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## IRREGULARITY OF RUN IN MECHANICALLY BALANCED DRIVES – THE PERSPECTIVES OF HYBRID BALANCING

### NIERÓWNOMIERNOŚĆ BIEGU W NAPĘDACH WYRÓWNOWAŻONYCH MECHANICZNIE – PERSPEKTYWY WYRÓWNOWAŻANIA HYBRYDOWEGO

#### Abstract

Irregularity of run of an internal combustion piston engine is a source of its basic drawback among which one should first of all mention noise and vibrations. In order to minimize the drawbacks listed above, flywheels are used. In recent years, a tendency to use more complicated methods of improving the degree of irregularity of run has been noticed. A distinct leveling of angular velocity is most of all obtained by the application of dual mass flywheels. Even better effects can be obtained in four-cylinder engines by differentiating towards each other the height of location of rollers balancing the resultant 2<sup>nd</sup> order force. The latter solution is however efficient for a strictly defined angular velocity. The mentioned defect does not occur in the case of the electrical machine of a hybrid unit used to increase the torque at the time of shortage of torque in the combustion engine and to reduce the torque – by braking – at the time of completion of the expansion stroke, namely the occurrence of the excess of torque. In the article, a broader analysis of the indicated solutions leading to the improvement of the degree of irregularity of an internal combustion engine running is presented.

*Keywords: hybrid drives, internal combustion engine, mechanically balanced drives*

#### Streszczenie

Nierównomierność biegu tłokowego silnika spalinowego jest źródłem jego podstawowych wad, wśród których należy przede wszystkim wymienić hałas i drgania. W celu ograniczenia wymienionych wad stosuje się koła zamachowe. W ostatnich latach można jednak zauważyć tendencje do stosowania bardziej skomplikowanych metod poprawy stopnia nierównomierności biegu. Wyraźne wyrównanie prędkości obrotowej zyskuje się przede wszystkim w wyniku zastosowania dwumasowych kół zamachowych. Jeszcze lepsze efekty można uzyskać w silnikach czterocylindrowych, różnicując względem siebie wysokość położenia wałków wyrównoważających wypadkową siłę drugiego rzędu. Ostatnie rozwiązanie jest jednak skuteczne dla ściśle określonej prędkości obrotowej. Wymieniona wada nie występuje w przypadku wykorzystania maszyny elektrycznej zespołu hybrydowego do zwiększania momentu obrotowego w chwili niedoboru momentu obrotowego silnika spalinowego i zmniejszania tego momentu – poprzez hamowanie – w momencie realizacji suwów rozprężania, czyli występowania nadwyżki momentu. W artykule przedstawiono obszerną analizę zasygnalizowanych rozwiązań zmierzających do poprawy stopnia nierównomierności biegu silnika spalinowego.

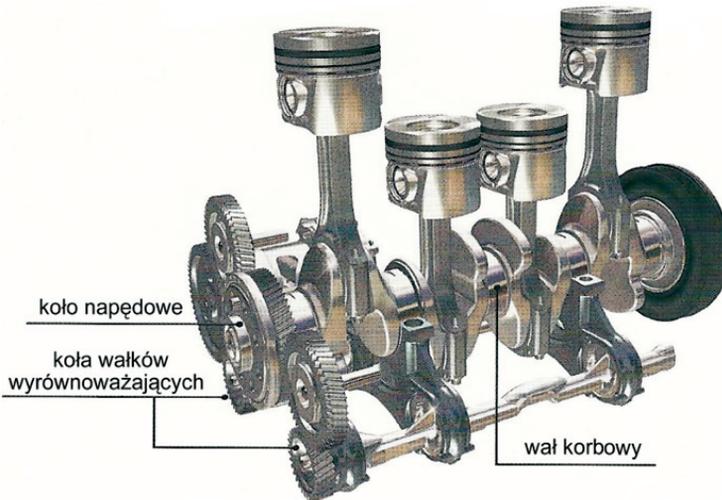
*Słowa kluczowe: napęd hybrydowy, silnik spalinowy, mechanicznie wyrównoważone napędy*

