Theoretical Performance Comparison between Inline, Offset and Twin Crankshaft Internal Combustion Engines

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Abstract

The twin crankshaft engine is anew configuration of internal combustion engine that introduced to solve the engine liner wear problems, increase the engine efficiency and it has other advantages over conventional engines.

In this research, a computational work was carried out to compare the performance of three l engine configurations, namely, the conventional (inline) engine, the offset crankshaft engine and the twin crankshaft engine, of the same cylinder bore, speed, crank arm, piston mass and heat addition. The performance measured was the side thrust force that causes liner wear and the output torque.

Results showed that the twin crankshaft engine is superior in terms of torque which means it has larger efficiency than the other configurations.

ملخص

المحرك مزدوج العمود القلاب شكل جديد لمحركات الاحتراق الداخلي الترددي ، مقدم لحل مشكلة تآكل الأسطوانات في المحركات التقليدية. حل هذه المشكلة يؤدي الى رفع كفاءة المحرك وزيادة قدرته بالإضافة الى محاسن اخرى.

في هذه الورقة تحلل ثلاث نماذج رياضية تمثل دينامية المحرك لكل من محرك تقليدي ، محرك مذاح مركز اسطوانته عن مركز دوران عموده القلاب ومحرك مزدوج العمود القلاب .من خلال هذه النماذج وبواسطة برامج تمه كتابتها بلغة الفورتوران فورنة القوة المؤثرة على حائط الأسطوانة والعزوم للمحركات الثلاث . خلاصة النتائج الى زيادة العزم في المحرك المزدوج (القدرة) وتلاشى القوة الناعمية فيه.

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1. Introduction

Twin crankshaft engine is solution for some conventional engines problems such as vibration, side thrust force, liners wear and as a result of all those factors engines poor efficiency [1].

Experimental work, which done in a twin crankshaft model built in Sudan university for science and technology-engineering faculty, proved the possibility of the twin crankshaft engine to reduce the liners wear, but what is the effect of the new arrangement in other engine's parameters, such like torque and efficiency? This work is trying to answer this question.

Starting from the equation of the state for an ideal gas, using Wiebbe function for heat release fraction, using piston force balance then, finally the engine's torque calculated.

2. Calculating Gas Pressure [2]

The equation of state for an ideal gas is:

$$pv = mRT \quad (2.1)$$

Taking the logarithm of both sides and differentiating with respect to crank angle gives

$$\frac{1}{p} \frac{dp}{d\theta} + \frac{1}{V} \frac{dV}{d\theta} = \frac{1}{T} \frac{dT}{d\theta} \quad (2.2)$$

The first law of thermodynamics in differential form for an ideal gas with constant specific heat is

$$mc_v \frac{dT}{d\theta} = \frac{dQ}{d\theta} - p \frac{dV}{d\theta} \quad (2.3)$$

Dividing the left –hand side by mRT and the right side by pV , and rearranging then yields

$$\frac{1}{T} \frac{dT}{d\theta} = (\gamma - 1) \left(\frac{1}{pV} \frac{dQ}{d\theta} - \frac{1}{V} \frac{dV}{d\theta} \right) \quad (2.4)$$

Combining equation (2.4) and equation (2.2) and introducing of $dQ = Q_{in} dx$ produces:

$$\frac{dp}{d\theta} = -\gamma \frac{p}{V} \frac{dV}{d\theta} + (\gamma - 1) \frac{Q_{in}}{V} \frac{dx}{d\theta} \quad (2.5)$$

In practice, it is convenient to normalize the equation by letting

$$\bar{p} = p / p_1 \quad \tilde{V} = V / V_1 \quad \tilde{Q} = Q_{in} / p_1 V_1 \quad (2.6)$$

In which case, equation (5) becomes

$$\frac{d\tilde{p}}{d\theta} = -\gamma \frac{\tilde{p}}{\tilde{V}} \frac{d\tilde{V}}{d\theta} + (\gamma - 1) \frac{\tilde{Q}}{\tilde{V}} \frac{dx}{d\theta} \quad (2.7)$$

Equation (2.7) is a linear first-order differential equation and can be solved by any numerical methods. Such as Rung-Kutta.

