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EFFECT OF CAM PROFILE ON CYLINDER PRESSURE IN REVETEC ENGINE

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ABSTRACT

Revetec engine is a new engine arrangement used to increase engine’s efficiency by replacing the crankshaft and the connecting rod used in conventional engines by cams to control the piston movement. Cam profile contributes great effect in combustion characteristics, so it is very important to find the suitable cam profile to achieve the maximum cylinder pressure. In this paper a computational work was created to make a comparison between three types of cam profiles, which gives a specific motion for the piston, mainly: simple harmonic, constant acceleration and Cycloidal motion**;** In order to calculate the cylinder pressure during compression and combustion strokes. Results showed that by using cam with constant acceleration motion profile, the maximum cylinder pressure has increased with 7 %, and with the Cycloidal motions the increase in maximum cylinder pressure reaches 14 %, compared with simple harmonic motion, at the same compression ratio and heat addition. The result obtained from this study has shown that by using a cam profile, with which Cycloidal motion was applied to the piston, the cylinder pressure can be increased.

***Keywords**:* Revetec engine, cylinder pressure, cam profile.

INTRODUCTION

Crankshafts are the main cause for many problems in the internal combustion engine, like vibration, noise and cylinder wear. These poor efficiencies of the crankshafts have leaded the engineers to invent other alternative to replace the crankshafts functions (Mikalsen, 2007). In 1996, an Australian engineer called Bradley Howell Smith, managed to produce a new mechanism to convert the reciprocating motion of the internal combustion engines pistons, to rotating motion in the drive line, by using a three-lobed counter rotating cams and called the new engine arrangement as Revetec engine (Bradley, 2006). In Revetec engine, shown in Figure 1, there are two opposite pistons controlled by two (three-lobed) cams. On both sides of each piston, there are two bearing which act as the follower for the cams. As each cam has three arms (three-lobed), meaning, in every tow cycles of engine there are three power stokes compared to one power stroke in the conventional engines, and every stroke in Revetec engine completed in just 60 degrees instead of 180 degrees in conventional engines. The cam profile contributes great effect in the engine performance, because the cam profile controls the piston motion, meaning that by changing the cam profile the piston motion will change too. There is a wide variety of cam motion schemes, but the main motions for cams followers, are: simple harmonic, constant acceleration and Cycloidal motion (Myszka, 2005).

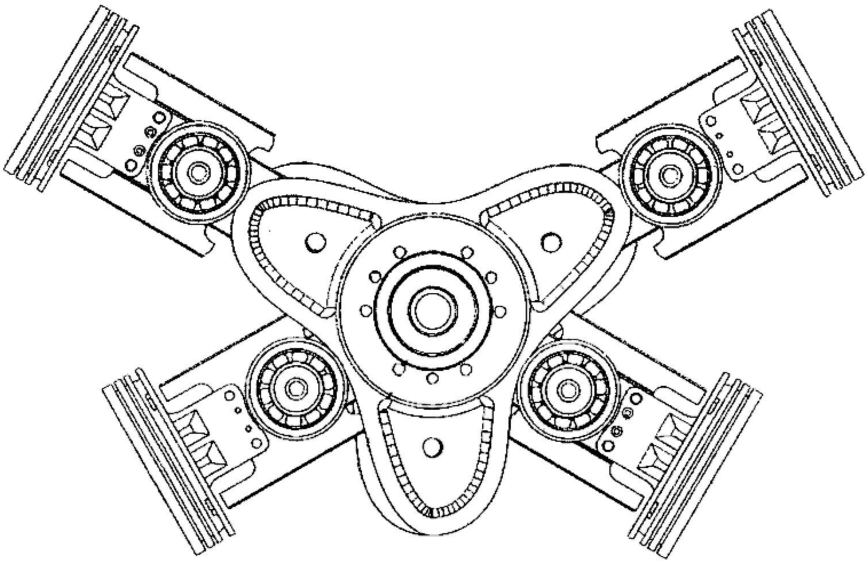

Figure 1: Revetec engine with four cylinders (Bradley, 2006)

CAM FOLLOWER DISPLACEMENT EQUATIONS

The following equations give the piston displacement, when using simple harmonic, constant acceleration and Cycloidal motion (Myszka, 2005):

Simple harmonic

$$X = \frac{s}{2}\left[1 - cos\frac{\pi\theta}{\beta}\right] \tag{1}$$

X: piston displacement,
s: piston stroke
θ: cam angle and
β : rotation angle of cam during the rise or fall interval.

