Smarter seal solutions achieving reduced machinery maintenance requirements

Special situations require special seals

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ABSTRACT

In any shaft-to-ground system where a lubricated bearing is applied, the bearing lubricant usually must be contained to avoid loss of lubricant and resulting bearing failure. In these situations, a mechanical seal is typically applied on either side of the bearing. There are numerous mechanical seal types that function in this capacity including, lip seals, labyrinth seals, spring loaded axial face seals and magnetic face seals. Each of these seal types have unique features which may work to the benefit or detriment of the user. In challenging and critical applications, conventional mechanical face seals may not be able to accommodate tolerances and extreme operating conditions. This could lead to unscheduled maintenance, system shut down or worse, complete system failure. The purpose of this paper is to delineate the features of these seal types to allow users to make informed decisions in selecting seals for their applications.

INTRODUCTION

A mechanical seal is a device that helps join systems or mechanisms together by preventing leakage (e.g. in a pumping system), containing pressure, or excluding contamination. They are used in a variety of rotating equipment such as pumps, drive motors, starters, secondary power systems, all the way up to large auxiliary power units and turbine engines. Selecting a seal for such applications is determined by a number of factors including but not limited to the available axial and radial envelope for the seal, shaft speed, available cooling mechanism (such as a lubricant) and the rate of cooling, axial movement, radial eccentricity, radial movement, heat generation , shock, and vibration, and thermal effects. Original equipment is often specified with adequate sealing for proper equipment performance through its warranty period. Operators can continue to use these seals, but often seals may be limited by the nature of their type. Though there are a plethora of axial and radial mechanical seal types, this paper will explore the strengths and limitations of the following major types of seals used in rotating equipment: lip seals, labyrinth seals, spring energized mechanical carbon face seals, and finally, magnetic seals.

LIP SEALS

Radial shaft seals, also known as lip seals (see Figure 1), are used to seal rotary elements, such as a shaft or rotating bore. Common examples include strut seals, hydraulic pump seals, axle seals, power steering seals, and valve stem seals. Early radial shaft seals utilized rawhide as the sealing element, and many elastomeric seal companies today once were tanneries. The advent of modern elastomers eventually replaced rawhide; the industry also added a garter spring which helps the sealing lip compensate for lip wear, shaft movement and elastomer material changes over operating time.

Lip seal construction consists of a spring energized main sealing lip which typically has a point contact with the shaft. The point contact is formed by two angles, with the air side angle usually less than the oil side angle. Depending on the seal type, these two angles are varied to create a pressure distribution at the seal contact point which has a steeper slope on the oil side of the seal. The shallower the slope on the lubricated side of the seal, the wetter or more lubricated the seal will run. The spring is positioned such that axially the centerline of the spring is biased to the air side of the lip contact point.

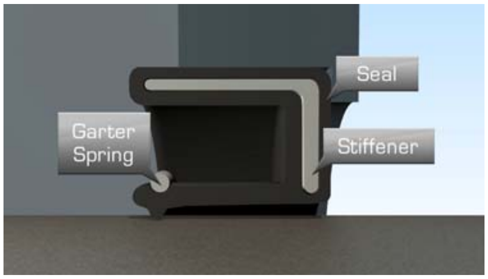

Figure 1

In order to resist wear, the compounds' durometer (or rubber hardness) is typically 70 to 85 Shore A (between that of an automobile tire and a soft inline-skate wheel).

Lip seals are low in mass but have speed and pressure limitations. The direct contact of the elastomer of the lip seal and a hard metallic rotating shaft results in rapid wear of the seal due to fretting, and shaft eccentricity relative to the housing bore. This is further exacerbated by speed and environmental temperature combined with frictional heat generation and shaft eccentricity.

Seal Type	Benefits	Limitations
Lip Seal	• Simple sealing solution • Low in mass and axial length • Positive sealing contact • Low leakage • Long legacy of use in rotating equipment • Handles mechanical vibration • Low initial cost • Many available standard sizes	• Requires low speed relationship between stator and rotor • Primary elastomeric sealing element is limited by environmental temperature and shaft speed • Positive contact results in frictional heat generation • Shaft eccentricity is manageable but only within modest limits • Frets interfacing surfaces (typically shafts and sleeves) • Usually limited to ~3,000 ft/min (15 m/s).