The volume V and its derivative $dV/d\theta$ are a known function of the crank angle θ [3]

$$\tilde{V} = \left[1 + \frac{r-1}{2} (1 - \cos \theta) \right] / r \quad (2.8)$$

$$\frac{d\tilde{V}}{d\theta} = \frac{(r-1) \sin \theta}{2r} \quad (2.9)$$

r = the compression ratio $= V_{(\pi)} / V_{(0)}$

The fraction of heat release x (assumed to take the form of a Wiebbe function) [3].

$$x = 1 - \exp \left[1 - \left(\frac{\theta - \theta_s}{\theta_b} \right)^n \right] \quad (2.10)$$

$$\frac{dx}{d\theta} = n(1 - x) \left(\frac{\theta - \theta_s}{\theta_b} \right)^{(n-1)} / \theta_b \quad (2.11)$$

To solve equation (2.7) and obtaining the values of p for both the compression and power strokes, a FORTRAN program was developed and used with the following prior values and assuming a spark ignition engine:

$$r = 10, \gamma = 1.3, \theta_s = -40^\circ, \theta_b = 40^\circ, n = 4, Q = 20$$

The results after running this program are in table (1) and figure (1).

Table (1): cylinder pressure

Crank angle (deg)	Pressure (bar)	Crank angle (deg)	Pressure (bar)
-180	1.0001	0	61.0034
-160	1.0405	20	57.6484
-140	1.1648	40	30.929
-120	1.4098	60	17.1119
-100	1.861	80	10.6047
-80	2.7133	100	7.3511
-60	4.4301	120	5.6201
-40	8.0837	140	4.6813
-20	18.6137	160	4.2134

Figure (1): p-V diagram resulting from the program

3. Inline Crankshaft Engine Performance

Stroke = .046 mm, Bore = .076 mm

Length of connecting rod = 0.092 = b

Crank arm = 0.023 mm = r

Piston and part of connecting rod mass = 0.3 kg, $\mu = 0.5$

Speed of the engine = 2500 rpm

Piston force balance:

Figure (2): Piston Force Balance

Now [4]:

$$F_c = [P \cdot A - m \cdot a \pm F_f] / \cos \varphi \quad (3.1)$$

$$a = r\omega^2 \left(\cos \theta + \frac{\cos 2\theta}{2 \cdot b/r} \right) \quad (3.2)$$

But:

$$\sin \varphi = r \cdot \sin \theta / b \quad (3.3)$$

Then

$$F_c = \frac{P * A - m * a \pm F_f}{\cos \sin^{-1}(r \sin \theta / b)} \quad (3.4)$$

By taking the reaction of F_c :

$$F_a = F_c * \cos \alpha \quad (3.5)$$

F_a is the vertical component of F_c , which causes the torque.

But

$$\alpha = 90 - (\theta + \varphi) \quad (3.6)$$

Then

$$F_a = F_c \cos(90 - (\theta + \sin^{-1}[r * \sin \theta / b])) \quad (3.7)$$

The torque:

$$T = F_a * r \quad (3.8)$$

The side thrust force

$$F_{th} = [P * A - m * a \pm F_f] * \tan \varphi \quad (3.9)$$

$$F_f = F_{th} * \mu \quad (3.10)$$

A FORTRAN computer program, also, made to calculate:

- 1- The torque.
- 2- The side thrust force.

Supposing that:

1- P_1 from equation (2.6) = 1 bar, so the pressure values from table 1, will multiply by 100000.

2- The values of the torque are through the compression and expansion strokes, so the crank angles are between -180 and 180 degrees.

The results obtained when running the program are shown in table (2) and figures (5) and (6).

4. Twin Crankshaft Engine Performance

Stroke = .047 m

Bore = .076 m

Length of connecting rod = 0.16 = b

Crank arm = 0.023 m = r

Offset=d= 0.03 m

Piston and part of connecting rod mass = 0.5 kg

Speed of the engine = 2500 rpm

Piston force balance:

Figure (3): Twin Crankshaft Engine Piston's Force Balance

Now:

$$F_c = [P * A - m * a] / \cos \varphi \quad (4.1)$$

$$a = -r \cos \theta \omega^2 - \left[(r \sin \theta + d)^2 r^2 \cos^2 \theta \omega^2 \right] / \sqrt{(b^2 - (r \sin \theta + d)^2)^3} \\ + \frac{(r \sin \theta + d) r \sin \theta \omega^2 - r^2 \cos^2 \theta \omega^2}{\sqrt{(b^2 - (r \sin \theta + d)^2)}} \quad [5] \quad (4.2)$$

But:

$$\sin \varphi = (r * \sin \theta + d) / b \quad (4.3)$$

Then

$$F_c = \frac{P * A - m * a}{2 * \cos \sin^{-1}((r \sin \theta + d) / b)} \quad (4.4)$$

By taking the reaction of F_c :

$$F_a = F_c * \cos \alpha \quad (4.5)$$

F_a is the vertical component of F_c , which causes the torque.

