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SHAPE OPTIMIZATION OF OLDHAM COUPLING IN SCROLL COMPRESSOR

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ABSTRACT

The Oldham coupling generally used to prevent the relative motion between orbiting and fixed scroll in scroll compressor applications. Keys of the Oldham coupling take the loads exerted by the orbiting scroll, so as to prevent the rotation of the orbiting scroll. The loads exerted by the orbiting scroll cause the wear on the keys and the vibration which brings about the noise level increase. The excessive wear causes the rotation of the orbiting scroll, resulting in the leakage of the refrigerant gas through the radial clearance. The reduction of the loads on the Oldham coupling keys is a challenging issue for most of the scroll machine design engineers. In order to realize it, consideration was taken for two approaches. One is the weight reduction of the Oldham coupling. The other is the extension of the distance between the confronting Oldham coupling keys. The magnitude of the averaged load exerted on each Oldham coupling key may be reduced through the second approach. In this study the first method is taken into account. This method decreases the magnitude of the fluctuation of the Oldham coupling key loads. The shape optimization of the Oldham coupling can realize the growth of its strength, resulting in the reduction of its mass. This approach helps to reduce the cost and the vibration, and to raise the efficiency and the reliability. The result shows that the maximum Mises stress is reduced to 10.8% and the maximum deformation is decreased to 6.8% with 59.8% of the mass, even without a consideration of the reduction of key loads due to smaller mass.

1. INTRODUCTION

A scroll machine operates based on the interaction of two interleaved spirals or so-called “scrolls”, with one scroll fixed and the other orbiting against it. Then the rotation of the orbiting scroll should be strictly prevented. Oldham coupling is usually used in order to make possible this. Oldham coupling is originally used for transferring rotation with equal angular velocity between two shafts in parallel but small distance away. In scroll compressor applications, it is used to prevent the relative rotation between fixed and orbiting scroll. Keys of the Oldham coupling take the loads exerted by the orbiting scroll, so as to play this role. The loads exerted by the orbiting scroll cause the wear on the keys and the vibration which brings about the noise level increase. The excessive wear causes the rotation of the orbiting scroll, resulting in the leakage of the refrigerant gas through the radial clearance. The reduction of the loads on the Oldham coupling keys is a challenging issue for most of the scroll machine design engineers. In order to realize it, consideration was taken for two approaches. One is the weight reduction of the Oldham coupling. The other is the extension of the distance between the confronting Oldham keys. The magnitude of the load exerted on each Oldham coupling key may be reduced through the second approach. In this study the first method is taken into account. This method decreases the magnitude of the fluctuation of the Oldham coupling key loads. The shape optimization of the Oldham coupling can realize the growth of its strength, resulting in the reduction of its mass. This approach helps to reduce the cost and the vibration, and to raise the efficiency and the reliability.

2. OLDHAM COUPLING REACTION FORCES

The main loads applied at Oldham coupling is shown in Figure 1 (Morishita *et al.*, 1984), where the friction terms from key loads and gravity force are ignored in order to simplify the optimization process and to make clear the effect of main loads. As seen from the figure, F_i is the only force due to inertial effect of Oldham coupling, which is restricted in linear motion. It makes the force have the harmonic characteristics.

There are two instants that the relative velocities become zero between Oldham coupling keys and their mating grooves for one period. It makes oil film broken so that the wearing can be occurred. For this reason the Oldham coupling keys are exposed in a feeble condition of wearing. The wearing may cause the relative rotation between orbiting and fixed scroll, so the leakage due to the relative rotation can reduce the cooling capacity of the cycle.

