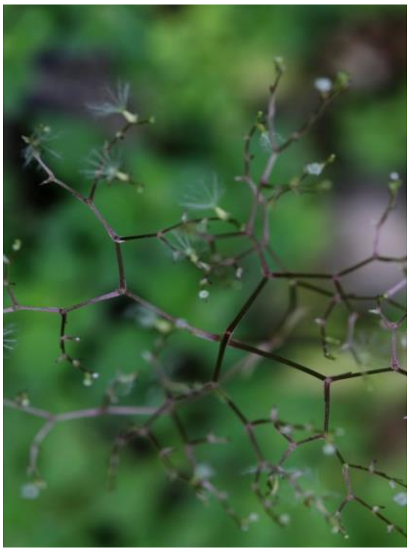
Fault Diagnostic Opportunities for Solenoid Operated Valves using Physics-of-Failure Analysis



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***Abstract*—Solenoid operated valves are vital components in many process control systems. They are components that are often critical to safety. Solenoid valve degradation is difficult to detect in situ, leading to failures, which are often sudden and unexpected. This paper reviews some of the common causes of solenoid valve degradation, presents strategies that leverage these mechanisms to detect and diagnose faults before they lead to failure, and discusses research opportunities aimed at improving solenoid valve diagnostics and prognostics.**

Keywords-solenoid valve; diagnostics; electrical coil; fault detection

I. INTRODUCTION

The Transocean Deepwater Horizon disaster in 2010 was a major incident resulting in 11 lives lost and an estimated 4.9 million barrels of oil discharged into the Gulf of Mexico. Tests performed by Transocean Ltd. and Cameron International after the incident revealed that the coil of a solenoid valve failed to energize, suggesting an electrical coil fault. The investigation team found no evidence to suggest that this fault was a result of the incident. Rather, they concluded that the electrical fault(s) likely existed prior to the accident [1]. Had the solenoid valve been working properly, it could have yielded at least a partial closure of the blind shear rams, resulting in a far less serious incident.

Solenoid operated valves (SOVs) are utilized to shut off, discharge, dose, allocate, or combine fluids. This action is accomplished by passing an electric current through a coiled wire, thereby producing a magnetic field, which magnetizes the plunger resulting in a position change. The position of the plunger controls the flow of the process fluid(s).

SOVs are integral components of many systems. Their popularity is primarily due to their simple and rugged construction, and their inexpensive cost. Within the automotive industry, solenoid valves are used to achieve intelligent control in electro-pneumatic braking systems of motor vehicles [2], control in diesel fuel injection systems [3], [4], and the control of automobile transmissions [5]. In the process and nuclear industry, solenoid valves are used for process fulid control and in critical safety instrumented functions (SIF). Approximately 2–4% of all solenoid valves in a typical chemical plant are part of a SIF [6]. Moreover, safety valves are generally the most important components in the safety loop [7]. Thus, their reliability and availability are critical.

Due to the pervasive use of SOVs in a variety of industries, interest continues to grow in estimating their health and remaining useful life (RUL). Understanding the underlying physics of their failure mechanisms can yield insight into the measurement techniques that may produce useful results for health estimation. This is referred to as the physics of failure (PoF) approach to diagnostics and prognostics. The first step in this process is to identify and analyze the hardware of the system. This yields an understanding of how the components connect and their functional relationships, which can be used in identifying loading conditions applied to system components. The loading conditions are a direct result of the life-cycle demands of the system. However, in a system where there is heavy interaction between the components, as seen in the SOV, life-cycle loads and demands can produce stresses that interact among the components. These stresses may be classified as mechanical, electrical, chemical, thermal, or environmental radiation. The presence of any particular load in the life-cycle depends on the specific application of the SOV. The next step is to perform a failure modes, mechanisms, and effects analysis (FMMEA) on the system. This, combined with a criticality analysis, is useful for identifying and prioritizing the failure mechanisms of the system. With an understanding of the failure mechanisms, a system can be designed to monitor key parameters in order to perform system diagnostics and prognostics.

The purpose of this paper is to identify the critical components and failure mechanisms of the solenoid valve system, and then explore existing and potential methods of performing health diagnostics and prognostics.

