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Design Method of Offsetting the Orbiting Scroll and Its Influence on the Self-Rotation Characteristics of the Orbiting Scroll

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Abstract. In order to reduce the diameter of compressor casing of the automotive scroll compressor, the orbiting scroll is sometimes offset along a certain direction. This paper summarizes the method of offsetting the orbiting scroll, and analyses the influence of the offset amount on the self-rotation characteristics of the orbiting scroll. The theoretical calculation results show that a larger offset amount is beneficial to increase the stroke volume, however it is easy to make the orbiting scroll rotate around its driving center in the negative direction which would cause an impact on the scroll wrap and the anti-rotation mechanism. At last, this paper affords some advices in how to offset the orbiting scroll.

1. Foreword

Scroll compressors have been widely used in automotive air conditioners due to their compact structure, stable operation and high volumetric efficiency. Research on structural optimization, leakage and seal, friction and wear, vibration and noise of the automotive scroll compressor is still underway.

Due to the small installation space on the car, the overall size of the automotive scroll compressor, especially the size of the waist, is strictly limited. In order to make the scroll compressor more compact and efficient, the scroll compressor is expected to have a larger stroke volume at the limited size of the waist. The most direct method is to increase the height of the scroll wrap, however this makes the orbiting scroll prone to overturn. Therefore, the axial size of the scroll compressor is also limited.

Another feasible way to increase the stroke volume of the scroll compressor without increasing the height of scroll wrap and the size of the waist is to offset the orbiting scroll. Generally speaking, the basic circle center of the orbiting scroll coincides with the driving center and the basic circle center of the fixed scroll coincides with the shaft center respectively. When the basic circle center of the orbiting scroll is offset along a certain direction, it is possible to arrange more scroll turns on the base plate of the orbiting scroll. The number of orbiting scroll turns depends directly on the outer diameter of the base plate of the orbiting scroll which cannot be changed randomly since it is determined by the inner diameter of compressor casing and the orbiting radius.

Up to now, just a few literatures, which referred to the offset or eccentricity of scroll wraps, can be found in public, and the details of the process has not been described [1-3]. Besides that, the influence of offsetting the orbiting scroll on the dynamic characteristics especially the self-rotation characteristics of the scroll compressor are rarely mentioned.

Bush J. W., Beagle W. P. and Housman M. E. firstly introduced the conception of offsetting scroll wraps and pointed that offsetting scroll wraps adds variation to the gas-induced moment carried by anti-rotation coupling [3]. It was found that for offset amount greater than one half of the orbiting radius, the minimum self-rotation moment would become negative, reversing the torque on the anti-rotation mechanism.

Mori T., Yanagisawa T. et al. carried out a theoretical analysis of the self-rotation characteristics of the orbiting scroll and verified it through the experiment [1] [2]. It was found that the orbiting scroll would rotate around its driving center and could not maintain a constant self-rotation direction during one orbiting cycle. Within most orbiting angle span, the orbiting scroll would rotate in the positive direction which coincides with the orbiting direction, however, the orbiting scroll would also rotate in the negative direction at certain condition.

Although those papers mentioned that a larger offset amount would cause unwanted dynamic behavior of the orbiting scroll, the influence of different offset design on the self-rotation characteristic of the

orbiting scroll was not further analyzed. In this paper, the general design method of offsetting the orbiting scroll for automotive scroll compressor is summarized, and the influence of the offset on the self-rotation characteristics of the orbiting scroll is discussed. Finally, a design method of offsetting the orbiting scroll is proposed to improve the self-rotational characteristics of the orbiting scroll.

2. General Design Method of Offsetting the Orbiting Scroll

In household air conditioning scroll compressor, the basic circle center of the orbiting scroll coincides with the driving center generally. However in automotive scroll compressor especially of the belt-driven type, the orbiting scroll is often offset to reduce the diameter of compressor casing due to the small installation space. The automotive scroll compressor can achieve the largest possible stroke volume under the same diameter of compressor casing by offsetting the orbiting scroll. For the scroll compressor, the stroke volume consists of two parts, one part is the closure volume of the suction chamber formed by the outer side of the orbiting scroll and the inner side of the fixed scroll, the other part is the closure volume of the suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll. How the orbiting scroll is offset determines the number of scroll turns that can be arranged on the base plate, thus has a direct influence on the stroke volume.

