THE ANALYSIS OF THE UNCONVENTIONAL PISTON MECHANISM CONCEPTION AND COMPARISON WITH THE CONVENTIONAL PISTON MECHANISM

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ABSTRACT: The IC engines construction is usually neglected by the engineers, so because of this, the last few decades cannot notice big changes from the aspect of the construction of engine mechanical parts. The greatest accent was given to the reduction of the exhaust emission, and with this on the IC engines equipment improvement. In the paper was conducted the analysis of the unconventional piston mechanism, as well as the comparison with classic/conventional piston mechanism. Results show a many advantages from the aspect of IC engine construction, reliability, working cycle and performances, which can be achieved with IC engine with this piston mechanism, and small number of disadvantages, which easy can overcome.

KEY WORDS: *IC engine, unconventional piston mechanism, construction, reliability*

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ANALIZA NEKONVENCIONALNE KONCEPCIJE KLIPNOG MEHANIZMA I UPOREĐIVANJE SA KONVENCIONALNIM KLIPNIM MEHANIZMOM

REZIME: Konstrukcija motora SUS uglavnom je zapostavljena od strane inženjera, te samim tim poslednjih nekoliko decenija ne mogu se uočiti velike promene sa aspekta konstrukcije mehaničkih delova motora. Najveći akcenat je bačen na smanjenje izduvne emisije, te samim tim na usavršavanje opreme motora. U radu je izvršena analiza nekonvencionalne konstrukcije klipnog mehanizma i upoređivanje sa klasičnim konvencionalnim klipnim mehanizmom. Rezultati pokazuju niz pogodnosti sa aspekta konstrukcije, pouzdanosti, radnog ciklusa i performansi, koje se mogu postići ukoliko bi se razmišljalo o proizvodnji motora sa ovakvim klipnim mehanizmom, uz veoma mali broj nedostataka koji se lako mogu prevazići.

KLJUČNE REČI: *motor SUS, nekonvencionalni klipni mehanizam, konstrukcija, pouzdanost*

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INTRODUCTION

IC engines by decades represent an irreplaceable type of drive train for almost all mobile systems. Nevertheless, over a past few years is discussing about the ecology and harmful effect of IC engines, so due this, is predicting their replacement with electric drive train, however, it doesn't exist clear image will be IC engine ever be replaced or not. All these predictions are related with the exhaust emission which cannot be avoided in the case of IC engines. However, the replacement of IC engines with the electric drive train doesn't mean suppression of exhaust emission, but only it dislocation. Also the introduction of a full vehicles electrification demands infrastructure and material resources, for which raises a question, whether they exist. Because all mentioned, it is quite clear that the IC engines are the past, but also and the future of automotive, shipbuilding and other industries, and they will be used in decades which come [1].

From the day of the origin, until today, IC engines have experienced a great progress, from the aspect of performances, economy and exhaust emission. All this changes have become possible thanks to the technology progress, and by its application through systems on IC engines. Nevertheless, the basic construction of the IC engine piston mechanism from the day of the origin, until today have stayed pretty much similar. So because of this, maybe future researches should be directed to the improvement of IC engine piston mechanism, in order to make a new types of IC engines with better characteristics.

Today, standards which are related to the fuel consumption are more and more strict, so from the vehicles with IC engines is expect to have as better possible performances with minimal fuel consumption. One of the solutions which are today widely used at gasoline IC engines, in order to reduce the fuel consumption and by this the exhaust emission is gasoline injection direct to the cylinder, instead to the intake port [2]. Fuel consumption also can be reduced by application of different engine conception [3, 4].

Besides the fuel consumption also should consider the thermal stresses which appear in the engine, and to reduce them to the minimum, how was conducted in the research of Hu et al. [5] on the engine with opposed piston opposed cylinder. Besides that, by application of such engine its obtain the very convenient ratio of surface/volume, shorter combustion, smaller heat loses and more efficient cylinder cleaning [6-8], a besides all of this, was obtained a greater brake thermal efficiency compare to the same power four stroke diesel engine, as well as, lower emission [9, 10]. The exhaust emission can be reduced in many ways by construction parameters. For example, the emission of NOx, directly is related to the temperatures which appear in the engine cylinder, son on this can be affected by application of engine with variable compression ratio [11], as well as, by application of HCCI (homogeneous charge compression ignition) engines which give a low emission of nitric oxides, and besides this can achieve a great efficiency [12]. High-pressure direct injection (HPDI) at diesel Wankel engine reduces the particle emission for 39.5% [13]. Besides using the specific engine constructions, and modern engine equipment, the emission of diesel engine can be reduced and by addition biodiesel [14]. Application of the Achates Power opposed-piston, two-stroke diesel engine provides better reliability and low fuel

consumption, which makes this conception good for application at commercial vehicles in the future.

