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Analysis of the Forces Acting on Apex Seal of A Wankel Engine

[1]A.K.N.Gerami, [2]M.S. Shadloo, [3]M. Ghasempour, [4]A. kimiaeifar,

[1]Department of Mechanical Engineering, Sharif University of Technology, Tehran, Iran.
[2]Faculty of Engineering and Natural Science, Sabanci University, Istanbul, Turkey.
[3]Department of Mechanical Engineering, Islamic Azad University, Dezful, Khozestan, Iran..
[4]Department of Mechanical Engineering, Aalborg University, Aalborg, Denmark.

Abstract: The acceleration acting on apex seals, and engine speed fluctuations together with the leading and trailing cells gas pressure forces are analyzed in the present work using the second Newton law. The research shows that cell gas pressure effects are important and inclusion of these effects will provide results which are more compatible with the reality and lead to a much more accurate analysis of the system. Theoretical calculations reveal that gas cell pressure forces represent about 78% of the overall calculated force and ignoring these pressure forces lead to the same magnitude of inaccuracy in predictions.

Key words: Rotary combustion engine, Wankel rotary compressor, Apex seal, Sealing force analysis

INTRODUCTION

In the rotary engines or compressors, seal friction losses are reported to be about 1.5 times to the losses in the bearings and gears (Yamamoto, 1981). On the other hand the long length of the side seals and the irregular path traversed by the apex seals have shown problems different from those encountered in sealing of the reciprocating piston engines.

Friction forces exerted on apex seal are proportional to the friction coefficient and perpendicular force acting on the seal. The friction coefficient is a constant factor which is a function of seal material and interior epitrochoidal wall type. On the other hand, the force exerted on the apex seal is variable and a function of its acceleration force, force of the spring connected to the seal, and the adjacent cells pressures. The acceleration of the apex seal is a function of the rotor geometry, the angular velocity, and acceleration of the crankshaft (ansdale and Lockley, 1969). Considering these parameters in determining the exact forces on the apex seal, will reveal the effects of these factors on the total force, and greatly help to improve future designs and friction-reduction considerations which all will lead to prolonged service life and higher efficiency of the rotary engines. According to the results presented by Pennock and Beard (Pennnock and Beard, 1997) friction forces between the apex seal side and rotor has a minor effect on the friction forces resulted from gas sealing. A schematics diagram of a rotary engine and its seals are illustrated in Fig. 1.

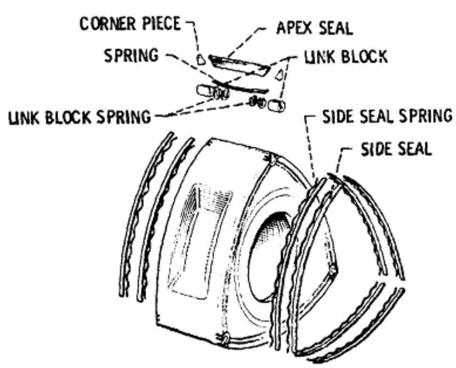

Fig. 1: Schematic drawing of a Wankel engine and its seals

Corresponding Author: A. kimiaeifar, Department of Mechanical Engineering, Aalborg University, Aalborg, Denmark.
Tel: +4529293402 E-mail: akf@me.aau.dk

Dynamic analysis of forces acting on the seals was widely analyzed by Vilmann and Knoll (1984). Prior to these studies, Yamamoto and Jones (1965) had shown that gas sealing losses were over 50% of the total normalized frictional losses in the rotary engine. Considering the primary laws of apex seals and according to their distance from epitrochoid walls, Knoll tried to investigate the probability of the apex seal separation from the wall and its magnitude. In his research, he concentrated on the gravity acceleration of the apex seal of a rotor at a constant rotary speed and he showed that the apex seal (in some operating conditions) tended to partially separate from the trochoid wall. The effects of different operating conditions on the performance of a rotary engine apex seal were investigated by Martin and Sadler (1979). At different constant shaft speeds, they studied the effects of three angular acceleration patterns, in order to identify the conditions and parameters that significantly affect the seal. Masaki Ohkubo (2004) mentioned some seal profiles due to a better lubrication.

Based on the research and analysis of dynamic forces on the seal, Beard and Pennock (1997) investigated crankshaft rotary speed fluctuation effects on the forces, and finally came to the conclusion that these effects were negligible. In their analysis, the cell gas pressure effects on the two sides of apex seal were not considered. Comparing the small values of the forces, calculated by this method, with those obtained from previous works, shows that cell gas pressure has a considerable effect on the forces. Crankshaft speed fluctuation due to inlet and outlet pressure pulses, changes the fluid inlet flow rate, and consequently leads to power fluctuation.