In the following, the general method of offsetting the orbiting scroll will be introduced in detail. The influence of offset amount and offset angle on the scroll compressor's stroke volume will be discussed as well.

The planar view of the orbiting scroll profile with and without offset is shown in Figure 1, the two scroll profile share some basic parameters such as basic circle radius, orbiting radius and so on. In the figure, the coordinate $X_sO_sY_s$ locates on the shaft center, the coordinate $X_mO_mY_m$ locates on the basic circle center of the orbiting scroll, edge A is the inner edge of compressor casing and edge B is the outer edge of the base plate of the orbiting scroll, E is the point at the end of the inner side of the orbiting scroll, F is the point at the end of the outer side of the orbiting scroll, T is the tangent point at the basic circle of the orbiting scroll, ρ is the orbiting radius, e is the distance between the basic circle center of the orbiting scroll and the driving center, that is, the offset amount, γ is phase angle of the vector from the basic circle center of the orbiting scroll to the driving center which is calculated from the positive direction of the X_m axis, that is, the offset angle.

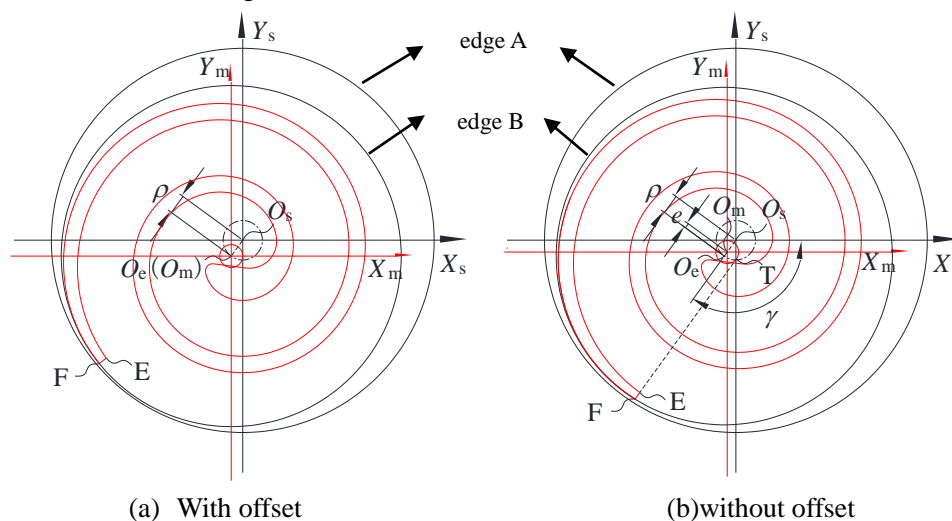(a) With offset   (b)without offset

Figure 1 planar view of the orbiting scroll profile with and without offset

If the orbiting scroll is not offset, the basic circle center of the orbiting scroll O_m coincides with the driving center O_e, as shown in Figure 1(a). If the orbiting scroll is offset, the basic circle center of the orbiting scroll O_m will move away from the driving center O_e, as shown in Figure 1(b). It is not difficult to find that the number of the orbiting scroll turns with offset is larger than that without offset when keeping other parameters the same.

Given the inner diameter of compressor casing and the orbiting radius, the outer diameter of the base plate of the orbiting scroll is certain, which should meet the following relationship

$$R_{orb} + \rho \le R_{shell} \tag{1}$$

where R_{shell} is the inner diameter of compressor casing, and R_{orb} is the outer diameter of the base plate of the orbiting scroll.

Generally, the orbiting scroll can be offset in the following way. Firstly, choose an offset amount no more than $\rho/2$. Then make a tangent line from point E to the basic circle of the orbiting scroll. Lastly offset the basic circle center of the orbiting scroll O_m along the tangent line ET and keep the driving center O_e unmoved. The distance that O_m moves is the offset amount which varies between 0 and $\rho/2$.

However point E is unknown in advance since it is associated with the number of the orbiting scroll turns which is also a parameter that needs to be determined. Therefore, it is necessary to determine the above parameters iteratively based on their underlying relationship.

