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RELATIONSHIP BETWEEN VIBRATIONS AND MECHANICAL SEAL LIFE IN CENTRIFUGAL PUMPS

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ABSTRACT

A reduction of vibrations in mechanical seals increases the life of the seals in centrifugal pumps by minimizing fatigue damage. Mechanical seals consist of two smooth seal faces. One face is stationary with respect to the pump. The other rotates. Between the faces a fluid film evaporates as the fluid moves radially outward across the seal face. Ideally, the film evaporates as it reaches the outer surface of the seal faces, thereby preventing leakage from the pump and effectively lubricating the two surfaces. Relative vibrations between the two surfaces affect the fluid film and lead to stresses on the seal faces, which lead to fatigue damage.

As the fluid film breaks down, impacts between the two seal faces create tensile stresses on the faces, which cycle at the speed of the motor rotation. These cyclic stresses provide the mechanism leading to fatigue crack growth. The magnitude of the stress is directly related to the rate of crack growth and time to failure of a seal. Related to the stress magnitude, vibration data is related to the life of mechanical seals in pumps.

NOMENCLATURE

rpm	revolutions per minute
SRS	Savannah River Site

INTRODUCTION

Mechanical seal failures are known to have numerous causes (Karrasik [1]), but the primary considerations here are failures due to vibration. Over the past ten years, seal failures have occurred on several different centrifugal pump designs at the Savannah River Site (SRS) (Leishear and Stefanko [2,3]). The failures were attributed to vibration.

In particular, mechanical seal failures due to vibrations in vertical pumps used to mix nuclear waste in storage tanks were considered. These vertical pumps are typically 45 feet in length and are referred to as long shaft vertical pumps. They consist of a motor on top of the tank; an impeller at the bottom of the pump submerged in the waste; a drive shaft with bearings along its length connecting the impeller to the shaft; a water filled pipe, or support column, surrounding the shaft; and mechanical seals at the top and bottom of the column to contain the water.

A brief discussion of vibration analysis, pump design, and seal construction is in order before seal failures are considered for these pumps. The seal failures in these pumps are caused by fatigue damage to the seals. This failure mechanism is discussed in detail below. Prior to this work, relationships between vibration magnitude, fatigue of mechanical seals, and the life of the seals were not established.

TYPICAL PUMP CONSTRUCTION

Several pumps with similar designs were supplied by different manufacturers. One such pump is shown installed in the test facility at SRS in Fig. 1. The only significant difference between the installation at the test facility and the final installation on waste tanks is the fact that the pump is accessible for inspection and testing at the test facility. At the top, the mounted motor is connected to the impeller at the bottom with a drive shaft surrounded by an encasing column of water. The pump suction at the bottom of the pump draws waste up through the impeller and discharges the waste to mix the material in waste tanks. The water in the column is used as a lubricant for bearings and also as a buffer between the waste and the environment. The location of the installed mechanical seal which typically leaks is located just above the impeller.

MECHANICAL SEAL CONSTRUCTION

The seal consists of stationary and rotating parts which contain lapped seal faces. The rotating part is fixed to the shaft with set screws. The stationary part is mounted to the pump. A fluid film prevents seal face contact during rotation. An appropriate fluid film thickness is maintained by applied pressure to the seal.

This design uses a metal bellows to apply the spring force to the seal faces. Several similar designs were used on different pumps. Both the rotating and stationary faces were made of a hard, brittle, silicon carbide. The primary function of the seal is containment of the water in the column surrounding the drive shaft. Ideally, the water passes along the seal face from the inner diameter to the outer diameter, and heats up to the boiling point at the outer diameter. Thus, water vapor is created at the outer diameter of the seal, and a minimum amount of fluid is required to keep the seal properly lubricated.

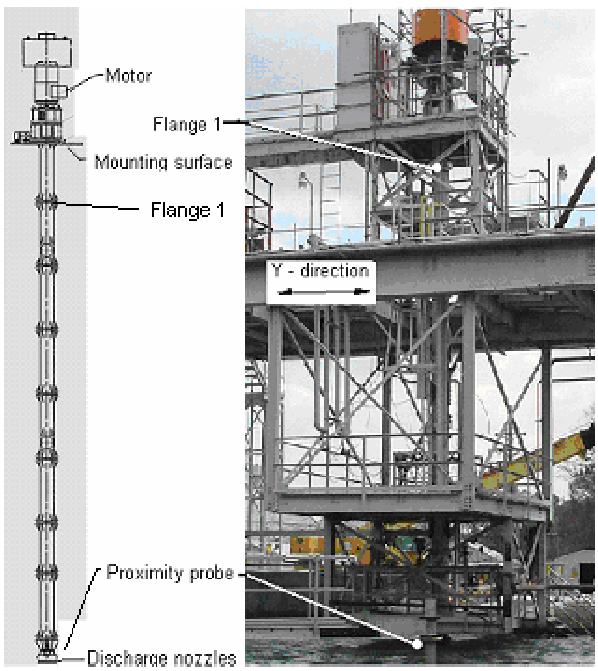

Figure 1: Long Shaft Vertical Pump Installed at the Test Facility

VIBRATION ANALYSIS

Vibration analysis determined the vibration magnitudes affecting mechanical seal life. Larger vibrations cause shorter seal lives. A relationship between seal life and vibration is established based on vibration analysis techniques.

