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CAM SYNTHESIS AND DESIGN OPTIMIZATION OF A MECHANICAL VARIABLE VALVE TIMING MECHANISM WITH CONTINUOUS VALVE LIFT

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ABSTRACT: An innovating solution for throttle-free load control for spark-ignition engines is variable valve timing system with continuous valve lift (VVTL System, or VVA - Variable Valve Actuation System). A variable valve timing mechanism which can provide continuous valve lift (VVL System) represents a good solution for internal combustion engines to become (1) more efficient, with an improved dynamic performance, to generate fewer emissions by reducing fuel consumption and, furthermore, allows technologies like gasoline direct injection (GDI), homogeneous charge compression ignition (HCCI) / controlled auto ignition (CAI), etc. to perform an optimized operation.
In this paper is presented the cam synthesis and design optimization of a valve timing mechanism with continuous valve lift variation and constant duration (2). The approached optimization objectives are: the minimum value of cam radius of curvature (geometric design parameter), the maximum and minimum valve lift which mechanism must assure (operation parameters). The analytical method used for the cam synthesis of the mechanism, which precedes the optimization procedure, is based on the theory of envelopes (3). It is also presented a numerical example, in which the solving principle is based on a numerical method.

1. INTRODUCTION

In Ref. (2) the present author described the mechanism and its operation. The mechanism's minimum adjustment is made by rotating the adjustment element R until O_8 is collinear with O_4 and O_7, Fig. 1. We mention that, in the presented configuration, the mechanism can not provide valves deactivation, the maximum valve lift related to minimum adjustment being above zero. So, we write one of the optimization objectives, i.e. the mechanism must assure valve deactivation which means that in the mechanism's minimum adjustment position, the valve must remains closed, and in the same time all contact joints must be maintained. Let us assume that the position of the adjustment element R is one in which the point O_8 is placed in the right side of the line defined by points O_4 and O_7. In this case the valve is deactivated (if the point O_8 is far enough from the adjustment curve), but within the mechanism's kinematic chain are introduced clearances caused by breaking the C_2 contact joint, or C_1 contact joint, or both. Therefore, when the cam rotates and a higher valve lift is operated, these clearances are eliminated and the contact joints are restored, and, as a consequence strong impacts occur accompanied by noise and vibration. This is the reason why all contact joints must be maintained.

Consequently, the mechanism must be redesigned to satisfy the conditions above. The solution is that in the minimum adjustment, the point O_8 to be coaxial with the point O_4. The effect of the rotational movement of the oscillating rocker 4 is transmitted only to the O_8 roller which rotates around O_8 joint (and O_4 joint, being placed on the same axis), but the push rod 6 remains unmoved like the lever 7 and the valve. Thus, in Fig. 2 are designed two constructive cases, both related to the same kinematic schema. In Fig. 2,A the initial mechanism is redesigned by keeping the initial adjustment curve and repositioning the O_4 joint. On the other hand, in Fig. 2, B the O_4 joint is maintained but it uses a larger radius adjustment curve.