Some basic parameters of the orbiting scroll are shown in Figure 2. In the figure, φ_o is the outer involute angle, φ_o is the inner involute angle, and α is the involute angle corresponding to half of wrap thickness [4].
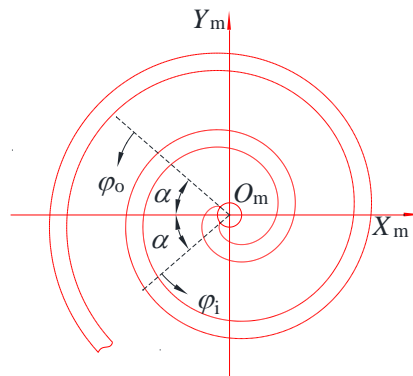

Figure 2 inner and outer involute angle of the orbiting scroll

Assume that the number of orbiting scroll turns is N_{orb}, then the inner involute angle φ_E at point E can be calculated by the following expression

$$\varphi_E = 2\pi N_{orb} - \alpha \tag{2}$$

In Figure 1(b), the coordinates of point E are

$$\begin{cases} x_E = r_b \left[\cos(\varphi_E + \pi + \alpha) + \varphi_E \sin(\varphi_E + \pi + \alpha) \right] + (\rho - e)\cos\gamma \\ y_E = r_b \left[\sin(\varphi_E + \pi + \alpha) - \varphi_E \cos(\varphi_E + \pi + \alpha) \right] + (\rho - e)\sin\gamma \end{cases} \tag{3}$$

The relationship between the offset angle γ and the number of orbiting scroll turns N_{orb} is as follows

$$\gamma = -\frac{3}{2}\pi + 2\pi \left(N_{orb} - [N_{orb}] \right) \tag{4}$$

where $[N_{orb}]$ denotes to round N_{orb} to the nearest integer that is not bigger than N_{orb}.

The coordinates of point F are

$$\begin{cases} x_F = x_E + t_E \cos\gamma \\ y_F = y_E + t_E \sin\gamma \end{cases} \tag{5}$$

where t_E is the local thickness of the scroll wrap at point E. It should be noticed that t_E is not equal to the thickness of the scroll wrap t necessarily. In most cases, the outer involute profile of the orbiting scroll at end will be modified to increase the number of scroll turns further, leading to a smaller value of t_E than t.

The coordinates of point O_e are

$$\begin{cases} x_{O_e} = \rho \cos\gamma \\ y_{O_e} = \rho \sin\gamma \end{cases} \tag{6}$$

Since point F also locates on the outer edge of the base plate of the orbiting scroll, so the distance

between point F and point O_e equals to the outer diameter of the base plate of the orbiting scroll

$$\left(x_F - x_{O_e}\right)^2 + \left(y_F - y_{O_e}\right)^2 = R_{orb}^2 \tag{7}$$

Equations (2) - (7) are solved simultaneously to obtain the number of orbiting scroll turns.

The closure volume of suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll at any orbiting angle can be calculated by following expression

$$V_s = \frac{1}{2}(\pi - 2\alpha) r_b^2 h \left[-\theta^2 + \theta\left(2\varphi_E + 2\alpha - \pi\right)\right] + \Delta V_s \tag{8}$$

where h is the height of scroll wrap, θ is the orbiting angle calculated from when the suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll closes, r_b is the basic circle radius, ΔV_s is the correction of suction volume and can be calculated by following expression[4]

$$\Delta V_s = \rho h r_b \left[-\left(\varphi_E + 2\alpha - \pi\right)\sin\theta - \left(\frac{\pi}{4} - \frac{\alpha}{2}\right)\sin 2\theta + \left(1 - \cos\theta\right)\right] \tag{9}$$

It is assumed that t_E equals to half of t after modification to the outer profile of the orbiting scroll in this paper. The parameters used in the calculation are shown in Table 1.

