Functional Description H-02 Series Pumps and Motors

21° Technology

Swash Plate vs. Bent Axis

Introduction: Linde has developed new technology to overcome limitations restricting swash plate piston pump and motor design for more than three decades. These breakthroughs have enabled the swash plate design to surpass that of the bent axis in virtually every area of performance. The long recognized power density and installation flexibility of the swash plate provides major performance improvements, making this design far superior to the bent axis. The new technology has yet to be applied to the larger sizes (140+ cc/rev), so the bent axis design is still needed to satisfy higher flow/torque requirements.

Design Considerations: The modern bent axis unit has evolved to a variety of piston designs enabling the swivel angle to be optimized. However, to eliminate the bulk and weight of trunnions, most manufacturers have resorted to sliding port plate design to vary the stroke.

These designs have two major drawbacks:

1) They depend on overlapping ports between the port plate and the head to direct the flow to and from the cylinder barrel. This necessarily increases flow restriction at either end of the swivel stroke and limits the change in total swivel angle. While swivel angles of 40° are in common use, most variable bent axis designs are limited to a change in swivel angle of 28° or less.
2) The mass and swivel forces are high and increase with a more pronounced swivel angle, requiring larger and relatively slower actuators to change and hold displacement.

Scope: This section compares the design and function of the bent axis to the swash plate (Inline) axial piston units. It explains the principle technological breakthrough allowing the swash plate design to exceed that of the bent axis.

Generation of Torque/Pressure. The process of transferring forces either from mechanical rotary power to hydraulic power (pump) or from hydraulic power to mechanical rotary power (motor) is the same but reversed. In a motor, hydraulic pressure is asserted to produce torque and flow to generate speed. In a pump, speed and torque are applied to create flow and pressure respectively.

Figures 1 and 2 show the force diagrams comparing the resolution of the piston forces F_p into the torsional forces F_t in swash plate and bent axis units. Since these forces are resolved in a plane perpendicular to the shaft, they are independent of whether the unit is of swash plate or bent axis design. However, they are related to the number of pistons acting under load. It is important not to confuse the increasing swivel angle effect with the impact of the number of pistons.

Here we will explain only the impact of the swivel angle from the generally accepted fact that, in the past, bent axis units were approximately ten percent more efficient at transmitting torque than swash plate units. We will compare units with the same displacement and torque rating, accepting the differences in physical design parameters that generate displacement.

Terminology:

Bent Axis: A pump or motor where displacement is achieved by offsetting the cylinder barrel's rotating axis at an angle from the axis of the input/output shaft.

Swash Plate (Inline): A pump or motor where cylinder barrel rotates on the input/output shaft and displacement is achieved by swiveling or tilting a cam or swash plate from a plane perpendicular to the rotating axis.

Drive Plate: The single piece in a bent axis unit that comprises the socket flange, to which the piston links are attached, and the input/output shaft.

Port Plate: The stationary valve plate that directs flow between the stationary head (flow input/output manifold) and the rotating cylinder barrel.

Impact of Increasing Swivel Angle.

The force diagram in Figure 1 for a bent axis unit shows that the torsional force F_t from a single piston is defined by the equation:

$$F_t = F_{P\text{-}BentAxis} \sin a$$

and from Figure 2 for a swash plate unit:

$$F_t = F_{P\text{-}Swash\ Plate} \tan a$$

A simple analysis of these equations shows the bent axis design moving to a direct transfer of the piston force at a 90° swivel angle (sine 90 = 1), while the swash plate design does so at 45° (tangent 45 = 1).

Note: It is important to remember, because of basic design differences, the relationship between piston forces for bent axis and swash plate units ($F_{P\text{-}Swash\ Plate}$, $F_{P\text{-}Bent\ Axis}$) and torque (t) are geometrically and mathematically different.