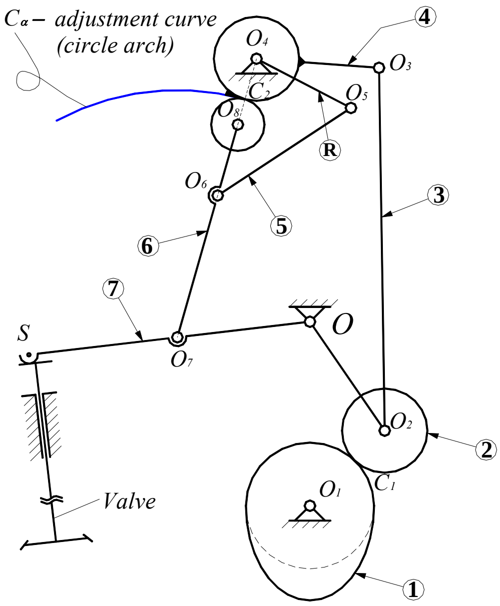

Fig. 1. The kinematic schema of the mechanism in its minimum adjustment position

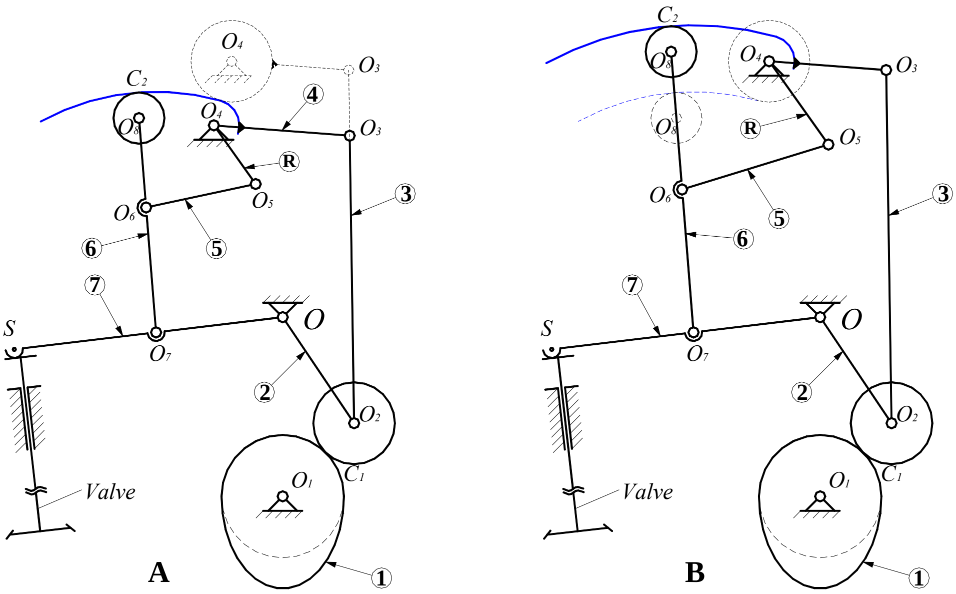

Fig. 2. Variants of mechanism which performs valve deactivation

In conclusion, an optimized design for the proposed mechanism it was established, the mechanism performing now continuous valve lift with valve heights starting from no lift to maximum valve lift which is imposed by the given law related with maximum adjustment.

2. THE KINEMATIC ANALYSIS

2.1. The reference position

The main dimensions and nomenclature (Fig. 3) are maintained accordingly with Ref. (2). Also the relations (3.1), …, (3.7) are valid.

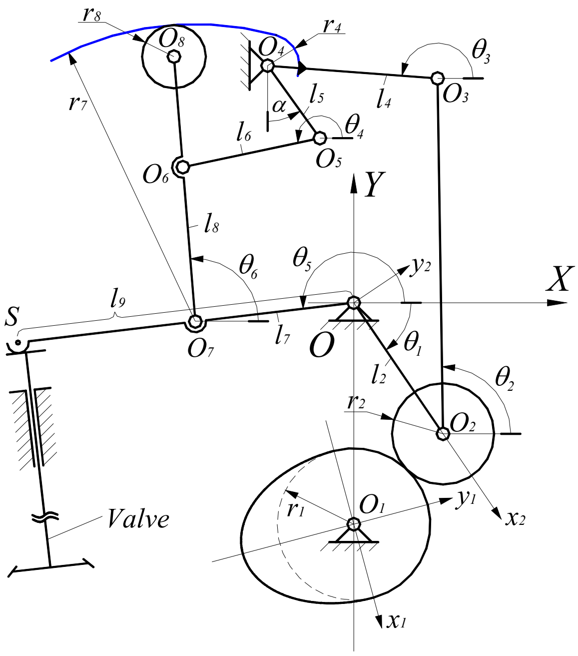

Fig. 3. Kinematic schema with nomenclature

2.2. A certain position

According with Ref. (2), the equations which describe the motion of the mechanism are

$$x_2 \cos\theta_1 + y_2 \sin\theta_1 - x_1 \cos\varphi + y_1 \sin\varphi = 0, \tag{2.1}$$

$$-x_2 \sin\theta_1 + y_2 \cos\theta_1 - Y_1 - x_1 \sin\varphi - y_1 \cos\varphi = 0. \tag{2.2}$$