Table 1 parameters used to calculate the volume of the suction chamber

parameter	r_b [mm]	α [rad]	ρ [mm]	t [mm]	h [mm]	R_{shell} [mm]	R_{orb} [mm]
value	3.2	0.711	5.5	4.55	35	53.5	47.5

As the offset amount of the orbiting scroll gradually increase from 0 to $\rho/2$, the closure volume of the suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll is shown in Figure 3. It is obviously that increasing the offset amount helps bringing about a larger closure volume for the suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll. This is because that more number of orbiting scroll turns can be arranged on the base plate of the orbiting scroll.
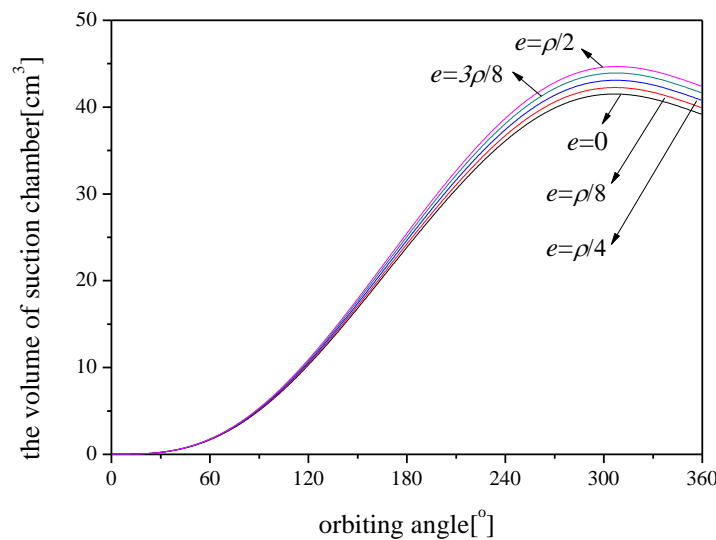

Figure 3 the variation of the closure volume of the suction chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll

Given the inner diameter of compressor casing, the orbiting radius and the thickness of the orbiting scroll at the end wrap, the maximal number of the orbiting scroll turns can be determined for every offset amount. The maximal number of the orbiting scroll turns N_{orb}, the offset angle γ and the closure volume of suction chamber V_s corresponding to different offset amount e are shown in Table 2.

Table 2 maximal number of the orbiting scroll turns, the offset angle
and the closure volume of suction chamber

e [mm]	0	$\rho/8$	$\rho/4$	$3\rho/8$	$\rho/2$
N_{orb} [-]	2.359	2.391	2.426	2.461	2.492
γ [°]	-140.6	-129.4	-116.7	-104.1	-92.8
V_s [cm³]	39.181	39.941	40.796	41.651	42.411

According to the calculation result in Table 2, the closure volume of suction chamber can be increased by 8.2% when the offset amount of the orbiting scroll reaches $\rho/2$ compared with the case where the orbiting scroll is not offset ($e=0$). Generally speaking, the offset amount would not be chosen so large in the actual design since a large offset amount is likely to cause a sudden change in the self-rotation state of the orbiting scroll and makes the amplitude of driven torque larger. In the following, the influence of different offset design on the self-rotation characteristics will be discussed.

3. Judgment of Self-Rotation State of the Orbiting Scroll

In order to judge the self-rotation state of the orbiting scroll, it is necessary to perform force analysis on the orbiting scroll and the eccentric bushing system. For this reason, it can be assumed that the orbiting scroll does not rotate, and there are two meshing points between the fixed scroll and the orbiting scroll without considering the effect of anti-rotation mechanism on the orbiting scroll [1] [2].

Without considering the frictional force on the meshing point between two scrolls and the frictional moment between the orbiting scroll and the eccentric bush, the forces acting on the orbiting scroll are shown in Figure 4. In the figure, F_t, F_r and F_a represent tangential gas force, radial gas force and axial gas force respectively, F_c is the centrifugal force acting on the center of gravity, F_{dr} and F_{dt} represent the radial and tangent driving force exerted by the eccentric bush, F_{s1} and F_{s2} represent the contact force on the meshing points between two scroll wraps, O_e is the center of the eccentric bush, that is, the driving center, O_g is the centroid of the orbiting scroll. It should be noticed that the primary balance has been conducted so the centroid of the orbiting scroll coincides with the driving center.
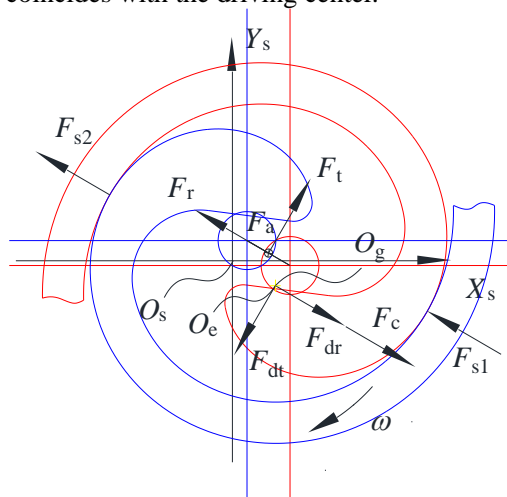

