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ALL-ELECTRIC ACTUATOR FOR MID-SIZE GAS TURBINES

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ABSTRACT

A number of actuators are available for mid-size industrial gas turbine engines in the marketplace today. These designs utilize pneumatic, hydraulic, electro-pneumatic, electro-hydraulic, and all-electric actuation technologies. The electro-hydraulic has been the most common mid-size industrial gas turbine actuation technology over the last 20 years.

This paper focuses on a new all-electric actuator technology developed specifically for mid-size gas turbines using an integrally mounted controller. This paper discusses the significant technical challenges to integrally mounting all-electric actuator motor controller.

Key words: Gas turbine, All-Electric, Actuator, Controller, Integral, Rugged, Explosion-proof

INTRODUCTION

The first practical industrial gas turbine engine was developed by Dr. J. F. (Franz) Stolze. Dr. Stolze developed the first gas turbine engine in 1872 with trials being made between 1900 and 1904 [1]. Due to a lack of knowledge of aerodynamics, ultimately his initial design was not successful. Despite the fact that the engine did not successfully run under its own power, the project did provide meaningful research. Much has happen since that time.

Quantum leaps in material science, manufacturing processes, and controls have all played a part in the advancement of the gas turbine engine. Today, gas turbine engines have a significant presence in a variety of industries. Industrial gas turbine engines have been successfully applied in the transportation, power generation, and natural gas transmission industries.

The advancements in turbine technology have focused on improved heat rate, emissions, stability, durability, reliability, and versatility. Many turbine technology advances have been accomplished, in whole or part, though control system improvement.

Physically, the motion control on a modern gas turbine engine is accomplished with actuators. Fuel valve(s), bleed valve(s), and compressor inlet guide vanes are turbine control applications using actuators for their motion control. In combination, these devices physically control the engine over its operating range.

BACKGROUND

Gas turbine manufacturers are continually being pressured to design engines that are environmentally friendly. Acceptable emission levels have dropped dramatically over the past decade. Technologies such as “dry low emissions” (DLE) have been used to achieve lower emission levels [2]. Manufacturers today are looking for technologies that will enable turbine engines to achieve single digit emissions.

To achieve low emissions, designers must control combustion. This means the optimum flame temperature must be maintained throughout the combustion zone. Flame temperature is a function of air/fuel ratio. Controlling the overall air/fuel ratio involves, by definition, fuel and air metering. Typically, actuators are used to control this mixture.

Being able to maintain the air fuel ratio, as operating conditions vary, requires a high degree of accuracy and repeatability, which has not always been consistently achievable using traditional actuation technologies [3].

COMPARATIVE ANALYSIS

Motion control requirements for gas turbine engines have traditionally been met with hydraulically powered devices. Hydraulically powered actuators require a source of high-pressure oil and a servomechanism for modulation.

Servo oil systems require very clean, high-pressure (up to 6.9 MPa) oil. This typically requires a separate servo oil system with pumps, regulators, relief valves, filters, and piping. It is the rare exception that a servo oil system does not develop oil leaks.

Increasing servo oil supply pressure can provide better response and higher force capability. However, to generate higher pressure takes more power. This parasitic power loss reduces gas turbine engine package efficiency.

When an engine driven pump is used for producing supply pressure, other problems can occur. During a turbine start, the engine is not at full speed, the servo supply pressure is low, and likely the servo oil is cold and more viscous. This can result in slow actuator response and, in some cases, failed start attempts.

All electric actuators are do not require pumps, regulators, relief valves, filters and piping. Furthermore, electric products do not typically develop oil leaks. All-electric actuators are not subject to supply pressure and servo oil viscosity issues.

All-electric actuator technology use on industrial gas turbines is not without disadvantages. Local authorities often classify industrial gas turbine installations as a hazardous location. Hazardous locations can require electric products packaged and certified explosion proof by an authorized agency. Most commercially available electric actuators and controllers are not packaged and certified explosion proof.

Furthermore, available actuator controllers are typically low temperature (below 50 °C ambient). Typical turbine ambient temperature environments are well above 50 °C (122°F).

Most commercially available electric actuators require a remote mounted controller. Two interconnect cables are generally required between the actuator and the controller. One cable is typically actuator power. The second is typically position feedback. These cables must be run separately because electrical currents within the power cable can cause electro-magnetic interference (EMI) on the position feedback cable.

There are two types of position control/feedback commonly used in electric actuator application. The first is “Stepper Motor” and the second is “Resolver” (See Figure 1 Brushless Pancake Style Resolver). The resolver can handle higher ambient temperatures. The position control/feedback, or in this case resolver cable, has a few limitations. First is maximum cable length. Second is the susceptibility to electromagnetic interference. This is due to the waveform signals carried by actuator motor cable. The motor cable typically supplying a brushless DC motor can potentially produce magnetic field spikes. The spikes come from a PWM (Pulse Width Modulation) signal.

The resolver cable is sensitive due to the way this technology works. A resolver is a device that measures angular position using three separate coils. The most common configuration has a coil located on the rotor. This rotor is coupled with the motor shaft. A reference sinusoidal waveform is sent from the controller and conducted through this coil via a transformer. The transformers primary windings are located on the stator. Also located on the stator are two additional coils. These coils are positioned at a 90^{o} from each other.

Figure 1 Brushless Pancake Style Resolver

The sinusoidal waveform on the rotor winding will induce a signal on the two stator windings. The phase shift of the two stator windings is used to determine the angular position of the rotor.

The issues of resolver cable electromagnetic induction can be controlled if the electronics are integrally mounted thereby reducing the resolver cable length.

