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MAXIMIZING SCROLL COMPRESSOR DISPLACEMENT USING GENERALIZED WRAP GEOMETRY

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ABSTRACT

In designing ever smaller compressors, a problem with scrolls is that conventional wraps require an operating space which is non-circular and off-center from the axis of the compressor assembly. Many scroll designs have unused volume around the outside of the wraps. In this paper, a method is adopted using general conjugacy relations to define a scroll geometry which fills a circular periphery and makes better use of available space for displacement. This provides as much as 18 percent or more increased capacity with no increase in size.

INTRODUCTION

Compressor size reduction is always a goal of designers working on new products. Scroll compressors lend themselves to compact designs with their inherently round shape. They fit well with the general size and shape of electric motors used to drive hermetic compressor designs and they are both easily integrated within a single cylindrical shell. However, the scroll form has some inherent asymmetry which leaves some unused space around the suction area.

At capacity levels of around six and a half tons (air conditioning), designs in use today seem to be nearing a boundary where the scroll mechanism begins to require a greater diameter than the motor which drives it. This may, in larger sizes, require designs of shell or structure more complex than the economical cylindrical shells popular today.

Better use of the unused space has been suggested by offsetting scroll wraps from the drive and housing centers. This technique "evens out" the asymmetries by, on average, centering them within a circular envelope. It also introduces potentially objectionable fluctuations and reversals in the torque applied to the oldham coupling or other rotation prevention device, requiring additional design measures to deal with this.

Here we use general conjugacy relations to design a "hybrid" scroll wrap tailored to fill a circular space while remaining centered with that space. This makes the most use of available space, increasing capacity over wraps of conventional or even offset form while limiting the introduction of coupling torque fluctuations and eliminating reversals.

BACKGROUND

Involute of Circle Limitations

Figure 1 shows a conventional scroll wrap for a fully enclosed fixed scroll. This general design is found in many different refrigerant compressors on today's market. The scroll wrap center is on the housing center. A reference outside diameter is shown whose center is on the scroll center and whose radius fully encloses the scroll set and provides strength to the surrounding structure. The area between the boundary of the space required for the operation of the scroll wraps and the minimum enclosing circle is essentially wasted space. Nothing takes place here.

Anything we can do to bring the working volume of the scroll closer to the outer periphery will help increase displacement. We will see how this is done by either repositioning the scroll or redesigning the basic wrap shape.

Offset Wraps

Hiraga and Terauchi [1,2] and later Yoshii et.al. [3], while designing free-standing fixed scroll wraps, understood the asymmetry of the scroll form and realized that scrolls need not be driven through their geometric center. They offset the wrap from the baseplate center by half the orbit radius, reducing the diameter of the orbiting scroll baseplate which had limited their minimum shell diameter.

Later, Shiibayashi [4] showed that the optimum value of the offset depends on the individual scroll design. He worked with a fully enclosed wrap geometry where the asymmetry was sensitive not to the orbit radius but instead to the scroll pitch. He reduced his housing size requirement by offsetting the wrap one-fourth of the involute spiral pitch. More recently, Fukanuma et.al. [5] refined the inclusion of radial running clearances to this technique.
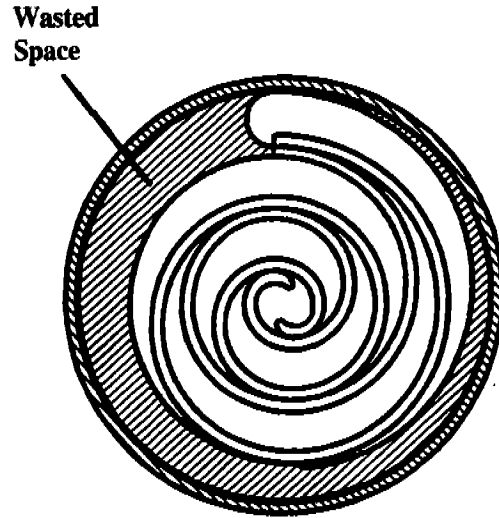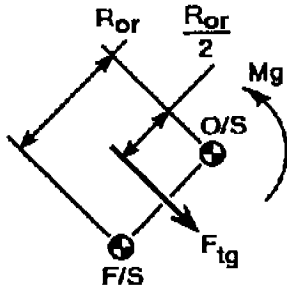
Wasted Space

Figure 1

Figure 2

Torque Load Variation

Offsetting scroll wraps adds variation to the gas-induced moment carried by the Oldham coupling or other anti-rotation coupling. In scroll machines with symmetric wraps (both wraps have the same working surface geometries) the tangential gas forces act through an axis normal to and at the midpoint of a line segment between the geometric centers of the two scrolls. See Figure 2. When the geometric centers of the scroll wraps coincide with the drive centers as in a conventional design, equal and opposite moments are generated at the two scrolls of magnitude

$$M_g = F_{tg} \cdot \frac{R_{or}}{2} \qquad (1)$$

Radial gas forces act through the line between geometric centers and induce no moment of their own.

