improve the shape of the torque curve on the external characteristics, the quality of selection of turbochargers in both ranges of the system operation has been assessed on the basis of the coefficient that takes into account, most of all, the dynamic properties of the engine. Assuming that an engine with a constant power will be a standard [Jaskuła A. *et al.* 1998], the dynamic optimisation criterion is defined by the condition to obtain a minimum coefficient of:

$$W_d = W_{d(I)} + W_{d(II)} = \int_n \left[T_{tq(P=const)} - \left(T_{tq(I)} + T_{tq(II)} \right) \right] dn, \tag{1}$$

where:

$T_{tq(P=const)}$ – the engine torque at its defined speed n from the useful range of characteristics (n_{min}–n_N), corresponding to the condition of the constant engine power (P=const),

$T_{tq(I)}, T_{tq\ (II)}$ – torque in the first (I) and the second sequence (II) of operation under conditions of the shaped external characteristics, with the same value of n.

The graphical illustration of the W_d coefficient has been shown in the Figure 1.

The values included in the W_d coefficient are the function of the decision variables of the optimisation process.

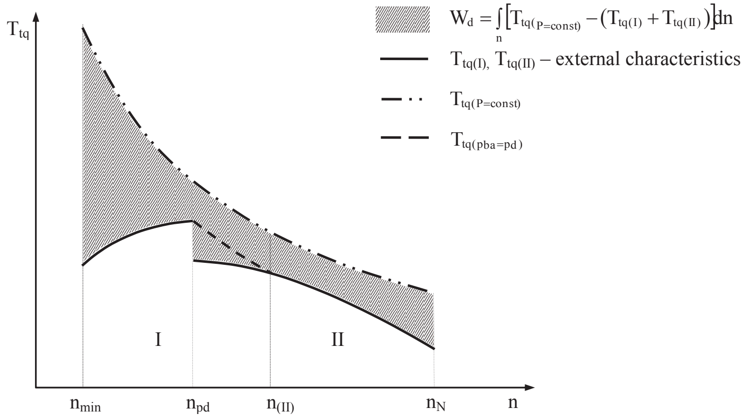

Fig. 1. Diagram illustrating the definition of the quality coefficient W_d

DECISION VARIABLES AND THEIR LIMITATIONS

Formulation of the task as a selection of turbochargers and the operational characteristics of the switching system in the conditions of the external characteristics suggests the adoption of the following decision variables:

x_1 – catalogue number of the rotor of the first sequence compressor,
x_2 – catalogue number of the rotor of the second sequence compressor,
x_3 – inlet cross section of the of the first sequence turbine box $A_{T(I),}$
x_3 – inlet cross section of the of the second sequence turbine box $A_{T(II),}$
x_5 – operating ranges of turbochargers in the conditions of the external characteristics,
x_6 – fuel delivery course.

On the basis of the initial research, the scope of changes in x_1 and x_2 with discrete values available from the particular series of compressor rotors has been limited to two – 309K and 60.

The descriptions of the characteristics of the turbines used in the model allow for determination of the required flow cross-sections that take values within a specified range. The range of variation of x_3, x_4 limits ‘from the top’ the value of the cross-section of A_T=21 cm^2, which corresponds to the initial construction (in the conventional supercharging). The lower limit results from the conditions of not exceeding the pumping limit by the compressors and the permissible values of compression required due to the supercharging characteristics. These conditions are taken into account as internal limitations of the simulation program. They can therefore be neglected in solving the task of selection of the design of turbochargers.

The variable x_5 has been defined as the value of engine speed, at which the second turbocharger is engaged into the cycle. It can act as a function protecting the turbocharger and engine against overload, for example in case of exceeding the permissible supercharging pressure. Thus it becomes the resulting value, losing at the same time the nature of the decision variable. This is equal to adopting the required characteristics of the operation of the switching system.