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## 1. Introduction

The source of vibration and noise generated by piston combustion engines is, inter alia, unbalanced external inertia forces, their moments and a variable torque transferred to the power receiver. An analysis of the named physical quantities requires understanding of the currently used motor units in the means of transport. Following the period of an absolute domination of 4-cylinder 4-stroke engines, such engines still prevail, but they are more often equipped with backward rollers balancing the summary forces of the second order. Figure 1 depicts a piston-crank system used in the new generation 4-cylinder Mercedes-Benz engine equipped with backward rollers balancing the 2<sup>nd</sup> order force caused by the inertia of reciprocating masses [1].

More and more often, in higher class automobiles in particular, the location of the balancing rollers is modified in order to partially balance the 4<sup>th</sup> order harmonic passed onto the power receiver. In more mature solutions, the vibrating masses are not equal, which improves the effect in a broader range of angular velocity [2] – Fig. 2.



Key:

koło napędowe – drive wheel

koła wałków wyrównowazających – balancing rollers' wheels

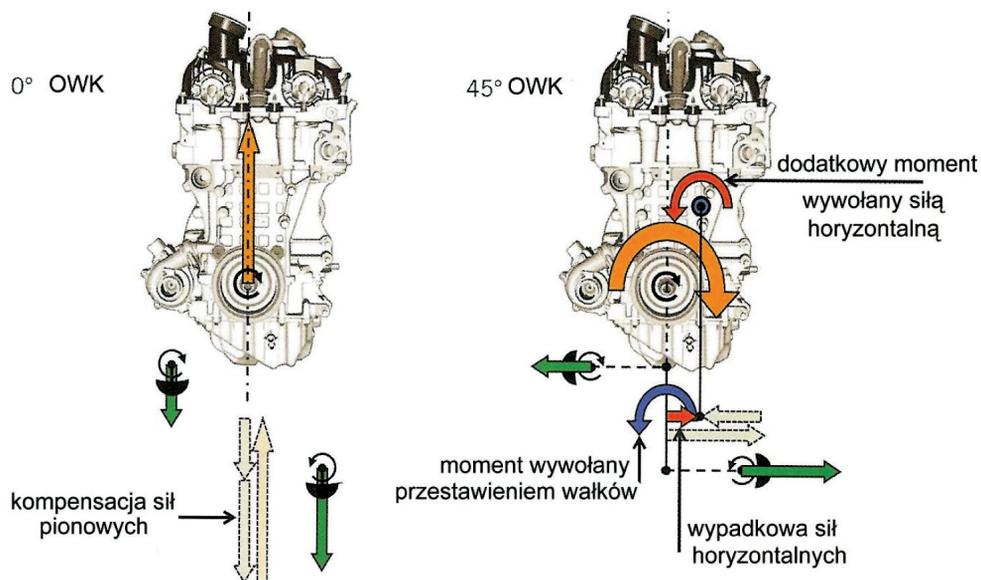
wał korbowy – crankshaft

Fig. 1. A piston-crank system used in the new generation 4-cylinder Mercedes-Benz engine equipped with backward rollers balancing the 2<sup>nd</sup> order force caused by the inertia of reciprocating masses

Rys. 1. Mechanizm tłokowo-korbowy nowego czterocylindrowego silnika produkcji firmy Mercedes-Benz wyposażonego w układ wałków wyrównowazających siły bezwładności drugiego rzędu

The BMW company has put such an engine into their models as a competitive one for the 6-cylinder engines. The 4-cylinder engine is then treated by the aforementioned company as the future one in luxurious models, while the conducted research indicates that replacing 6 and 8-cylinder engines does not lead to the increase in noise and vibrations generated by the

vehicle if the engine is equipped with properly located asymmetrical balancing rollers. The effect which is obtained owing to the new engine concept means decreasing fuel consumption as well as engine production costs in luxurious automobiles.