Figure 3

Figure 3 diagrams a scroll set whose geometric centers are offset a distance e. The normal distance from the line of action of the tangential gas forces to the drive center is not constant. The gas moment is governed by the relationship

$$M_g = F_{tg} \cdot [\frac{R_{or}}{2} + e \cos(\theta - \beta)] \qquad (2)$$

The gas torque now has an additional fluctuating component which increases with the offset of the scroll centers. Extreme values load on the coupling become

$$M_g = F_{tg} \cdot [\frac{R_{or}}{2} \pm e] \qquad (3)$$

For offsets greater than one half R_{or}, the minimum load becomes negative, reversing the torque on the anti-rotation coupling. The maximum load can similarly increase by double or more. Dealing with both increasing and especially reversing peak loads puts additional demands on the rotation prevention mechanism and adds to its design complexity, as well as adding additional noise and vibration during operation.

One solution, proposed by Terauchi [6], uses asymmetric conventional wraps with unequal ending angles to induce

unbalanced pocket pressures. His design shifts the line of action of the tangential gas force toward the fixed scroll center and can prevent it from crossing over the orbiting scroll bearing center. The gas moment does not reverse, but the peak loads on the coupling become correspondingly higher. This may be acceptable in the ball thrust coupling he used, which is already highly loaded, but can be troublesome in other designs.

Hybrid Wraps

It is interesting to consider that the advantage of offset wraps lies in the effective reconfiguration of the outer wraps to better fill the available space while the disadvantage lies in the similar reconfiguration of the inner wraps where the greater portion of the gas forces are generated. A more satisfactory solution would reconfigure the outer wraps to provide good displacement characteristics while specifically not substantially changing the geometry or position of the inner wraps. This cannot be done solely with a conventional involute of a circle.

A method exists [7] which allows us to design scroll wraps of a general form to meet any of a number of specialized boundary conditions. They can then be joined or spliced to wraps of other, perhaps more conventional, form. This method of generating so-called "hybrid" scroll wraps permits a scroll form to be built up segment by segment, with each segment designed to fulfill a particular specialized role in the compression process.

In defining equations for any given scroll section [7], it is only necessary that the equation describing the swing radius be related to the generating radius equation according to

$$\frac{\partial R_s}{\partial \alpha} = R_g \qquad (4)$$

Note that the swing radius may have arbitrary degrees of freedom while the generating radius may now be variable.

DESIGN METHOD

We wish to formulate an outer scroll wrap which fills as much of the peripheral space as possible. This maximizes displacement within the given space. We also wish for the inner wraps to retain the property of having their portion of the tangential gas force act directly between the scroll centerlines as in a conventional on-center scroll. This will minimize fluctuation or reversal of loading of the anti-rotation device. If these are of two incompatible forms, that is if they are difficult to join together, we can add a third segment defined by a swing radius equation with sufficient degrees of freedom to make the transition.

Hybrid Wrap Formulation

Our hybrid wrap for this example is composed of three distinct portions. The inner section of the wrap is a conventional involute of a circle. This will generate uniform symmetrical gas loading where the pressures are the highest and where most of the loads are generated. This conventional scroll wrap is the special case of the conjugacy relation where the swing radius is a first order polynomial and its derivative, the generating radius, is a constant.

The outer portion of the wrap is a constant radius arc concentric to the baseplate. This outer radius will fill as much of the wasted space as possible, throughout its extent, where the suction volume is formed. This is a degenerate case of the conjugacy relation where the swing radius is a constant and its derivative, the generating radius, is always zero. This, incidentally, is also the conjugacy condition for the rotary or standing vane type compressor.

The only theoretical requirement in splicing scroll wraps of different form is that at the point of transition the values of swing radius and generating radius are both the same for both curves. An involute of a circle and a circular arc have generating radii which are two different constants and this set of equalities is impossible to satisfy. We require a third segment to join between the two curves.

Since all we have to do is join the two endpoints of the transition segment, with two end conditions each, to the outer and inner wraps, the swing radius equation needs to be of a form with at least four degrees of freedom. We can arbitrarily specify the angle over which the transition takes place.

Hybrid Wrap Design

In Figure 4 the involute of a circle and the high order curve meet at point "A". At the wrap angle defining this position the pitch line swing radius R_{sA} and generating radius R_g must be equal for both the involute of a circle and the high order curve.

The high order curve and the outer radius meet at blend point "B". At the wrap angle defining this position, the pitch line swing radius R_{sB} on the high order curve must be equal to the outer radius and the generating radius must be zero.