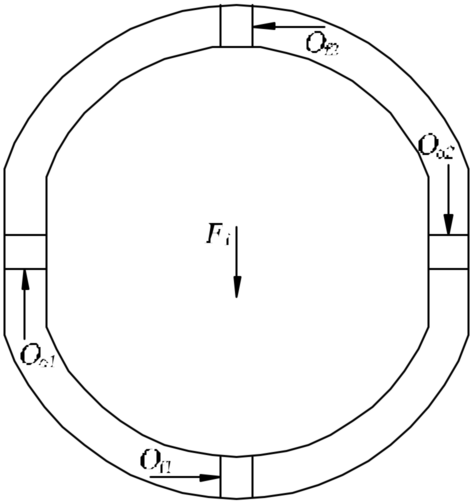


Figure 1: Loads at Oldham coupling

Equations (1) ~ (3) show the dynamics of Oldham coupling. O_{o1}, O_{o2}, O_{f1}, and O_{f2} are the forces inevitably exerted at the Oldham coupling keys in order to prevent orbiting scroll from rotating, during the process of operation of scroll compressors. The moment to rotate orbiting scroll mainly results from the eccentricity of the tangential gas force and the viscous relative motion between orbiting scroll boss and crankshaft pin. It transmits the loads O_{o1} and O_{o2} to Oldham coupling to offset the moment. And the transferred moment can also be cancelled out from fixed part of Oldham coupling key loads O_{f1} and O_{f2}.

$$\sum F_X = O_{f1} - O_{f2} = 0 \tag{1}$$

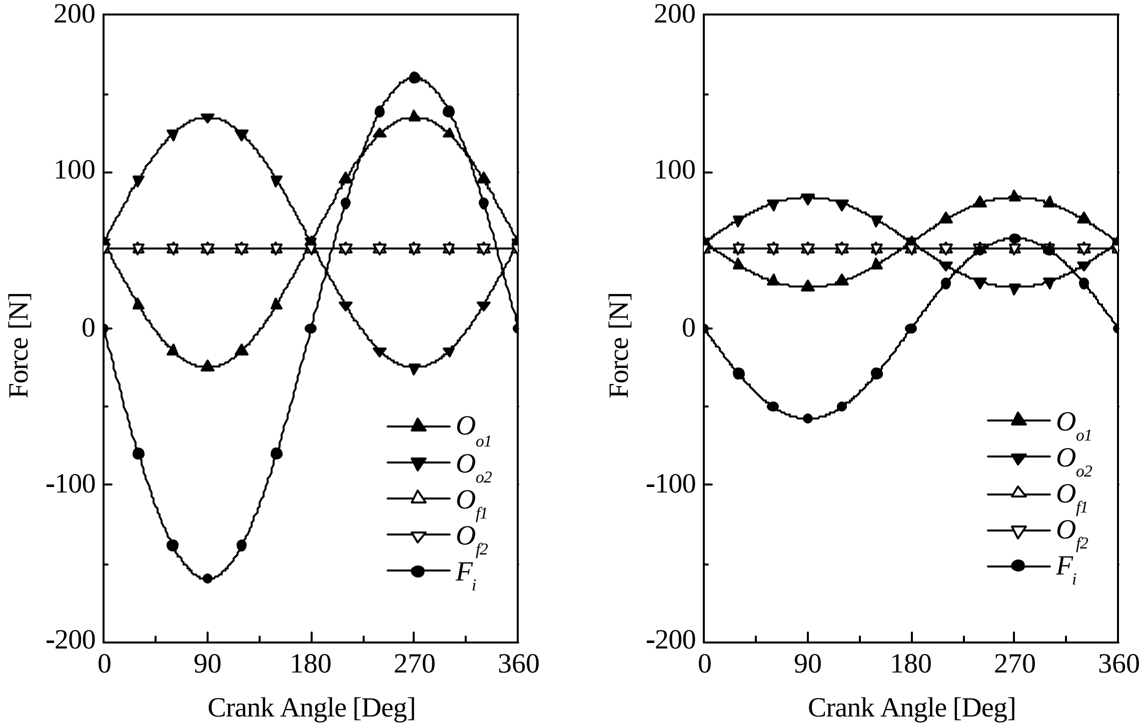
$$\sum F_Y = O_{o1} - O_{o2} - F_i = 0 \tag{2}$$

$$\sum M_Z = \left(O_{f1} + O_{f2}\right) \cdot L_f - \left(O_{o1} + O_{o2}\right) \cdot L_o = 0 \tag{3}$$