II. HARDWARE ANALYSIS

Solenoid operated valves are used in many different operating environments and thus can have a variety of designs. The fundamental differences can usually be understood using the following terms: normally open versus normally closed; direct-acting versus pilot-controlled; and two-way versus three-way versus four-way. Normally open (closed) refers to a valve where the inlet port is open (closed) when the valve is de-energized. A direct-acting valve is one where all flow passes through an orifice that is opened directly by an electromagnet and plunger. Pilot-controlled refers to a solenoid valve that operates by means of a minimum and maximum pressure differential and uses an electromagnet and plunger to open or close a small orifice thus controlling the pressure differential across a piston or diaphragm. A two-way valve, as shown in Figure 2.1, is one where there are two ports and a single orifice that can be opened or closed. Two-way valves are used to control a single working fluid. In a three-way valve, there are three ports and two orifices, similar to what is shown in Figure 2.2. Three-way valves can have several possible functions. They are commonly used to alternately apply pressure to and exhaust pressure from the diaphragm operator of a control valve, single-acting cylinder, or rotary actuator. It can operate with an inlet port, an outlet port, and an exhaust port for operating a single acting cylinder; one inlet port and two outlet ports for selecting or diverting flow; or two inlet ports and one outlet port for mixing fluids. Four-way valves are generally used to operate double-acting cylinders or actuators. They have four or five pipe connections: one pressure, two cylinder, and one or two exhausts. In this paper, a two-way, direct-acting solenoid valve will be analyzed, not because it is necessarily the most common, but because it provides an opportunity to analyze components and loading conditions that are common to the valves previously mentioned.

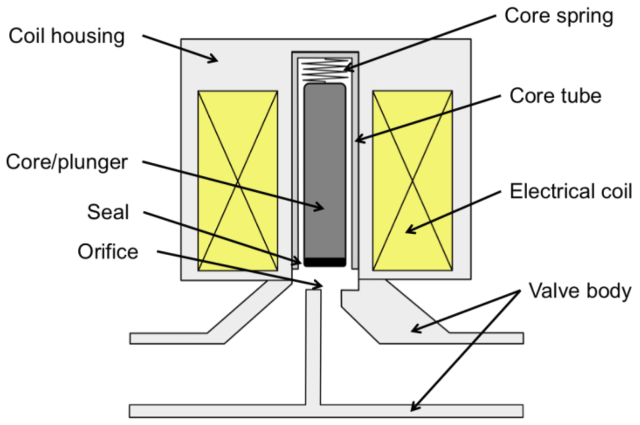

Figure 2.1. Two-way, direct-acting normally open solenoid valve

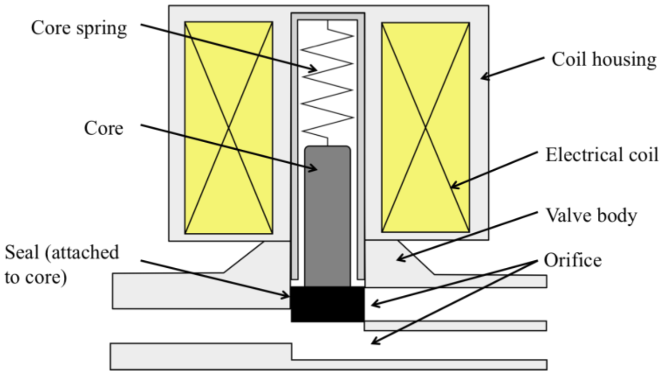

Figure 2.2. Three-way, direct-acting solenoid valve

In a two-way valve design, the spring, core, and core tube are exposed to the process fluid. This type of design is common, though there are available designs where these components are separated from the process fluid by a membrane, used with ultra-pure or extremely aggressive process fluids.

III. LOADING CONDITIONS

In order to assess the reliability of a SOV, environmental and operational loads must be understood. For most applications, there are chemical and contamination loads arising from the process fluid and airborne environment, and thermal loads arising from the process fluid and the electrical coil. Further, due to the interaction of the components, friction and impacts will be present during the lifetime of the SOV. Each component in the valve will be subjected to a different combination of loads. A less general load is radiation loading, in the case where a SOV is used in a nuclear facility. In providing an FMMEA for SOVs, motivation is given for further research into diagnostic and prognostic methods for SOVs.