This forms a system of four equations describing the four end conditions. They are solved for coefficients of the high order curve, satisfying the four transition end point conditions. To maximize displacement, we maintain the circular arc segment for as long as possible for each pocket set, performing the wrap formulation and solution separately for each pocket set. The resulting design has asymmetric suction pockets and requires different starting angles to maintain balanced displacement volumes and avoid unbalanced pressures in the inner wraps.
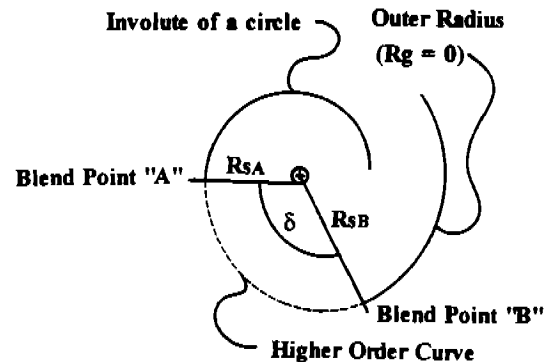

Figure 4

Figure 5 shows a hybrid fixed scroll with the defining angles. The outward facing wall of the wrap is labelled (B) and the inward facing wall of the wrap is labelled (A).

DESIGN EXAMPLE

This example compares the application of hybrid wraps to conventional and offset wraps. It is based on a commercially available design with a maximum capacity of a little over six tons at the ARI air conditioning rating point with conventional scroll wraps. It has a maximum circular envelope within which we will maximize and compare displacement using hybrid and offset wrap scroll forms. We will also compare tangential gas force and coupling moment at the rating point for a series of hybrid, offset, and standard scroll forms normalized to a constant displacement.

Design constraints for the example include, for involute of a circle sections: common orbiting radii, generating radii, and wrap heights. All designs are sized for a common volume ratio of 2.6. The non-working clearance between the outer half wrap of the orbiting scroll and the fixed scroll is common at 1.5 mm.
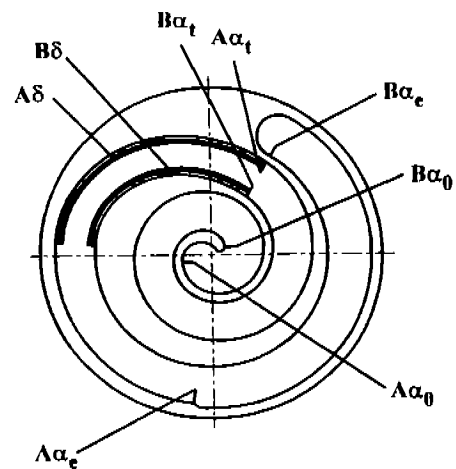

Figure 5

Capacity Comparison

The diametric envelope for the design example is 120 mm. The maximum capacity hybrid, offset wrap, and involute of circle scroll forms which fit the envelope and conform to the constraints listed above yield the following capacities:

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DESIGN TYPE	AIR CONDITIONING CAPACITY
Involute of a Circle Wrap	76,000 BTU/hr
Offset Involute of Circle Wrap	85,300 BTU/hr (+12.2 percent)
Hybrid Wrap	90,000 BTU/hr (+18.4 percent)

The hybrid wrap design always yields higher capacity than offset wraps. Offset wraps do a good but not exact job of filling the available space. The outer wrap of the hybrid scroll may be tailored to fit whatever available space there is.
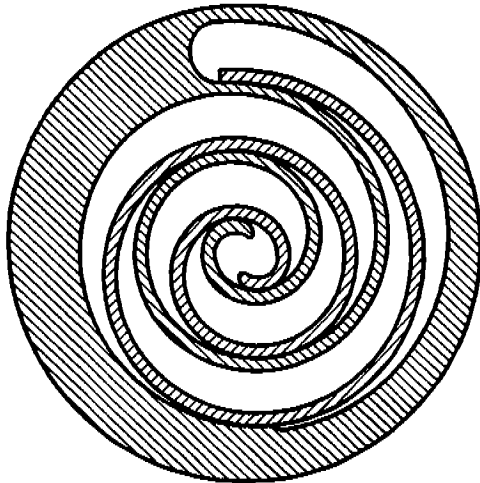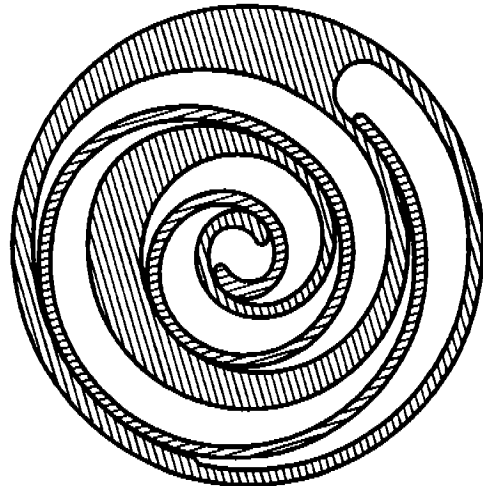

Figure 6

Figure 7

Figure 6 displays the scroll set for the involute of circle scroll form used in the above example. Figure 7 displays the scroll set for the hybrid scroll form of the above example and which has 18.4 percent greater displacement than the scroll form of Figure 6 while still fitting into the same physical space.

