Abstract: Increasing the performances of supercharged Diesel engines and reducing their specific fuel consumption and environment pollution suppose not only the application of some efficient constructive solutions, but also the improvement of their control and adjustment, otherwise the above goals cannot be reached. The present paper forwards an original concept and several solutions related to the optimisation of the regulating system’s characteristics with the PGAV governor for supercharged Diesel engines equipping diesel-electric locomotives or variable-pitch propeller ships. In this respect we presented the calculus algorithm and computer software used for the numerical simulation of the PGAV Woodward governor with the purpose of determining an optimised governor characteristic.

Key words: Diesel engine, Woodward governor, optimizing characteristics

1. INTRODUCTION

The regulating system optimisation supposes determining the governor characteristics that should ensure the supercharged Diesel engines operation on its optimal drive characteristic P=f(n’), power depending on speed, where we obtain the engine’s optimal functioning, on all speed steps, as well as the minimum specific fuel consumption.

For optimising the regulating system of supercharged Diesel engines we need to known exactly: the governor characteristic T=f(n), the governor travel depending on supercharging pressure, as well as, the levers system characteristic R=f(T), the engine injection pumps rack travel depending on the governor travel.

The practical establishment of the governor characteristic T=f(n) is essential in the optimising process of the regulating system, since the engine’s propulsion characteristic, in steady state operation, depends on this characteristic.

The governor fuel limiter characteristic T=f(p_lim) is decisive during the accelerating process of any variable-speed supercharged Diesel engine and the dynamic performances of such engines depend on this characteristic.

The characteristic R=f(T) of the levers system between governor and engine is particularly important in the optimisation process of the regulating system since through this system the main adjusting parameters are correlated.

In the adjusting system of variable-speed supercharged Diesel engine for locomotives or ships we encounter a PGAV or PGEV Woodward governor. The PGAV Woodward governors, in present-day construction, is described by a “two-slope” characteristic as seen in Fig.1 [5], still up-to-date, which generates a similar characteristic P=f(n’), power depending on speed, of the Diesel engine overlaps over the propulsion characteristic of the engine only in maximum four points, resulting thus surcharge and undercharge areas. The surcharge areas generate an incomplete combustion in the engine, resulting in the increase of the specific fuel consumption and of environment pollution as well as in the reduction of the engine life span.
2. NUMERICAL SIMULATION OF THE PGAV WOODWARD GOVERNOR OPERATION

In order to improve the PGAV governor characteristic in Fig.1, schematically presented in Fig.2, the author conceived a numerical simulation computer software using the Visual Fox Pro programming language.

The aim of the numerical simulation software is to determine the cam profile from the levers mechanism of the governor (Fig.1), which decisively contributes to the reaching of the desired governor characteristic $T=f(n)$. This is done by imitating, by means of mathematical relations, the actual position occupied, in balance state, by each element of the mechanism, for a chosen number of speed steps within the governor adjusting range. In this respect, when determining the calculus algorithm for the mechanism in Fig.2, we take into account the fact that the joint point A follows the movement of the servo-speed piston rod through $S=f(n)$ relation, experimentally determined, whereas the joint point E strictly follows the movement of the power piston tail rod (T), calculated with $T=f(n^2)$ or $T=f(n^3)$ relation [1], the governor travel depending on the governor speed.

The imitation of the balance operation of the mechanism in Fig.2, during simulation is performed by maintaining constant the lever $\ell_3$ length and the fixed position of joint O. The joint O connects the lever $\ell_3$ and the eccentric, fixed in the adjusting block of the load control pilot valve plunger (s. Fig.1).

In order to determine the calculation algorithm necessary for the elaboration of the numerical simulation software, the mechanism in Fig.2 has been transposed in a conveniently chosen system of co-ordinates.

From the ABCOA quadrilateral (Fig.2) we determine the angle $\varphi_2$, knowing the $\ell_1$, $\ell_2$, $\ell_3$ and $\ell_4$ lengths (from the governor construction) and partially the calculated value of $\varphi_1$ angle.

The angle $\varphi_2$ represents the momentary tilt of the floating lever BD, in relation to the OX$_C$ axis represented by the straight line $\Delta$.

The initial value of the $\varphi_1$ angle, for each position of the mechanism, in the numerical simulation process is determined.
with the equation (1):
\[ \psi = 180^\circ - \psi \quad (1) \]

The angles \( \varphi_1, \alpha \) as well as the \( \ell_4 \) length are determined from \( \Delta AOO' \) (Fig. 2)
\[ \psi = 90^\circ - \alpha \quad (2) \]
\[ \alpha = \arctg \frac{O'A}{O'O} \quad (3) \]
\[ \ell_4 = OA = \sqrt{O'A^2 + O'O^2} \quad (4) \]
\[ O'A = 35.2 - S \quad (5) \]

where: \( S \) – represents the translation travel of the joint point A, performed for each speed step within the considered adjusting range, calculated with the formula deduced by the author [1].