The pressure forces of the cells around the apex seal, as well as acceleration forces exerted on the seal, and crankshaft speed fluctuation, are studied in this research in order to analyze the amounts of the housing force exerted on the apex seal, and the importance of this parameter in the total friction existing in rotary engines and compressors.

2- Apex seal acceleration analysis:

Beard and Pennock (1997) introduced an analytical model to calculate the acceleration force exerted on the apex seal in terms of the geometrical coordinates of seal position. A schematic geometry of a rotary Wankel engine is shown in Fig. 2. In this Figure O_1 and O_2 are the centers of the fixed pitch circle and the rolling (or generating) pitch circle respectively, T is the number of generating lobes fixed to the rolling pitch circle, C is the center of the generating pin, $r_c = O_2C$ is the radius of the epitrochoidal path of point C,$e = O_1O_2$ is the trochoid eccentricity, α is the crank position relative to the X_f-*axis* in the fixed Cartesian reference frame, $\dot{\alpha}$ and $\ddot{\alpha}$ are the crankshaft speed and acceleration respectively. The radial direction is defined along the connecting line from O_2 to the center of point C.

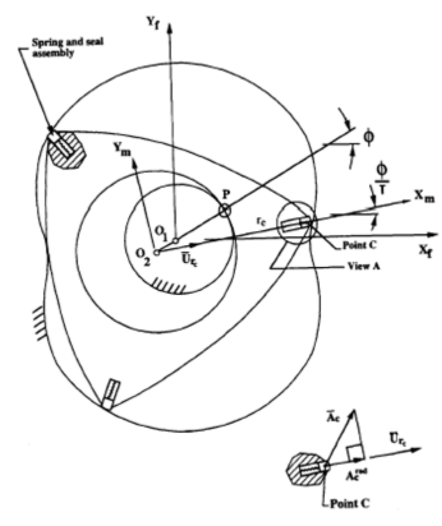

Fig. 2: Geometry of a Wankel engine

The coordinates of point C expressed in the fixed Cartesian reference frame are:

$$C_X = e\left\{-\cos\alpha + \mu T\cos\left(\frac{\alpha}{T}\right)\right\} \tag{1}$$

$$C_Y = e\left\{-\sin\alpha + \mu T\sin\left(\frac{\alpha}{T}\right)\right\} \tag{2}$$

Where $\mu = r_c / r_2$, is referred to the trochoid ratio. Differentiating equations (1) & (2) with respect to the crank position will provide the first-order and second-order kinematics coefficients.

$$f_X = \frac{dC_X}{d\alpha} = e\left\{\sin\alpha - \mu\sin\left(\frac{\alpha}{T}\right)\right\} \tag{3}$$

$$f_Y = \frac{dC_Y}{d\alpha} = e\left\{-\cos\alpha + \mu\cos\left(\frac{\alpha}{T}\right)\right\} \tag{4}$$

$$f'_X = \frac{d^2C_X}{d\alpha^2} = e\left\{\cos\alpha - \frac{\mu}{T}\cos\left(\frac{\alpha}{T}\right)\right\} \tag{5}$$

$$f'_Y = \frac{d^2C_Y}{d\alpha^2} = e\left\{\sin\alpha - \frac{\mu}{T}\sin\left(\frac{\alpha}{T}\right)\right\} \tag{6}$$

The radial component of the acceleration of point C can be expressed as $A_C^{rad} = \overline{A_C}\,\overline{U}_{rad}$ where:

$$\overline{A_C} = (f_X\bar{i} + f_Y\bar{j})\ddot{\alpha} + (f'_X\bar{i} + f'_Y\bar{j})\dot{\alpha}^2 \tag{7}$$

$\overline{U}_{rad}$ is the unit radial vector (unit vector directed along the line of action of the seal) and expressed as:

$$\overline{U}_{rad} = \cos\left(\frac{\alpha}{T}\right)\bar{i} + \sin\left(\frac{\alpha}{T}\right)\bar{j} \tag{8}$$

Therefore,

$$A_C^{rad} = (f_X\ddot{\alpha} + f'_X\dot{\alpha}^2)\cos\left(\frac{\alpha}{T}\right) + (f_Y\ddot{\alpha} + f'_Y\dot{\alpha}^2)\sin\left(\frac{\alpha}{T}\right). \tag{9}$$

