Hydrostatic bearings work by supporting the radial load applied to a pump shaft with a pressurised cushion of cryogenic fluid. This type of system provides a method to support the shaft with no mechanical contact between the shaft and the bearing, unlike the way traditional roller bearings do. Analysis of the failures of some pumps shows that due to a high carbon content in the operating fluid, the traditional roller bearings are experiencing abnormal wear. This wear is most likely caused by the small carbon particles wearing down the bearing balls over time, decreasing their diameter and eventually leading to failure. Due to the fact that hydrostatic bearings do not rely on physical contact to support the shaft, and that the clearance between moving parts is so large, these carbon particles will not affect the bearing system. This will lead to a much longer lifetime between overhauls, improved efficiency and smoother running operation.

Demand of technological development for bearings
Bearings are one of the most important mechanical elements for rotary machines, including pumps, expanders and turbines. Roller, ball and slide bearings have been mainly applied to rotary machines and these bearings often determine the performance of rotor machines, including product lifetime. Development of bearing technology has also contributed to the field of LNG.
Although current LNG pumps have a few years of lifetime between overhauls, it used to be shorter than one year before the development of bearing technology.

Ebara International Corp. Cryodynamics Division (EIC Cryo) has been developing bearing technology for LNG pumps since the 1970s. Even now, bearings in LNG pumps have been subjected to increasing demand for longer lifetime between overhauls, improved efficiencies and smoother running operation. On the other hand, the load conditions and rotational speed acting on the bearings are becoming more severe, as demand and application expand. Furthermore, analysis of the current failures of some LNG pumps shows that abnormal wear to bearings is due to the inclusion particle content in the operation fluid, accelerating wear and damage. Even the latest bearing technology cannot precisely estimate the influence of inclusion particles on bearing lifetime. Now, an innovative development for bearing technology is required because the cause of problems in traditional bearings, including fatigue and wear damage, stems from the mechanical structure of traditional bearings (i.e. physical contact between bearing parts and stationary parts).

Development of non-contact bearings
EIC Cryo has developed two types of non-contact bearings to solve these specific problems with traditional bearings.

Both magnetic bearings and hydrostatic bearings can support the radial load with no physical contact between the pump shaft and the bearing. Therefore, damage due to load and wear theoretically does not have an effect on the bearing lifetime. On the other hand, non-contact bearings require additional equipment (i.e., inverter controllers, oil pressure units, compressors, wiring installation, etc.) to generate the supporting force. The initial and maintenance cost increases, as the additional equipment has historically prevented the wide scale application of non-contact bearings. To address this, EIC Cryo has developed a hydrostatic bearing system that does not rely on additional equipment.

Characteristics and advantages of hydrostatic bearings
Figure 1 shows the basic structure of a hydrostatic journal bearing to support the pump shaft. As depicted, the hydrostatic journal bearing has several recesses within the internal surface and liquid feed ports. The lubrication film is formed within the recess area and sliding surface by pressurised fluid supplied through liquid feed ports. The actual supporting force of the lubrication film depends on the bearing shape, diameter and length of bearing, recess shape and orifice diameter of the liquid feed port. Liquid properties, specific gravity, supply pressure, and rotation speed also have an influence. Due to the fact that hydrostatic bearings do not rely on physical contact to support the shaft and that the clearance between moving parts is so large, fatigue and wear damage will not affect the bearing system and pumps have a much longer lifetime between overhaul. Theoretically, any kind of material can be applied in the hydrostatic bearing assembly.

Hydrostatic bearings also provide smoother running operation compared to mechanical bearing systems. As shown in Figure 2, when the shaft moves from one side to the other, the differential pressure generated between the opposing recesses creates a counter force and it restores the shaft to the proper position. The restoration force provides hydrostatic bearing rotation accuracy and damping performance that contributes to smoother running operation. Furthermore, comparatively thick lubrication film also contributes to the rotation accuracy because the influence of sliding surface roughness is insignificant.

Actual design of hydrostatic journal bearings
The adjustable operating range of hydrostatic bearings is very wide. Figure 3 shows the relationship between the shaft eccentricity ratio and support force of several hydrostatic journal bearings with different recess and liquid feed port sizes. All other properties, including bearing length (5 in.), internal diameter (5 in.), number of recesses (6 recesses), and supply pressure (3 MPa) are constant. As shown in this Figure, support force can be widely arranged by the smallest internal dimensional change but does not affect the outer shape. The average support force (at 0.5 shaft eccentricity) is approximately 100, 600, and 900 lbs for small, medium and large recess cases, respectively. Furthermore, design changes of the outer geometry enable
a much wider arrangement of support force. This means that every conventional bearing can be replaced by a hydrostatic bearing having almost the same size as the conventional bearing, with no change to design or neighbouring structure and additional parts are not required.