By projecting the outline ABCOA on the axes of co-ordinates, we obtain:
\[
\begin{align*}
\ell_3 \cdot \cos \varphi_1 &= \ell_4 + \ell_1 \cdot \cos \varphi_1 - \ell_2 \cdot \cos \varphi_2 \\
\ell_3 \cdot \sin \varphi_1 &= \ell_1 \cdot \sin \varphi_1 + \ell_2 \cdot \sin \varphi_2
\end{align*}
\quad (6)
\]

We eliminate the angle \( \varphi_3 \) from the equations (6) by rising to square power and addition and then by substituting:
\[ a = \ell_4 + \ell_1 \cdot \cos \varphi_1; \quad b = \ell_1 \cdot \sin \varphi_1; \]
\[ c = \ell_3^2 - a^2 - b^2 - \ell_2^2; \quad d = \frac{b}{a}; \]
we obtain eq. (7):
\[ d \cdot \sin \varphi_2 - \cos \varphi_2 = c \quad (7) \]

Substituting in eq.(7) \( \sin^2 \varphi_2 = 1 - \cos^2 \varphi_2 \), we obtain eq.(8) with the solutions (9):
\[ (1 + d^2) \cos^2 \varphi_2 + 2c \cdot \cos \varphi_2 + c^2 - d^2 = 0 \quad (8) \]
\[ \varphi_2', \varphi_2'' = \arccos \frac{-c \pm \sqrt{c^2 - (1 + d^2)(c^2 - d^2)}}{1 + d^2} \quad (9) \]

We select the smaller value of the angle \( \varphi_2 \). We may determine the co-ordinates of the joint point B(\( x_B, y_B \)), returning to the xO’y’ system of co-ordinates axes as follows:
\[
\begin{align*}
x_B &= 0 \\
y_B &= (35.2 - S) + \ell_1 \quad (10)
\end{align*}
\]

We intersect the straight line eq.(12), crossing the joint point B, with the tilt \( \beta \) eq.(11), with the circle eq.(13) having the center in E and the radius \( \ell_6 \):
\[ \beta = \alpha - \varphi_2 \quad (11) \]
\[ y_D - y_E = - \tan \beta \cdot (x_D - x_E); \quad \tan \beta = m \quad (12) \]
\[ (x_D - x_E)^2 + (y_D - y_E)^2 = \ell_6^2 \quad (13) \]

where: \( y_E = 29.3 + T \)
and \( T \) – represents the governor tail rod travel corresponding to each speed step.

From the intersection of the straight line eq.(12) with the circle eq.(13) there results the eq.(14):
\[ p \cdot x_D^2 - q \cdot x_D + rr = 0 \quad (14) \]

where:
with the solutions (15) 

\[
x_D' = \frac{q + \sqrt{dd}}{2 \cdot p} \quad ; \quad x_D'' = \frac{q - \sqrt{dd}}{2 \cdot p} \quad (15)
\]

We select the smaller value of the abscissa \(x_D\). The ordinate \(y_D\) is determined by the condition that the distance between joints B and D be equal with \(\ell_2 + \ell_5 = BD:\)

\[
y_D = y_B + \sqrt{(\ell_2 + \ell_5)^2 - (x_D - x_B)^2} \quad (16)
\]

Practically we start from the initial value of the angle \(\varphi_1\), determined with the equation (1), adding for each step a calculated \(\Delta \varphi_1\) angle and then we resume calculation from the equation (1), in which the angle \(\varphi_1\) becomes \((\varphi_1 + \Delta \varphi_1)\), as far as the equation (16). The return to the \(xO'y'\) system of co-ordinates is made with the equations (17):

\[
\begin{align*}
x_B &= -\ell_1 \cdot \sin \Delta \varphi_1 \\
y_B &= 35,2 - S + \ell_1 \cdot \cos \Delta \varphi_1
\end{align*} \quad (17)
\]

where \(\Delta \varphi_1\) represents the angle obtained with the help of the numerical simulation, which correspond to the condition imposed by equation (16). Knowing the co-ordinates of joints \(D(x_D, y_D)\) and \(E(x_E, y_E)\), we determine the tilt \(\gamma\) of straight line DE (\(\ell_6\)) in respect to the \(O'x\) axis, with the eq.(18):

\[
\gamma = \arctg \frac{y_E - y_D}{x_E - x_D} \quad (18)
\]

