Balancing act

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The service life of rotating equipment is often dependent upon the successful operation of their rolling element bearings. For successful operation, a bearing should be installed properly, provided with a contamination free environment, sufficiently lubricated or cooled, and relieved of load conditions that exceed their design specifications. Provided with these conditions, a rolling element bearing can be expected to provide thousands of hours of service. Submerged electric motor pumps (SEMP), operating at a cryogenic temperature in a liquid hydrocarbon environment, provide a rolling element bearing design application that meets the criteria. The success of rolling element bearing operation in this application is often dependent solely upon bearing load management, particularly axial thrust loads.

Bearings

Vertical SEMPs operating in a liquefied hydrocarbon environment, at cryogenic temperatures, have very specialised design and service requirements. Bearings operating in this environment rarely fail due to service fatigue, however bearings service life can be compromised as a result of improper installation or handling; outside influences such as contamination or debris; a lack of lubrication or improper cooling; or the mismanagement of loading during operation.

Due to installation and operating conditions, maintenance activities are closely monitored and often conducted under direct supervision of the pump supplier. Bearings are generally replaced at each service interval and installed without load being applied to the bearing's inner or outer raceway. As a result of stringent maintenance practices, bearing operation is rarely compromised as a result of improper installation or handling.

As a pumping fluid, liquefied hydrocarbons (LNG, LPG, ethylene, etc.) often provide an ideal operating environment. With some exceptions, liquefied hydrocarbons are very clean fluids, free of debris and foreign material. As a result, bearing failure as a result of fluid contamination is rarely exhibited. Where hydrates, processing residue or foreign particles may be expected, bearings that utilise a ceramic rolling element are often installed. In these applications, the hardness of the ceramic rolling element prevents bearing raceway damage, further extending bearing service life in harsh environments.

In addition, the cryogenic operating temperature of the liquefied hydrocarbon environment requires a special bearing design. In a warm temperature operating environment, bearings that are lubricated with oil or grease are often installed. In a cryogenic fluid environment, oil or grease would freeze, inhibiting bearing operation. For this reason, bearings that utilise oil or grease as a lubricant cannot be used. For pumps operating in a cryogenic fluid environment, open cage type bearings are typical. In this application, a fraction of the discharged fluid is routed through the bearing for use as both a lubricant and a coolant. This fluid, moving through the bearing, precludes the necessity for oil or grease by preventing the buildup of heat. This lack of heat, and the fluid film provided by the pumping fluid, prevent damage to bearing components during normal bearing operation.

To help manage bearing loads, deep-groove radial ball bearings are used in many vertical SEMP applications. Where these bearings are well designed to manage the radial loads anticipated during normal pump operation, they are not as robust in their ability to support large axial loads. To alleviate damage to rolling element bearings generated by thrust loads during normal pump operation, vertical SEMPs often rely on thrust balance systems within the pump design.

Bearing radial and thrust loads

During normal operation of a vertical submerged-motor centrifugal pump, the rotating assembly can be subjected to both radial and axial loading. These loads are transmitted directly to the pump bearing system and, if left unchecked, can result in greatly reduced pump service life.

Radial loads are generated by the dynamic imbalance of the rotating components and by variations in hydraulic forces, either through impurities in the pumped fluid or manufacturing tolerances.

Axial thrust loads are generated by variations in force, due to the distribution of fluid pressure across the surfaces of the impeller. For example, an upward force is generated at the eye of an impeller due to the distribution of suction pressure across the surface of the impeller inlet. A second upward force is generated across the front of the impeller due to the distribution of discharge pressure across the surface of the impeller front shroud. Finally, a downward force is generated across the back of the impeller due to the distribution of discharge pressure across the surface of the impeller back shroud. For a vertical submerged-motor centrifugal pump, designed with a single front wear ring, the combined upward forces are less than the downward force. This difference in axial force results in a net downward thrust force acting on the rotating assembly during normal pump operation.