IV. FAILURE MODES, MECHANISMS, AND EFFECTS ANALYSIS

Failure modes, mechanisms, and effects analysis (FMMEA) is a systematic methodology of finding root cause failure mechanisms of a given product [8]–[10]. An effect is the observable result of a failure on the product. Failure mode is a way in which a component, system, or subsystem may fail to meet its intended function. Failure mechanism is the mechanical, chemical, thermodynamic or other physical process or combination of processes that result in a failure. FMMEA helps to identify potential failure mechanisms and models for expected failure modes and prioritize them. An important result from FMMEA is an understanding of possible parameters to be monitored for diagnostics and prognostic purposes.

A. *Potential Failure Modes*

The major components of the solenoid valve are selected from the analysis of hardware given in Section 2 for a two-way, direct-acting solenoid valve. An overview of the potential failure modes, mechanisms, and effects is given in Table 4.1.

1) Valve Body

The valve body is exposed to the process fluid and must therefore be resistant to corrosion and contamination. The materials used to construct the valve body are most commonly brass, bronze, cast iron, or stainless steel. Some alternative materials are used in specialized applications. Polyvinylidene fluoride (PVDF) is suitable for valves in acidic and solvent applications. Polyether ether ketone (PEEK) has desirable mechanical properties but is susceptible to attack by nitric and sulphuric acid.

The failure of the valve body will be evidenced by leakage of the process fluid. This could be caused by loosening of the outside connections or, in extreme cases, plastic deformation of the valve body. In cases where there is a mechanical loading, such as vibration or impacts, applied to the valve body, the failure mechanisms are fatigue leading to fracture or overstress fracture. However, since contaminants and corrosive media are present in most solenoid valve applications, the expected failure mechanism for the valve body is corrosion fatigue or corrosion fracture, depending upon the ambient environment.

2) Seal

The seal is used to control the flow of the process fluid through the valve. Implied by this function is the requirement to prevent leakage from the input to the output inside the valve, referred to as seal leakage. Since the seal is exposed to the process fluid, there are several different materials used for seal construction. Some examples are: NBR (nitrile butadiene rubber), EPDM (ethylene propylene diene monomer rubber), FPM (fluorocarbon rubber), and FFPM (perfluorinated elastomer).

The seal will experience impact loading from the core and will also experience chemical loading from the process fluid. Further, the process fluid or the electrical coil could cause the temperature of the seal to increase. Some valve designs locate the seal on the tip of the core, exposing the seal to friction. A failure of the seal would result in seal leakage. This could be caused by a combination of mechanisms: corrosion, embrittlement, erosion of the seal material caused by the process fluid, impacts from the core and friction, and fatigue caused by impacts from the core.

3) Core Spring

The function of the core spring is to return the core to its default position when de-energized. In many valve designs, the core spring is exposed to the process fluid and must be resistant to corrosion from the process fluid. Thus, it is generally constructed from paramagnetic stainless steel.

As the spring is subjected to cyclic motions, the stiffness will decrease over time. Further, as the spring is commonly exposed to the process fluid, it could corrode and further fatigue. This loss of stiffness will cause the valve to improperly meter the process fluid, as the orifice will not be properly plugged or fully opened. If allowed to continue in operation, the spring could eventually fracture, resulting in a total loss of function.

4) Core/plunger

The core/plunger is responsible for allowing or preventing the flow of process fluid through the solenoid valve. In common designs, the core is exposed to the process fluid. The core must be a soft ferromagnetic material in order to perform the functions necessary for the valve. The most common material used for this purpose is stainless steel 430F, a low carbon, high chromium stainless steel, which was developed specifically for solenoid plunger applications in corrosive environments.

As the core is often exposed to the process fluid, corrosion frequently acts on the core material. Additionally, the core is in contact with the core tube, which introduces friction, wear, and material loss. This will be evidenced by stick slip behavior or a failure to fully seal the valve when closed. The core is also exposed to the magnetic field created by the electrical coil. Prolonged exposure to this field can result in permanent magnetization of the plunger, resulting in improper behavior of the core, and improper metering of the process fluid.