One more important thing for IC engine, besides its emission, are its performances. Always is tend to develop such IC engine, which will have a good performances. So because of this are developed some unconventional engines, which performances were compared to the performances of convention engines. One type of unconventional engine which was developed and tested is the crank-rocker engine. By application of the crank-rocker engine, it achieves 6.28% greater torque and power compare to the conventional slider-crank engine [15]. Other variant of engine with which are achieving better performances compare to the conventional engine is the Duke engine [16].

The main aim of this paper is kinematic-dynamic analysis of unconventional piston mechanism and comparison with the conventional piston mechanism, in order to represent the potential advantages and disadvantages of analysed solution.

1. UNCONVENTIONAL PISTON MECHANISM

Related to the construction and kinematic characteristics, the existing, more or less used piston mechanisms, can be divided on two types and that:

- Piston mechanism with translational piston movement and
- Piston mechanism with the rotational piston movement.

For the piston mechanism with the translational piston movement freely can be said that this piston mechanism is the classic piston mechanism which is present in almost all IC engines, different from this piston mechanism, engine with piston mechanism with the rotational piston movement, widely known as Wankel engine, represents an engine with quite different piston mechanism. The greatest advantage of engines with the rotational piston movement compare to the mechanism with the translational piston movement is the smaller number of moving parts, as well as the great power for smaller engine displacement. Nevertheless, the disadvantages pf this type of engines, which are the consequence of the engine construction are next:

- Difficult engine sealing,
- Uneven thermal stresses,
- Faster wear and
- Relatively short life cycle.

In order to take advantages and to remove the disadvantages of both types of engines, sometimes the most obvious solution is to make the combination of both of them. Therefore, the analysed type of piston mechanism, in some way can be considered as the combination of the piston mechanism with translational piston movement and piston mechanism with rotational piston movement, Figure 1.

The created model from the Figure 1 corresponds to piston mechanism of a six cylinder engine with the displacement of 2977 cm^3, that is, 3.0 L engine. Of course, the same principle can be applied and for engines with less or more cylinders. The application of translational piston movement provides good sealing between the cylinder block and cylinder head, which is characteristic for the engines with the translational piston movement. Different from that, the application of gears instead the connecting rods, as at the Wankel engine, provides the reduction of the entire engine dimensions as well as engine

mass. Further the mass reduction will positively affect on the fuel consumption reduction and by that on the exhaust emission reduction.
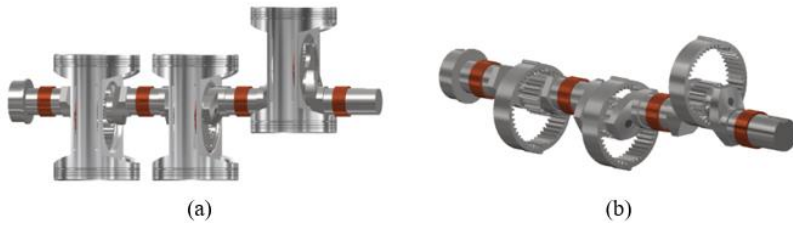

(a)   (b)

Figure 1 3D model of (a) analysed unconventional piston mechanism and (b) connection between the crankshaft and pistons

2. KINEMATIC-DYNAMIC ANALYSIS AND COMPARISON

How the main difference between conventional and unconventional piston mechanism is in construction, main differences which lead to the advantages or disadvantages should look for in the kinematic and dynamic characteristics, which further have influence on the engine work. Kinematic schemes of conventional and unconventional piston mechanism on basis of which can be determined kinematic characteristics are given on the Figure 2.
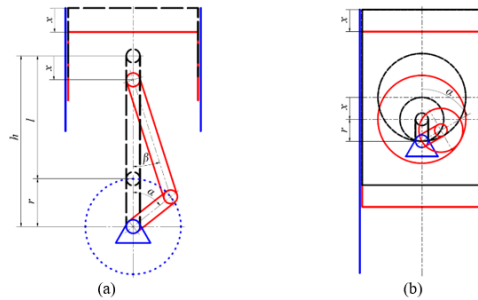

(a)   (b)

Figure 2 Kinematic scheme of (a) conventional piston mechanism and (b) unconventional piston mechanism