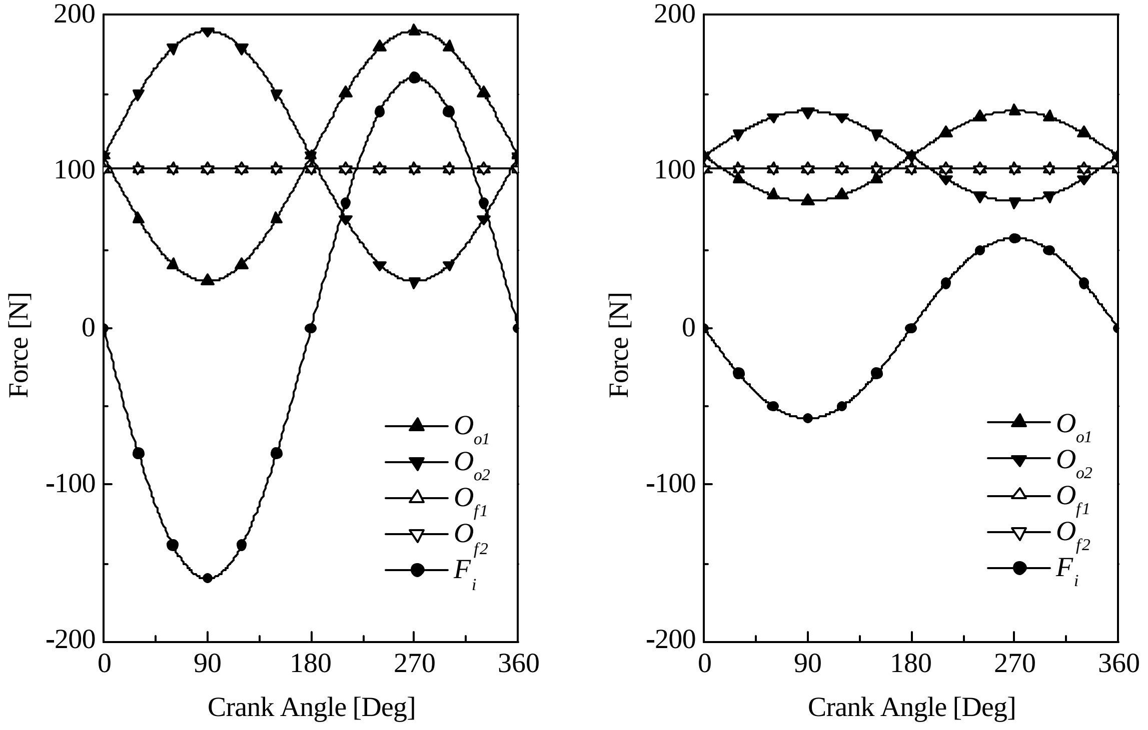
Where, the inertial force F_i should take the value as in equation (4). It is assumed that the compression process is steady, so the angular velocity and the orbiting radius are constants. From this assumption the second term of equation (4) becomes zero, and the results of F_i is shown in equation (5).

$$F_i = m \cdot \frac{d^2}{dt^2}\left(e \cdot \sin q\right) = m \cdot e \cdot \left(-\sin q \cdot \dot{q}^2 + \cos q \cdot \ddot{q}\right) \tag{4}$$

$$F_i = -m \cdot e \cdot w^2 \cdot \sin q \tag{5}$$



(a) Steel Oldham coupling with L_o & L_f (b) Aluminum Oldham coupling with L_o & L_f



(c) Steel Oldham coupling with $L_o/2$ & $L_f/2$ (d) Aluminum Oldham coupling with $L_o/2$ & $L_f/2$

Figure 2: Oldham coupling key loads for one period

Figure 2 shows the results of Oldham coupling key load analysis. In the figure, (a) and (c) represent the loads of Oldham coupling keys made up of steel. On the other hand (b) and (d) stand for that of aluminum. The difference is only in the mass of Oldham coupling. (c) and (d) show the cases of reduced distance between keys about a half of the cases of (a) and (b).