5) Coil Housing

The coil housing performs three functions for the SOV: it completes the electromagnetic flux path of the solenoid, provides protection from contact with the coil, and protects the coil against environmental conditions. For this reason, it is generally constructed using a soft ferromagnetic stainless steel.

The housing will be directly exposed to the environmental conditions. If the SOV were used in extreme environments, the combination of corrosion and temperature from the process fluid and electrical coil could produce a loss of material resulting in the decrease of magnetic flux. In environments with high hydrogen concentration, hydrogen embrittlement could potentially be a failure mechanism.

6) Core Tube

The core tube functions as a barrier between the core and the electrical coil. It helps to protect the coil from the process fluid and direct the magnetic flux into the core instead of around the core. Most designs call for the core tube to be constructed of aluminum or paramagnetic stainless steel. (A ferromagnetic core tube would provide a shunt path for the magnetic field lines, which would reduce the efficiency of the SOV.)

Aggressive process fluids and friction produced by interaction with the moving core result in wear of the core tube. This produces wear particles that can inhibit the movement of the core.

7) Electrical Coil

The electrical coil is responsible for producing the magnetic field that magnetizes the core and produces the necessary motion of the valve. The wire used is generally referred to as magnet wire and is usually constructed of copper. Within the solenoid valve field, there are three main types of insulation used to coat the wire. Class E insulation is rated for temperatures up to 120°C; class F is rated for temperatures up to 155°C; and class H is rated for temperatures up to 180°C. Electrical coil construction is generally divided into two methods: tape wrapped coils and encapsulated coils. Tape wrapped coils are manufactured by winding wire around a spool or bobbin, and then protecting the winding with insulation tape. Encapsulated coils also have a wire wound around a spool or bobbin, but the wire is then encapsulated or molded over with a suitable resin.

As an electric current is passed through the wire, Joule heating causes an increase in the wire temperature. If the temperature is too great, the dielectric material between the wires could degrade, fail, and two neighboring wires would form an electrical connection, producing a turn-to-turn or layer-to-layer short. These shorts cause the coil resistance to decrease, thus pulling a greater current into the valve. At the location of the short, a hot spot can form, where the local temperature is great enough to cause the wire to burn out, resulting in an open circuit. Corrosion can also play a role in the failure of the electrical coil by causing necking and loss of material in the wire.

B. Prioritization of Potential Failure Mechanisms

In order to prioritize the potential failure mechanisms of the SOV, one must utilize past experience, stress analysis, accelerated tests, and engineering judgment. In 1987, Oak Ridge National Laboratory (ORNL) gathered and analyzed data taken from the Nuclear Plant Reliability Data System

(NPRDS) records of the Institute of Nuclear Power Operations (INPO) for SOVs, covering September 5, 1978-July 11, 1984, and the NRC Licensee Event Reporting (LER) system records for January 26, 1981-July 11, 1984 [11]. The data showed that over 50% of SOV failures resulted from 4 sources: worn or degraded parts, contamination by foreign materials, short circuit in the SOV coil, and open circuits in the SOV coil. The remaining failures were attributed to manufacturing defects, improper installation, incorrect assembly, corroded parts, loose or misaligned parts, or their failure source was unspecified. Overall, the dominant failure source was shorts in the electrical coil, followed by foreign material contamination, and then electrical coil open. Importantly, there was no further breakdown into specified failure sites for the cases of worn, degraded, or broken parts and foreign materials.

Table 4.1. Potential Failure Effects, Modes, and Mechanisms of Solenoid Operated Valves

Failure site	Potential failure effect	Failure mode	Failure mechanism
Valve body	Body leakage	Loosening of connection seals, opening in material	Corrosion, fatigue fracture, overstress fracture
Seal	Improper media flow (e.g. seal leakage), noise	Loosening or deterioration of seal, impacts with core, friction	Polymer embrittlement, erosion, overstress, fatigue
Core spring	Improper media flow	Weakening of spring strength, spring breakage, material defects	Corrosion, fatigue, hydrogen embrittlement
Core/ plunger	Irregular movement, seal leakage	Loss of material, stick slip	Wear, residual magnetism, debris build-up
Coil housing	Disruption of magnetic flux path (reduced magnetic efficiency)	Loss or discontinuity of material in housing from corrosion or overstress	Corrosion, overstress
Core tube	Irregular core movement resulting in seal leakage	Debris build-up, excessive friction	Corrosion, wear
Electrical coil	SOV unable to operate (coil open), leakage resulting from reduced magnetic field strength (coil short)	Fracturing or necking of wire; degraded insulation from temperature, conductor thermal expansion, or electrical transients; material defects	Dielectric breakdown, corrosion, thermal overstress of conductor, fatigue fracture