The kinematic characteristics of both mechanism can be simply determined by application of the trigonometric equations and functions. Kinematic characteristics determined in this paper for both types of mechanism are piston path, piston speed and piston acceleration. The equations for listed characteristics are next:

- piston path for the conventional piston mechanism

$$x = h - r \cdot \cos\alpha - l \cdot \cos\beta \tag{1}$$

where is:

$$\beta = \arcsin\left(\frac{r \cdot \cos\alpha}{l}\right) \tag{2}$$

- piston path for the unconventional piston mechanism

$$: x = 2 \cdot r - 2 \cdot r \cdot \cos\alpha \tag{3}$$

- piston speed for the conventional piston mechanism

$$v = \frac{dx}{dt} \cdot \frac{d\alpha}{d\alpha} = \omega \cdot \frac{dx}{d\alpha} = \omega \cdot \left(r \cdot \sin\alpha + l \cdot \frac{d\beta}{d\alpha} \cdot \sin\beta \right) \qquad (4)$$

- piston speed for the unconventional piston mechanism

$$v = \frac{dx}{dt} \cdot \frac{d\alpha}{d\alpha} = \omega \cdot \frac{dx}{d\alpha} = 2 \cdot \omega \cdot r \cdot \sin\alpha \qquad (5)$$

- piston acceleration for the conventional piston mechanism

$$a = \frac{dv}{dt} \cdot \frac{d\alpha}{d\alpha} = \omega \cdot \frac{dv}{d\alpha} = \omega^2 \cdot \left(r \cdot \cos\alpha + l \cdot \frac{d^2\beta}{d\alpha^2} \cdot \sin\beta + l \cdot \left(\frac{d\beta}{d\alpha} \right)^2 \cdot \cos\beta \right) \qquad (6)$$

- piston acceleration for the unconventional piston mechanism

$$a = \frac{dv}{dt} \cdot \frac{d\alpha}{d\alpha} = \omega \cdot \frac{dv}{d\alpha} = 2 \cdot \omega^2 \cdot r \cdot \cos\alpha \qquad (7)$$

By analysis of equations from (1) to (7), can be noticed that the equations for the kinematic characteristics of the unconventional piston mechanism are much more simple compare to the equations for the determination of kinematic characteristics of conventional piston mechanism. Even more, for the determination of the piston acceleration, in the case of the unconventional piston mechanism, it is not necessary to use nonlinear differential equation as in the case for the conventional piston mechanism. Differences in the equations lead to conclusion that are existing differences in kinematic characteristics. For better understanding, what main differences are, it was performed the determination of kinematic characteristics for conventional and unconventional piston mechanism with the same geometrical characteristics of engine (cylinder bore and piston stroke), Figures 3 to 5.
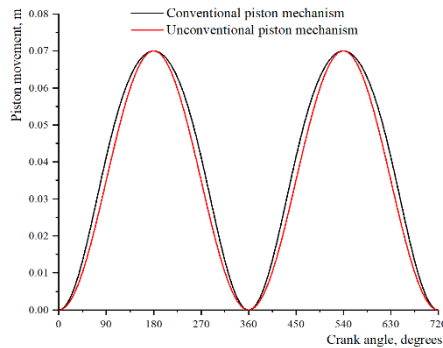

Figure 3 Piston path

By analysing diagram from Figure 3, it can be seen that exist a noticeable difference in the piston path of the conventional an unconventional piston mechanism. The most important difference that can be crucial for the engine work is the piston path behaviour in the area of TDC (Top Dead Centre). In the case of unconventional piston mechanism, piston stays a little bit longer in the area of TDC, which means that the combustion will happen in the conditions which are more similar to the combustion at constant volume. This means that unconventional piston mechanism can approach the engine working cycle to the ideal Otto cycle and in this way to increase the efficiency.
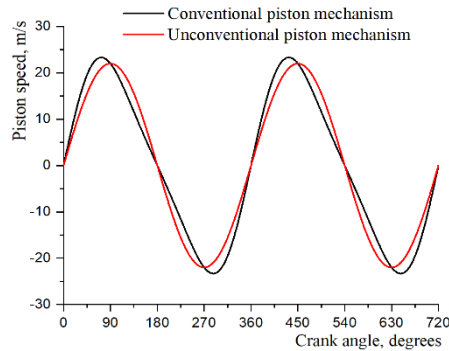
Figure 4 Piston speed