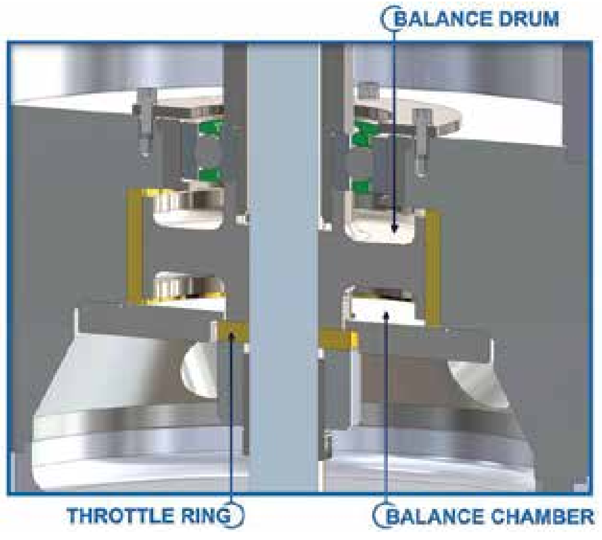

Figure 1. Please provide caption.

Balancing methods

Over the years, different methods or designed balancing systems have been developed to maintain a zero-thrust load on the bearings. For example, one method may be to use two impellers, installed back-to-back, in a double suction pump design. Where this is possible, the thrust force generated by one impeller is countered by the thrust force of the second impeller, providing for a 'net-zero' thrust force acting on the rotating assembly. While this method is very common in horizontal pumps, it is more difficult to achieve in vertical pumps or pumps where an odd number of impeller stages is required. To provide more flexibility in pump specification and design, other thrust balancing systems are often used. These systems may include impeller balance holes, impeller wear ring combined with a throttle plate, or throttle ring combined with a balance drum.

In a balance hole balancing system, small holes are drilled through the back shroud of the impeller in order to reduce axial thrust loading by alleviating differential pressure between the impeller back shroud and the impeller eye. In this system, the size, number and placement of the balance hole is vital to its ability to manage thrust loading. The thrust force imbalance between the front and back of the impeller is relieved, resulting in a 'net-zero' thrust force acting on the rotating assembly.

The wear ring combined with a throttle plate balance system can be modelled as a fixed orifice, a pressure chamber, and a variable orifice in series. The fixed orifice provides pressurised fluid upstream of the pressure chamber. The variable orifice regulates the rate of pressurised fluid leaving the pressure chamber.

For the design of this system, a wear ring is installed on the back shroud of the last stage impeller. The clearance between this wear ring and the associated housing constitutes the fixed orifice. Upstream of the wear ring clearance, a pressure chamber is generated by the machined configuration of the components. This pressure chamber is supplied with fluid through the wear ring clearance, based on discharge pressure during pump operation. At the downstream exit from this pressure chamber, a fixed throttle plate is installed in the pump and regulates fluid exiting the pressure chamber.

In the wear ring/throttle plate balance system, the installation of the back wear ring at the last stage impeller reduces the impeller back shroud surface area, acted upon by discharge pressure. This diminished surface area reduces the downward thrust force generated by the discharge pressure of the last stage impeller. When this reduced downward force is combined with the normal upward force generated across the impeller front shroud and impeller eye, the resulting force shifts to a net upward thrust force acting on the rotating assembly.

To counter this net upward thrust force, fluid within the pressure chamber accumulates and builds in pressure. When the force generated by this chamber pressure exceeds the net upward force, the clearance at the throttle plate increases and fluid is allowed to exit the pressure chamber. This interaction of fluid supply, pressure build, and pressure release provides a dynamic thrust force balance system that allows for neutral thrust force operation across a wide range of capacity, regardless of the number of impeller stages.

In a wear ring/throttle plate balance system, the pressure within the balance chamber provides a downward thrust force opposing the upward thrust force generated by the impeller(s), resulting in a 'net-zero' thrust force acting on the rotating assembly.

In comparison, a throttle ring in combination with a balance drum system can be modelled as a variable orifice, a pressure chamber, and a fixed orifice in series. The variable orifice regulates fluid flow upstream of the pressure chamber. The fixed orifice provides a constant restriction for the determination of fluid leaving the system.