$$\left(x_{1p}x_{2p} + y_{1p}y_{2p}\right)\sin(\varphi + \theta_1) + \left(y_{1p}x_{2p} - x_{1p}y_{2p}\right)\cos(\varphi + \theta_1) = 0, \tag{2.3}$$

for the contact and tangency joint between cam and the O_2 point centered circle,

$$l_2 \cos\theta_1 + l_3 \cos\theta_2 - X_4 - l_4 \cos\theta_3 = 0, \tag{2.4}$$

$$-l_2 \sin\theta_1 + l_3 \sin\theta_2 - Y_4 - l_4 \sin\theta_3 = 0. \tag{2.5}$$

for the contact from the point O_3, and finally, expressing the lengths O_7O_8, O_6O_8, O_6O_7, it results

$$(X_8 - X_7)^2 + (Y_8 - Y_7)^2 - (r_7 - r_8)^2 = 0, \tag{2.6}$$

$$(X_8 - X_6)^2 + (Y_8 - Y_6)^2 - (r_7 - r_8 - l_8)^2 = 0, \tag{2.7}$$

$$(X_7 - X_6)^2 + (Y_7 - Y_6)^2 - l_8^2 = 0. \tag{2.8}$$

For the reference position we get:

$$\xi_1^* = \frac{\pi}{2} - \cos^{-1}\frac{Y_1^2 + (r_1 + r_2)^2 - l_2^2}{2|Y_1|(r_1 + r_2)}, \tag{2.9}$$

$$\xi_2^* = \pi - \cos^{-1}\frac{l_2^2 + (r_1 + r_2)^2 - Y_1^2}{2l_2(r_1 + r_2)}, \tag{2.10}$$

$$\theta_1^* = \frac{\pi}{2} - \cos^{-1}\frac{l_2^2 + Y_1^2 - (r_1 + r_2)^2}{2l_2|Y_1|}, \tag{2.11}$$

$$\theta_2^* = \frac{\pi}{2} - \sin^{-1}\frac{X_3 - X_2}{l_3}, \tag{2.12}$$

$$\theta_3^* = \sin^{-1}\frac{Y_3 - Y_4}{l_4}. \tag{2.13}$$

The positions of the points O_6, O_8, O_7 expressed in the general reference system OXY are:

$$X_6 = X_5 + l_6\cos\theta_4;\ Y_6 = Y_5 + l_6\sin\theta_4, \tag{2.14}$$

$$\begin{aligned} X_8 &= X_4 + (r_7 - r_4)\cos(\gamma - \theta_3^* + \theta_3) + (r_7 - r_8)\cos\theta_6; \\ Y_8 &= Y_4 + (r_7 - r_4)\sin(\gamma - \theta_3^* + \theta_3) + (r_7 - r_8)\sin\theta_6, \end{aligned} \tag{2.15}$$

$$X_7 = l_7\cos\theta_5;\ Y_7 = l_7\sin\theta_5, \tag{2.16}$$

wherein

$$\gamma = \frac{3\pi}{2} - \sin^{-1}\frac{X_4 - X_7}{r_7 - r_4} \tag{2.17}$$

and

$$\theta_4^* = \pi + \tan^{-1}\frac{Y_5 - Y_7}{X_5 - X_7} - \cos^{-1}\frac{l_6^2 + (X_7 - X_5)^2 + (Y_7 - Y_5)^2 - l_8^2}{2l_6\sqrt{(X_7 - X_5)^2 + (Y_7 - Y_5)^2}}, \tag{2.18}$$

$$\theta_5^* = \pi + \tan^{-1}\frac{Y_4}{X_4} + \cos^{-1}\frac{l_7^2 + X_4^2 + Y_4^2 - (r_7 - r_4)^2}{2l_7\sqrt{X_4^2 + Y_4^2}}, \tag{2.19}$$

$$\theta_6^* = \frac{\pi}{2} - \sin^{-1}\frac{X_6 - X_7}{l_8}. \tag{2.20}$$

Solving the equations (2.1), …, (2.8) in which the unknown parameters are ξ_1, ξ_2, θ_1, θ_2, θ_3, θ_4, θ_5, θ_6, for $\varphi = 1 \div 360°$, it results the movement of the mechanism.