From these results, one can easily find out 2 rules of thumb. One is that the fluctuations of 2 loads at the part of orbiting scroll get bigger if the mass of Oldham coupling is increased. And the other is that the average magnitude of the load can be reduced from the extension of the distance of the mating keys.

But in almost all cases the geometric margins of Oldham coupling are confined from the shell or the main frame that are surrounding it. Therefore, consideration must be taken into account in the first approach due to the limitation of the second one.

3. REDUCTION OF THE MASS OF OLDHAM COUPLING

One of the easiest ways to reduce the mass is changing the material of Oldham coupling. For example one might use a low density material as that of Oldham coupling like aluminum instead of steel. But in many cases, the low density materials are more flexible than the heavy ones. The other simple way to reduce mass is decreasing the volume of an Oldham coupling. It can also cause the excessive deformation of Oldham coupling at the similar loads.

Not only wear of keys but also deformation can bring about the relative rotation between orbiting and fixed scroll.

So it is necessary to optimize of the shape of Oldham coupling to improve the stiffness for a given density and volume or to minimize the mass with the same stiffness.

3.1 Topological Optimization

In order to maximize the stiffness for a given mass of Oldham coupling, topological optimization scheme in a commercial finite element package, ANSYS was used.

In this study we are concerned only in 2 dimensional optimization, because in many cases the out-of-plane space of Oldham coupling body was already fixed in earlier design processes. And the inertial load F_i was applied at a averaged constant value over a period.

The finite element model was made up of 22,500 elements and 68,101 nodes with 2-D 8-node 2nd order quadrilateral solid plane stress element. The domain size was 150x150, and an individual element in the domain is made up of 1x1 element in millimeters.

Figure 3 shows that the progressing state of optimization process. In these figures the contour indicates the internal pseudodensities that are assigned to each finite elements. The pseudodensity for each element varies from 0 to 1. 0 represents material to be removed, and 1 represents material that should be kept. From the result of the figure it is obvious that the optimum shape of Oldham coupling body is lozenge-shaped. The neighboring key should be connected with linear shaped body.

The loads exerted between neighboring keys can be converted to tension or compression with the proper shapes of Oldham coupling body. So it is obvious that the shape of the body between keys are best to be linear.

3.2 Classical Beam Theory

In the consideration of the Classical beam theory, the beam in the state of compression or tension can be applied much less stress than that of bending. Figure 4 shows the different shaped beams exerted by the same loads, *i.e.* the same magnitude, direction and applying position. Though the loads of the beams are identical, the maximum stress and deformation are somewhat different because of their shapes. These beams can be thought as one of the Oldham coupling body side. Figure 4 (a) and (b) correspond to Oldham coupling body shape of lozenge and circle respectively. It is assumed in both cases that the width of the beams are b, so the size of cross sectional areas are equal. And in case (b), the distance between pin joint and loading position is L, and the angle of the arc is 90 degree. Of course the mass of the two cases are not equal for its different length.

The volume of case (a) and (b) at Figure 4 are shown in Equation (6) and (7) respectively. The volume of case (b) is about 11% greater than that of case (a). It represents the difference of mass *i.e.* key load fluctuation.

$$V_l = b \cdot h \cdot L \tag{6}$$

$$V_c = \frac{\pi}{2} \cdot b \cdot h \cdot R = \frac{\pi}{2\sqrt{2}} \cdot b \cdot h \cdot L = \frac{\pi}{2\sqrt{2}} \cdot V_l \tag{7}$$