A study in 2009 by Angadi *et al*. [5], [12] revealed that solenoid valves are susceptible to coupled electrical-thermo-mechanical failure mechanisms. In particular, they emphasized the role of Joule heating in the thermal expansion of the magnet wire, causing the degradation and failure of the insulation between the wires. This mechanism results in a turn-to-turn short, and ultimately in a coil burnout.

With these cases, and the variety of failure mechanisms acting on each component, in mind, it is difficult to draw conclusions on the prioritization of failure mechanisms with respect to failure sites. However, it is clear that electrical faults and valve contamination are prevalent and critical to the health of the SOV.

V. AVAILABLE METHODS OF SOLENOID VALVE DIAGNOSTICS

Oak Ridge National Laboratory evaluated several methods of health monitoring for solenoid valves in nuclear facilities [13], [14]. The evaluation methods were chosen based upon what the researchers considered to be the most prominent sources of failure, namely, open-circuited coils, short-circuited coils, worn or degraded mechanical parts, and contamination by foreign materials. They suggested measuring coil temperature via coil resistance or impedance. This is useful for instances where the temperature of the coil is high enough to degrade the insulation. By measuring the resistance, an unsafe operating condition can be detected. This method was deemed to be ready for immediate use. However, this approach only measures the mean coil temperature, which could be attributed to the operating environment or the process fluid. It does not sense hot spots in the coil or the valve body temperature, thus failing to isolate turn-to-turn or layer-to-layer shorts within the electrical coil.

In order to diagnose mechanical binding, failure to shift, or sluggishness as a result of worn or improper parts or the presence of foreign material in the valve, a method was proposed which used coil impedance measurements to indicate the position of the core. As the core becomes magnetized and moves through the magnetic field, its altered position is reflected in increased impedance of the coil. It was shown that the impedance change can be used to determine the position of the core to within a few thousandths of an inch and thus, detect any anomalous movement of the core due to contaminants, deformation, debris build-up, or residual magnetism. This method was deemed as having high promise for in-plant use, though the method was only useful for AC SOVs and required the introduction of a special ramp-voltage power supply. In a subsequent study [15], a methodology was developed for in situ diagnostic testing of DC SOVs by analysis of the characteristics of the transient current waveform accompanying valve actuation. This method was most sensitive to mechanical valve faults such as impeded or incomplete plunger motion, and reduced plunger spring force.

In ORNL’s 1990 study [14], to address the electrical failure of a solenoid coil caused by high-voltage turn-off transients in combination with insulation weakened by prolonged operation at high temperatures, it was suggested to measure the characteristics of the electrical transient response generated upon de-energizing a DC SOV. To model the electrical characteristics of the valve, an equivalent circuit was employed. This equivalent circuit is shown in Figure 5.1.

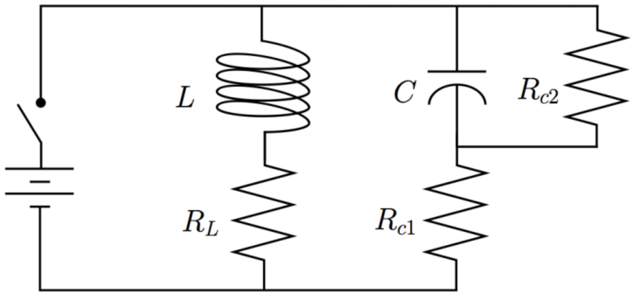

Figure. 5.1. Equivalent circuit model for solenoid operated valve

In this circuit, R_L is the series resistance of the coil, L is the coil inductance, C is the distributed capacitance of the coil, R_{c1} is the series resistance due to the distributed capacitance, and R_{c2} is the parallel resistance due to the distributed capacitance. For their simulations, the resistances R_{c1} and R_{c2} were neglected. They tested a healthy solenoid valve and a solenoid valve with approximately 6 percent of its turns shorted. The test consisted of measuring the voltage response of the valves after stepping down to 0V DC from 30V DC. The equivalent circuit model was able to reproduce the response of the healthy valve, as it behaved like a damped oscillator system. However, the response of the faulty valve was not reproduced using the equivalent circuit model. An expected advantage of this approach was the ability to detect faults in the valve that were undetectable using other methods, since the ECM could take advantage of direct electrical measurements and observe any faults existing only in the coil. As the equivalent circuit could not accurately reproduce the response of the faulty valve, this method was deemed as having low promise in the field.