3. CAM SYNTHESIS

In the analytical development of cam profiles, desired positions of the follower are obtained for an inversion of the system (with the cam stationary). The desired cam profile is then obtained by fitting a tangent curve to the successive follower positions. The theory of envelopes from calculus is used below for this purpose, Ref. (5).

Solving the cam synthesis requires a valve lift law, $s = s(\varphi)$. From the valve lift function given by relation (3.32) in Ref. (2), it results the movement law of the lever arm 7:

$$\theta_5(\varphi) = \psi + \theta_5^* - \sin^{-1}\left[\sin\psi - \frac{s(\varphi)}{l_9}\right] \tag{3.1}$$

The obtained equations which govern the movement of the mechanism are (2.1), …, (2.8). From the last five equations we get the functions θ_1, θ_2, θ_3, θ_4, θ_6, for $\varphi = 1 \div 360°$. From the first two equations we get the equations of circles family, in the cam local reference system $O_1x_1y_1$, which depends by φ and ξ_2:

$$\begin{aligned} x_1 &= x_2 \cos(\theta_1 + \varphi) + y_2 \sin(\theta_1 + \varphi) - Y_1 \sin\varphi \\ y_1 &= -x_2 \sin(\theta_1 + \varphi) + y_2 \cos(\theta_1 + \varphi) - Y_1 \cos\varphi \end{aligned} \tag{3.2}$$

equations which comply the condition, Ref. (3):

$$\begin{vmatrix} \dfrac{\partial x_1}{\partial \varphi} & \dfrac{\partial x_1}{\partial \xi_2} \\ \dfrac{\partial y_1}{\partial \varphi} & \dfrac{\partial y_1}{\partial \xi_2} \end{vmatrix} = 0 \tag{3.3}$$

wherefrom it results

$$tg\xi_2 = \frac{Y_1 \cos\theta_1}{l_2 \cos(\theta_{1p} + 1) + Y_1 \sin\theta_1} \tag{3.4}$$

where θ_{1p} is the derivative of θ_1 with respect to cam rotation angle φ. Equations (3.2) which respect the condition (3.4) represent the equations of the synthesis cam, expressed in its local reference system $O_1x_1y_1$.

4. THE MECHANISM DIMENSIONALLY OPTIMIZATION

The approached optimization objectives are: the minimum value of cam radius of curvature (geometric design parameter), the maximum and minimum valve lift which mechanism must assure (operation parameters).
In a cam synthesis problem the elements dimensions are chosen respecting the constructive and functionality constrains, and after that a cam synthesis proceeds, using a particularly valve lift law, $s = s(\varphi)$. As a result the maximum valve lift objective is always fulfilled, assuming that the cam profile is technically correct, i.e. it has no loops and the contact with the next element is permanently assured, accordingly with Ref. (4). The minimum valve lift is achieved by changing the mechanism adjustment angle, in this case the α angle, so the valve lift can reach the needed height.
As regards the cam's radius of curvature, we can achieve an optimum value by resizing the mechanism. Due to the practical design considerations such as contact stress, grinding wheel radius and undercutting, it may be necessary to determine its radius of curvature. For the cam profile given by the parametric equations of $x_1 = x_1(\xi_1)$ and $y_1 = y_1(\xi_1)$, its radius of curvature can be expressed as, (6):

$$\rho(\varphi) = \frac{\left(x_1'^2 + y_1'^2\right)^{1.5}}{x_1' y_1'' - x_1'' y_1'} \tag{4.1}$$

where the prime denotes differentiation with respect to φ.

5. NUMERICAL EXAMPLE AND RESULTS

First, let us consider another approximate dimensions used to validate the kinematic analysis of the optimized model, as follows: $\alpha = 0 \div 62.35434°$, $O_1(0, -35)$ mm, $O_4(-10, 37)$ mm, and the constant parameters given by the values: $l_2 = OO_2 = 25$ mm, $l_3 = O_2O_3 = 52$ mm, $l_4 = O_3O_4 = 23$ mm, $l_5 = O_4O_5 = 20$ mm, $l_6 = O_5O_6 = 23$ mm, $l_7 = OO_7 = 25$ mm, $l_8 = O_6O_7 = 28$ mm, $l_9 = OS = 53$ mm, $l_{10} = OP = 52.8344$ mm, $r_1 = 15$ mm, $r_2 = 8$ mm,

$r_4 = r_8 = 5\,\text{mm}$, $r_7 = 47\,\text{mm}$. The final dimensions of the mechanism will be established after a complete mechanism optimization procedure.