Gas Load Comparison

In this part of the example, the conventional involute scroll is designed with the same constraints except that it is allowed to fill whatever space is needed for a capacity of 90,000 BTU/hr at the rating point. The tangential gas force of the hybrid wrap scroll and involute of circle wrap scroll are compared in Figure 8. Only a minor variation in load history results from the hybrid wrap, requiring no special bearing design consideration over the conventional scroll form.
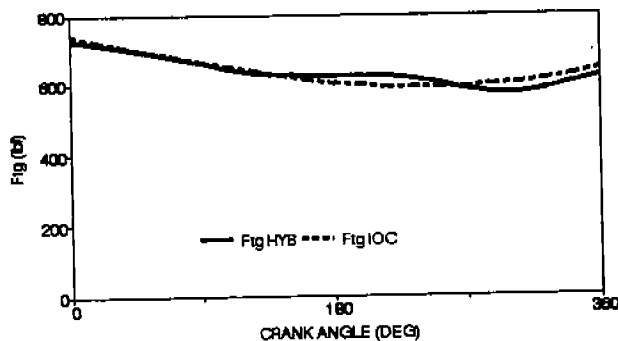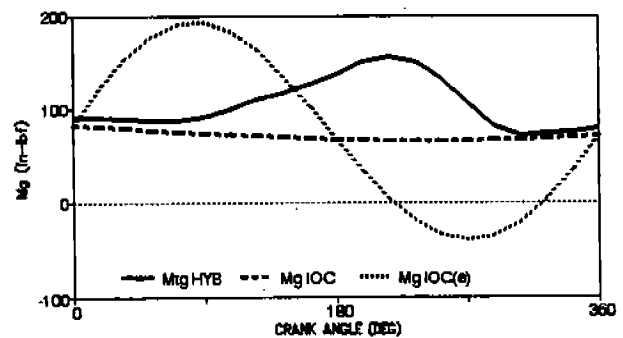

Figure 8

Figure 9

The hybrid scroll has asymmetric pockets and the gas-induced moment must be calculated pocket-by pocket. R_t is variable so the moment includes a radial gas force component. Gas moments for conventional, offset, and hybrid wraps are compared in Figure 9. The hybrid scroll has greater variation of gas-induced moment than the conventional wrap but peak moments are lower than experienced by the offset wraps and do not reverse.

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CONCLUSION

In general, the effectiveness of this method is related to the ratio of the scroll wrap pitch to the overall diameter of the scroll set. The smaller the ratio, the more nearly the conventional scroll will come to filling the outside space on a relative basis. In our study, we evaluated different commercially applicable scroll wrap designs which yielded practical capacity increases ranging from twelve to eighteen percent. In theory, using more severe transitions from the outer to inner wrap forms would yield a greater capacity increase, but this will begin to become undesirable as a practical matter.

Use of hybrid wraps will always yield at least as much capacity increase as offsetting wraps and usually around five to seven percent more. They will not induce rotational torque variations as high in magnitude as offset wraps, nor will the torque reverse. This helps minimize the strength and backlash requirements of the anti-rotation coupling as well as reducing potential rattle, wear, and other effects of load reversal in the mechanism.

In this example, a hybrid wrap design was used to provide different geometric working characteristics at two different portions of a scroll set. This method can become even more powerful when used to optimize scroll characteristics over smaller, more numerous localized zones within the scroll set for specialized purposes.

LIST OF SYMBOLS

α_0	Starting angle of scroll wrap	F_{tg}	Tangential gas force
α_e	Ending angle of scroll wrap	H	Scroll wrap height
α_t	Starting angle for high order involute section	HYB	Hybrid scroll wrap
β	Angular direction of scroll wrap offset	IOC	Involute of circle scroll wrap
δ	Angular extent of high order involute section	IOC(e)	Offset involute of circle scroll wrap
θ	Crankshaft position angle	M_g	Gas force induced moment
π	3.14159265...	R_g	Circular involute generating radius
e	Magnitude of scroll wrap offset from center	R_{or}	Orbiting radius
F_{rg}	Radial gas force	R_s	Circular involute swing radius

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