Logically, the differences in the piston path have caused the differences in the piston speed. In the case of the unconventional piston mechanism, the piston speed can be described by sine function which depends only from the crankshaft angle, while in the case of the case of conventional piston mechanism, piston speed depends and from the position angle of the connecting rod. However, the piston speed is not interest from the aspect of engine work. More interesting is the piston acceleration, which is given on the Figure 5.
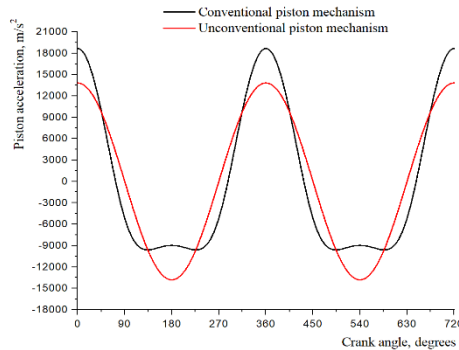

Figure 5 Piston acceleration

Piston acceleration is quite important, because directly influences on the inertial force which acts on the piston. Also, a good know fact is that acceleration is directly related to the vibrations and instability. By observing accelerations curves from Figure 5, it can be seen that the piston acceleration of unconventional piston mechanism corresponds to cosine function, which confirms and equation (7). However in the case of the conventional piston mechanism, the piston acceleration is described by nonlinear differential function. All these difference are appearing exactly because conventional piston mechanism has and unconventional piston mechanism doesn't have the connecting rod. According to the shape of the piston acceleration curves, it can be said that the engine with unconventional piston mechanism will have more stable work.

Further analysis and comparison of conventional and unconventional piston mechanism is based on the dynamic of the piston mechanism, that is, on forces which act inside the piston mechanism during the engine work. Dynamic schemes which were used for determination of dynamic characteristics are given on Figure 6.

For detail dynamic analysis, it is necessary to know the values of the cylinder pressure for the entire working cycle. Therefore, how the unconventional piston mechanism is not made

yet, in continues will be conducted only an analytical analysis, on the basis of the equations which describe the forces from Figure 6.

The gas force which is directly related to the cylinder pressure, in both cases, and for conventional and for unconventional piston mechanism, can be calculated by the same equation, equation (8):

$$F_g = \frac{D^2 \cdot \pi}{4} \cdot (p_g - p_0) \qquad (8)$$

where are:
- p_g – cylinder pressure,
- p_0 - pressure in the crankcase under the piston (approximately equal to the environment pressure).
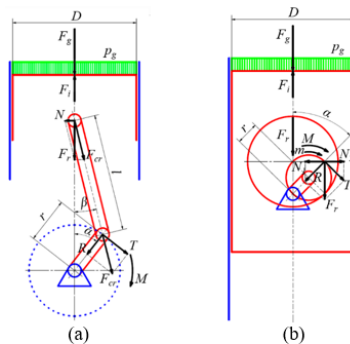

Figure 6 Dynamic scheme of (a) conventional piston mechanism and (b) unconventional piston mechanism

In both cases can be used the same equation for calculation of the gas force. However, on the gas force, the greatest influence has the cylinder pressure, which means that the gas force will have the greatest value in the area of TDC. If take into consideration, previous said that the cylinder pressure will be affected due to the different piston path (piston stays longer in the area of TDC in the case of unconventional piston mechanism and this influences on the combustion process), it can conclude that the gas force will surely be different for unconventional in respect to the conventional piston mechanism.

Inertial force also ca be calculated with the same equation for both piston mechanisms, conventional and unconventional, equation (9):

$$F_i = m \cdot a \qquad (9)$$

where are:
- m – mass of the piston group and
- a - piston acceleration.

As in the case of the gas force, also in this case, the same equation doesn't mean that the values of the inertial force will be the same. First of all the piston acceleration in the case of the unconventional piston mechanism is quite different than the piston acceleration of the conventional piston mechanism. Also the value of the acceleration in the area of the TDC in the case of the unconventional piston mechanism is less than in the case of the conventional piston mechanism which will lead to the greater resulting force (equation (10)) in this area. Also second parameter which influences on the inertial force is the mass of the piston group which in the case of the conventional piston mechanism consists from masses of: piston,

piston rings, wrist pin, snap rings (if they are exist) and one part of the connecting rod mass, while in the case of unconventional piston mechanism, mass of the piston group consists from: piston, piston rings, piston cap, piston gear, piston bearing, snap ring. So all told leads to the conclusion that surely will exist differences in the values of the inertial force.

$$F_r = \pm F_g \pm F_i \qquad (10)$$

The force which doesn't exist in the case of the unconventional piston mechanism is the connecting rod force, which in the case of the conventional piston mechanism can be calculated by the equation (11).

$$F_{cr} = \frac{F_r}{\cos \beta} \qquad (11)$$

The greatest mechanical advantage of the unconventional piston mechanism is because it doesn't have a connecting rod. Thanks to this in the case of the unconventional piston mechanism doesn't exist normal force, which in the case of the conventional piston mechanism can be calculated by equation (12).

$$N = F_r \cdot tg\,\beta \qquad (12)$$

Normal force is undesirable force which pushes piston along the cylinder wall. This causes friction force between piston and the cylinder, which eventually leads to the wear and the engine failure. Different than the conventional piston mechanism, in the case of unconventional piston mechanism are appearing two normal forces, shown on Figure 7.