LABYRINTH SEALS

A labyrinth seal (See Figure 2) is a type of mechanical seal that provides a tortuous path to help prevent leakage. An example of such a seal is sometimes found within an axle's bearing to help reduce the leakage of the oil lubricating the bearing.

A labyrinth seal may be composed of many grooves that press tightly inside another axle, or inside a hole, so that the fluid has to pass through a long and difficult path to escape. Sometimes screw threads exist on the outer and inner portion. These interlock, to produce the long characteristic path which slows leakage. For labyrinth seals on a rotating shaft, a very small clearance must exist between the tips of the labyrinth threads and the running surface.

Labyrinth seals on rotating shafts provide non-contact sealing action by controlling the passage of fluid through a variety of chambers by centrifugal motion, as well as by the formation of controlled fluid vortices. At higher speeds, centrifugal motion forces the liquid towards the outside and therefore away from any passages. Similarly, if the labyrinth chambers are correctly designed, any liquid that has escaped the main chamber becomes entrapped in a labyrinth chamber, where it is forced into a vortex-like motion. This acts to prevent its escape, and also acts to repel any other fluid. Because these labyrinth seals are usually designed to be non-contacting, they do not wear out. Wear does occur when shaft excursions cause contact between rotor and stator.

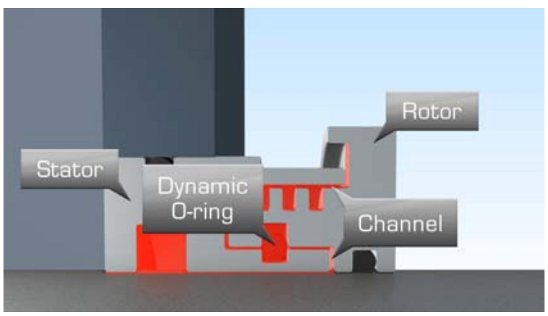

Figure 2

Gas turbine engines, having high rotational speeds, often use labyrinth seals due to their lack of friction and long life. In recent years with improvements to gas turbine design to improve range, thrust and/or fuel consumption, labyrinth seals have been exchanged for carbon seals or high speed, high temperature brush seals depending upon location in the engine. They are also used in bearing isolation applications. Labyrinth seals can also be applied as propulsion shaft seals at the hull penetration in surface ships, and to aeroderivative variants of gas turbine engines.

A well known weakness in utilizing labyrinth seals is their propensity to high leakage rates.

Seal Type	Benefits	Limitations
Labyrinth Seals	• Moderately simple and robust sealing solution • Rotational speed expends debris and leakage to an extent • Non-contacting for low friction	• High mass • Higher leakage rates • Temperature limited by application of o-rings in bearing isolation applications

Seal Type	Benefits	Limitations
	• Usually high temperature capable • Long legacy of use in rotating equipment, particularly in high speed, high temperature rotating equipment	• Shaft excursions can cause contact resulting in frictional heat generation and high wear. • High wear quickly yields higher leakage. • Not suited for vertical sealing applications

MECHANICAL FACE SEALS

Mechanical face seals (See Figure 3) provide a hermetic seal between an axial rotor and stator. These seals are often spring energized and utilize an o-ring as a secondary seal which allows for modest axial movements.

During operation, the lubricant forms a thin, dense hydrodynamic film between seal faces while a mechanical load sets and maintains the seal interface initial loading. This provides excellent leak and contamination protection; however, the mechanical load and seal interface present engineering challenges.

Most mechanical face seals use a solid wave or coil spring housed in a stamped or machined housing. Due to a combination of spring and operating length tolerances, the mechanical spring produces a sizeable variation in face load. If a conventional lobed wave spring is applied, upon compression, the unevenness of the lobes can transfer uneven loading through thin interfacing washers distorting the carbon seal face, creating out-of-flatness. Furthermore, lubricating oil can become trapped in the spring cavity. In a high heat environment, the oil can bake or carburize and develop into what the industry recognizes as coke, a hardened slag of baked and hardened oil residue. The formation of coke in any mechanical seal essentially dooms its proper operation over time. Coke can build between the seal interface, lifting the faces, causing more leakage and even further coking in a diverging failure mode. Coking also erodes the effectiveness of the spring load by contaminating the wave spring. High unit load, face unevenness, and coking all result in leakage, power consumption, further heat generation, inexorably moving the seal to its ultimate failure mode.