Finally substituting equations (5) & (6) into equation (9), result is:

$$A_C^{rad} = e\left\{\sin\left(\alpha - \frac{\alpha}{T}\right)\ddot{\alpha} + \left[\cos\left(\alpha - \frac{\alpha}{T}\right) - \frac{\mu}{T}\right]\dot{\alpha}^2\right\} \tag{10}$$

To determine the fluctuations in the nominal value of crankshaft speed, the crankshaft speed will be approximated by a simple harmonic function. Beard and Pennock determined this harmonic function for operating conditions as below (Pennock and Beard, 1994):

$$\dot{\alpha} = \dot{\alpha}_0 + \frac{\Delta\dot{\alpha}_0}{2}\left\{1 - \cos\left[\frac{\alpha(T-1) - \pi}{T}\right]\right\} \tag{11}$$

and

$$\ddot{\alpha} = \frac{\dot{\alpha}\Delta\dot{\alpha}_0(T-1)}{2T}\sin\left[\frac{\alpha(T-1) - \pi}{T}\right] \tag{12}$$

Where $\dot{\alpha}_0$ is the nominal operating speed (a constant value) and $\Delta\dot{\alpha}_0$ is the nominal operating speed fluctuation. Since the operating speed is constant, $\ddot{\alpha}_0$ and $\Delta\ddot{\alpha}_0$ are zero. Substituting equations (11) & (12) in equation (10), A_c^{rad} acceleration is driven as a function of crank angle.

3- Gas pressure forces on apex seal:

The leading and trailing cells of apex seal face different conditions at suction, compression, and discharge processes during crank rotation which results in different magnitudes of internal gas pressure. Schock (1981) experimentally investigated the cell pressure of a 12A Mazda turbo-charged engine and as illustrated in Fig. 3, he plotted variation of pressure of a cell, with crank angle. The start of suction has minimum pressure value. Fig. 4 shows the schematic drawing of an apex seal inside a rotor channel. H is the contact point of append with epitrochoid wall. The angle difference between the apex seal radial direction and its contact direction with the cell, is called seal obliquity angle, which is shown by φ and can be calculated as following:

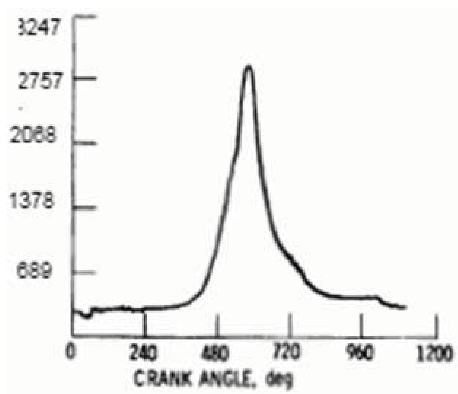

Fig. 3: variation of cell pressure with crank angle for a 12A Mazda

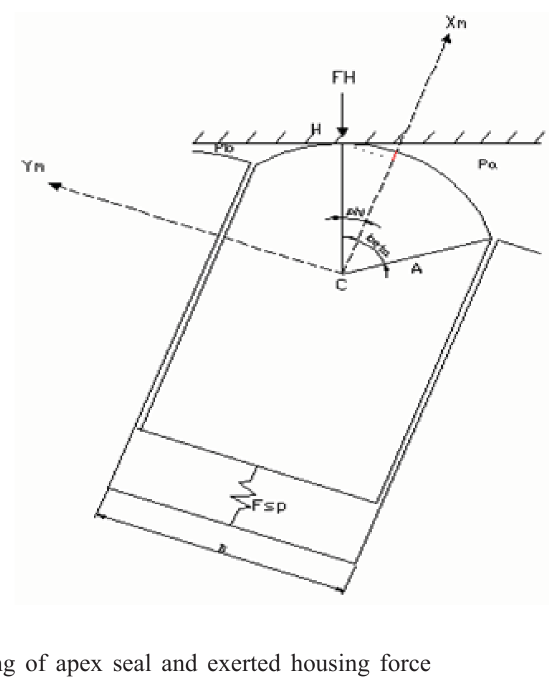

Fig. 4: Schematic drawing of apex seal and exerted housing force

$$\varphi = \cos^{-1}\left[\frac{r_c + 3e\cos 2\alpha}{(9e^2 + r_c^{\,2} + 6e\,r_c\cos 2\alpha)^{\frac{1}{2}}}\right] \tag{13}$$

Neglecting the red area in Fig. 4 (at the top of the seal head) and gas emission to the channel, the resultant forces at Y_m direction would be:

$$F_{PY} = -P_a W(A\cos\varphi - A\cos\beta) + P_b W(A\cos\varphi - A\cos\beta) \tag{14}$$

And the resultant forces at X_m direction is:

$$F_{PX} = -P_a W(\frac{B}{2} + A\sin\varphi) - P_b W(A\sin\varphi - \frac{B}{2}) \tag{15}$$

In equations (14) and (15), *2β* is the angle subtended by the cylindrical seal head and is equal to Sin^{-1} *[B/2A]* and also *W* is the width of the rotor. To calculate housing force on the seal, F_H, the image of pressure forces at any desired direction must be calculated.