The decision variable x_6 is a characteristic of the fuel delivery derived from discrete values, found for the determined speeds n in the conditions of the external characteristics of the engine. For particular values of n, the maximum delivery of fuel has been determined for a defined course of the excess air ratio (as in a conventionally supercharged engine) with taking into account the internal limitations covered by the numerical program, and resulting from not exceeding the permissible values of the exhaust gases temperature and the supercharging pressure. Given the adopted directions of search for the optimum value of the criterion function in the scope of the action of these limitations, the possibility of correcting the delivery of fuel has been allowed. In such conditions of calculations, the fuel delivery also becomes the resulting value, which is synonymous with defining the requirements put for the injection pump, operating at the maximum inclination of the control lever.

OPTIMISATION RESEARCH PROCEDURE

The torque values T_{tq} depending on the variables $\{x_{1,}\ x_{2,}\ x_{3,}\ x_{4,}\ x_{5,}\ x_6\}$ determining the objective function have been defined by including a simulation program into the optimisation procedure. The T_{tq} values have been calculated separately for each engine speed with a variable step Δn within its useful range. The characteristics obtained in this way have been used to determine the values of the W_d coefficient in the particular steps of the selection of the optimised parameters. Given that the developed simulation program allows for calculation of the parameters of the engine in a discrete and determined way, in order to solve the optimisation task, a gradientless method has been selected to search for optimum values of the decision variables. The minimum quality coefficient values have been determined using the Hooke-Jeeves method [Kusiak J. *et al.* 2009].

In order to facilitate interpretation of the results, three auxiliary coefficients have been used, which should be considered when interpreting the coefficient of optimality $W_{d.}$ The first of them $W_{(I)}$ expresses the correctness of shaping the engine torque due to its driving characteristics, which requires a possibly large torque supply field within the first operating range (at low and medium engine speeds). This coefficient has been defined as follows:

$$W_{(I)} = \int_{n_{min}}^{n_{II}} \left[T_{tq(P=const)} - T_{tq(I)} \right] dn, \qquad (2)$$

where:

n_{min} – the minimum engine speed,

n_{II} – speed for switching the turbochargers.

According to the adopted structure of the $W_{(I)}$ coefficient, compliance with this criterion requires obtaining the minimum of its value.

The second auxiliary coefficient W_N allows for assessing the shaping of the engine torque within the first range of operation in the conditions of the fuel dosing correction, required due to the characteristics of supercharging (for the turbine with specific flow characteristics). It is proposed to define this coefficient by the expression of:

$$W_N = \frac{\pi}{60} \cdot \left[\frac{(n_{min} + n_{pd})}{(n_{pd} - n_{min})} \cdot \int_{n_{min}}^{n_{pd}} T_{tq(I)} dn - \frac{(n_{pd} + n_{II})}{(n_{II} - n_{pd})} \cdot \int_{n_{pd}}^{n_{II}} T_{tq(I)} dn \right], \tag{3}$$

where:

n_{min} – the minimum engine speed,

n_N – rated speed,

n_{pd} – speed, at which the maximum supercharging pressure is reached,

n_{II} – speed for switching the turbochargers.

It is desirable to obtain even distribution of average power values within the range of speeds without correction and with correction of the delivery, which requires reaching the absolute minimum of the value of the W_N coefficient.

The third coefficient W_k determines the relative value of the delivery corrections required to keep the permissible values of the supercharging pressure within the first range. The changes in the positions of points of the engine operation on the compressor characteristics related to that, depending on the flow cross-section of the turbine are reflected in the values of the λ coefficient forming a part of the coefficient, which is defined by the expression:

$$W_k = \int_{n_{pd}}^{n_{II}} (\lambda - \lambda_z) dn \Big/ \int_{n_{min}}^{n_{II}} \lambda_z dn, \tag{4}$$

where:

λ_z – the set value of the excess air ratio at determined engine speed n from the range of characteristics (n_{pd}–n_{II}) – Figure 1,

λ – corrected excess air ratio in the conditions of shaped external characteristics within the range under consideration at the same speed n.

The assessment of the torque curve has also taken into account the range of speeds covered by the correction (n_{pd}–n_{II}) and the position of the point of switching of turbochargers n_{II}/n_N.