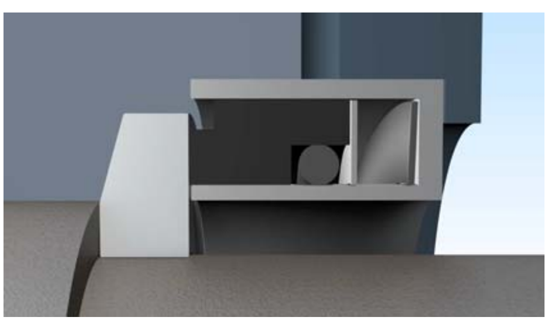

Figure 3

Seals stators in such designs can be a solid carbon block or a carbon ring pressed into a carrier or metal shell. The former design is low mass, and allows for better dynamic tracking in high speed environments but have limited pressure differential capability. The latter, though higher mass, are usually applied in applications where high pressure is a factor and where shaft speed and eccentricity is less of a factor.

Finally, all spring energized face seals have limitations beyond face friction: system vibration can resonate with and weaken the spring leading to seal face separation, the mechanical drive design transfers vibration to the carbon face which can cause chipping.

Space requirements for a conventional mechanical face seal require sufficient axial space that they usually cannot be applied in places where a lip seal upgrade is called for.

Seal Type	Benefits	Limitations
Mechanical Face Seals	• Conventional and moderately simple yet relatively robust sealing solution • Low leakage • Long legacy of use in rotating equipment, particularly in high speed, moderate temperature gearboxes and secondary power systems. • Accepts high and low positive pressure and can be designed for reverse pressure. • Moderately high shaft speed. Limited to 17,000 ft/min (86 m/s).	• Conventional wave springs used to energize the seal can produce uneven loading onto carbon faces – usually 3 or 4 point high points corresponding to spring waves – making for out of flat condition • Oil deposited into the seal inner cavities can result in coke which exacerbates seal condition leading ultimately to a failure mode. • Proper selection of design is essential for high speed or high pressure applications. • Conventional Wave springs can be affected by vibration and resonance reacting at the sealing interface deteriorating stator or rotor. • O-ring drag internal to the seal can produce high hysteresis. • Require too much axial space to upgrade a standard lip seal. • Coking can develop and will affect function and spring load. • Temperature limited. • Higher cost due to customization.

OTHER ENHANCED SPRING ENERGIZED MECHANICAL SEALS

One enhancement that can be made to conventional spring energized mechanical face seals is to employ precision engineering and material optimization to maximize spring loaded seal performance.

A means to do this is to invoke the use of a precision spring. This may be done with the application of a welded metal bellows, but these are costly and require control over plate geometries. Another means is by invoking the use of an edge wound crest-to-crest wave spring which provides an even load and lower variation across the operating range (see Figure 4). This provides a reduced and fairly uniform face load. A further enhancement is to house the wave spring in a military grade, precision machined housing rather than a stamped cup. The machined housing avoids the surface variation found in the stamped cup. As a result, the combination offers zero seal face warping and longer operating life. This feature can be combined with using a small section of carbon to improve thermal performance and a lapped seal face with industry leading flatness of 2 helium light bands.

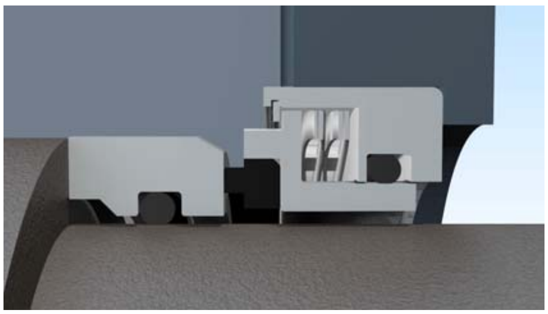

Figure 4

Such applied features have proven to offer significantly improved service life. On an aircraft variable bleed valve gear motor, this type of seal increased service life from 1,500 hours to 18,000 hours relative to the conventional mechanical face seal it replaced.