For the mechanism's reference position and $\alpha = 0°$ we obtain: $\xi_1 = 44.527°$, $\xi_2 = 86.460°$, $\theta_1 = 49.013°$, $\theta_2 = 94.134°$, $\theta_3 = -10.032°$, $\theta_4 = 159.864°$, $\theta_5 = 185.208°$, $\theta_6 = 103.839°$, $\gamma = 249.226°$.

In order to generate the family of valve lift laws, we consider the cam is half circle half ellipse, its equation being written in $O_1x_1y_1$, as follows:

$$\begin{cases} x_1 = r_1 \cos\xi_1 \\ y_1 = \bar{r}_1 \sin\xi_1 \end{cases}, \tag{5.1}$$

where

$$\bar{r}_1 = \begin{cases} r_1, \text{for } \xi_1 \in [0,\pi] \\ 1.4r_1, \text{for } \xi_1 \in (\pi,2\pi) \end{cases}. \tag{5.2}$$

Solving the equations (2.1), …, (2.8), in which the initial approximation results from the reference position of the mechanism, i.e. for $\varphi = 0$, we get the eight parameters. The obtained results represent the initial approximation for $\varphi = 1°$. The procedure is repeated until $\varphi = 360°$. By modifying the adjustment angle α within the mentioned range the mechanism performs different valve heights, represented in Fig. 4.

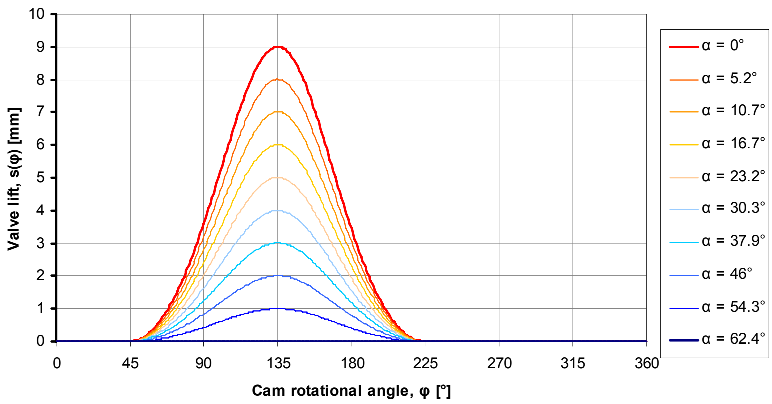

Fig. 4. The valve lift family of laws obtained with a semi-ellipse cam

In Fig. 5 is represented the mechanism adjustment procedure. When the contact C_1 belongs to cam base circle, any variation of the adjustment angle α does not affect the valve's position, i.e. the valve remains closed, and in the same time contacts C_1 and C_2 are maintained. This fact is due to the shape of the adjustment curve C_α, which is a circular shape.

Proceeding to the cam synthesis, we consider the synthesis function the law with maximum height from Fig. 4, which corresponds to $\alpha = 0°$. Solving the equations (2.4), …, (2.8) for $\varphi = 1 \div 360$ degrees, and using relations (3.2) and (3.4) we obtain the cam profile (designed in Fig. 6), which actually represents the initial semi-ellipse cam which was used to generate the family of vale lift laws. This procedure it is used to validate the cam synthesis algorithm.

Next, if we use a certain valve lift law, like the one from Fig. 8 related to $\alpha = 0°$, we obtain the synthesis cam from Fig. 7. By varying the adjustment angle α it results different valve lift laws characterized by different heights.