Bent Axis: at 90°

$F_t = F_{P\text{-}BentAxis} \sin 90 = F_{P\text{-}BentAxis}$

Swash Plate: at 45°

$F_t = F_{P\text{-}Swash\ Plate} \tan 45 = F_{P\text{-}Swash\ Plate}$

The restrictions in achieving optimum force transfer have mainly been geometric mechanical design limitations. The mechanical limits for common designs of bent axis units, in addition to those having to do with manifolding and swivel forces discussed above, is 40° for fixed displacement and 28° for variable units. The mechanical design limit for swash plate units has been 18°. The advantage of increasing the maximum swivel angle is more force/torque transmitted without the increase in losses associated with larger components. If bent axis variable units could be increased 3°, from 28° to 31°, the increase in force transmitted would be:

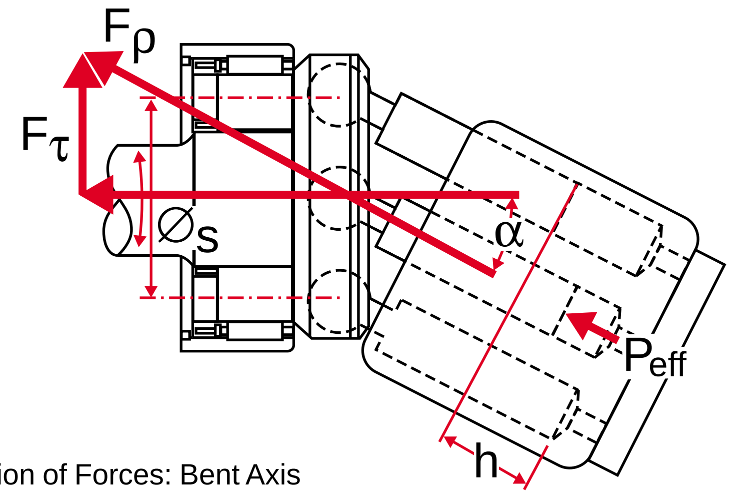

Figure 1.
Transmission of Forces: Bent Axis

From 28°:

$F_t = F_{P\text{-}BentAxis} (\sin 28) = 0.469 * F_{P\text{-}BentAxis}$

To 31°:

$F_t = F_{P\text{-}BentAxis} (\sin 31) = 0.515 * F_{P\text{-}BentAxis}$

An increase of

(0.515 - 0.469)/0.469 = 9.7%

Or from 40°

$F_t = F_{P\text{-}BentAxis} (\sin 40) = 0.643 * F_{P\text{-}BentAxis}$

To 43°

$F_t = F_{P\text{-}BentAxis} (\sin 43) = 0.682 * F_{P\text{-}BentAxis}$

An increase of

(0.682 - 0.643)/0.643 = 6.1%

Compare these improvements to the benefit in the swash plate design for an increase of the same 3,° from 18° to 21°:

From 18°:

$F_t = F_{P\text{-}Swash\ Plate} (\tan 18) = 0.325 * F_{P\text{-}Swash\ Plate}$

To 21°:

$F_t = F_{P\text{-}Swash\ Plate} (\tan 21) = 0.384 * F_{P\text{-}Swash\ Plate}$

An increase of

(0.325 - 0.384)/0.325 = 18.1%

This dramatic improvement of force transmission in the swash plate unit could not be completely transferred without some additional losses associated with the longer stroke and greater swivel angle. But the physical results more than offset the historic advantages bent axis units enjoyed. Physical data comparisons are made below.

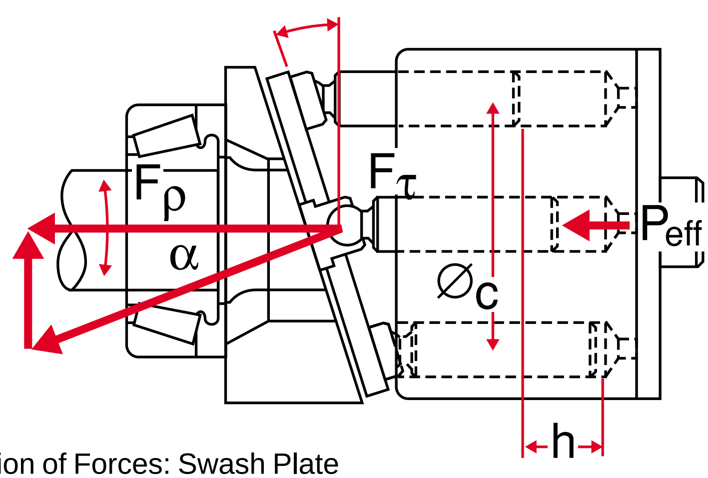

Figure 2.
Transmission of Forces: Swash Plate

Swash Plate Design Breakthrough.