Figure 4 forces acting on the orbiting scroll

The force balance equations of the orbiting scroll along the tangent and radial direction are as follows

$$F_{s1} + F_{s2} + F_r - F_{dr} - F_c = 0 \tag{10}$$

$$F_{dt} - F_t = 0 \tag{11}$$

The moment balance equation around the center of eccentric bush O_e is

$$\mathbf{r}_{s1} \times \mathbf{F}_{s1} + \mathbf{r}_{s2} \times \mathbf{F}_{s2} + \mathbf{r}_r \times \mathbf{F}_r + \mathbf{r}_t \times \mathbf{F}_t + \mathbf{r}_c \times \mathbf{F}_c = 0 \tag{12}$$

where $\mathbf{r}_{s1}$ and $\mathbf{r}_{s2}$ are position vectors of forces $\mathbf{F}_{s1}$ and $\mathbf{F}_{s2}$ directed from O_e to its own meshing point

alternatively, $\mathbf{r}_r$, $\mathbf{r}_t$ and $\mathbf{r}_c$ are position vectors of forces $\mathbf{F}_r$, $\mathbf{F}_t$ and $\mathbf{F}_c$ directed from O_e to its own acting point alternatively.

The forces acting on bushing system are shown in Figure 5, the frictional force between the eccentric shaft pin and the eccentric bush, and the frictional moment between the orbiting scroll and the eccentric bush are neglected here. In the figure, F'_{dr} and F'_{dt} represent reaction forces exerted by the orbiting scroll, F_{pr} and F_{pt} represent driving forces exerted by the eccentric pin, F_{cb} is the centrifugal force acting at the center of gravity of the bushing system, ζ is the angle between the arm O_pO_s and arm O_sO_e, λ is the angle between the arm O_sO_p and arm O_pO_e.
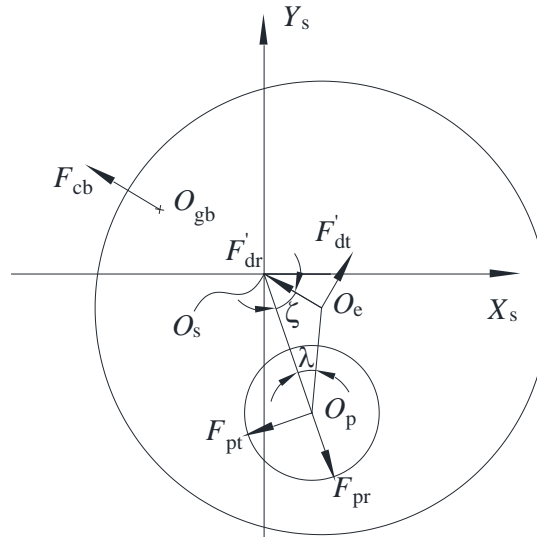

Figure 5 forces acting on the eccentric bushing system

The force balance equations are as follows

$$F_{pr}\cos\zeta - F_{pt}\sin\zeta - F'_{dr} - F_{cb} = 0 \tag{13}$$

$$F_{pr}\sin\zeta + F_{pt}\cos\zeta - F'_{dt} = 0 \tag{14}$$

The moment balance equation around the center of the eccentric bush O_e is

$$\mathbf{r}_{pr} \times \mathbf{F}_{pr} + \mathbf{r}_{pt} \times \mathbf{F}_{pt} = 0 \tag{15}$$

where $\mathbf{r}_{pr}$ and $\mathbf{r}_{pt}$ are position vectors of $\mathbf{F}_{pr}$ and $\mathbf{F}_{pt}$ directed from O_e to the center of the eccentric pin. It should be noticed that acting line of $\mathbf{F}_{cb}$ is almost the same as $\mathbf{F}'_{dr}$, so the force $\mathbf{F}_{cb}$ does not appear in the moment balance equation.

In above equation (10) - (15), the unknown parameters are F_{s1}, F_{s2}, F_{dr}, F_{dt}, F_{pr} and F_{pt}. The number of unknown parameters equals to the number of equations, so the equations can be solved.