The state-of-the-art in solenoid valve fault detection is partial stroke testing (PST) [7]. In PST, the plunger is moved a small amount of its total stroke length in order to measure the dynamic response. With the help of a position sensor, a PST can detect sluggishness, leakage, wear of valve seals, stick slip friction, or deposit build-up by comparing the test responses to a reference response [16], [17]. This type of testing can be carried out if three conditions hold: the valve must have a position sensor; the solenoid valve must have a sufficiently long stroke length; and the movement of the valve should not produce a significant disturbance to the process or the safety function of the valve. Otherwise, partial stroke testing can yield little information into the health state of the valve or cannot be utilized.

Visual inspection is occasionally used in solenoid valve diagnostics. This entails inspecting the solenoid valve for damage easily observed in a periodic inspection of the system as a whole, or in some cases, removing the valve for inspection in a workshop. This can be advantageous for some failure modes such as leakage or, using the workshop, contamination of the plunger pathway. However, faults within the electrical coil can be difficult to diagnose without destruction of the valve.

VI. CONCLUSIONS

As shown in the Section 5, there are several techniques available for diagnosing SOV faults such as binding, sluggishness, leakage, and wear of seals. ORNL developed a method of measuring the position of the core using coil impedance. They also proposed an in situ method of detecting faults in the core motion by using the current waveform. Partial stroke testing is capable of performing fault detection of the valve. Interestingly, based upon the data from ORNL’s 1987 study, two of the top four contributors to SOV failure have been addressed, namely: worn or degraded parts and contamination by foreign materials. Unfortunately, the remaining two sources of SOV failure (coil short and coil open) have not yet been successfully addressed, despite the efforts of ORNL in 1990. Since then there has been a relatively small amount literature studying SOV failures, especially those failures originating from coil faults. There is a significant amount of industry-focused literature addressing the use of PST in increasing safety instrumented function reliability (see e.g. [16]–[23]). Yet, it is surprising that such a significant problem, as coil faults in SOVs, could remain unaddressed and having no available solutions.

It remains necessary to develop a technique to assess the health of the SOV electrical coil without disrupting the process. The dielectric insulation around the wires can be degraded given the temperature of the wire, the thermal expansion of the conductor, and the presence of environmental contaminants and/or humidity. Moreover, the dielectric is likely subjected to temperature cycles, as the SOV is not generally in consistent use. Thus, a method to measure the health state of the dielectric insulation material could be valuable.

Further work is needed in developing a fundamental physics-based model of the electrical coil. A problem with the equivalent circuit model is that the model parameters of the coil experience minute changes due to local faults in the wire. In the ORNL research, the measured capacitance of the healthy coil was 12.6nF, whereas for the faulty coil it was 2.89nF; the resistance changed from 100.4Ω to 97Ω; and inductance changed from 113.9mH to 106.2mH. Thus, the introduction of these altered parameters does very little to simulate the true response of the SOV to shorts in the coil. Some work has been performed to develop physics models for multiple layer inductors [24]–[26]. There has also been work to develop new ECMs for coils involving fractional derivatives [27], [28]. These models could be adapted for modeling the coils in solenoid valves. Simulations should be performed using these or similar models, in order to determine the best parameters to be measured in order to diagnose localized coil faults.

Research efforts can also be directed to developing sensor techniques for probing the health of the insulation material. Werynski *et al.* used a magnetic field sensor to detect the migration of the bulk capacitance of the windings in an AC machine [29]. Adapting this work for detecting insulation deterioration in solenoid valves would be a valuable asset in the pursuit of improved diagnostic and prognostic methods for SOVs.

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