Key:

- dodatkowy moment wywołany siłą horizontalną – additional moment generated by horizontal force
- kompensacja sił pionowych – compensation of vertical forces
- moment wywołany przestawieniem wałków – moment generated by repositioning rollers
- wypadkowa sił horizontalnych – resultant of horizontal forces

Fig. 2. The impact of balancing rollers of unequal masses displaced vertically in the new generation 4-cylinder BMW engine [2]

Rys. 2. Wpływ zastosowania wałków wyrównowazających o różnych masach rozmieszczonych w płaszczyźnie pionowej nowego czterocylindrowego silnika produkcji BMW [2]

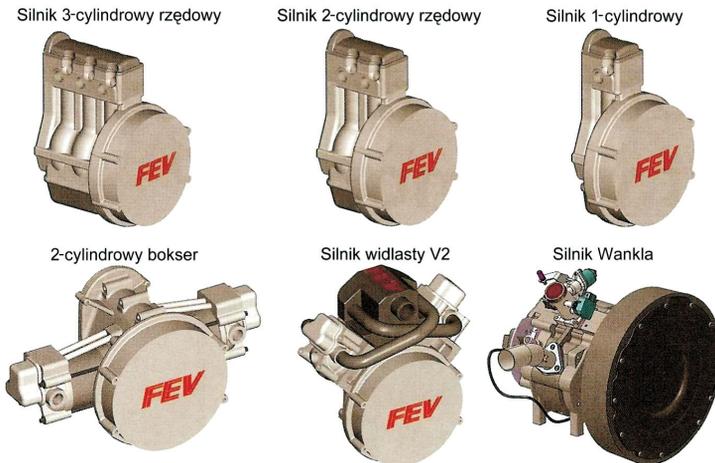
In connection with the tendency to introduce 4-cylinder engines into luxurious automobiles as the main source of drive, the question arises whether one should introduce engines with less than 4 cylinders but equipped with proper balancing rollers as the source of drive in middle-class automobiles.

A hint is that there is research on the concept of an additional internal combustion engine in the so-called Range Extender system. The system is to be applied in cars using mainly electric drive but giving a possibility of extending the range of the car to 500 km, while electric batteries give an opportunity of obtaining the range of 50 km.

Very advanced works on the engines of the Range Extender System are carried out by FEV company [3] pointing to the possibility of limiting forces and external moments for 1–3 cylinder engines and Wankel engines summarized in Tab. 1.

Mass and gas forces and external moments

	1	R2			V2(90°)	B2	R3	Wankel
Angle between cranks		360°	180°	90°	360°	180°	120°	
Angle between ignition	720°	Equal 360°	Unequal 180°–540°	Unequal 270°–450°	Unequal 270°–450°	Equal 360°	Equal 240°	Equal 360°
Balancing mass		Rollers 1 order		Rollers 1 order	Counter weigh		Rollers 1 order	Counter weigh
1st order mass forces	1 $F_{01}$ vert. osc.	2 $F_{01}$ vert. osc.	0	1,4 $F_{01}$ vert. osc.	1 $F_{01}$ rot.	0	0	0
2nd order mass forces	1 $F_{02}$ vert. osc.	2 $F_{02}$ vert. osc.	2 $F_{02}$ vert. osc.	0	1,4 $F_{02}$ osc.	0	0	0
1st order mass moment	0	0	a $F_{01}$ hor. osc.	0,7 a $F_{01}$ hor. osc.	0,5 b $F_{01}$ rot.	b $F_{01}$ vert. osc.	1,7 a $F_{01}$ hor. osc.	0
2nd order mass moment	0	0	0	a $F_{02}$ hor. osc.	0,7 b $F_{02}$ hor. osc.	b $F_{02}$ hor. osc.	1,7 a $F_{02}$	0
a – cylinder-axis-to-cylinder-axis distance b – the boxer engine block shift					$F_{01}$ – amplitude of 1st order oscillating mass forces generated in 1 cylinder $F_{02}$ – amplitude of 2nd order oscillating mass forces generated in 1 cylinder			