But

$$\alpha = 90 - (\theta + \varphi) \quad (4.6)$$

Then

$$F_a = F_c \cos (90 - (\theta + \sin^{-1}[(r * \sin \theta + d) / b])) \quad (4.7)$$

The torque for each crank:

$$T = F_a * r \quad (4.8)$$

Then for both cranks:

$$T = 2 * F_a * r \quad (4.9)$$

The side thrust force

$$F_{th} = \{[P * A / 2 - m * a] / 2\} * \tan \varphi \quad (4.10)$$

A computer program was written in FORTRAN language to calculate:

- 1- Torque
- 2- Side thrust force

The results obtained when running the program are shown in table (3) and figures (5) and (6).

5. Offset One Crankshaft Engine Performance

Stroke = .047 m

Bore = .076 m

Length of connecting rod = 0.16 = b

Crank arm = 0.023 m = r

Offset=d= 0.01 m

Piston and part of connecting rod mass = 0.5 kg

Speed of the engine = 2500 rpm

Piston force balance:

Figure (4): Offset Crankshaft Engine Piston's Force Balance

Now:

$$F_c = [P \cdot A - m \cdot a] / \cos \varphi \quad (5.1)$$

$$a = -r \cos \theta \omega^2 - \left[(r \sin \theta + d)^2 r^2 \cos^2 \theta \omega^2 \right] / \sqrt{(b^2 - (r \sin \theta + d)^2)^3} + \frac{(r \sin \theta + d) r \sin \theta \omega^2 - r^2 \cos^2 \theta \omega^2}{\sqrt{(b^2 - (r \sin \theta + d)^2)}} \quad (5.2)$$

But:

$$\sin \varphi = (r \sin \theta + d) / b \quad (5.3)$$

Then

$$F_c = [P * A - m * a] / \cos \sin^{-1}[(r * \sin \theta + d)/b] \quad (5.4)$$

By taking the reaction of F_c :

$$F_a = F_c * \cos \alpha \quad (5.5)$$

F_a is the vertical component of F_c , which causes the torque.

But

$$\alpha = 90 - (\theta - \varphi) \quad (5.6)$$

Then

$$F_a = F_c * \cos (90 - (\theta - \sin^{-1}[(r * \sin \theta + d)/b])) \quad (5.7)$$

The torque:

$$T = F_a * r \quad (5.8)$$

The side thrust force

$$F_{th} = [P * A - m * a] * \tan \varphi / 2 \quad (5.9)$$

A computer program was written in FORTRAN language to calculate:

- 1- Torque
- 2- Side thrust force

The results obtained when running the program are shown in table (4) and figures (5), (6).

6. Results

The torque and side thrust force for the three engines arrangements calculated through the compression and expansion strokes are presented in table (2), (3) and 4 below. With figures (5), (6) are plots of the results:

Table (2): Inline Engine Performance

Crank angle (deg)	Pressure (bar)	Acceleration (m/s^2)	Torque (N.m)	Thrust force (N)
-180	1.0001	-1370.93	0.0188	0.2734
-160	1.0405	-1322.59	-4.9832	-74.3233
-140	1.1648	-1166.83	-9.6025	-142.843
-120	1.4098	-882.173	-13.9532	-200.405
-100	1.861	-457.095	-18.529	-249.232
-80	2.7133	87.09	-24.8855	-306.033
-60	4.4301	684.753	-36.0454	-400.184
-40	8.0837	1233.843	-53.4711	-536.916
-20	18.6137	1622.212	-74.0548	-683.088
0	61.0034	1762.631	0.0008	0
20	57.6484	1622.212	238.8552	2203.208
40	30.929	1233.843	221.5533	2224.665
60	17.1119	684.753	150.9801	1676.212
80	10.6047	87.09	98.8327	1215.407
100	7.3511	-457.095	65.5523	881.7399
120	5.6201	-882.173	43.4263	623.7161
140	4.6813	-1166.83	27.0395	402.2306
160	4.2134	-1322.59	13.2386	197.4526