For this system, a throttle ring is installed onto the pump shaft. The clearance between this throttle ring and a fixed plate constitute the variable orifice. Downstream of this variable orifice, a pressure chamber is generated by the machined configuration of the components and is supplied with fluid passing through the throttle ring clearance. At the downstream exit from this pressure chamber, the radial clearance between the balance drum and the associated housing constitute a fixed orifice, allowing fluid to leave the pressure chamber.

In the throttle ring/balance drum system, the discharge pressure within the balance chamber provides an upward thrust force opposing the downward thrust force generated by the impeller(s), resulting in a 'net-zero' thrust force acting on the rotating assembly.

Effectivity of balancing methods

The thrust force transmitted to the rolling element bearings is directly attributed to the differential pressure generated by the pump assembly. For a single stage pump, where the discharge pressure is limited to that pressure generated by a single impeller, differential pressure can be readily calculated and verified through testing. For multi-stage pump units, the higher discharge pressure combined with pressure losses within the pump unit can be more difficult to calculate during the pump design phase.

For single stage pump units, or for existing pump designs where the discharge pressure has been proven and is repeatable, thrust force elimination through the application of balance holes is very practical. For these pump units where limited design modifications are applied, the size, number, and location of balance holes can be approximated, then proven during subsequent testing. In operation, this design can be greatly affected by fluid-borne contamination and may produce a greater reduction in overall efficiency due to recirculation within the impeller. Additionally, for multi-stage pump units, or for designs that are subject to frequent modifications, thrust force elimination through the application of balance holes can be difficult to apply. Furthermore, the recirculating flow of fluid from the back of the impeller shroud into the eye of the impeller introduces turbulence into the fluid stream, affecting the performance of the impeller.

For multi-stage pump units, or for pump designs that are often subject to modification due to contract requirements, both the wear ring/throttle plate and throttle ring/balance drum systems have been proven to be very effective. In the wear ring/throttle plate balance system, the net upward thrust force generated through the impeller is balanced by downward thrust force generated within the balance chamber. As the impeller wear ring to housing clearance increases through normal wear, the pump differential pressure subsides (for a given capacity) and the upward force generated onto the rotating assembly can decrease. In addition, the downward force generated within the balance chamber will also be diminished due to this reduction in pump differential pressure. Since the pressure within the balance chamber provides a force in the downward direction, changes in operating clearances resulting in reduced upward thrust loading can overcome the effects of the thrust balance system and result in axial loading of the main bearings.

In the throttle ring/balance drum system, the downward thrust force generated by the impeller(s) is balanced by an opposing upward thrust force generated within the balance chamber. As the impeller wear ring to housing clearance increases through normal wear, the pump differential pressure subsides (for a given capacity) and the upward force generated onto the rotating assembly can decrease. In addition, the upward force generated within the balance chamber will also be diminished due to this reduction in pump differential pressure. As the pressure within the balance chamber provides a force in the upward direction, changes in operating clearances, resulting in reductions in thrust loading, have limited impact on the equilibrium of this system. Only when the discharge pressure of the pump unit is no longer capable of providing sufficient pressure to lift the rotating assembly weight, will the thrust balance system become ineffective and result in axial loading of the main bearings, due to the weight of the rotating assembly.

Conclusion

During normal pump operation, thrust loads generated by each impeller stage can be directly transmitted to the main bearings and greatly reduce pump operating life if not addressed through design methods. There have been a number of methods used in pump design to alleviate the effects of thrust loads, including opposed impeller installation, balancing holes, wear ring/throttle plate, and throttle ring/balance drum systems. In order to provide longevity of operation and continued effectiveness of any thrust balance system, the design should be simple to define, capable of operating across a wide range of capacities, and should function independently of the effects of normal pump wear.

Given these criteria, the throttle ring/balance drum thrust balance system has proven to be highly effective in vertical SEMPs operating in a liquefied hydrocarbon environment. This type of system can be readily sized based on known impeller dimensions, is effective across all pump design capacities and will remain effective throughout the pump operational life. **LNG**