Constant acceleration motion:

$$\begin{cases} X = 2s\frac{\theta^2}{\beta^2} & 0 \leq \theta \leq \frac{\beta}{2} \\ X = s - 2s\left(1 - \frac{\theta}{\beta}\right)^2 & \frac{\beta}{2} \leq \theta \leq \beta \end{cases} \tag{2}$$

Cycloidal motion:

$$X = s\left(\frac{\theta}{\beta} - \frac{1}{2\pi}\sin\left(\frac{2\pi\theta}{\beta}\right)\right) \tag{3}$$

CYLINDER PRESSURE CALCULATION

Cylinder pressure (P) in conventional internal combustion engines depends on cylinder volume (V), the amount of heat addition (Q), the specific heat ratio ( ), and the fraction of heat released (x), the cylinder pressure can be calculated using the following equations (Ferguson, 1986):

(4)

The fraction of heat release x

$$x = 1 - exp\left[1 - \left(\frac{\theta-\theta_s}{\theta_b}\right)^n\right] \quad (5)$$

$$\frac{dx}{d\theta} = n(1-x)\left(\frac{\theta-\theta_s}{\theta_b}\right)^n / \theta_b \quad (6)$$

θ_s: start of heat release
θ_b: the time scale for heat release
n: a value used to fit experimental data
The volume V and its derivative $dV/d\theta$ can be calculated as following:

Case 1: Simple Harmonic Motion

The cylinder volume V at any crank angle θ with reference Figure 2:

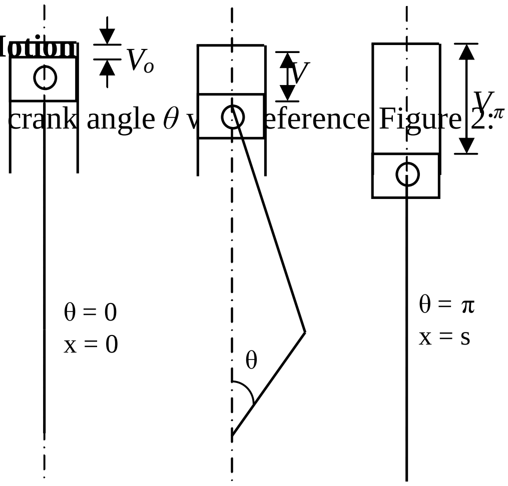

Figure 2: Cylinder volume at different positions

$$V = A \times X + V_o \quad (7)$$

A : represents the cylinder cross-section area, X is the piston displacement and V_o is the minimum cylinder volume(at $\theta = 0$), then by substituting x from Eq. (1) in Eq. (5):

$$V = A \times \frac{s}{2}(1 - \cos 3\,\theta) + V_o \quad (8)$$

The displacement volume, which is difference between the maximum volume V_π (at $\theta = \pi$) and the minimum volume V_o is:

$$V_\pi - V_o = A \times s \quad (9)$$

The compression ratio is defined as:

$$r = \frac{V_\pi}{V_o} \rightarrow V_\pi = V_o \times r \tag{10}$$

Substituting Eq. (8) into Eq. (7):

$$V_o(r-1) = A \times s \tag{11}$$

By using Eq. (6)

$$V = V_o \frac{(r-1)}{2}(1-\cos 3\theta) + V_o \tag{12}$$

To normalize the equation:

$$\tilde{V} = \frac{V_o}{V_\pi} = \frac{V_o}{V_\pi}\frac{(r-1)}{2}(1-\cos 3\theta) + \frac{V_o}{V_\pi} \tag{13}$$

$$\tilde{V} = \left[1 + \frac{(r-1)}{2}(1-\cos 3\theta)\right]/r \tag{14}$$

And its derivative:

$$\frac{d\tilde{V}}{d\theta} = 3\frac{r-1}{2r}\sin 3\theta \tag{15}$$

Case 2: Constant Acceleration:

By using the same procedure, and using Eq. (2), the volume and its derivative equations are:

$$\begin{cases} \tilde{V} = \dfrac{\left(1+(r-1)\times 2\frac{\theta^2}{\beta^2}\right)}{r} \\ \dfrac{d\tilde{V}}{d\theta} = 4\dfrac{r-1}{r}\times\dfrac{\theta}{\beta^2} \end{cases} \quad 0 \le \theta \le \frac{\beta}{2} \tag{16}$$

$$\begin{cases} \tilde{V} = \dfrac{\left(1+(r-1)-2(r-1)\left(1-\frac{\theta}{\beta}\right)^2\right)}{r} \\ \dfrac{d\tilde{V}}{d\theta} = 4\dfrac{(r-1)}{r\beta}\left(1-\dfrac{\theta}{\beta}\right) \end{cases} \quad \frac{\beta}{2} \le \theta \le \beta \tag{17}$$

Case 3: Cycloidal Motion:

By using the same procedure, and using Eq. (3), the volume and its derivative equations are:

$$\tilde{V} = \left[1 + (r-1)\left(\frac{\theta}{\beta} - \frac{1}{2\pi}\sin\left(\frac{2\pi\theta}{\beta}\right)\right)\right]/r \tag{18}$$

$$\frac{d\tilde{V}}{d\theta} = \frac{r-1}{r\beta}\left(1-\cos\left(\frac{2\pi\theta}{\beta}\right)\right) \tag{19}$$

Eq. (4) is a linear first-order differential equation and easily can be solved by numerical integration methods, in this case by using Runge- Kutta method.

THE COMPUTER PROGRAM AND COMPUTATIONAL PROCEDURE

To solve Eq. (4) and obtaining the values of P for the compression and power strokes, a FORTRAN program was written. The computer program consists of: a main part, a subroutine and one function. The program firstly predicts the increase of cylinder pressure due to decrease of cylinder volume before the ignition. Then the program predicts the heat release rate after the ignition. Figure 3 shows the program flow chart.

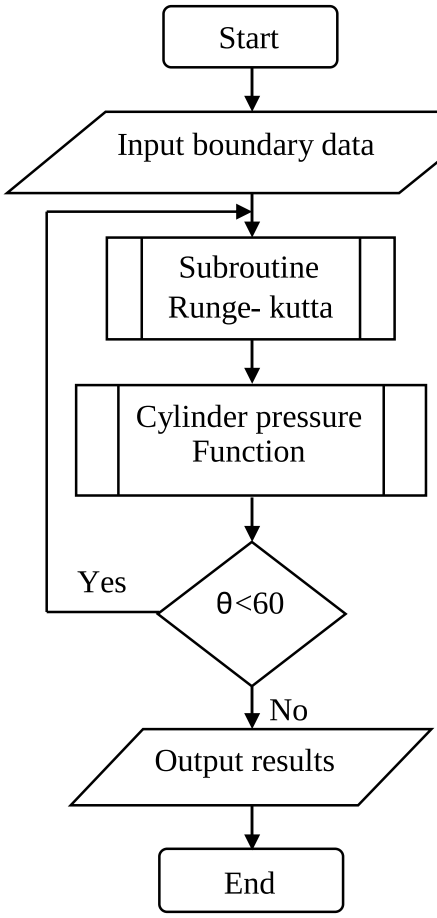

Figure 3: program flow chart

RESULTS AND DISCUSSION

The results after running the program are shown in Table 1 and Figure 4, by taking the following prior values and assuming a spark ignition engine:

$$r = 10, \gamma = 1.3, \theta_s = -13^{o}, \theta_b = 13^{o}, n = 4, Q = 40$$

The piston motion for the conventional internal combustion engines can be considered as simple harmonic motion (Hannah, 1984), so by replacing the crankshaft in conventional engines with cams in Revetec engine, the same motion still remains the same. From Figure 3, the cylinder pressure when using simple harmonic motion is similar to cylinder pressure in conventional engines at the same conditions.