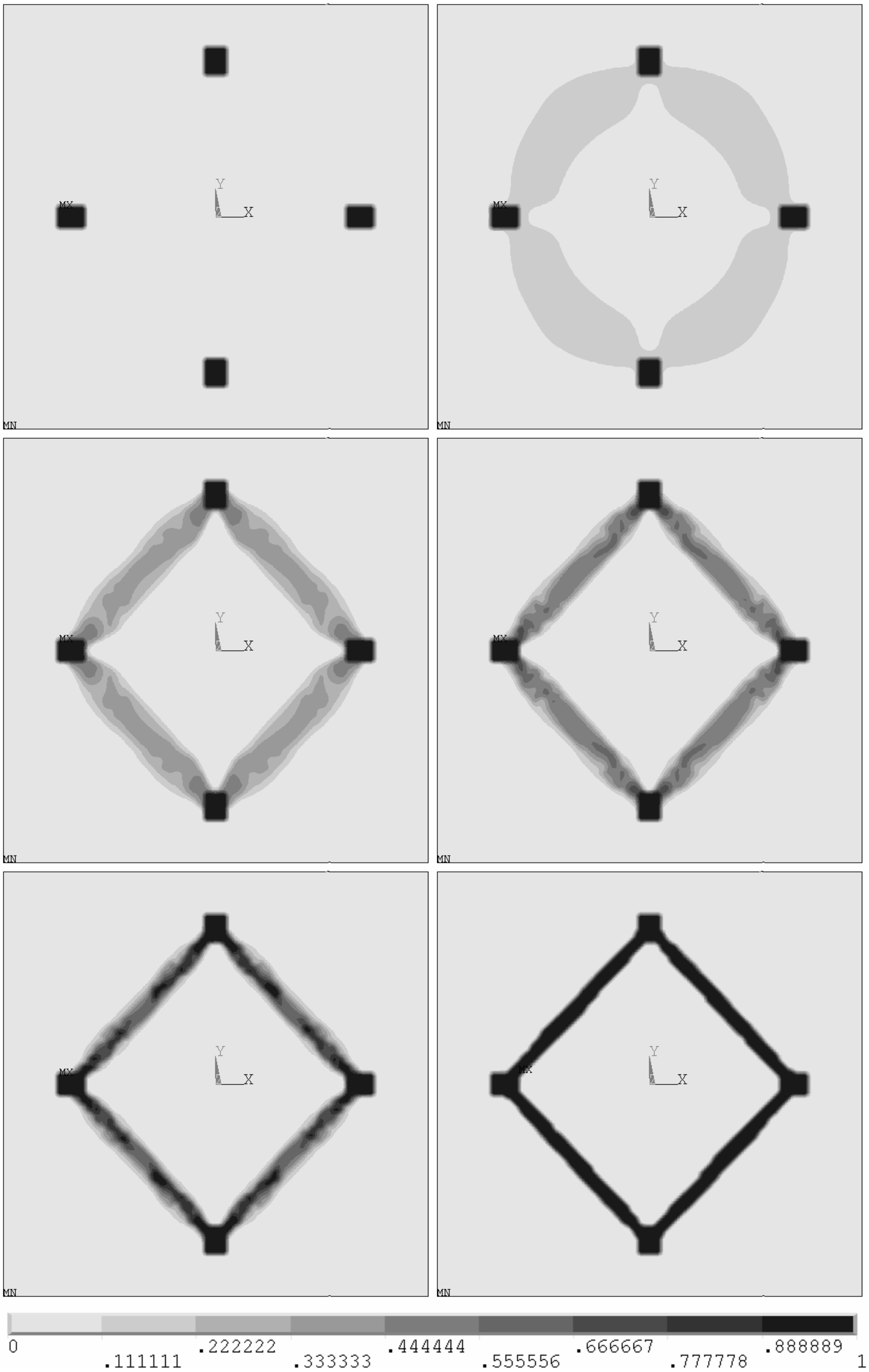
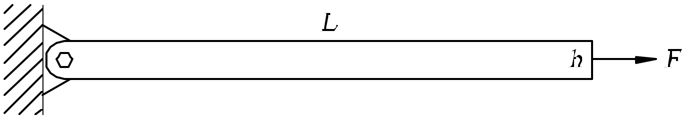
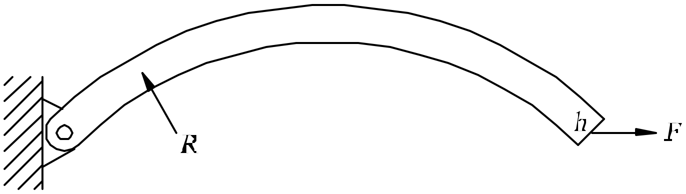


