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

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Abstract -**The twin crankshaft engine is a new configuration of internal combustion engine that introduced to solve the engine liner wear problems, increase the engine efficiency in addition to other advantages over conventional engines.**

In this paper, a computational work was carried out to compare the performance of three l engine configurations, namely, the conventional (inline), the offset crankshaft and the twin crankshaft engines, 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 two configurations.

Keyword: twin crankshaft, thrust force, liner wear, performance torque.

I. INTRODUCTION

Twin crankshaft engine is solution for some conventional engines problems such as vibration; side thrust force, liners wear and consequently poor engine efficiency [1].

Experimental work, which done in a twin crankshaft model built by us, proved the capability of the twin crankshaft engine to reduce the liners wear, but what is the effect of the new arrangement on other engine's parameters, such as torque and efficiency? This work tries to answer this question.

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

II. CALCULATING GAS PRESSURE [2]

The equation of state for an ideal gas is:

$$pv = mRT \tag{1}$$

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

$$\frac{1}{p}\frac{dp}{d\theta}+\frac{1}{V}\frac{dV}{d\theta}=\frac{1}{T}\frac{dT}{d\theta} \tag{2}$$

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

$$mc_v\frac{dT}{d\theta}=\frac{dQ}{d\theta}-p\frac{dV}{d\theta} \tag{3}$$

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

$$\frac{1}{T}\frac{dT}{d\theta}=(\gamma-1)\left(\frac{1}{pV}\frac{dQ}{d\theta}-\frac{1}{V}\frac{dV}{d\theta}\right) \tag{4}$$

Combining (4) and (2) and introducing of $dQ = Q_{in}\, dx$ produces:

$$\frac{dp}{d\theta}=-\gamma\frac{p}{V}\frac{dV}{d\theta}+(\gamma-1)\frac{Q_{in}}{V}\frac{dx}{d\theta} \tag{5}$$

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

$$\bar{p}=p/p_1 \qquad \tilde{V}=V/V_1$$
$$\tilde{Q}=Q_{in}/p_1V_1 \tag{6}$$

In which case, (5) becomes:

$$\frac{d\tilde{p}}{d\theta}=-\gamma\frac{\tilde{p}}{\tilde{V}}\frac{d\tilde{V}}{d\theta}+(\gamma-1)\frac{\tilde{Q}}{\tilde{V}}\frac{dx}{d\theta} \tag{7}$$

Equation (7) is a linear first-order differential equation and can be solved by any numerical method, e.g., Rung-Katta's.

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

$$\tilde{V}=\left[1+\frac{r-1}{2}(1-\cos\theta)\right]/r \tag{8}$$

$$\frac{d\tilde{V}}{d\theta}=\frac{(r-1)}{2}\frac{\sin\theta}{r} \tag{9}$$

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

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

$$x=1-\exp\left[1-\left(\frac{\theta-\theta_s}{\theta_b}\right)^n\right] \tag{10}$$

$$\frac{dx}{d\theta}=n(1-x)\left(\frac{\theta-\theta_s}{\theta_b}\right)^{(n-1)}/\theta_b \tag{11}$$

To solve (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 assuming a spark ignition engine:

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

Table (1) and figure (1) summarize the results obtained after running the program

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

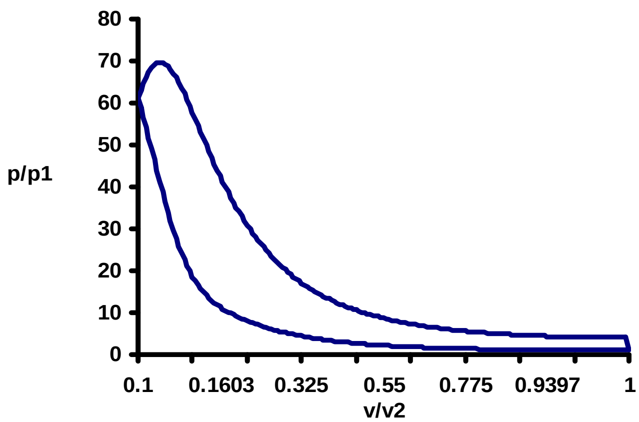

Figure (1): P-V Diagram Resulting from the Program

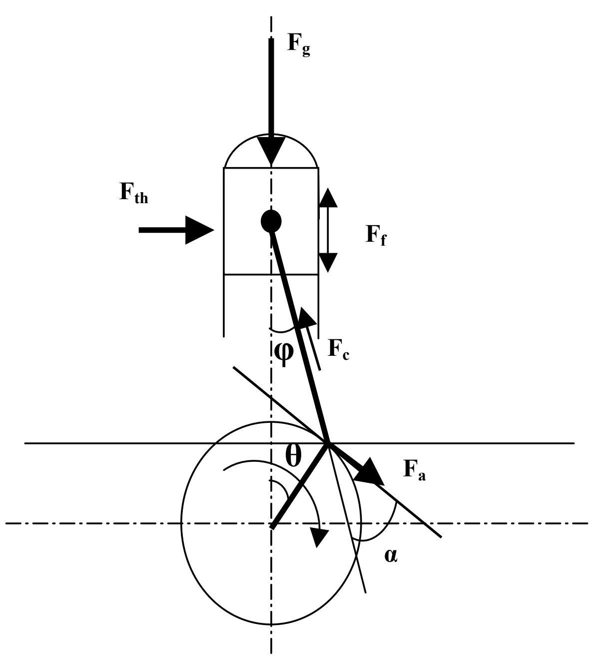

Figure (2): Piston Force Balance

I. 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, μ = 0.5
Speed of the engine = 2500 rpm
Piston force balance:

Now [4]:

$$F_c = [P*A - m*a \pm F_f] / \cos\varphi \tag{12}$$

$$a = r\omega^2\left(\cos\theta + \frac{\cos 2\theta}{2*b/r}\right) \tag{13}$$

But:

$$\sin\varphi = r*\sin\theta/b \tag{14}$$

Then

$$F_c = \frac{P*A - m*a \pm F_f}{\cos\sin^{-1}(r\sin\theta/b)} \tag{15}$$

By taking the reaction of F_c:

$$F_a = F_c * \cos\alpha \tag{16}$$

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

But

$$\alpha = 90 - (\theta + \varphi) \tag{17}$$

Then

$$F_a = F_c \cos(90 - (\theta + \sin^{-1}[r*\sin\theta/b])) \tag{18}$$

The torque:

$$T = Fa * r \tag{19}$$

The side thrust force:

$$F_{th} = [P*A - m*a \pm F_f] * \tan\varphi \tag{20}$$

$$F_f = F_{th} * \mu \tag{21}$$

A FORTRAN computer program has been also written to calculate:

-the torque

-the side thrust force assuming that:

1-P_1 from (17) = 1 bar, so the pressure values from table (1), will multiply by 100000.

2-The values of the torque is due to the compression and expansion strokes, the crank angles are, therefore, between –180 and 180 degrees.

The results obtained after running the program are tabulated in table (2) and depicted by figures (5) and (6).

IV. 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:

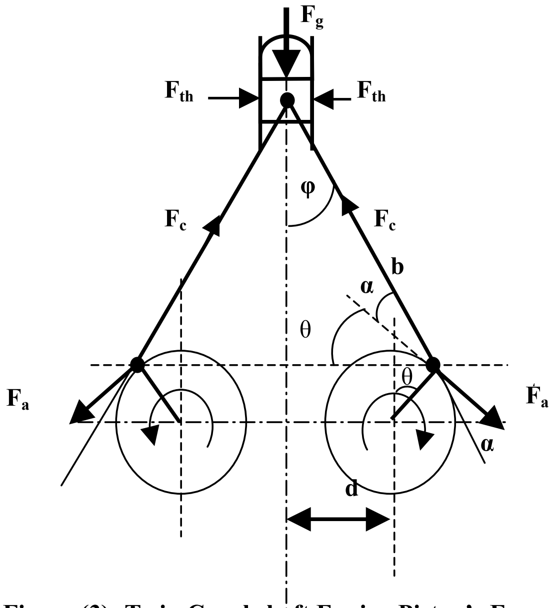

Figure (3): Twin Crankshaft Engine Piston's Force Balance

Now:

$F_c = [P*A - m*a] / \cos\varphi$ (22)

$$a = -r\cos\theta\omega^2 - \left[(r\sin\theta + d)^2 r^2\cos^2\theta\omega^2\right] / \sqrt{\left(b^2 - (r\sin\theta + d)^2\right)^3} + \frac{(r\sin\theta + d) r\sin\theta\omega^2 - r^2\cos^2\theta\omega^2}{\sqrt{\left(b^2 - (r\sin\theta + d)^2\right)}} \quad [5] \qquad (23)$$

But:

$\sin\varphi = (r*\sin\theta + d)/b$ (24)

Then

$$F_c = \frac{P*A - m*a.}{2*\cos\sin^{-1}\left((r\sin\theta + d)/b\right)} \qquad (25)$$

By taking the reaction of F_c:

$F_a = F_c * \cos\alpha$ (26)

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

But

$\alpha = 90 - (\theta + \varphi)$ (27)

Then

$F_a = F_c \cos(90 - (\theta - \sin^{-1}[(r*\sin\theta + d)/b]))$ (28)

The torque for each crank:

1) $T = Fa * r$ (29)

Then for both cranks:

T = 2*Fa * r *(30)*

The side thrust force

$F_{th} = \{[P*A/2 - m*a]/2\} * \tan\varphi$ (31)

A computer program was written in FORTRAN language to calculate:

- -Torque
- -Side thrust force

The results obtained after running the program are shown in table 3 and illustrated by figures (5),(6).