Key: 3-cylinder inline engine, 2-cylinder inline engine, 1-cylinder engine, 2-cylinder boxer engine, V2 engine, Wankel engine

Fig. 3. The outer looks of the engines specified in table 1

Rys. 3. Widok zewnętrzny silników wymienionych w tabeli 1

Reduction or elimination of a specific external impact of the engine can be achieved by means of additional rollers and/or counterweights coupled to the crankshaft. In Fig. 3 the outer looks of the engines specified in Tab. 1 are presented.

Based on the analysis of properties of the engines described in Tab. 1 there arises a certain possibility to eliminate external forces in a 2-cylinder inline engine of the angle between the double cranking equaling  $360^\circ$ . Similar opportunities are given by a 2-cylinder boxer engine, but such an engine shows less favorable external dimensions than a 2-cylinder inline engine. The further part of this article will define the opportunities to reduce or fully balance the resultant oscillating forces and moments in a 2-cylinder inline engine by applying two backward rollers.

## 2. Balancing the resultant 1st order oscillating forces

Balancing the resultant 1st order oscillating forces in a 2-cylinder inline engine requires applying two rollers rotating backwards at the angular velocity identical to the one of the crankshaft. The distance of the rollers from the plane axis of the cylinders must be the same so as not to generate additional moment. An exemplary arrangement of the balancing rollers is presented in Fig. 4.

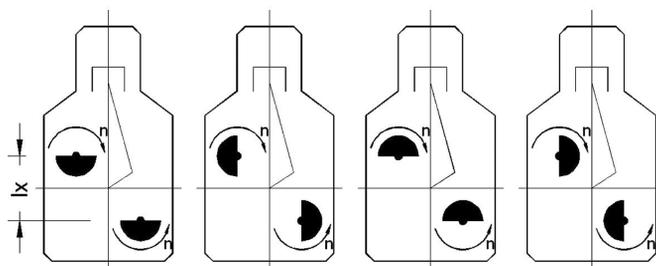


Fig. 4. A diagram presenting the arrangement of rollers balancing 1st order oscillating forces in a 4-stroke 2-cylinder inline engine

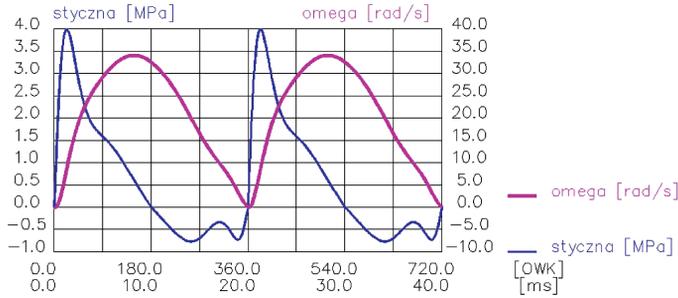
Rys. 4. Wykres obrazujący układ wałków wyrównujących siły drgań 1-go stopnia w czterosuwowym dwucylindrowym silniku rzędowym

Vertical components of inertia forces imposing a load on the counterweights balance the resultant 1<sup>st</sup> order inertia forces generated by oscillating masses. Since the axes of rollers of counterweights are displaced by  $I_x$  distance, an extra moment balancing the harmonic component of the torque loading the crankshaft is generated. Unfortunately, in order to balance the above mentioned harmonic in the whole range an possible angular velocities and loads one should relate the arm  $I_x$  of inertia force to the parameters of engine work. However, there is no doubt that eliminating 1<sup>st</sup> harmonic from the moment loading the crank will quite significantly limit vibrations and noise generated by a 2-cylinder inline engine. Figure 5 presents the course of the specific tangential force generated for  $I_x = 0$ , and Fig. 6 depicts a corresponding parameter for the optimal value of  $I_x$ .