RESULTS OF CALCULATIONS

The optimisation calculations have been carried out for discrete values of the turbine inlet box cross-sections from the range of $A_{T(I)}$=16.8–15 cm^2 and $A_{T(II)}$=6.6–5.1 cm^2. Limitation of ranges has resulted both from the method of the optimisation procedure and the need for proper selection of the step of searching the ranges, and due to the area of permissible solutions defined by the characteristics of the engine supercharging. It has been arbitrarily assumed that the supercharging pressure cannot exceed the value of p_{ba}=0.18 MPa.

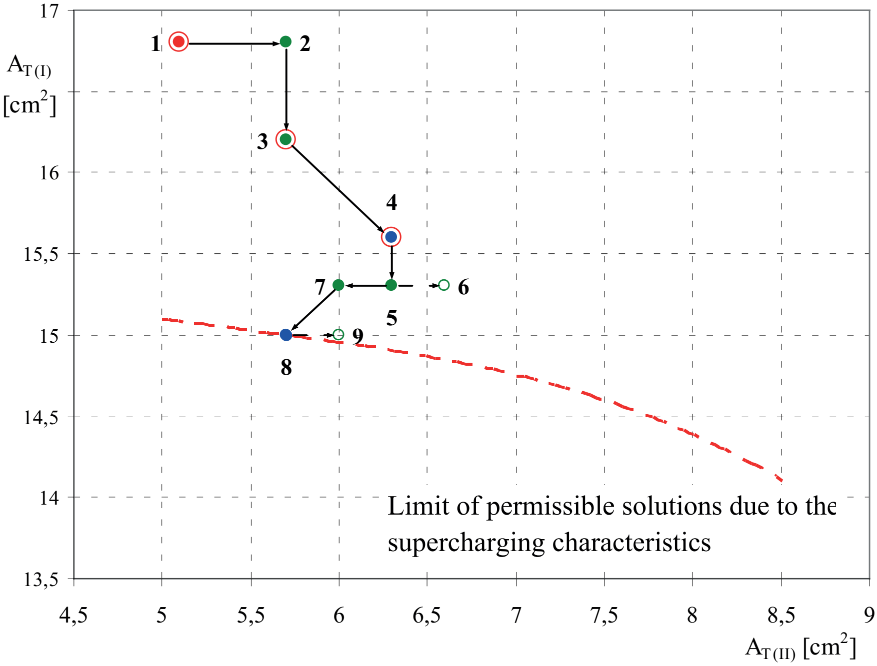

Fig. 2. Search for the minimum of the quality coefficient W_d with Hooke-Jeeves method (subsequent steps of the search have been marked with figures; green points indicate the test steps, and the blue ones – working steps; the red edge marks further basis points, and the dashed line – unsuccessful steps)

In anticipation of the practical use of the optimisation results and their experimental verification, in determining the limits of these ranges and their distinctiveness, one has also included the values of cross-sections of $A_{T(I),}$ $A_{T(II)}$ available for each series of turbochargers.

The effects of the applied optimisation procedure can be seen in the Figure 2, where subsequent steps of search for optimum values of cross-sections of $A_{T(I)}$ and $A_{T(II)}$ have been marked in the area of permissible solutions. For certain compressors, the limit of that area for various associations of the flow cross-sections $A_{T(I)}$ and $A_{T(II)}$ (dashed line) have been determined from the condition of not exceeding the permissible value of the supercharging pressure at the maximum speed of the second range (rated speed). Obtaining of the quality coefficient W_d improvement of less than 1% has been taken as the criterion for the search completion. The results of the W_d coefficient calculation and other coefficients in the next steps of this procedure have been summarised in the Table 1. As it can be seen, the completion of search for the optimum $A_{T(I)}$ and $A_{T(II)}$ cross-sections has taken place in the eighth step of the optimisation procedure due to the characteristics of the engine supercharging for the values of $A_{T(I)}$=15, $A_{T(II)}$=5.7 cm^2. The run of the limiting line does not allow for confirmation of the conjectures about the existence of the global minimum of the W_d coefficient determined in such a way. The decrease in the value of W_d results from the rapid increase in the torque for smaller cross-sections of $A_{T(I)}$ at the first range of operation, as demonstrated by favourable changes in the values of $W_{(I)}$ and $W_{N.}$ However, attention is drawn to the fact of deterioration of the W_k coefficient along with the decrease in the $A_{T(I)}$ cross-section due to the increasing value of the fuel delivery correction at increasing the speed with regards to the set course of the λ coefficient. This confirms the decrease in the speed range covered by the correction ($n_{pd}-n_{II}$). This leads to the offset of the switching point for turbochargers towards smaller speed values (reduction of n_{II}/n_N).