Table (3): Twin Engine Performance

Crank angle (deg)	Pressure (bar)	Acceleration (m/s ²)	Torque (N.m)	Thrust force (N)
-180	1.0001	-1329.49	-4.8712	106.6013
-160	1.0405	-1140.41	-11.3239	72.8657
-140	1.1648	-784.274	-15.1451	44.0188
-120	1.4098	-303.837	-16.332	25.0065
-100	1.861	241.9036	-16.5122	16.6336
-80	2.7133	786.322	-18.8205	19.2514
-60	4.4301	1263.699	-26.4484	43.4673
-40	8.0837	1617.158	-37.4617	136.4797
-20	18.6137	1805.036	-36.5813	526.5565
0	61.0034	1804.429	117.5261	2554.899
20	57.6484	1612.723	332.8618	3086.848
40	30.929	1249.484	267.093	1954.327
60	17.1119	758.4147	174.9526	1212.313
80	10.6047	204.1759	113.1862	820.3818
100	7.3511	-340.097	74.4726	610.5778
120	5.6201	-808.72	47.6356	484.8568
140	4.6813	-1151.37	25.9865	393.3051
160	4.2134	-1332.05	6.6466	313.6734

Table (4): Offset Engine Performance

Crank angle (deg)	Pressure (bar)	Acceleration (m/s ²)	Torque (N.m)	Thrust force (N)
-180	1.0001	-1340.36	1.1995	53.4329
-160	1.0405	-1210.14	-4.2827	93.6996
-140	1.1648	-906.315	-8.8653	125.3835
-120	1.4098	-466.903	-12.5062	148.3376
-100	1.861	55.713	-16.1723	172.4656
-80	2.7133	600.0876	-22.1027	219.0423
-60	4.4301	1100.513	-33.5883	319.7136
-40	8.0837	1494.944	-52.0204	504.7082
-20	18.6137	1735.105	-76.8822	890.4061
0	61.0034	1793.334	-39.7915	1699.143
20	57.6484	1663.992	196.2128	341.5777
40	30.929	1362.393	205.6815	-407.872
60	17.1119	923.7077	149.7285	-465.116
80	10.6047	400.4283	103.4616	-372.064
100	7.3511	-143.905	72.4165	-267.835
120	5.6201	-643.585	50.9774	-170.162
140	4.6813	-1038.67	34.1266	-72.5778
160	4.2134	-1281.01	18.7574	30.9609

Figure (5): Torque Comparison between Inline, Offset and Twin Crankshaft Engines

Figure (6): Side Thrust Force Comparison between Inline, Offset And Twin Crankshaft Engines

7. Discussion

7.1 Figure (5) shows the torque comparison between inline (conventional) crankshaft engine, offset crankshaft engine and twin crankshaft engine.

The figure shows that the torque of twin crankshaft engine is larger than the inline crankshaft engine. And that can be explained by looking to the crank angle θ , the angle between the force F_a and extension of force F_c , which is α , and the cylinder's pressure.

From the figure, the maximum torque occurs when $\theta = 20^\circ$ and the cylinder pressure = 57.6484bar, $\alpha = 56.3^\circ$ in twin crankshaft engine. And when $\theta = 20^\circ$, $\alpha = 65.1^\circ$ in inline crankshaft engine,

That means in twin crankshaft engine the angle α is smaller, and that gives a higher torque, see equations (3.6), (3.7), (4.6), (4.7).

In other words the twin crankshaft engine uses the cylinder pressure - in his highest values - better than the inline crankshaft engine.

7.2 Figure (6) shows the side thrust force comparison between the three engine arrangements.

In twin crankshaft case: there are two opposite forces, because of using two crankshafts, and that makes the resultant of the side thrust force equals zero.

In offset crankshaft case: the side thrust force is smaller than the inline crankshaft, and that is because of reducing the angle ϕ in expansion stroke. See equations (3.9), (5.9). But unfortunately the torque reduces too; because of the increase of angle α . see equation (5.6).

8. Conclusions

1. The twin crankshaft engine increases the torque and that means increases the efficiency.
2. The side thrust force in twin crankshaft engine equals zero.
3. The offset crankshaft engine decreases the side thrust force, when compared with the conventional engine. But it has a smaller torque.

9. Nomenclatures

A	Piston cross-section area
c_v	Specific heat
F_a	Vertical component of F_c
F_c	Connecting rod force
F_f	Friction force
F_g	Gas pressure force
F_{th}	Side thrust force
m	Mass
n	A parameter used to curve fit experimental data
p	Pressure
P	Cylinder pressure
Q	Heat addition
R	Gas constant
T	Temperature
V	Volume
x	Fraction of heat release
γ	Specific heat ratio
θ	Crank angle
θ_b	Time scale of heat release
θ_s	Start of heat release
φ	The angle between the connecting rod and the line joining the center of the crankshaft to the piston
α	The angle between the force F_a and extension of force F_c
μ	Friction factor

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