When the scroll compressor is operating, the orbiting scroll would rotate around its driving center due to the self-rotation moment. According to the value of F_{s1} and F_{s2} just resolved, the self-rotation state of the orbiting scroll can be judged. If F_{s1} and F_{s2} are both positive, the orbiting scroll will not rotate. If F_{s1} is positive and F_{s2} is negative, the orbiting scroll will rotate in the positive direction. If F_{s1} is negative and F_{s2} is positive, the orbiting scroll will rotate in the negative direction.

4. Influence of Offset Amount on the Self-Rotation State of the Orbiting Scroll

According to the method of judging the self-rotation state of the orbiting scroll, the self-rotation characteristic when the offset amount is $\rho/2$, $\rho/4$ and 0 will be compared and analyzed in the following.

The number of the orbiting scroll turns and the number of the fixed scroll turns of the scroll compressor studied in this paper are not equal, and the number of the fixed scroll turns is larger and fixed at 2.5. For the sake of discussion, it is assumed that the orbiting angle is zero when the end point of inner profile of the fixed scroll just contact with the outer profile of the orbiting scroll.

In the thermodynamic calculation, the refrigerant leakage between different chambers is not considered, and the compression process is assumed to be adiabatic compression [5]. The refrigerant used

in automotive air conditioner is R134a and the operation condition used for calculation is shown in Table 3.

Table 3 the operation condition used for calculation

Operation condition	Suction pressure p_s [kPa]	Discharge pressure p_d [kPa]	Suction temperature t_s [℃]	Compressor speed n [rpm]	Isentropic efficiency η_c [−]
value	280	1600	8.7	4200	0.65

When the offset amount is $\rho/2$, the maximal number of the orbiting scroll turns is 2.492 and the offset angle is -92.8° according to the calculation result in Table 2. The contact force on two meshing points and the corresponding self-rotation moment of the orbiting scroll during one orbiting cycle are shown in Figure 6. According to the value of F_{s1} and F_{s2}, the self-rotation state of the orbiting scroll can be divided into three cases:

(1) When the orbiting angle varies in the interval $\left[61^\circ, 251^\circ\right)$, the orbiting scroll rotates in the positive direction.

(2) When the orbiting angle varies in the interval $\left[292^\circ, 360^\circ\right) \cup \left[0^\circ, 13^\circ\right)$, the orbiting scroll rotates in the negative direction.

(3) When the orbiting angle varies in the interval $\left[13^\circ, 61^\circ\right) \cup \left[251^\circ, 292^\circ\right)$, the orbiting scroll does not rotate around its driving center.
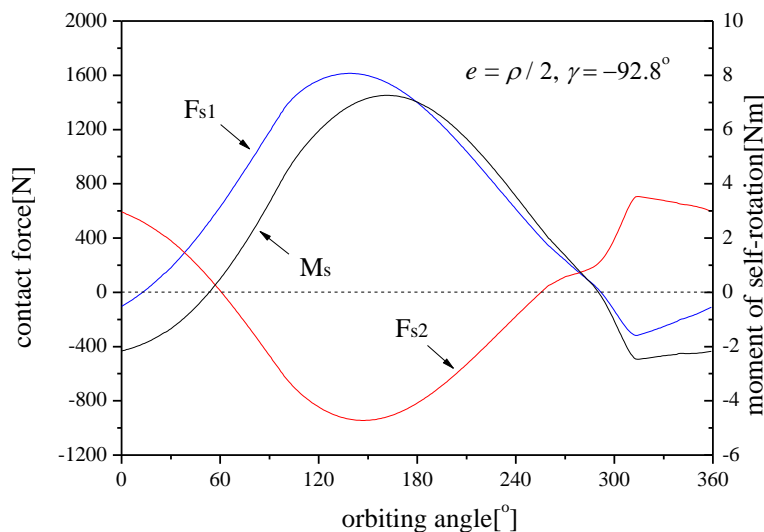

Figure 6 the contact force and self-rotation moment of the orbiting scroll
when the offset amount is $\rho/2$

In addition, the variation tendency of the self-rotation moment M_s is quite similar with the contact force F_{s1} as shown in Figure 6. It is obvious that the self-rotation state of the orbiting scroll changed with the self-rotation moment. During most orbiting angle, the self-rotation moment M_s varies between zero and the maximum peak. As the orbiting angle approaches 290°, the self-rotation moment M_s decreases and the orbiting scroll tends to rotate in the reverse direction.