4- Analysis of the Forces Acting on the Seal:

The second Newton law is used to calculate the housing force on the apex seal. F_{sp} is the force of spring connected to the apex seal. Channel forces acting on the apex seal, and the induced friction are neglected. In the present analysis, the seal is regarded as a particle, with the mass center at point C.

$$F_H = m_s A_c^{rad}\cos\varphi - F_{sp}\cos\varphi - F_{PY}\sin\varphi + F_{PX}\cos\varphi \tag{16}$$

Where $A^{rad}{}_c$ is calculated using equation (10) and m_S is the mass of the seal. For the theoretical calculations, the data given in Table1 is assumed. To find the cell pressure effects on the accuracy of the results, calculations are carried out for two cases of with and without considering the pressure forces on the seals.

5- Assumptions and Results:

To perform theoretical calculation, the following assumptions are considered:

1- The friction force between the side of the seal and rotor is ignored.

2- Nominal operating speed is taken to be constant ($\ddot{\alpha}_0$ and $\Delta\ddot{\alpha}_0$ are zero)

3- The red area in Fig. 4 is very small and thus is neglected.
4- There is no gas emission to the channel

Calculation results for an engine with specifications indicated in Table (1) are as following:

A- Ignoring cell pressure effects:
B- The results for the case when cell pressure is neglected are obtained and compared with those presented by Beard and Pennock (1997) for the same conditions. The 3D diagram of the housing force acting on apex seal at different crank angles reported by Beard and Pennock is shown in Fig. 5 and the corresponding predicted diagram obtained by present model is shown in Fig.6

Also Fig.7 compares the present predicted values with those reported by Beard and Pennock (1997) and as seen, a deviation of about 7% is concluded which indicates the acceptable accuracy of the model.

Table 1: Specifications and assumptions

Nominal speed fluctuation	Nominal operating speed	Trochoid ratio	Generating lobes	eccentricity	Spring force	Seal mass
170rpm> $\Delta\dot{\alpha}_0$ >17rpm	$\dot{\alpha}_0$ =1700 rpm	μ=2.289	T=3	e=15 mm	Fsp=24.46 N	M=14 gr

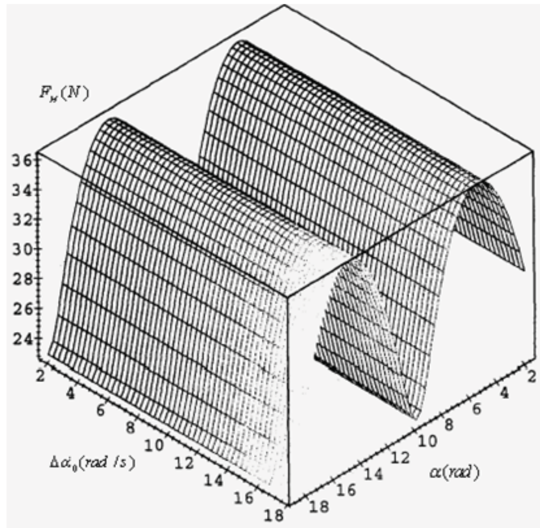

Fig. 5: Housing force acting on the apex seal as a function of crank angle for different speeds (for trochoid ratio of 2.289) (Pennock and Beard, 1997)

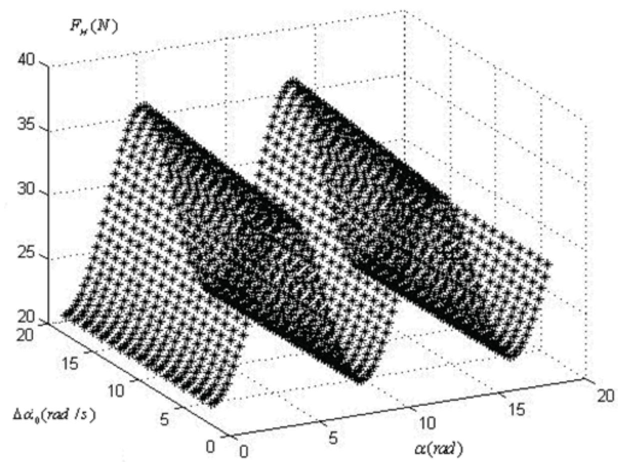

Fig. 6: Housing force acting on the apex seal as a function of crank angle for different speeds (for trochoid ratio of 2.289) calculated from the present work