The hydrostatic bearing design’s Degree of Freedom (DOF) enables optimisation of not only support force but also smoother running operation and vibration properties. The most important design factor for safe operation is the dependence of the support force on shaft eccentricity. As shown in the behaviour curves in Figure 3, every curve is proportional to the shaft eccentricity, and the hydrostatic bearing must make a balance at a certain level of shaft eccentricity. When support force is stronger than bearing load, balance eccentricity becomes smaller. In general, a small margin of eccentricity reduces the damping performance, which may cause the rotor system to become unstable. On the other hand, the risk of physical contact between the internal surface of the hydrostatic bearing and a shaft become higher when the supporting force is too small and hydrostatic bearing and shaft are balanced at high eccentricity. For the appropriate design, EIC Cryo accurately estimates the bearing load condition based on its experience, technical background and by performing rotor dynamic simulations for vibration risk reduction. Furthermore, complete control is performed to reduce the clearance errors due to parts manufacturing, assembly, and thermal deformation of materials in cryogenic temperatures. This process enables EIC Cryo to manufacture hydrostatic bearings as designed.

**Internally pressurised fluid supply structure**

Although additional equipment (e.g. oil pressure units and compressors) has traditionally been required to supply pressurised fluid to hydrostatic bearings, they can now be replaced by an internal fluid supply structure, as shown in Figure 4. In this structure, the discharge pressure and flow of the pumped fluid is applied as the bearing supply fluid. The performance of this lubrication film does not rely solely on liquid viscosity, and the pumped fluid can generate a sufficiently large supporting force because of its relatively high pressure. The supply fluid is recovered by the discharge flow for the last time, hence there are no waste fluids from the internal fluid supply system. EIC Cryo’s bearing design has also overcome the disadvantages due to an internal fluid supply structure. Head loss resulting from the application of a part of the discharge flow can be reduced by adequate design. With the current design, head loss is reduced by the same amount as with traditional ball bearings.

**Touchdown bearing**

Another challenge of a typical internal fluid supply structure is the potential for instability in the hydrostatic bearings due to inadequate supply pressures during transient operation. This can be solved by installing an additional touchdown bearing that would support the shaft, working in place of the hydrostatic bearing during the transient operation of the pump, namely start-up and shut-down. As shown in Figure 5, touchdown bearings are a mechanical element composed of a ball bearing and a tapered sleeve. Although the lifetime of a touchdown bearing affects the product

![Figure 3. The relationship between shaft eccentricity and support force of hydrostatic journal bearings with different recess shapes.](image)

![Figure 4. Internal fluid supply structure.](image)

![Figure 5. Touchdown bearing (ball bearing type).](image)
lifetime (because they support the shaft through physical contact, as with conventional bearings), the lifetime of touchdown bearings is much longer than traditional mechanical ones (because of the short operation time and small imposed load conditions). The hydraulic axial balance system installed on every EIC Cryo pump prevents physical contact condition between a touchdown bearing and shaft in normal operation.

The axial balance system supports the axial load and the hydrostatic bearing supports the radial load. Therefore, operation time of the touchdown bearing is only present when in the start and stop operating condition; usually no greater than several tens of seconds. Furthermore, several components of the bearing load due to the shaft eccentricity can be ignored if the shaft eccentricity is sufficiently restricted by the touchdown bearing. As for damage of the tapered sleeve, surface wear due to physical contact is limited because the frictional resistance on the tapered surface that causes surface wear is much smaller than the rotational friction resistance of the ball bearing. EIC Cryo confirms the lifetime of every touchdown bearing through an endurance test under actual load, rotation speed and temperature conditions.

**Conclusion**

EIC Cryo has developed a hydrostatic bearing system that does not rely on additional equipment. As a result, the rotating machine’s mean time between overhaul has been extended while providing smoother running operation. These bearings do not require expensive ancillary equipment, so upfront and lifecycle costs are actually less than existing non-contact designs as well as traditional mechanical bearing systems. Not only can these bearing systems be used with cryogenic submerged pumps, but they can also be used with single and two-phase cryogenic expanders.

**References**