It turns out that generating corresponding work parameters by the most popular 4-cylinder inline engine of the same total cubic capacity results in only slightly better regularity of run. In the case of a 2-cylinder engine, the rate of irregularity of run equals  $\delta = 1/27$  and for a 4-cylinder engine  $\delta = 1/34$  – see Fig. 7.

Applying balancing rollers in a 4-cylinder inline engine gives an opportunity to significantly improve the parameters of this engine shown in Fig 7. The obtained result is pictured by the courses specified in Fig. 8.

```
Zbiór - 30290      c:\silnik\WYNIKI\st30290om.scr
Lc=2      om=314   Dt=0.096   r=0.048   etam=0.810
eps=10.00 fic=3.62 ro=1.00   n1=1.35   n2=1.38   pa=0.194
rnp=0.84  mo=2.20 kz=0.100   lam=0.263 mi=0.000   pd=0.206
Moc NI    - 65.6 [kW]      Max. norm. - 0.902 [MPa]
Moc/V    - 51.99 [kW/l]    Max. pred. - 15.472 [m/s]
Max. nar. - 6.583 [kN]     czas obrotu - 20.0 [ms]
Nier. delta - 1/9
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Key: zbiór – file, Lc – numebr of cilinders, Moc – power rating, czas obrotu – revolution time

Fig. 5. The course of the specific tangential force generated on the crank of a 2-cylinder inline engine and the fluctuations of the angular velocity [omega] for  $l_x = 0$

Rys. 5. Przebieg właściwej siły stycznej generowanej na korbie dwucylindrowego silnika rzędowego oraz fluktuacje prędkości kątowej [omega] dla  $l_x = 0$

```
Zbiór - 30292      c:\silnik\WYNIKI\st30292om.scr
Lc=2      om=314   Dt=0.096   r=0.048   etam=0.810
eps=10.00 fic=3.62 ro=1.00   n1=1.35   n2=1.38   pa=0.194
rnp=0.84  mo=2.20 kz=0.100   lam=0.263 mi=0.000   pd=0.206
Moc NI    - 65.6 [kW]      Max. norm. - 0.902 [MPa]
Moc/V    - 51.99 [kW/l]    Max. pred. - 15.472 [m/s]
Max. nar. - 6.583 [kN]     czas obrotu - 20.0 [ms]
Nier. delta - 1/27       lx=0.270 [m] Mh=560+209 [Nm]
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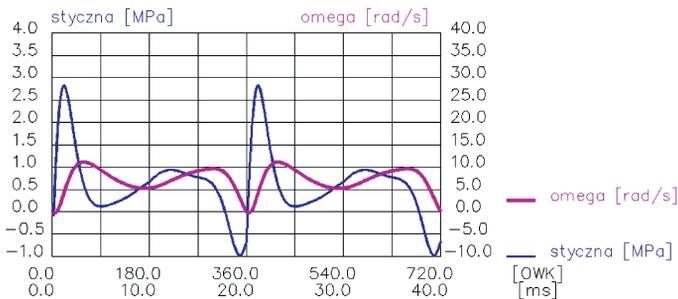


Fig. 6. The course of the specific tangential force generated on the crank of a 2-cylinder inline engine and the fluctuations of the angular velocity [omega] for  $l_x = 0,270$  m

Rys. 6. Przebieg właściwej siły stycznej generowanej na korbie dwucylindrowego silnika rzędowego oraz fluktuacje prędkości kątowej [omega] dla  $l_x = 0,270$  m