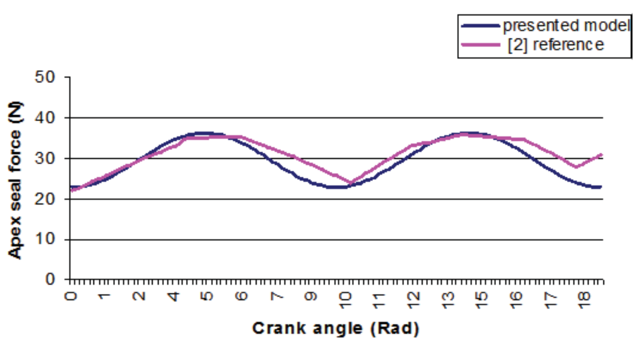

Fig. 7: Variation of housing force with crank angle (neglecting cell pressure effect)

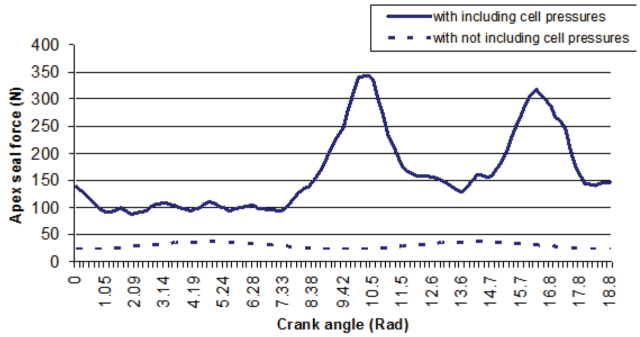

Fig. 8: Comparison of variations of housing force with crank angle

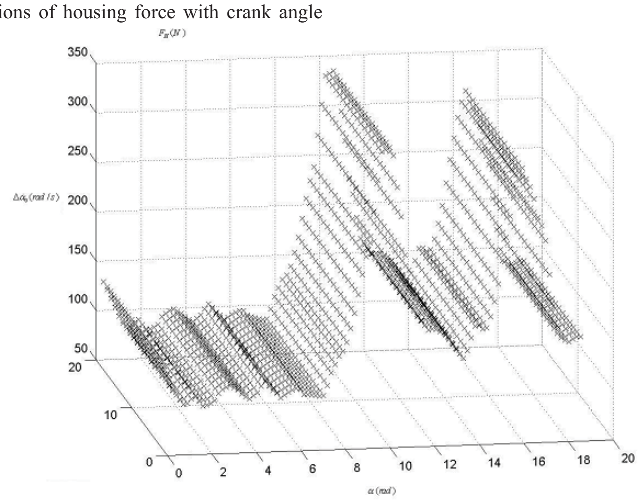

Fig. 9: Housing force acting on the apex seal as a function of crank angle for different speeds (for trochoid ratio of 2.289)

C- Considering cell pressure effects:

Considering cell pressure effects on apex seal provides a greater value of force comparing with the case where pressure effects where neglected (see Fig.8). As seen from this Figure, a maximum value of 344 N is obtained for force where the minimum value is about 88 N. These values are much higher than the corresponding values of 38 N and 24 N for the case where cell pressure effects were ignored.

Variation with crank angle of housing force which includes the effects of cell pressure is shown in Fig.9. This Figure indicates the minor effect of rotary speed variations on the acting force.

The results show that cell pressure forces have considerable contribution on the forces acting on the apex seal in a rotary combustion engine and forms about 78 percent of the overall force. Therefore considering the cell pressure in dynamic analysis of the force and friction calculations will result in a much higher perpendicular force, with a much better accuracy.

Conclusion

Based on the results obtained from the present research:

1- Pressure force of cells around the apex seal has a considerable effect on the perpendicular forces acting on seals and also on the friction calculations of Wankel rotary engine. Based on present calculations, ignoring this pressure will induce about 78% errors in the results.
2- Engine speed fluctuation has not significant effect on the forces acting on the apex seal and may be neglected in friction and force calculations.

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