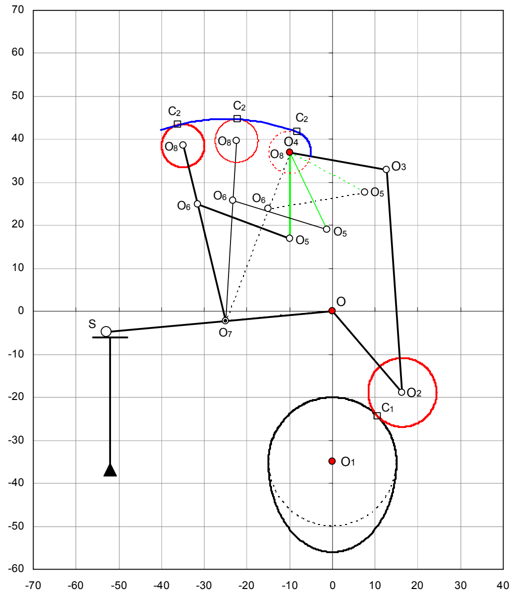

Fig. 5. The adjustment of mechanism in the reference position ($\varphi = 0°$)

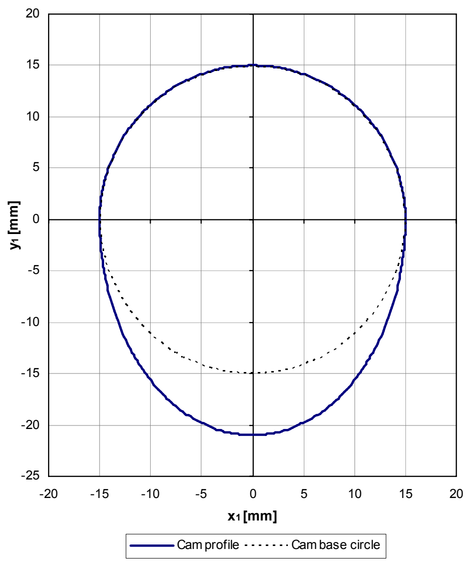

Fig. 6. The synthesis cam obtained from the mechanism's valve lift law which corresponds to the adjustment angle $\alpha = 0°$