Table 1: The computed cylinder pressure

θ (deg)	Cylinder pressure (P/P_1) Simple Harmonic motion	Constant Acceleration motion	Cycloidal motion
-60	1.000	1.000	1.000
-55	1.021	1.138	1.004
-50	1.085	1.306	1.035
-45	1.202	1.511	1.117
-40	1.394	1.768	1.286
-35	1.696	2.093	1.600
-30	2.177	2.529	2.175
-25	2.967	3.675	3.255
-20	4.314	5.56	5.332
-15	6.694	8.705	9.176
-10	10.918	13.805	14.919
-5	23.744	27.214	26.980
0	58.866	61.936	58.144
5	66.148	70.914	75.396
10	44.008	49.73	59.469
15	27.250	31.622	36.917
20	17.564	20.198	21.453
25	12.077	13.351	13.096
30	8.864	9.185	8.752
35	6.905	6.872	6.437
40	5.674	5.643	5.174
45	4.895	4.931	4.495
50	4.416	4.514	4.163
55	4.155	4.292	4.041
60	4.071	4.222	4.023

Also in Figure 4, shows an increase in cylinder pressure when using a cam with Cycloidal motion. Around the maximum pressure point, $\theta = 5$, the increase in pressure reaches 14 %, and 7% when using constant acceleration motion compared to simple harmonic motion.The interpretation of the increasing in cylinder pressure can be shown from the basic equation of pressure calculation: From Eq. (4)

$$\frac{d\tilde{P}}{d\theta} = -\gamma \frac{\tilde{P}}{\tilde{V}} \frac{d\tilde{V}}{d\theta} + (\gamma - 1) \frac{\tilde{Q}}{\tilde{V}} \frac{dx}{d\theta}$$

The specific heat ratio γ, the heat addition $\tilde{Q}$ and the rate of fraction of heat release change $\frac{dx}{d\theta}$ are equal in both cases, meaning, the difference comes from the volume $\tilde{V}$

and the rate of volume change is $\frac{d\tilde{V}}{d\theta}$. Table 2 and Figures 5 and 5 shows values of $\frac{d\tilde{V}}{d\theta}$ and $\tilde{V}$.