Seal Type	Benefits	Limitations
Enhanced Spring Energized Seals	• Uniform loading of the seal ring produces no anomalies to the seal interface. • Proven to enhance life over conventional method of face sealing by over an order of magnitude. • Fits in compressed space in comparison to conventional seal, and can be applied for upgrading standard lip seals.	• Temperature limited. • Expense of welded metal bellows if applied.

MAGNETIC SEALS

An alternative to energizing mechanical seals using conventional springs is to use magnetics to provide mechanical loading. This has several advantages including a lower, more controlled and uniform load at the seal face, vastly improving performance in high shaft speed and high vibration applications, and smaller axial length requirements for lip seal replacement.

Magnetic seals (See Figure 5) are rotary shaft face seals. They apply a rare earth magnetic material as a stator and a rotor with a small section of carbon press fit into a precision machined steel carrier or housing. Unlike a spring load, the magnet places a uniform load across the entire seal face calibrated by a precise air gap and the magnetizing process of the Alnico 5. The seal faces are also lapped to industry leading flatness of 2 helium light bands. The low load and seal face flatness reduce friction, power consumption, and heat generation while the small section of carbon and thermal conductive housing accelerates heat dissipation. This increases seal life and renders a magnetic seal as an ideal solution for high shaft speed applications. Furthermore, unlike a spring seal's mechanical drive, which transmits vibration and system liberation, the magnetic seal's o-ring drive actually damps vibrations maintaining seal performance. The magnetic seal o-ring drive and low weight rotor is capable of withstanding extreme accelerations and decelerations in aerospace or similar high precision applications. Finally, the magnetic seal's elegant design and compressed axial length requirement allows for simple replacement and upgrade of lip seals and can eliminate the costly need to replace a fretted shaft.

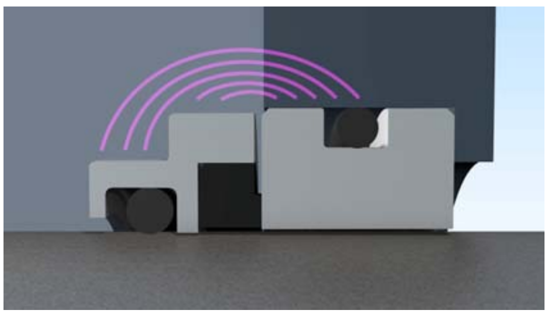

Figure 5

Magnetic seals can be applied to upgrade system performance and improve mean time between failure. In a mission critical US Air Force program, the replacement of a conventional spring energized welded metal bellows mechanical face seal with a magnetic seal more than doubled service life.

Seal Type	Benefits	Limitations
Magnetic Seals	• Uniform loading of the seal ring produces no anomalies to the seal interface. • Proven to enhance life over conventional method of face sealing. • Fits in compressed space in comparison to conventional seal, and can be applied for upgrading standard lip seals. • Accepts low and high face pressure and has designs for reverse pressure. • Accepts high vibration environmental conditions. • Low life cycle cost.	• Temperature limited by secondary seal.

CONCLUSIONS

Maximizing critical systems reliability is dependent on proper material and design selection for medium being sealed, operating parameters, and equipment condition coupled with proper handling and installation. Only when all these critical components are addressed can a sealing system realize optimum performance.

There are a variety of ways to seal lubricated bearings in shaft to ground applications. This paper has attempted to define the most salient methods and to define the advantages and disadvantages of each to be useful to operators and engineers charged with the maintenance and sustainment of mission-critical equipment in the Fleet. New technologies, such as the use of edge welded crest to crest wave springs in spring energizing seals and the use of magnetic stators provide designers and end users upgrading equipment with greater choice and higher chances for long life and reliability.

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ACKNOWLEDGMENTS

Chuck Nevola, Director of Marketing and Customer Relations, Magnetic Seal Corp.

Steve Kelley, Captain, US Navy (Ret), Logistics Consultant - Ship Systems, Navy Logistics Network, Dutch Valley Supply/ECI Defense Group

Paul Ryan, Chief Engineer, Magnetic Seal Corp.

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