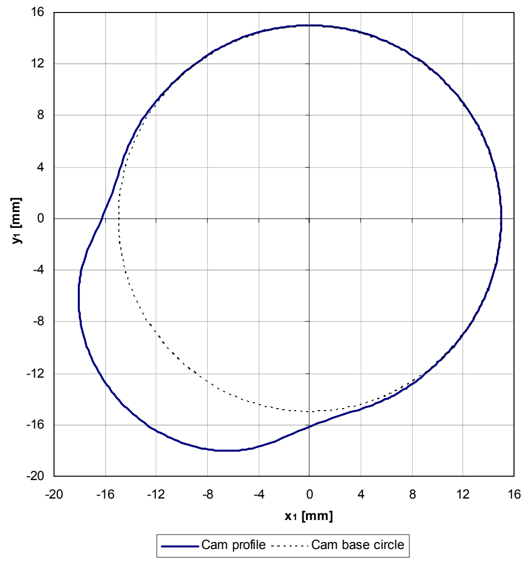

Fig. 7. The synthesis cam obtained from a certain valve lift law

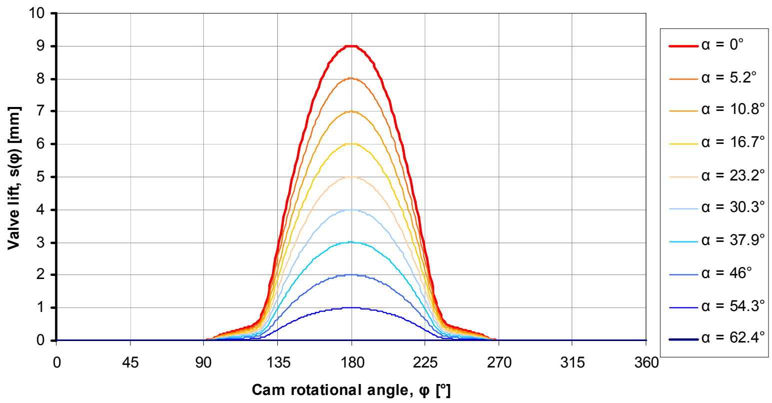

Fig. 8. The valve lift family of laws obtained with the synthesis cam

In Fig. 8 is designed the family of valve lift laws which the mechanism can generate, using the synthesis cam from Fig. 7. The maximum valve lift, according to the imposed law, is $9\,\text{mm}$ at the adjustment angle $\alpha = 0°$, and for the mechanism's minimum adjustment $\alpha = 62.3543°$ the valve remains closed. The mechanism performs continuous valve lift, so any valve lift can be achieved in this range.
Also, the valve opening and closing points remain unchanged during the adjustment variation, which means that the duration of effective valve opening remains the same, as it is showed in Fig. 9. Therefore this mechanism is a Constant Duration Variable Valve Actuation (CDVVA), according to reference (7).

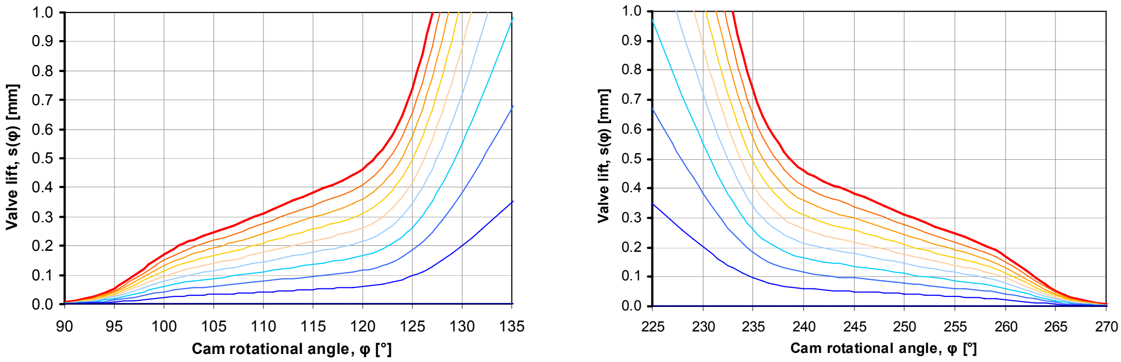

Fig. 9. The valve opening and closing points remain unchanged during the adjustment variation

Until now is established the mechanism's architecture so it performs valve deactivation and also we defined the cam synthesis procedure. We did not approach the issue of the value of cam radius of curvature (geometric design parameter). For the cam profile designed in Fig. 6 the minimum value of cam radius of curvature is $1.810\,\text{mm}$ which is not enough to ensure the mechanism optimum operation. Therefore we impose the minimum radius of curvature $\rho_{\min}$, $\rho_{\min} = 6\,\text{mm}$. Also we have to reconsider the valve axis position, which in a real case is almost perpendicular on the acting lever, as it is drawn in Figs. 1, 2 and 3.

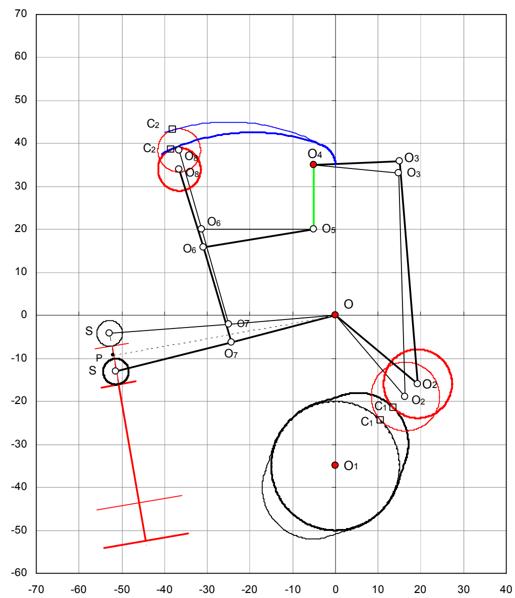

Fig. 10. The final (optimized) design of the mechanism in overlapped positions, $\varphi = 0°$ and $\varphi = 180°$

After optimization procedure the mechanism's final dimensions are: $\alpha = 0 \div 72.36988°$, $O_1(0,-35)$ mm, $O_4(-5,35)$ mm, $l_2 = OO_2 = 25$ mm, $l_3 = O_2O_3 = 52$ mm, $l_4 = O_3O_4 = 20$ mm, $l_5 = O_4O_5 = 15$ mm, $l_6 = O_5O_6 = 26.3$ mm, $l_7 = OO_7 = 25$ mm, $l_8 = O_6O_7 = 23$ mm, $l_9 = OS = 53$ mm, $l_{10} = OP = 52.7587$ mm, $r_1 = 15$ mm, $r_2 = 8$ mm, $r_4 = r_8 = 5$ mm, $r_7 = 47$ mm.