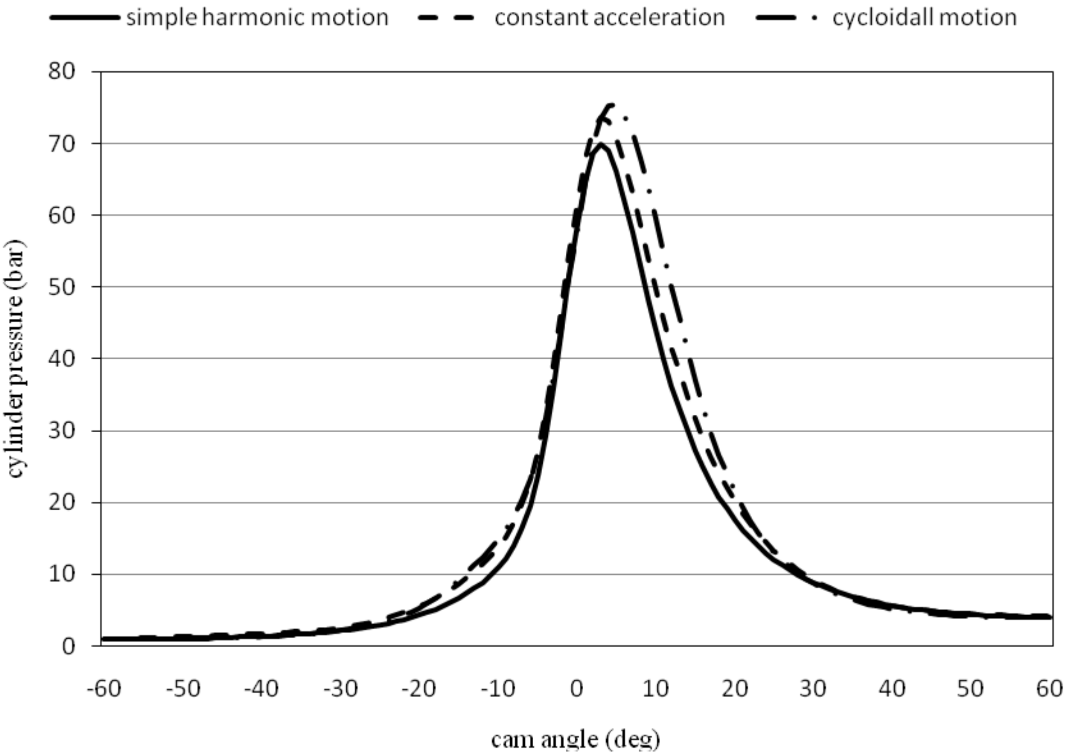

Figure 4: Pressure diagram during the compression and power strokes.

Table 2: Cylinder volume and cylinder volume changing rate during compression and power strokes

θ (deg)	$\frac{d\tilde{V}}{d\theta}$			$\tilde{V}$		
	Simple harmonic motion	**Constant acceleration motion**	**Cycloidal motion**	**Simple harmonic motion**	**Constant acceleration motion**	**Cycloidal motion**
-60	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000
-50	-0.0118	-0.0100	-0.0075	0.9394	0.9500	0.9741
-40	-0.0204	-0.0200	-0.0225	0.7746	0.8000	0.8241
-30	-0.0236	-0.0300	-0.0300	0.5496	0.5500	0.5500
-20	-0.0204	-0.0200	-0.0225	0.3248	0.3000	0.2760
-10	-0.0118	-0.0100	-0.0075	0.1602	0.1500	0.1260
0	0.0000	0.0000	0.0000	0.1000	0.1000	0.1000
10	0.0118	0.0100	0.0075	0.1602	0.1500	0.1260
20	0.0204	0.0200	0.0225	0.3248	0.3000	0.2760
30	0.0236	0.0300	0.0300	0.5496	0.5500	0.5500
40	0.0204	0.0200	0.0225	0.7746	0.8000	0.8241
50	0.0118	0.0100	0.0075	0.9394	0.9500	0.9741

