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Thomas H. Batzer

April 15, 1964

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MECHANICAL MOTION IN VACUUM*

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ABSTRACT

Mechanical motion in vacuum is described in terms of how it is achieved, its purpose, the effect of vacuum on the mechanism and the effect of the mechanism on the vacuum. A vacuum environment permits certain processes to proceed which might otherwise be impracticable. Mechanical motion in vacuum processing is often needed. The seals and motion mechanisms, including lubrication, must not adversely affect the permissive vacuum environment. Conversely, in the case of very low pressure ($<10^{-9}$ torr) the motion mechanism needs protection from the vacuum. Based on these considerations, some current means and methods of providing mechanical motion in vacuum are discussed.

A vacuum is usually defined as a space filled with gas at a pressure less than atmospheric. Such a space at reduced pressure provides an

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environment in which certain processes can be accomplished that would otherwise be impossible. Examples of processes requiring vacuum range from food processing and packaging to space simulation.

Pressure requirements vary widely from a few torr (one atmosphere is 760 torr) as required in a steam turbine condenser to less than 10^{-10} torr (one ten trillionth of an atmosphere) in some plasma physics experiments. Mechanical pumps and sorption pumps will produce vacuums to about 10^{-3} torr. Below pressures of 10^{-3} torr the equipment required is more elaborate. In conjunction with the mechanical pump or sorption pump one of several gas removal methods may be chosen: among these are diffusion pumps, ion getter pumps, and cryopumps.

All earth-bound vacuum spaces require a wall of some kind to keep the air out. Mechanical motion, when required, is usually transmitted through the vacuum wall, and seals are needed to prevent or reduce leakage. Motion seals are an ever-present challenge to the vacuum designer.

There are two broad requirements for vacuum motion seals. First, the seal should not contaminate the vacuum beyond limits acceptable to the process. The contamination can take the form of leakage through the seal or vapors from the seal materials and lubricants. Second, the seal should reliably survive the vacuum environment including, in some cases, large temperature excursions. The requirements for the mechanisms which are actuated through the seals are similar; that is, no unacceptable contamination and reliability under vacuum and temperature extremes.

The requirements for motion seals and vacuum mechanisms seem simple, but satisfying them often is not. Seals frequently used in systems

having moderate vacuum requirements (pressures no less than 1×10^{-7} torr and room temperature) include the following:

1. Wilson Seal: The Wilson seal shown in Fig. 1 uses a rubber disk with a hole in the center. The hole is slightly smaller than the shaft diameter over which it fits. The shaft finish should be about 8 rms and both shaft and gasket require lubrication in the form of vacuum grease. The sealing force is provided by the atmospheric pressure differential on the rubber washer.

2. Chevron Seal: The chevron seal shown in Fig. 2 is similar in concept to the Wilson seal. However, the chevron seal permits load adjustment, and Teflon as well as rubber can be used. If rubber is used the seal must be lubricated.

3. "O" Ring Seals: Many special shaft seals have been designed using O ring gaskets of rubber or Teflon or both. Again the rubber O ring requires liberal application of vacuum grease if it is used to make the running seal. Figure 3 shows a typical combination Teflon-rubber O-ring seal not requiring lubrication.

4. Teflon Washer Seal: Figure 4 shows the washer seal which also is similar to the Wilson seal. The Teflon washers are a push fit on the shaft and in the body. The metal spacers clear the shaft. A belleville type spring is used to maintain sufficient loading on the washer stack to force the Teflon against the shaft.

5. Carbon Face Seal: A carbon face seal is shown in Fig. 5. The plane of the rubbing seal is perpendicular to the shaft. These seals, unlike those previously described, can be used only for rotation and must be lubricated with oil.