Figure 3: Topological optimization of Oldham coupling



(a) Linear beam



(b) Curved beam

Figure 4: Beams with two different shapes

In a linear beam like Figure 4 (a), there is no bending moment exerted. So, the stress is just normal tensile stress. Equation (8) shows the value of the stress. It is constant all over the cross sectional area and all through the length of the beam. On the other hand, in a curved beam like Figure 4 (b), a bending moment is applied. The maximum value of it can be found in the center of the beam and the value is shown in Equation (9). The maximum stress is also applied in the bottom of center at the value of Equation (10). Where, the beam takes the load of bending and tension simultaneously. The first term of Equation (10) represents the bending stress, and the second term stands for the normal stress from tension. The second term has the same value as the linear beam case of (a). In almost all the cases, *R*/*h* is much greater than 1, so the effect of the bending is much larger than that of tension. For example, in the case of *R*/*h* is 5.0, the maximum stress of a curved beam is 9.8 times greater than that of a linear beam.

$$s_l = \frac{F}{b \cdot h} \tag{8}$$

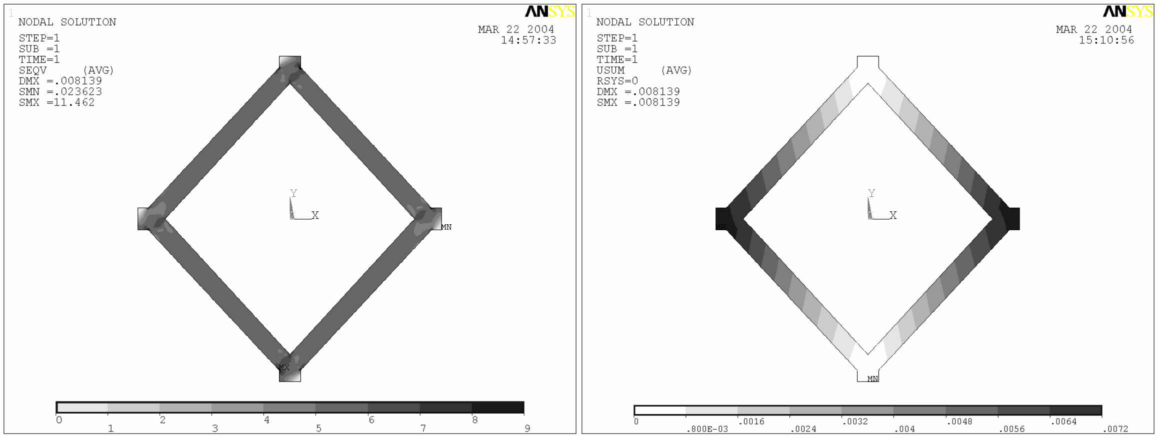
$$M_{c\max} = F \cdot R \cdot \left(1 - \cos 45^\circ\right) = \left(1 - \frac{1}{\sqrt{2}}\right) \cdot F \cdot R \tag{9}$$

$$s_{c\max} = \frac{M_{c\max} \cdot h/2}{I} + s_l = \left\{3 \cdot \left(2 - \sqrt{2}\right) \cdot \frac{R}{h} + 1\right\} \cdot s_l \tag{10}$$