60	0.0000	0.0000	0.0000	1.0000	1.0000	1.0000

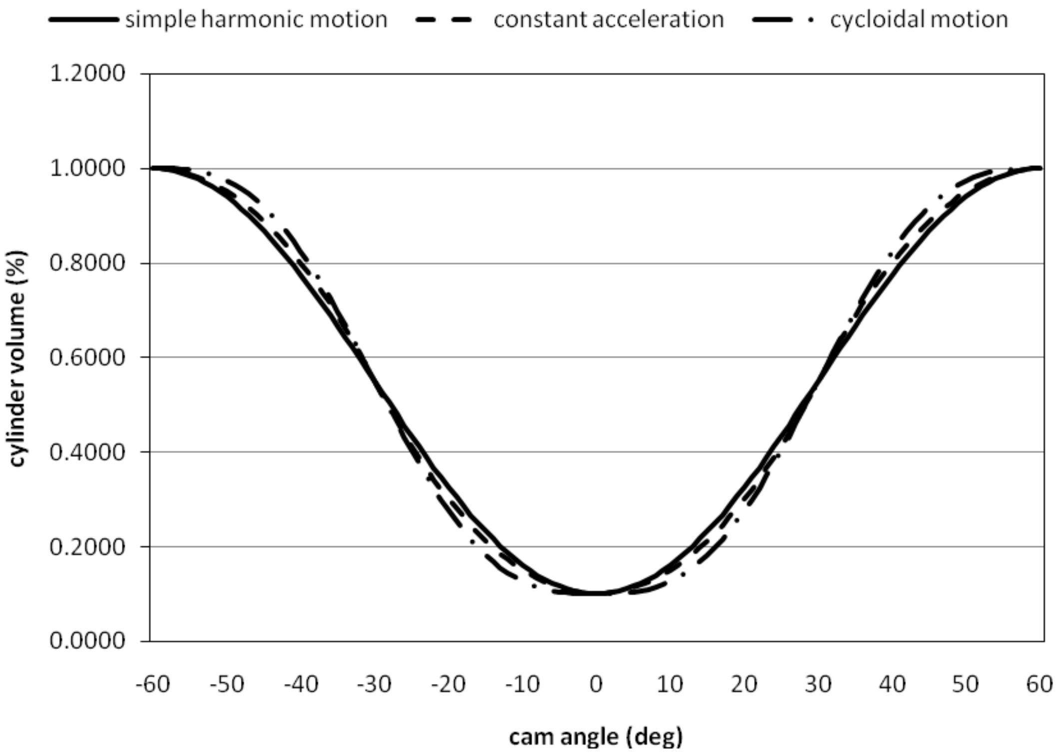

Figure 5: Cylinder volume during compression and power strokes

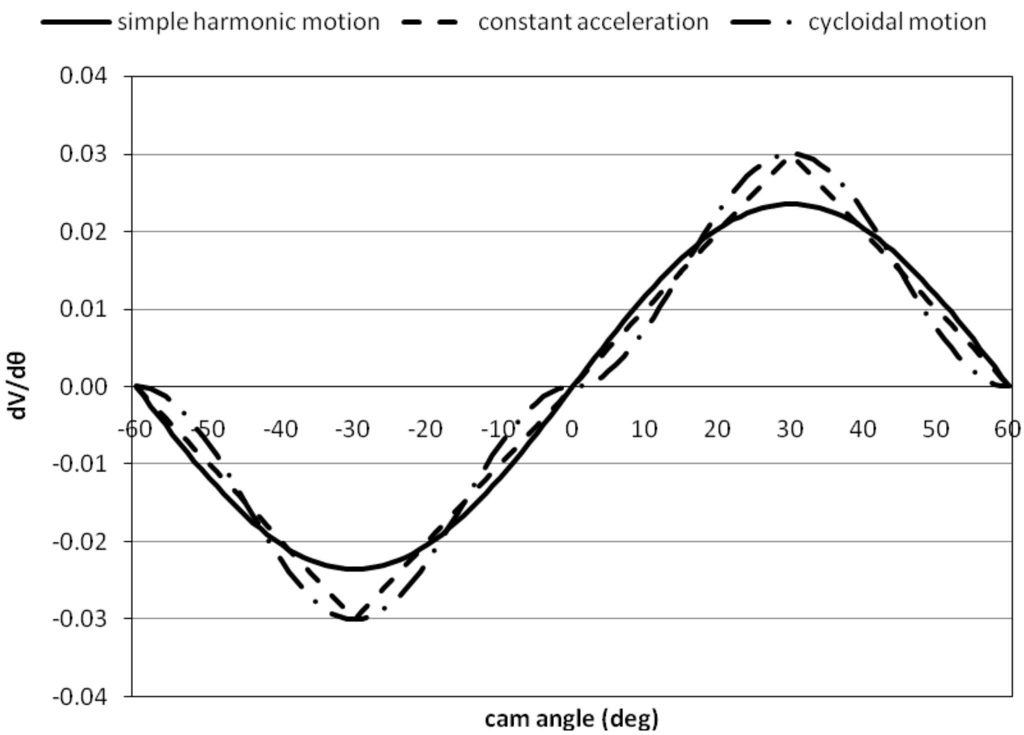

Figure 6: Cylinder volume changing rate during compression and power strokes

From figure 5 the increase in cylinder pressure when using Cycloidal motion occurred immediately after the top dead center. So this area was scrutinized by calculating *(dV/dθ)/V* during the first five degrees after the top dead center. Table 3 and Figure 7 shows the results.