Vibration testing was performed at the test facility prior to installing the pumps in nuclear waste tanks. Vibrations were measured in orthogonal directions near the top of the pump at a point denoted as flange 1 shown in Fig. 1. Two transducers were attached to the pump to measure vibrations transmitted in the two directions, X and Y. The Y direction is shown in Fig. 1, and the X direction is perpendicular to the Y direction in a horizontal plane.

Fundamentals of Vibration Analysis

The vibration data is presented in different forms and formats, e.g., acceleration, velocity, or displacement; filtered or unfiltered. For this work, the vibration is typically measured as a velocity using Velomitors, which transform a piezoelectric acceleration signal to a velocity. Once the velocity data was obtained, the analyzer software converted the data into unfiltered vibration plots, which represent a summation of sine waves associated with each of the discrete vibrations comprising the unfiltered wave. That is, the unfiltered vibration is decomposed into several filtered vibrations. A display of these vibrations is shown in Fig. 2, which shows the maximum value of the unfiltered vibration at numerous operating speeds of a pump. The peak value of the unfiltered vibration is displayed for the vibrations, which were measured in two orthogonal directions, X and Y. In this graph, the 1X vibration shows the vibrations which occur at the operating speed of the pump.

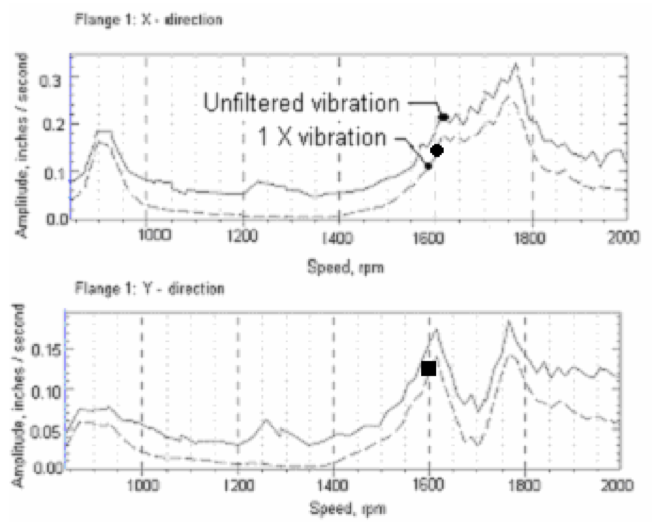

Figure 2: Vibration Plots of Vibration Amplitude vs. Speed

Interpretation of Vibration Data

The plots provide a representation of the vibration data for the long shaft pumps under consideration. Data was measured on several different designs of pumps prior to installation and use. Facility records documented the operating speeds and life spans of the various pumps, where the life spans of the pumps were dictated by leakage of the seals. If the seals leak, the pumps are typically removed from service. A tacit assumption of this work is that the magnitude of a vibration, measured as a velocity, can be used to evaluate the life span of the seals. Knowing the operating speed of a pump, the plots were used to find the vibration magnitudes during operation. The hours of operation to seal failure were also known. Consequently, vibrations were compared to seal life.

ANALYSIS OF SEAL FAILURES IN VERTICAL PUMPS

Several seal failures were investigated at SRS. One specific investigation resulted in a failure analysis of a failed seal, which included electron microscopy of the fracture surfaces of the failed seal. Note that several critical speeds are indicated by the vibration peaks shown in Fig 3. At each critical speed the vibration increases. The pump was operated at one of the critical speeds (1400 rpm), during testing and a seal was damaged.

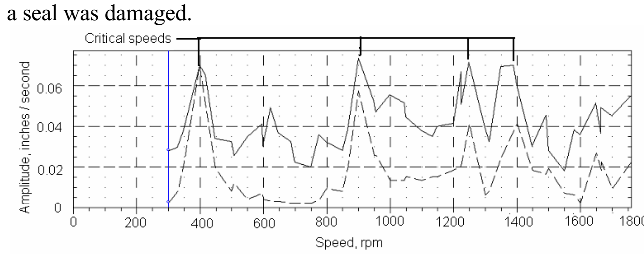

Figure 3: Critical Speeds of a Long Shaft Pump

W. Daugherty [4] performed electron microscopy on this damaged seal. Spalling is observed at the seal surface shown in Fig. 4. These spalls, or chips, provided nucleation sites for the cracks to commence and extend into the seal face. At the time the crack was investigated, the crack had not fully extended through the seal. That is, the crack was still in progress.