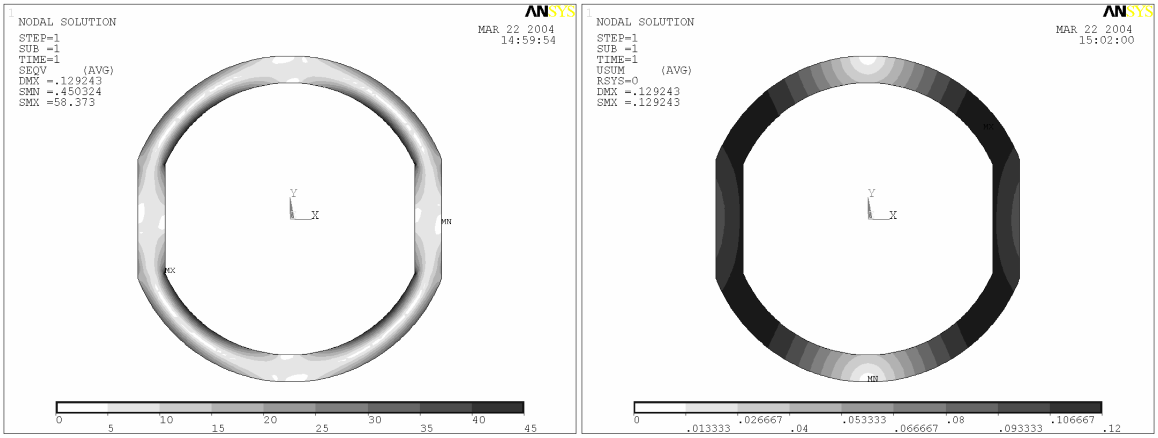
4. RESULTS

From the synthesis of above all the results, we can conclude the shape of Oldham coupling. Figure 5 shows that the results of finite analysis results of two cases considered. Figure 5 (a) shows Mises stress distribution of optimized lozenge-shaped Oldham coupling. The body stress is about 5.05 MPa through the length. Figure 5 (c) shows Mises stress distribution of the conventional curved type. The body exerted the bending load shows the stress distribution that is varied from 0 to 46.6 MPa. The volume and the mass of linear type is 59.8% of curved type, and the key loads of two cases are assumed to be identical. Putting aside the reduction of key loads from smaller mass, the maximum Mises stress is reduced to 10.8% with 59.8% of the mass. Figure 5 (b) and (c) shows the displacement of lozenge-shaped Oldham coupling and conventional curved type respectively. The maximum value of the optimized shape is about 8 µm, and that of the conventional type is 129 µm. The optimized shaped one is just 6.3% of the maximum deformation with 59.8% of the mass.

Figure 6 represents the variation of Mises stress and deformation of each type along with the upper right body side. The peak value of the (a) results from the singularity of non-filleted edge.



(a) Mises stress of lozenge-shaped Oldham coupling (b) Displacement of lozenge-shaped Oldham coupling



(c) Mises stress of circular Oldham coupling (d) Displacement of circular Oldham coupling

Figure 5: Results of 2-dimensional finite element analysis

5. DISCUSSIONS

We performed the shape optimization of Oldham coupling with respect to mass reduction. It is considered with 3 steps. One is the topological optimization with commercial finite element software, where we can obtain the optimized shape of Oldham coupling to maximize the stiffness with given volume. The other is from classical beam theory in which the maximum Mises stress is compared in the aspect of strength, and another is verification of the optimized shape with the finite element analysis in both aspect of stiffness and strength.

But in this study we considered only 2-dimensional model with averaged constant inertial effect. So, the further study is required about 3-dimensional model with varying inertial effect considered.