V. 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:

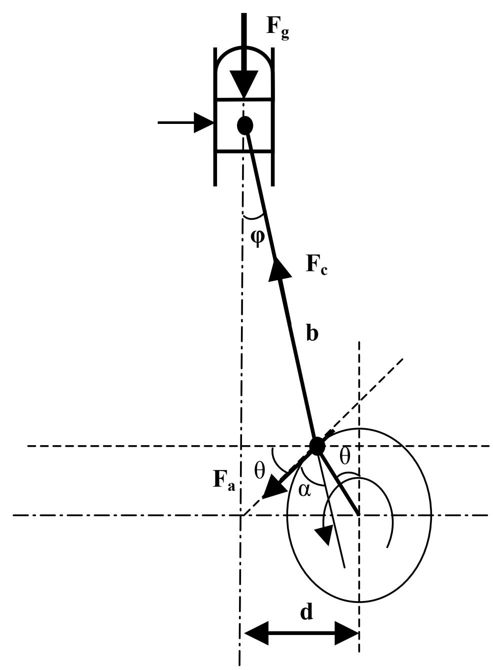

Figure (4): Offset Crankshaft Engine Piston's Force Balance

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Now:

$$F_c = [P*A - m*a] / \cos\varphi \quad (32)$$

$$a = -r\cos\theta\omega^2 - \left[(r\sin\theta + d)^2 r^2 \cos^2\theta\omega^2\right] / \sqrt{\left(b^2 - (r\sin\theta + d)^2\right)^3} + \frac{(r\sin\theta + d) r\sin\theta\omega^2 - r^2\cos^2\theta\omega^2}{\sqrt{\left(b^2 - (r\sin\theta + d)^2\right)}} \quad (33)$$

But:

$$\sin\varphi = (r*\sin\theta + d)/b \quad (34)$$

Then

$$F_c = [P*A - m*a] / \cos \sin^{-1}[(r*\sin\theta + d)/b] \quad (35)$$

By taking the reaction of F_c:

$$F_a = F_c * \cos\alpha \quad (36)$$

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

$$\alpha = 90 - (\theta - \varphi) \quad (37)$$

Then

$$F_a = F_c * \cos(90 - (\theta - \sin^{-1}[(r*\sin\theta + d)/b])) \quad (38)$$

The torque:

$$T = Fa * r \quad (39)$$

The side thrust force:

$$F_{th} = [P*A - m*a] * \tan\varphi / 2 \quad (40)$$

A computer program was written in Fortran language to calculate:

- torque
- side thrust force

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

VI. 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. figures (5), (6) depict 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

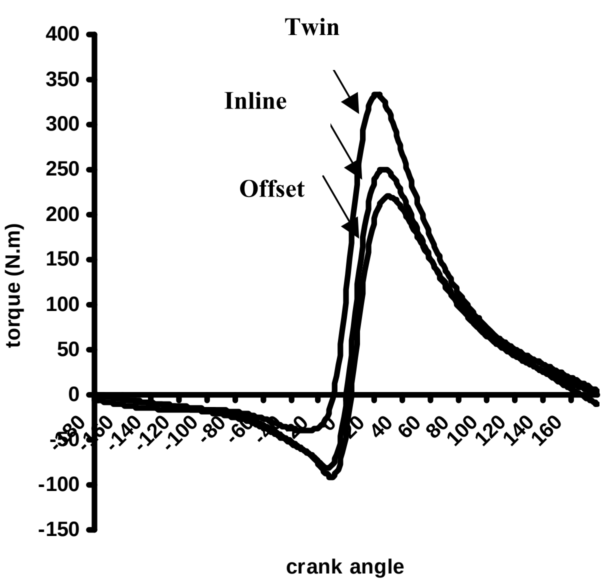

Figure (5): Torque Comparison Between inline, Offset and twin Crankshaft Engine

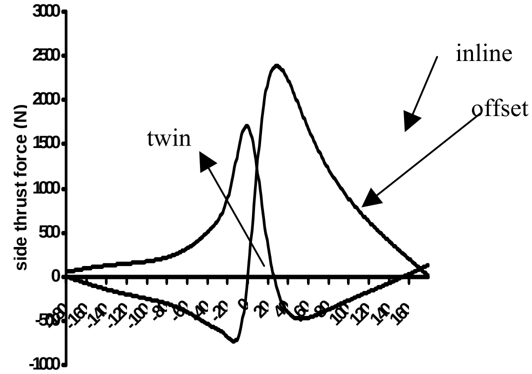

Figure (6): Side Thrust Force Comparison Between Inline, Offset and Twin Crankshaft Engines

VII. DISCUSSION

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

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

From the figure, the maximum torque in twin crankshaft engine occurs when θ $=20^o$ and the cylinder pressure = 57.6484bar, $\alpha = 56.3^o$, whereas, in case of inline crankshaft, it occurs when θ $=20$, $\alpha = 65.1^o$ in,

That means in twin crankshaft engine the angle α is smaller, and that gives a higher torque, [see (17), (18), (27), (28)].

In other words the twin crankshaft engine uses the cylinder pressure more efficiently than the inline crankshaft engine.

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

In twin crankshaft case, there are two opposite forces, 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, due to reduction of the angle φ in expansion stroke [See (20), (40)], unfortunately the torque is reduced too; because of the increase of angle α. see (37).

VIII. CONCLUSION

1. The twin crankshaft engine increases the torque hence 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.

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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
$_{th}$	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 Fa and extension of force Fc
μ	Friction factor

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