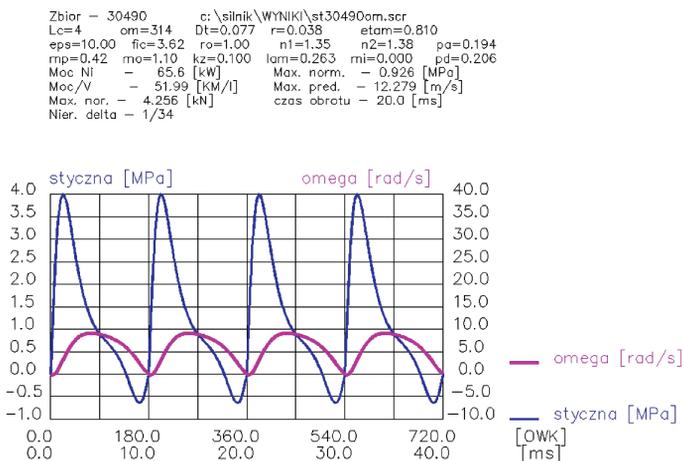


Fig. 7. The course of the specific tangential force generated on the crank of a 4-cylinder inline engine and the fluctuations of the angular velocity [omega]

Rys. 7. Przebieg właściwej siły stycznej generowanej na korbie czterocylindrowego silnika rzędownego oraz fluktuacje prędkości kątowej [omega]

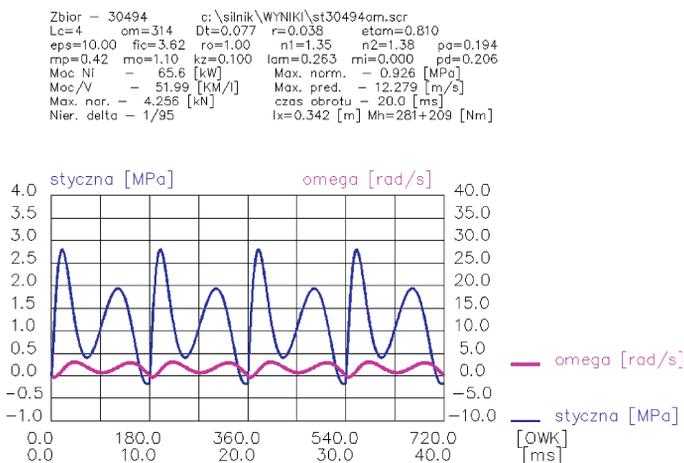


Fig. 8. The course of the specific tangential force generated on the crank of a 4-cylinder inline engine and the fluctuations of the angular velocity [omega] for  $l_x = 0,342$  m

Rys. 8. Przebieg właściwej siły stycznej generowanej na korbie czterocylindrowego silnika rzędownego oraz fluktuacje prędkości kątowej [omega] dla  $l_x = 0,342$  m

In the case of a 4-cylinder engine, the rollers presented in Fig. 4 rotate at the speed of  $2n$  because the summary 2<sup>nd</sup> order oscillating forces and the 4<sup>th</sup> harmonic the specific tangential force are balanced. Applying balancing rollers in a 4-cylinder inline engine and of corresponding parameters of work as it was assumed for the simulation presented in Fig. 7. leads to an improvement of the coefficient  $\delta$  from the value of  $1/34$  to the value of  $1/95$ .

### 3. Conclusions

1. Widespread use of balancing rollers will allow for a replacement of the present 4-cylinder inline engines with 2-cylinder ones with no significant increase in vibrations and noise generated by vehicles equipped with such engines.
2. The solutions applied in engines being introduced currently as the drive units in luxurious models of automobiles produced by prominent European firms [1, 2] prove that in the future a 4-cylinder inline engine equipped with balancing rollers will replace 6- and 8-cylinder engines which are expensive to produce and operate.
3. In the automobiles of the future described as “electric” ones, there will be an additional internal combustion engine – the so-called “range extender” – in the form of a 2-cylinder inline unit [3] equipped with backward balancing rollers.

### References

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