Likewise, when the offset amount is $\rho/4$ and 0, the maximal number of the orbiting scroll turns is 2.426 and 2.359 respectively, the offset angle is -116.7° and -140.7° (the offset angle is meaningless for the case where the offset amount is 0) respectively according to the calculation result in Table 2. The contact force on two meshing points and the corresponding self-rotation moment of the orbiting scroll in both cases are shown in Figure 7 and Figure 8 respectively.

Compare the above three cases and it can be found that as the offset amount decreases from $\rho/2$ to 0, the variation amplitude of contact force and self-rotation moment decrease as well. It is not difficult to understand since the larger offset amount which corresponds to the larger compression force arm will lead to the larger self-rotation moment when the operation condition stays almost the same. The most important is that when the offset amount decreases, the probability that the orbiting scroll rotate in the negative direction becomes smaller. It can be seen from Figure 8 that when the offset amount is 0, the contact force F_{s1} always varies above the abscissa, meaning that the orbiting scroll will never rotate in the negative direction.
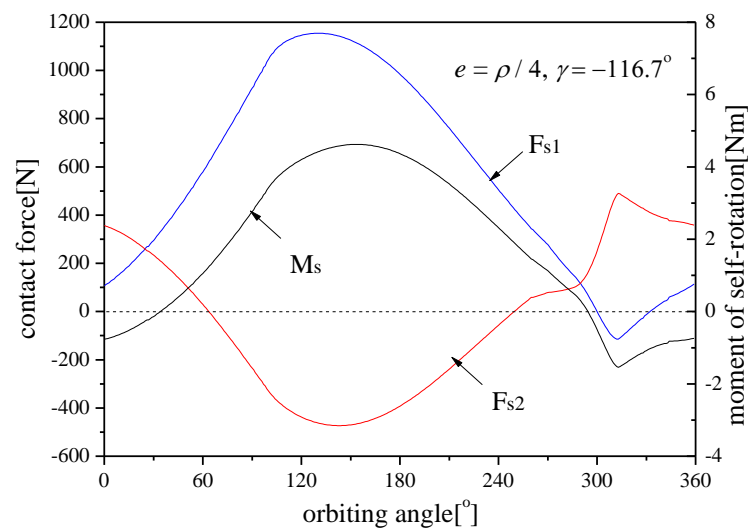

Figure 7 the contact force and self-rotation moment of the orbiting scroll
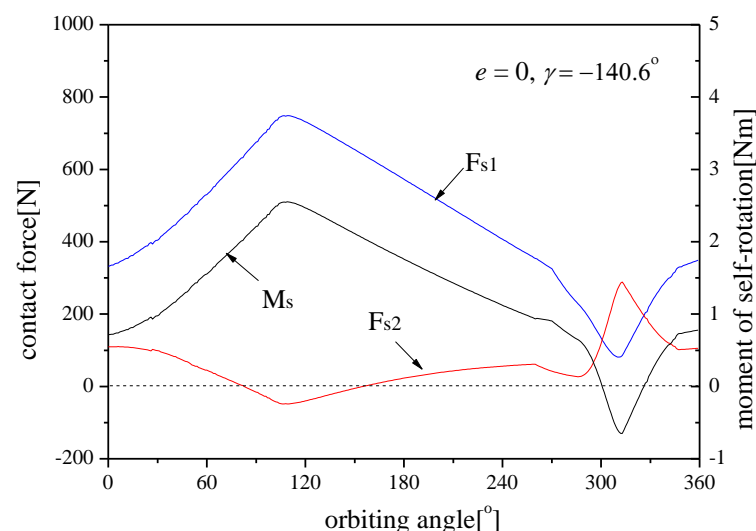when the offset amount is $\rho/4$

Figure 8 the contact force and self-rotation moment of the orbiting scroll
when the offset amount is 0

It should be noticed that in above calculation the leakage between different chambers and the friction on the meshing points are neglected and this would not cause too much error on the judgement of the orbiting scroll. According to previous paper [6], when only the leakage is considered, the orbiting angle

8

span in which the orbiting scroll rotates in the positive direction is a little larger. This is because that leakage occurs in the meshing gaps owing to the self-rotation in the positive direction, leading to the increment of the pressure in the compression chamber formed by the inner side of the orbiting scroll and the outer side of the fixed scroll, thus enhancing the tendency of the self-rotation of the orbiting scroll in the positive direction further. Meanwhile the friction on the meshing points is one of obstruction factors that prevent the self-rotation of the orbiting scroll, the influence of the leakage on the self-rotation of the orbiting scroll can be offset by the friction. Therefore calculation results in this paper are quite acceptable though neglecting the leakage and the friction at the same time.