The technological breakthrough allowing the increase in swivel angle is accomplished through the piston assembly's redesign, where the ball of the piston to slipper ball joint is part of the slipper, rather than the piston. As shown in Figure 3, this allows the increase in angle and allows the piston to run into the cylinder bore to the top of the retraction plate. In the previous designs, the swage collar of the slipper limits how far into the barrel the piston could travel. The 21° design actually allows the rotating pistons' center of mass to move closer to the resultant of reaction forces at the center cylinder barrel spline. This improves the balancing of inertial forces without sacrificing speed capabilities and minimizes the increases in compressibility losses from trapped volumes at lower displacements.

Figure 3.
Previous vs. New Piston Design.

In the new design, the slipper and the piston are made of steel, which greatly improves the structural integrity of the piston assembly. This improves the unit's durability and enables it to take high rates of angular acceleration, which remain a weakness in many bent axis designs.

Closing the Gap with Evolutionary Improvements in Design.

Since Linde introduced its first swash plate unit in the mid 1960s, a steady progression of design improvements has reduced noise, improved power density and improved reliability. These improvements have all been incorporated in the 21° Degree Technology:

1) All forces are hydrostatically balanced, virtually eliminating metal to metal wear points and improving mechanical efficiency. This feature makes all force transmission interfaces self-compensating; the higher the force, the higher the hydrostatic pressures and, consequently, their force carrying capability. Balancing technology has improved to eliminate such dated concerns as slipper tipping.
2) Mechanical bearings have been eliminated, except for those carrying the shaft. Mechanical bearings tend to compromise size and durability. Replacing mechanical bearings with hydrostatics has the added benefit of significantly reducing internal structural noise.
3) Any point in the rotating kit subject to separation is positively, mechanically held down. This includes the swash plate to cradle, the slipper to swash plate and cylinder barrel to port plate interfaces.
4) Manufacturing technology has improved to allow repetitive production of more sophisticated designs at closer tolerances and greater accuracy.

Definition of Symbols

- **P_{eff}** - Effective pressure operating on the pistons: the differential between inlet and discharge pressure.
- **F_P** - Piston force; the axial force on the piston.
- **F_t** - Torque creating force from a single piston, acting perpendicular to the input/output drive axis, in the direction of swivel.
- **F_n** - Normal force resulting from piston force (**F_P**) perpendicular to the plane of force transfer.
- **t** - Torque from a single piston.
- **T** - Total torque.
- **f_C** - Cylinder circle diameter; the diameter of the cylinder bores' centers.
- **f_S** - Socket circle diameter in bent axis drive plate; the diameter of the link sockets' centers.
- **a** - Swivel angle of a swash plate unit from a plane perpendicular to its drive axis, or bent axis cylinder barrel angle of offset from its drive axis.
- **q** - Rotational position of **F_t**

Test Results and Design Comparisons:

The area of performance most challenged by the bent axis design is torque efficiency, especially starting torque. Figure 4 shows the performance measured at two rpm of a bent axis and a 21° swash plate motor. The test results show that not only does the swash plate unit have higher starting torque, as illustrated in Figure 5, it also exhibits less torque ripple. This significantly reduces stuttering (clocking) at low speeds and makes the unit less susceptible to the barrel's rotational position in starting.

Conclusions: The flexibility of the swash plate design has long been recognized. The compactly designed drive-through capability that allows for attachments and the elimination of pump drives offsets the perceived negatives of the design, particularly for pumps. These negatives were traditionally contamination sensitivity and lower efficiencies, particularly in torque transmission.

The new Linde design has effectively eliminated all of these concerns; the relative inefficiencies are more than compensated for by the 21° Technology. The use and refinement of hydrostatic bearings that self compensate for wear have made the new units more reliable than their bent axis predecessors.

When the improved compactness, cost effectiveness and power density are added to the equation, it becomes clear that bent axis units have a limited future.