6. CONCLUSIONS

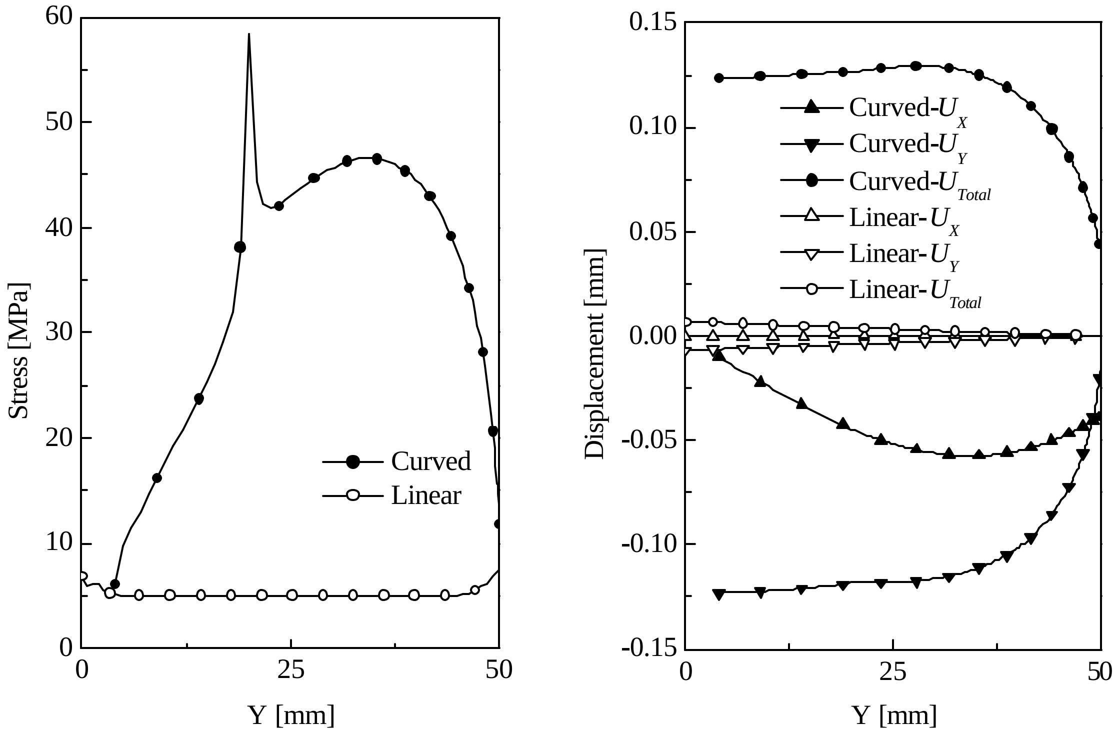
The reaction forces exerted at Oldham coupling keys should be minimized, because it influences on performance, vibration and noise. To attain this goal, it is recommended the followings:

- The distance between keys should be as long as possible.
- The mass of Oldham coupling should be as light as possible.

To reduce the mass of Oldham coupling:

- Use the low density material.
- Reduce the volume.

- Design the shape of the Oldham coupling body to guarantee the stiffness and the strength.
- The optimum shape of Oldham coupling body is a lozenge.



(a) Mises stress

(b) Displacement

Figure 6: Results along the body side

NOMENCLATURE

			Subscripts	
F	force	(N)		
I	moment of inertia	(mm4)	*c*	curved beam
L	distance between keys	(mm)	*f*	fixed part
M	moment	(N mm)	*i*	inertia
O	force of Oldham coupling key	(N)	*l*	linear beam
R	curvature	(mm)	max	maximum
U	displacement	(mm)	*o*	orbiting part
b	beam width	(mm)	*X*	X-coordinate
h	beam height	(mm)	*Y*	Y-coordinate
q	crank angle	(rad)	*Z*	Z-coordinate
s	stress	(MPa)		
w	angular velocity	(rad/sec)		

REFERENCES

Morishita, E., Sugihara, M., Inaba, T., Nakamura, T., 1984, Scroll Compressor Analytical Model, *Proceedings of the 1984 International Compressor Engineering Conference at Purdue*, p. 487-495.