All of the motion seals above, except No. 5, have similar characteristics:

1. They rely on a close running fit between a compliant material and the shaft.
2. Lubrication is required either as provided by Teflon or in the form of grease.
3. Both rotary and reciprocating motion are possible. Rubbing speed is limited by the operating temperature allowed by the sealing material. For example, a 1-in.-diameter shaft, sealed with lubricated rubber is capable of about 100 rpm. A similar seal using Teflon can reach 2000 rpm or better.
4. The probability of leak tightness is small.
5. The temperature limits range from 0 to 200 °C for elastomers such as Viton A, and from approximately -40 to +300 °C for Teflon. Consideration must be given in the design of Teflon seals to the ease with which it cold flows and its high wear rate.

As the probability of leak tightness is small, dynamic seals of the type so far discussed are usually designed in pairs and differentially pumped. This is accomplished by placing two seals on a shaft separated axially by an enclosed volume to which a vacuum pump is attached. The leakage into the high vacuum space will then be reduced by the ratio of the pressure between the two seals to atmospheric pressure. This can be seen in Fig. 6.

A further advantage to differential pumping between dynamic seals is seen in the case of reciprocating motion. When a shaft is moved through a sliding seal from high vacuum to atmosphere the surface of the shaft adsorbs gas. When it is moved back into the vacuum, it carries in gas that is quickly released, resulting in a pressure rise. This problem can be virtually eliminated by spacing the differentially pumped seals a distance apart that is comparable to the length of the shaft stroke.

The application of sliding (organically sealed) seals was limited in this discussion to moderate vacuum conditions. However, with clever designs, differential pumping, and the use of low-vapor-pressure, high-temperature materials, such as Teflon, these seals are often used on bakeable ultra-high vacuum (pressure $< 1 \times 10^{-9}$ -torr) systems.

When essentially no contamination can be tolerated and temperatures may range from 10 to 700 °K, metal seals must be used. The seal usually takes the form of a bellows or a thin metal membrane.

Figure 7 is a simple bellows seal for reciprocating motion. The stroke is limited by the stress in the bellows and the number of cycles required of the seal. Except for temperature extremes lubrication is no problem as the bearing can be located on the air side of the seal.

Figure 8 is an example of a low-torque, high-rpm (several hundred), rotary bellows seal. Figure 9 shows a high-torque, low-rpm rotary bellows seal used primarily as a valve actuator. In both cases these seals require bearings and lubrication on the vacuum side.

Another seal arrangement that can be adapted to either rotary or reciprocating motion is the magnetic coupling. The vacuum wall is locally thinned to minimize the magnetic reluctance between the driver and the driven magnet. A typical example is shown in Fig. 10. Properly modified electric motors can also be operated in a similar way.

The mechanisms actuated through motion seals as mentioned earlier encounter unusual problems in meeting the contamination and reliability requirement. In general, the requirements involving no temperature extremes and moderate vacuum are quite easily met. Usually, conventional oil or grease lubricated bearings and gears work quite well. But, when the situation calls for minimum contamination and large temperature extremes, an entirely different approach is required.

Consider the large gate valve shown in Fig. 9. This valve is required to operate between the pumping system and the vacuum chamber of a plasma physics experiment. The valve must withstand a bake temperature of 400°C for prolonged periods, like days. The contamination originating from the valve must be comparable to the outgassing rate of the baked metal walls of the system. That is, the gas evolving from each square centimeter of internal valve surface, including lubricated surfaces, should be the same as that of the chamber wall. For well baked stainless steel the specific outgassing rate should be less than 1×10^{-13} torr-liter/sec-cm². The operating pressure consistent with such a situation is usually less than 5×10^{-10} torr.

Under such conditions of pressure, cleanliness and temperature, metals rubbed together tend to weld. The degassed surfaces are unable to replenish the oxide films that are worn away by the rubbing. The lubrication used must either prevent welding and provide a reasonable coefficient of friction or if welding is allowed to occur, the bond must be sufficiently weak to permit the desired motion. Considering the contamination and temperature requirements, only lamellar powders such as MoS₂ and plated metal films such as silver or gold have provided acceptable performance.

In the valve mechanism shown, all rubbing surfaces are coated with MoS₂ in a sodium silicate binder, and all rolling contacts are burnished with MoS₂ powder. The bearings, both needle and ball, are 52100 steel. The maximum design load on the four carriage support bearings is 10,000 pounds. The maximum actuator torque is 800 pound-inches.