Figure 7 Forces

For the calculation of normal forces which appear in the case of the unconventional piston mechanism, it is necessary to know the values of tangential force and radial force, which can be calculated by equations (13) and (14).

$$T = F_r \cdot \sin \alpha \qquad (13)$$

$$R = F_r \cdot \cos \alpha \qquad (14)$$

While in the case of the conventional piston mechanism, tangential force and radial force can be calculated by equations (15) and (16).

$$T = F_{cr} \cdot \cos\left(90° - (\alpha + \beta)\right) \qquad (15)$$

$$R = F_{cr} \cdot \sin\left(90° - (\alpha + \beta)\right) \tag{16}$$

So according to the Figures 6 and 7, and equations (13) and (14), the equations for the calculation of normal force for the unconventional piston mechanism are next:

$$N_1 = T \cdot \cos\alpha = F_r \cdot \sin\alpha \cdot \cos\alpha \tag{17}$$

$$N_2 = R \cdot \cos(90° - \alpha) = F_r \cdot \cos\alpha \cdot \cos(90° - \alpha) = F_r \cdot \sin\alpha \cdot \cos\alpha \tag{18}$$

By analysis of relations (17) and (18), it can be seen that the normal forces have the same value, and from Figures 6 and 7 can be seen that this forces have opposite direction, which means that the one will suppress another, that is, in the case of the unconventional piston mechanism, the normal force which push the piston along the wall of the cylinder doesn't exist. This leads to the conclusion that is real to expect a longer life cycle from the engine with unconventional piston mechanism, as well as better mechanical efficiency.

At the end, one more advantage of the unconventional piston mechanism, can be found in better performances of the engine. This can be proved by comparing the equations for torque for conventional (19) and unconventional piston mechanism (20).

$$M = T \cdot r \tag{19}$$

$$M = T \cdot 2 \cdot r + F_r \cdot 2 \cdot r \cdot \sin\alpha = T \cdot 2 \cdot r + m \tag{20}$$

By analysing equations (19) and (20), it can be seen that in the case of the unconventional piston mechanism, torque is equal to the sum of two torques, where one comes from the tangential force as in the case of conventional piston mechanism, and other appears due the translation of resulting force, which means that engine with unconventional piston mechanism easy can have a greater torque and by that and greater power than the engine with the conventional piston mechanism.

3. CONCLUSIONS

In the paper was conducted analytical analysis of the unconventional piston mechanism and comparison with the conventional piston mechanism. The unconventional piston mechanism analysed in the paper represents the combination of the piston mechanism with translational piston movement and piston mechanism with rotational piston movement. By analysis of: geometrical, kinematic and dynamic characteristics, it can conclude, that the unconventional piston mechanism provides a many advantages compare to the conventional piston mechanism such are: smaller dimensions and by that less mass of the entire engine, combustion at almost constant volume, more stable work, nonexistence of normal force (wear reduction and by that increment of the reliability and life cycle), and compare to the classic rotational engines, unconventional piston mechanism provides better sealing, more even thermal stresses. All these advantages lead to the conclusion that this type of engine is maybe ideal for implementation in branches where a high reliability is necessary, for example military industry or shipbuilding industry. Also should not forget and the fact that this type of piston engine can lead to a possibility to obtain greater power for the same displacement of engine with the conventional piston mechanism. However, the main disadvantage is relatively complex construction, and because of this probably a greater

price. However in the braches such are military and shipbuilding industry these disadvantage should not be an obstacles. How all claims are based on the analytical analysis, it should made a many more researches related to the analysed piston mechanism. In future it is necessary to calculate and analyse the loads of the gear couple. This demands a concrete values of forces, which means that is necessary to know the values of the cylinder pressure. So the next step should be to made a model of working cycle of IC engine with unconventional piston mechanism, for example in some specialized software, in order to obtain the values of the cylinder pressure, and in the case of encouraging results, the next step will be the construction and manufacturing of engine prototype which will be tested.

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