Table 1. Values of the quality coefficient and auxiliary coefficients

Step No.	$A_{T(II)}$	$A_{T(I)}$	W_d	$W_{(I)}$	W_N	W_k	$n_{II}-n_{pd}$	n_{II}/n_N
1	5.1	16.8	123.9	90.2	-21.3	0.0435	340	0.759
2	5.7	16.8	123.6	90.2	-21.3	0.0435	340	0.759
3	5.7	16.2	119.0	87.1	-18.6	0.0505	310	0.727
4	6.3	15.6	114.6	70.8	-16.2	0.0589	300	0.705
5	6.3	15.3	111.1	69.2	-15.3	0.0596	280	0.686
6	6.6	15.3	112.7	70.2	-15.1	0.0622	290	0.691
7	6	15.3	110.3	68.3	-15.4	0.0571	270	0.682
8	**5.7**	**15**	**107.4**	**68.6**	**–14,6**	0.0616	**270**	**0.673**
9	6	15	108.3	68.7	-14.5	0.0617	270	0.673

The mentioned changes in the coefficients of quality for selection of turbochargers can be traced in the Figure 3, which compares the course of the external characteristics for the optimum values of $A_{T(I)}$ and $A_{T(II)}$ and for the cross-sections sections of $A_{T(I)}$=16.8, $A_{T(II)}$=5.7 cm^2 available for each series of turbochargers, that within the areas of permissible solutions are the most similar - in the sense of the adopted criterion - to the optimum solution. Approximately 5.5% increase in the torque value of T_{tq} and the offset of its maximum towards lower values of speed in the case of optimum completion of turbochargers (point line) result from this comparison. For the smaller cross-section of $A_{T(I)}$ one has also obtained a clear increase in the torque throughout the second range at lower specific fuel consumption b. At the same time the engine meets the imposed constraints. However, the earlier mentioned increase in the excess air ratio λ required due to the characteristics of the supercharging, leads to a too strong decrease in the torque at the increasing speed of the first range, which does not allow for further reduction of the W_d coefficient. This fact enforces the earlier engaging of the second turbocharger into the cycle.