The angle \(\delta\) is known, and thus the tilt \(\theta\) of the straight line EF, in respect to \(O''y''\) axis of the \(xO''y''\) system will be:

\[
\theta = \delta - (90^\circ - \gamma) \quad (19)
\]

With the calculated values of the \(\theta\) angle we calculate the co-ordinates of joint \(F(x_F, y_F)\) which represents the pivot point of the bellcrank DEF roller:

\[
\begin{align*}
x_F &= x_E + \ell_7 \cdot \sin \theta \\
y_F &= y_E - \ell_7 \cdot \cos \theta
\end{align*} \quad (20)
\]

The numerical simulation software calculate and display, for each speed step (\(s. N''\) in Tab.1), S(Sx)-travel, T(Tx)-travel and the co-ordinates of the bellcrank D,E,F joints (\(x_D, y_D, y_E, x_F\) and \(y_F\) in Tab.1), \(X_E=ct.\) (s. Fig.2). The results are synthetized in Table 1.

The co-ordinates of point \(F(X_F, Y_F)\) (s. Table 1) were used to process the cam profile on a numerical control machine and also for the graphic plotting of the cam profile, the objective aimed by the computer numerical simulation.

Table 1
3. CHARACTERISTICS OPTIMISING

3.1 The Governor Characteristic

Using the simulation software in a concrete application we determine the cam profile which can generate a governor characteristic of second square grade \( T = f(n^2) \), compatible with a propeller curve \( P = f(n^3) \) of the engine.

The cam profile generated through numerical simulation is plotted in Fig.3 by a continuous line along with the cam profile in the existing solution, drawn by the dot-dash line tilted at 74°.

Fig.3. Cam profile

Fig.4 shows the plotting of the correspondent characteristics obtained: a – the optimised governor characteristic reached by simulation; b – the governor characteristic in the existing cam solution [4]. Thus, theoretically, the engine running on the optimal characteristic is achieved, as we have reached the set goal, i.e. obtaining of the governor characteristic \( T = f(n^2) \).

3.2 The Levers System Characteristic

We must find what kind of characteristic is transmitted from governor to engine by the levers system. In this respect it is necessary to determine the characteristic of this system \( R = f(T) \) (Fig.5) for which the author forwards an original concept in the paper [3]. An accurate transmission is reached when this characteristic exhibits a straight-line shape.

For an optimal adjustment of the engine it is important to know not only the shape of this characteristic, but also the concrete values of the rack travel (R) which will be realized at the engine in correlation with the governor travel (T).

Fig.5. Typical characteristics \( R = f(T) \)

From this characteristic, the system designing engineer can find if the regulating parameters adopted in the calculus are reached and, if not, he can intervene in the levers system adjustment in order to modify the characteristic, as shown in Fig.5 so that the optimal solution could be found.
3.3 The Fuel Limiter Characteristic

By optimising the fuel limiter characteristic, shown in Fig.6, we aim at matching this characteristic with the supercharging characteristic of the Diesel engine so that, during the accelerating process, an optimal air to fuel ratio be obtained in view of reaching a complete combustion in the engine. The travel difference, realized between the supercharging and limiting characteristics, indirectly expresses the excess fuel fed to the engine in the accelerating process.

![Fig.6. Typical fuel schedule curve](image)

The amount of the “governor travel reserve” is very important since it serves to decide the duration and quality of the engine accelerating process. An excessively low “reserve” will lead to a difficulty and defective acceleration of the engine. An excessively high “reserve” will generate a delayed acceleration with smoke emission at exhaust, increased fuel consumption and pollution.

When practically realising the optimal “reserve”, an important part is played by the establishment and realization of the correlation between adjusting parameters $R_p|_{lim=0}$ and $T_p|_{lim=0}$ from the levers system characteristic $R=f(T)$ (s. Fig.5) as well as by the establishment of an adequate value for the $p_{n,lim}$ (s. Fig.6).

4. CONCLUSIONS

The numerical computer simulation, using the original concept forwarded in this paper, allows the determination of the optimal characteristic of the PGAV Woodward governor.

The solution obtained from the numerical simulation is applicable for all PGAV governors equipping variable-speed supercharged Diesel engines for diesel-electric locomotives or for variable-pitch propeller ships. Thus, the engine operation is assured and guaranteed on the optimal propulsion characteristic where obvious, the minimal specific fuel consumption and the smallest environment pollution are reached. Practically, the original constructive solution, presented in this paper, was successfully tested on our Woodward governor stand and on engine.

5. REFERENCES


6. ADDITIONAL DATA

Author: Gruescu Constantin Andrei
“Eftimie Murgu” University of Resita
Piata Traian Vuia, nr.1-4, 320085 Resita Romania, tel:+40255210227, www.uem.ro e-mail: andy_gruescu@yahoo.com