Crack propagation. The crack shown in Fig. 4 is characteristic of cracks observed during Mode I fatigue testing. During Mode I testing, a specimen is cyclically stressed in direction perpendicular to the crack surface. The similarity between the crack observed here and typical crack propagation indicates that Mode I fracture is the probable cause of failure. Furthermore, cracks are known to propagate only with the application of a load to the crack.

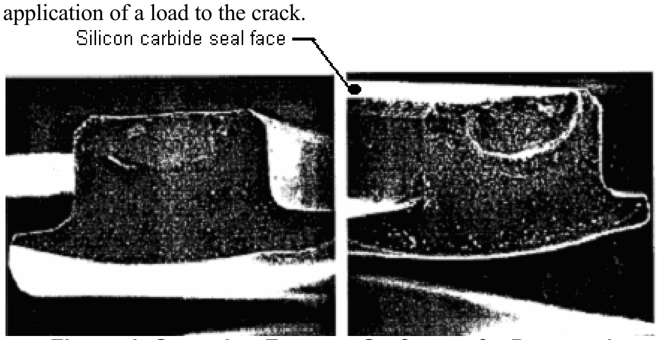

Figure 4: Opposing Fracture Surfaces of a Damaged Mechanical Seal, W. Daugherty, SRS

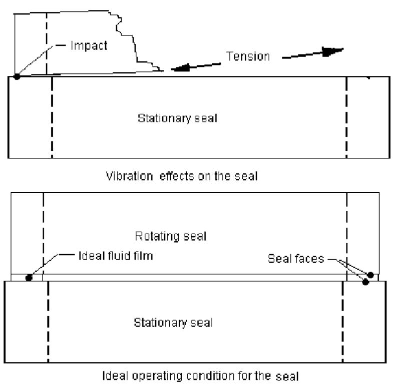

Figure 5: Impact of Seal Faces

For the cracks to grow into the face, tensile stresses must exist on the seal face. Vibration provides an explanation for the tensile stresses. As the shaft deflects due to vibrations, the rotating seal face effectively wobbles with respect to the stationary seal face creating an impact load to the faces on each revolution of the shaft. An exaggerated depiction of the impact is shown in Fig. 5. The magnitude of the impact load depends on the film thickness which damps any impacts between the faces. As the film thickness is reduced during impact, damping is also reduced. The life of this specific pump was increased by avoiding operation at critical speeds.

COMPARISON OF VIBRATION MAGNITUDE TO SEAL LIFE

Vibration data and seal life data was available for numerous vertical pumps, and a comparison was made between vibration and life span. A question needed to be answered. What is the magnitude of a vibration needed to cause failure? This question is answered for this style of pump by Fig. 6. This figure shows the results of an evaluation of seal failures with respect to vibration. In fact, the figure may be used to predict seal life on these pumps when a measured whirl vibration is available. A failure analysis was performed on numerous pumps built by different manufacturers, and a common problem was discerned [5]. The magnitude of the vibration due to whirl was related to the time until failure of the seal.

While this data may not be generally applicable to all centrifugal pumps, the data indicates a definite relationship between vibration and seal life. Coupled with the fact that the seal failure mechanism is fatigue of the seal surfaces, a general conclusion can be reached with respect to seal failures. A reduction of the vibration by a factor of two increases the pump life by a factor of ten.

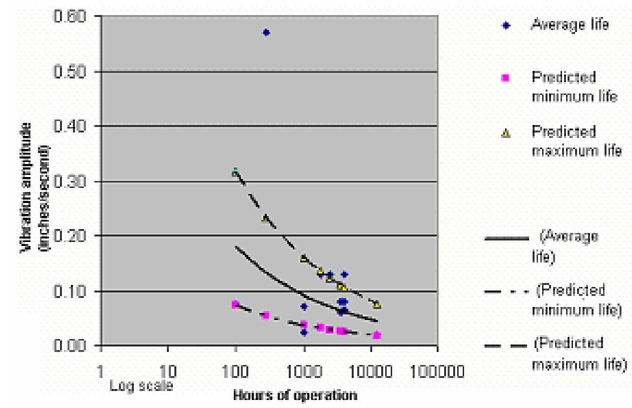

Figure 6: Prediction of Mechanical Seal life

CONCLUSION

Vibration causes fatigue failures in mechanical seals. That is, a principle cause of mechanical seal failure in centrifugal pumps is related to fatigue failure of the seal faces. The initial failure mechanism results from spalling of the faces, which leads to cracking in hard materials like silicon carbide. Both spalling and cracking require a tensile stress across the surface to propagate. Tension across the surface results from a wobbling action of the seal faces, which changes the applied force to the faces during every rotation of the shaft. This constant change in the applied load impacts the seal face to provide the cyclic stressing of the faces required to propagate cracks. Seal failures were examined here, and vibration induced fatigue was the cause of failure. The relationship between vibration and failure is markedly nonlinear. A vibration decrease of fifty percent can increase the life of the bearing by a factor of ten. This relationship provides critical insight into the importance of vibration control to improve seal life.

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