In summary, the problems involved in generating motion in vacuum are divided into two distinct categories. The first category has moderate contamination, vacuum and temperature requirements wherein conventional organic lubricants and seals can be used. The second category requires minimum

contamination, pressures less than 1×10^{-9} torr and temperature extremes from 10 to 700°K. In this case metal seals and inorganic or solid film lubricants are required.

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1. BODY
2. SEAL WASHER
3. PUMPOUT RING
4. COMPRESSION RING
5. COMPRESSION NUT
6. SHAFT

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WILSON SEAL
FIG. 1

1. BODY
2. SEAT RING
3. GASKET
4. PRESSURE AND PUMPOUT RING
5. PRESSURE
6. COMPRESSION SPRING
7. COMPRESSION NUT
8. SHAFT

GLL-644-1067

CHEVRON SEAL

FIG. 2

1. BODY
2. SEAT RING
3. BODY 'O'RING
4. PRESSURE RING
5. COMPRESSION SPRING
6. SHAFT 'O'RING
7. COMPRESSION NUT
8. SHAFT

GLL-644-1068

'O'RING SEAL

FIG.3

1. BODY
2. METAL WASHER
3. TEFLON WASHER
4. PUMPOUT RING
5. SPRING WASHER
6. FOLLOWER
7. CLAMP RING
8. SHAFT

GLL-644-1069

TEFLON SEAL

FIG. 4

1. LOCKING COLLAR
2. COMPRESSION SPRING
3. PRESSURE RING
4. SHAFT SEAL
5. CARBON FACE SEAL
6. SEAT SEAL
7. SEAT
8. SHAFT

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CARBON FACE SEAL (ROTARY MOTION)

FIG. 5

P_a = Atmospheric pressure

P_i = Intermediate pressure

P_h = High vacuum pressure

C_1 = Leakage conductance through seal no. 1

C_2 = Leakage conductance through seal no. 2

ASSUME—

$P_a \gg P_i \gg P_h$, $C_1 = C_2$

$Q_{ai} = P_a C_1$ = Leakage to differential space

$Q_{ih} = P_i C_2$ = Leakage to high vacuum space

$Q_{ai} - Q_{ih} = P_a C_1 - P_i C_2$ = Gas pumped from differential space

$$\frac{Q_{ih}}{Q_{ai}} = \frac{P_i C_2}{P_a C_1} = \frac{P_i}{P_a} = \text{Ratio of leakage reduction by differential pumping the seals.}$$

TYPICALLY $\frac{P_i}{P_a} = \frac{10^{-2} \text{ torr}}{760 \text{ torr}} = 1.3 \times 10^{-5}$

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DIFFERENTIAL PUMPING

FIG. 6

- 1. GUIDE BUSHING
- 2. STOP COLLAR
- 3. BELLOWS
- 4. SHAFT

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BELLOWS - SEALED
(RECIPROCATING MOTION)

FIG. 7

- 1. GUIDE BUSHING
- 2. COLLAR
- 3. DRIVE SHAFT
- 4. BELLOWS
- 5. DRIVE ROTOR
- 6. DRIVEN ROTOR
- 7. BUSHING
- 8. DRIVEN SHAFT

GLL-644-1073

BELLOWS-SEALED
(ROTARY MOTION)

FIG. 8

1. VALVE BODY
2. BEARING
3. VACUUM SEAL
4. BELLOWS (OUTER HANDLE)
5. ACTUATOR HANDLE (INNER)

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ALL METAL GATE VALVE

FIG. 9

1. DRIVEN SHAFT
2. VACUUM SEAL
3. INNER ROTOR (NON-MAGNETIC)
4. PERMANENT MAGNET
5. HOUSING
6. OUTER ROTOR (NON-MAGNETIC)
7. DRIVING SHAFT
8. POLE PIECES (SOFT IRON)

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MAGNETIC COUPLING

FIG. 10

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