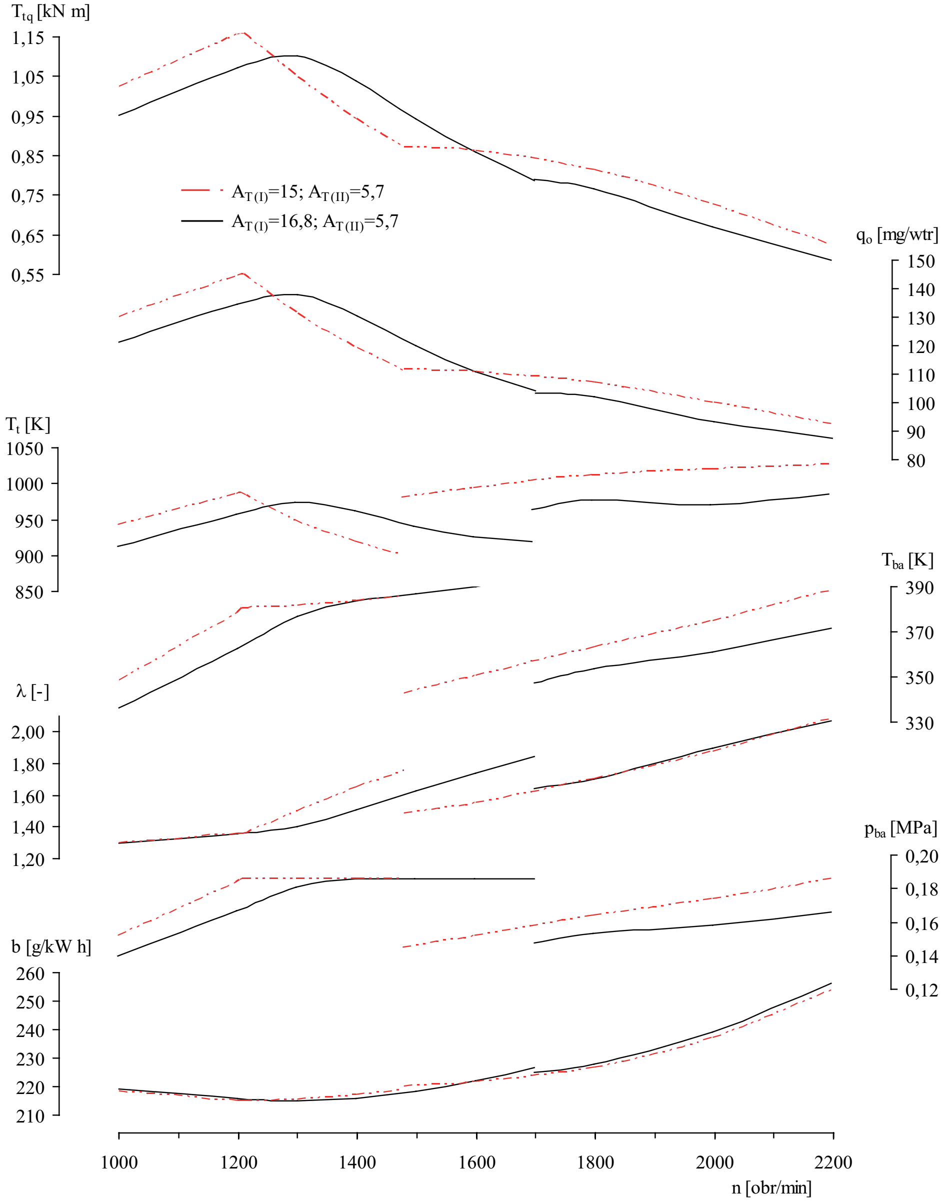

Fig. 3. Results of the optimisation of the selection of the areas of turbine inlet box cross-sections on the curve of the external characteristics of the SW 680 engine: T_{Tq} – torque, λ – excess air ratio, p_{ba} – supercharging pressure, T_{ba} – supercharging temperature, T_t – temperature of exhaust gases, q_o – delivery of fuel per cycle, b – specific fuel consumption

CONCLUSIONS

The results of the works for the optimisation of selection of parameters of turbochargers for the diesel traction engine with sequential turbocharging presented in this paper have demonstrated the usefulness of the proposed models for the simulation research in this field. On the basis of the obtained results it can be concluded that the method discussed in the article allows - in a satisfying way - for the predicting and shaping of the external characteristics of the engine, according to the imposed requirements. However, this method is laborious and requires a complex numerical program. The functions of speed determined during the execution of the optimisation task that describe the maximum values of the delivery of the injection pump as well as the coordinates of the switching points for turbochargers are essentially the solution to the problem of the optimum control. They can thus be used to develop models and algorithms for the numerical system of engine control.

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ZASTOSOWANIE OPTYMALIZACJI DO WYZNACZANIA CHARAKTERYSTYKI ZEWNĘTRZNEJ TRAKCYJNEGO SILNIKA WYSOKOPRĘŻNEGO Z DOŁADOWANIEM ZAKRESOWYM

Streszczenie. Przedstawiono sposób kształtowania charakterystyki wysokoprężnego silnika z doładowaniem zakresowym przez racjonalny dobór turbosprężarek oraz przebiegu prędkościowej charakterystyki maksymalnego dawkowania pompy wtryskowej przy uwzględnieniu nałożonych ograniczeń. Zaproponowano wskaźniki jakości doboru wartości optymalizowanych parametrów według kryterium dynamicznego ujmującego ukształtowanie krzywej maksymalnego momentu obrotowego. Do wyznaczenia wartości tych wskaźników w kolejnych krokach procedury optymalizacyjnej wykorzystano bezgradientową metodę Hooke'a–Jeevesa.

Słowa kluczowe: silnik spalinowy, turbodoładowanie, optymalizacja