Generally speaking the orbiting scroll without offset will never rotate in the negative direction under normal operation condition, however the case is different when the orbiting scroll is offset. When the orbiting scroll is offset, the orbiting scroll would frequently rotate in the negative direction especially for the larger offset amount according to above analysis. When the orbiting scroll rotates in the negative direction even for a while during one orbiting cycle, the reliability of scroll compressor would encounter some problems. The sudden change of the self-rotation direction would cause an impact to the two scroll wraps and the anti-rotation mechanism and generate noise and vibration especially when the compressor operates at high speed. Therefore, when designing a scroll compressor, especially an automotive scroll compressor, care must be taken to avoid reverse self-rotation of the orbiting scroll.

5.   Some Suggestion on Offsetting the Orbiting Scroll

According to the previous analysis results, given the inner diameter of compressor casing and the orbiting radius, the larger the offset amount, the more orbiting scroll wraps can be arranged on the base plate of the orbiting scroll. However, the orbiting scroll with a larger offset amount is more likely to rotate in the negative direction during the operation of the compressor, resulting in a decrease in compressor performance and reliability.

Therefore, it is necessary to reasonably select the offset amount so that it can achieve the effect of increasing the stroke volume without making the orbiting scroll rotate reversely. There is no need to follow the one-to-one correspondence relationship between the offset amount and the offset angle to maximize the stroke volume. By adjusting the offset angle while keeping the offset amount unchanged, the effect of increasing the stroke volume and improving the self-rotation characteristics of the orbiting scroll can both be achieved.

It may be a laborious work to determine the limiting offset amount for various sizes of automotive scroll compressors since the self-rotation state of the orbiting scroll depends on not only the offset design but also the compressor operation condition. Just as mentioned in previous paper [3], the optimum value of the offset depends on the individual scroll design. One general rule should be followed to offset the orbiting scroll is that the orbiting scroll will not rotate in the negative direction under most operation conditions, the specific design process is as follow:

(1) According to the required stroke volume, determine the minimum number of orbiting scroll turns which meets the requirement, then determine the minimum offset amount e_{min} and optimal offset angle γ_{opt} that matches the minimum number of orbiting scroll turns by resolving equations (2) – (9) simultaneously;

(2) Resolve equations (10) – (15) simultaneously and analyze the self-rotation characteristics of the orbiting scroll according to the method mentioned in this paper. If the orbiting scroll does not rotate reversely under most operation conditions, the minimum offset amount e_{min} determined in previous step is suitable, otherwise enter the next step;

(3) Increase the offset mount to $e_{min} + \Delta e$ ($\Delta e > 0$) on the basis of minimum offset amount but assure it is not more than $\rho/2$, and adjust the offset angle to $\gamma_{opt} + \Delta\gamma$ or $\gamma_{opt} - \Delta\gamma$ ($\Delta\gamma > 0$) accordingly. Resolve equations (10) – (15) simultaneously and analyze the self-rotation characteristics of the orbiting scroll according to the method mentioned in this paper. Repeat this step repeatedly until the orbiting scroll does not rotate reversely under most operation conditions.

6. Conclusion

This paper summarizes the method of offsetting the orbiting scroll, and analyses the influence of the offset on the self-rotation characteristics of the orbiting scroll. The theoretical calculation results show that a larger offset amount is beneficial to increase the stroke volume, however, a larger offset is likely to make the orbiting scroll rotate around its driving center in the negative direction which would cause an impact on the two scroll wraps and the anti-rotation mechanism. When there is no offset ($e = 0$), the orbiting scroll will not rotate in the negative direction, getting rid of the sudden change of the self-rotation state. At the end, this paper gives some suggestion on offsetting the orbiting scroll.

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