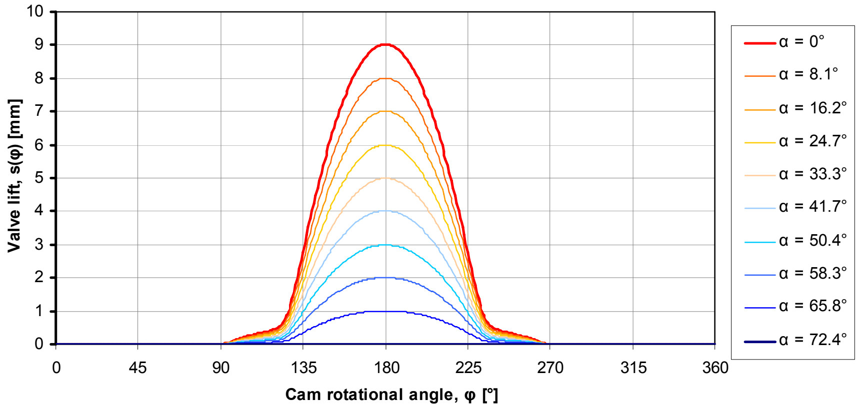

Fig. 11. The valve lift family of laws obtained with the optimized synthesis cam

The optimized synthesis cam is represented in Fig. 12 and is characterized by a minimum radius of curvature $\rho_{\min} = 6.10$ mm, and the family of valve lift laws related to this cam profile is designed in Fig. 11.

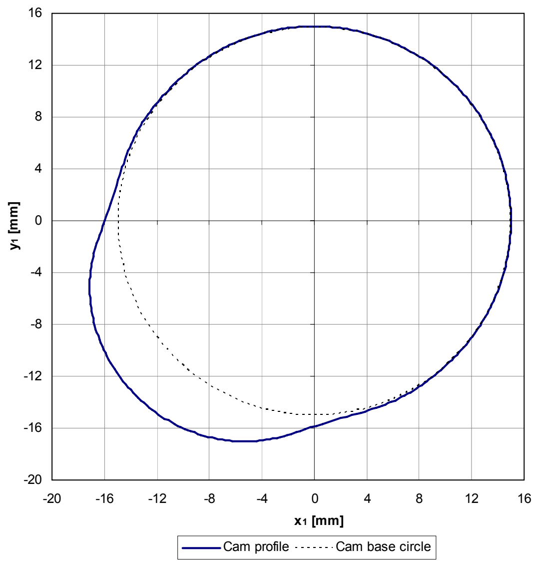

Fig. 12. The optimized synthesis cam obtained from a certain valve lift law

6. CONCLUSIONS

After this study on the variable valve lift mechanism with continuous valve lift the following conclusions were reached:

– The kinematic analysis shows that the mechanism offers a continuous variation of the valve lift, with valve displacement starting from no lift to a maximum lift around 9 mm, without changing the valve opening and closing points. The minimum valve lift must be set on a precise value, around $0.4 \div 0.5$ millimeters, correlated with the engine idling;

– An optimized design of the mechanism was established which also allows valve deactivation;
– After the cam synthesis procedure the minimum radius of curvature reached $\rho = 6.10\,\text{mm}$ which complies the imposed condition $\rho_{\min} = 6\,\text{mm}$.

In this paper are approached only three optimization criteria which means there is a small number of constraints which leads to various configurations which respect the optimization criteria, but if we impose more and more conditions (for example, we did not discussed about the dynamics of the mechanism), the optimum design of the mechanism will be more refined and even closer to a real situation. The numerical example is a step by step optimization in which the initial mechanism is transformed into an optimum solution, via the imposed criteria.

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