Table 3: values of *(dV/dθ)/V* during 5 degrees after TDC

θ (deg)	$\dfrac{d\tilde{V}}{d\theta}\Big/\tilde{V}$		
	Simple harmonic motion	**Constant acceleration**	**Cycloidal motion**
0	0	0	0
1	0.012224	0.00995	0.0008
2	0.024009	0.019608	0.003293
3	0.034872	0.028708	0.007246
4	0.044527	0.037037	0.012778
5	0.05281	0.044444	0.019443

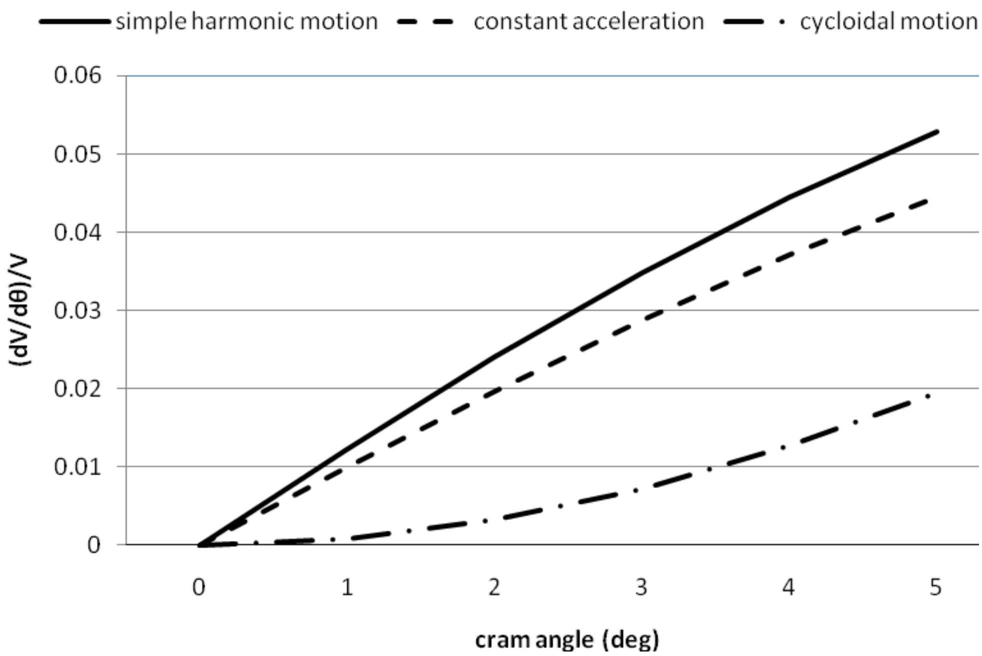

Figure 7: values of *(dV/dθ)/V* during 5 degrees after TDC

From Figure 6 the rate of *(dV/dθ)/V* increasing for Cycloidal motion is less than the other two motions, that means the pressure loss due to piston movement downwards during the power stroke is less when using Cycloidal motion, and that gives more maximum pressure.Cycloidal motion scheme gives a very smooth curves and does not have the sudden change in acceleration [ ] , which makes the Cycloidal motion the best choice when using cams instead of crankshafts in internal combustion engines.

CONCLUSION

1- Three types of cam motion schemes (simple harmonic, constant acceleration and Cycloidal motion) were investigated to find the motion, which provides the maximum cylinder pressure, when replacing the conventional crankshaft with cams.

2- The results showed that the best motion, which provided the maximum cylinder pressure, is the Cycloidal motion with a cylinder pressure exceeds 75 bar, when compared to the other two motions.

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NOMENCLATURES

A	piston cross-section area, m^2.
c_v	specific heat ratio, kJ.kg.^{o}k
n	a parameter used to curve fit experimental data
P	cylinder pressure, kPa.
Q	heat addition, kJ.
R	gas constant
s	Piston stroke, m.
T	Temperature, ^{o}K .
V	*Volume*, m^3.
X	*Piston displacement ,m.*
x	fraction of heat release

Greek symbols

γ	specific heat ratio
θ	crank angle (deg)
θ_b	time scale of heat release (deg)
θ_s	start of heat release (deg)