Figure 6 outlines the size comparison between a 21° Technology unit and its current production competitors, including its Linde bent axis and swash plate predecessors.

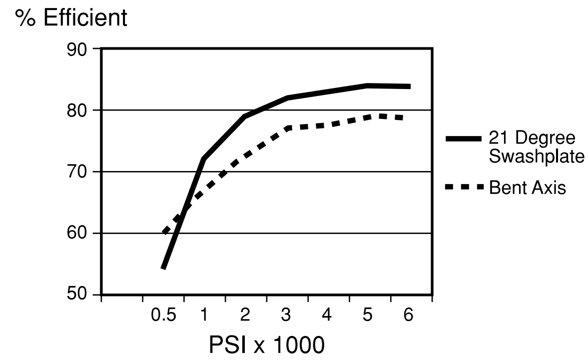

Figure 4. Starting Torque Comparison.

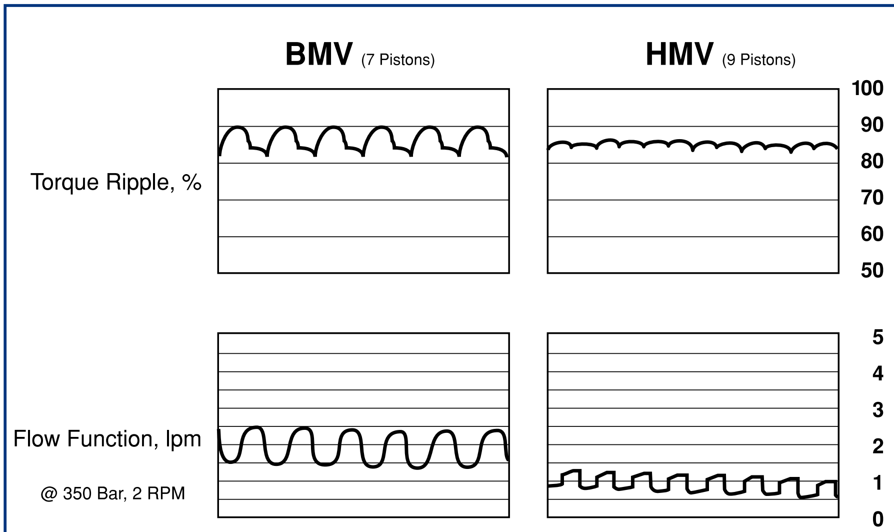

Figure 5. Starting Torque Comparison: Torque and Flow Ripple

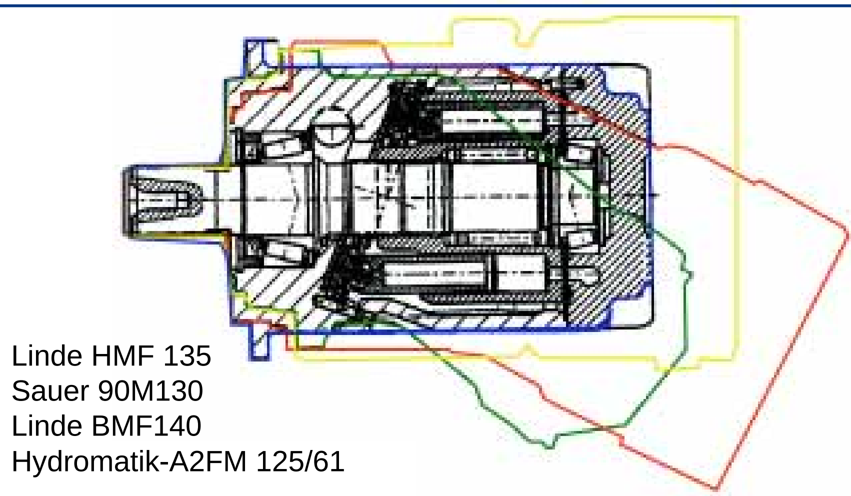

Figure 6. Size Comparison H-02 vs. Other Designs.

LINDE HYDRAULICS CORPORATION

P.O. Box 82 Canfield, Ohio
330-533-6801 ■ Fax 330-533-8383
www.lindeamerica.com