TECHNICAL CHALLENGES

A decision was made to develop a new all-electric actuator that minimizes the above stated disadvantages. The program goal was to develop an all-electric actuator with integrated electronics that was suitable for use on a mid-size gas turbine engine. The new actuator would need to meet hazardous area classifications and temperature requirements unique to the turbine environment.

In addition, the actuator would be designed to meet mid-size gas turbine engine applications including bleed valve, compressor variable guide vane, and fuel metering valve. Target specifications for the project included linear force up to 4,448 N (1000 lbf) with ± 1% full-scale position accuracy. In addition the actuator must have a small form factor and be designed for a continuous 93 °C (200 °F) ambient operating environment.

RUGGED, INTEGRAL ELECTRONICS

Integrating the all-electric actuator and controller for turbine use present significant packaging challenges. First, the integrated actuator and controller package must be small and generally light weight. Next, the actuator must comply with hazardous area design requirements. Vibration and thermal management must be considered in order for the controller to survive the rigorous turbine environment. In short, the all-electric actuator with integral controller must be compact, rugged, high temperature and explosion-proof.

COMPACT ELECTRONICS

Until recently, the electronics technology has not been available to reduce required controller circuitry to within the actuator envelope. A typically motor controller would fit into a Personal Computer (PC) envelope. In order to fit within a typical turbine actuator envelope, the motor controller must be much smaller; less than a typical shoebox.

Using Surface Mount Technology (SMT), developed in the 1980's, allows electronic engineers freedom to reduce part size. SMT components do not have traditional solder leads. SMT components are soldered directly to printed wiring board (pwb) pads thereby dramatically increasing available area.

Furthermore, recently available digital signal processors (DSP) allow electronic engineers to incorporate many circuit functions into a single chip. Motor controller encoding, decoding, analog to digital conversion functions can now be located within the DSP. Integrating all these functions reduces required circuitry thereby reducing electronics envelope.

EXPLOSION PROOF ENCLOSURE DESIGN

Electrical products generate heat and may generate sparks that can ignite explosive gas mixtures. The integral electronics enclosure design must, therefore, consider explosive gas containment. Further, heat rejection must be managed to ensure enclosure surface temperatures do not approach the Auto-Ignition Temperature (AIT) for the gas environment.

Several organizations worldwide have generated stringent requirements for electronic equipment designed for use in hazardous locations. Underwriters Laboratory (UL) and Canadian Standards Association (CSA) have generated electronics enclosure design standards for use in hazardous locations. UL and CSA design standards are applicable throughout North America. UL and CSA have full service laboratories available to test electronic equipment. CSA standards 22.2-139 [4] and 22.2-30 [5] apply to electrically operated valves and actuators used in a hazardous environment.

One way to comply with these standards is through the use of a "flameproof enclosure". A flameproof enclosure is defined as an enclosure which will withstand an internal explosion of a gas or vapour without rupture and without causing the ignition of an external gas or vapour surrounding the enclosure. To prevent ignition of the surrounding explosive gas mixture, the enclosure must have sufficient containment strength and entry points must be tight enough to cool escaping explosion gases [6].

Figure 2 shows an all-electric actuator with integral controller layout. A brushless DC motor stator is affixed to the housing enclosure. Coupling the DC motor rotor to a screw mechanism (prevented from rotation) converts rotary to linear motion. An extension rod is attached to the screw mechanism. The extension rod penetrates the housing enclosure. The integral controller requires power and signal cables that also penetrate the housing enclosure.

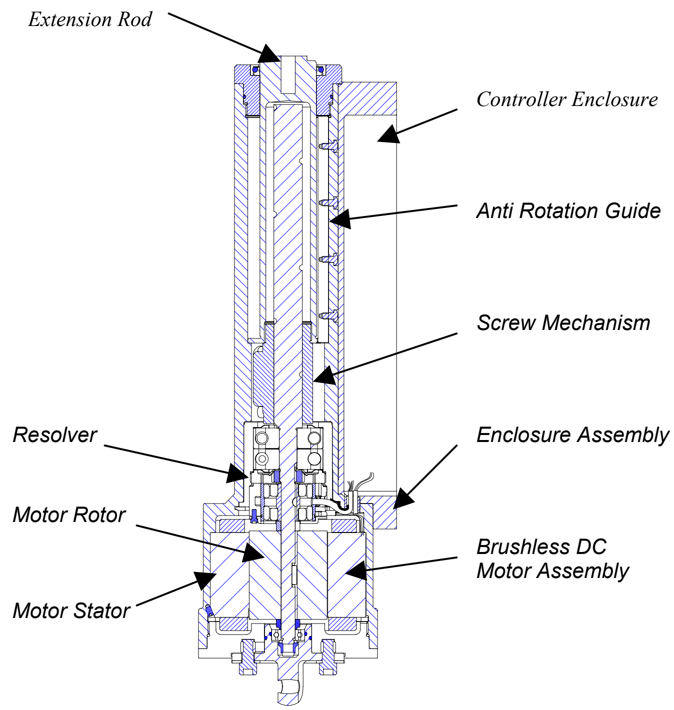

Figure 2 All Electric Linear Actuator 6" Stroke

Each enclosure entry joint must be considered for compliance with the above design standards. Figure 2 all-electric actuator enclosure makes use of several entry joint technologies. Entry joints typically consist of two metal surfaces that have controlled length and clearance. Figure 3 shows a typical entry joints [5].

These joints work via three basic principles; heat absorption, refrigeration effect and gas entrapment [6]. Keeping near zero gap between the two surfaces allows the metal to cool explosive gases below the gas environment AIT. If there is a small gap, explosive gases can escape from high pressure to low pressure while cooled via adiabatic expansion. The Maximum Experimental Safe Gap (MESG) is defined within the CSA standard and represents that largest gap that does not ignite an explosion external to the enclosure. [6]

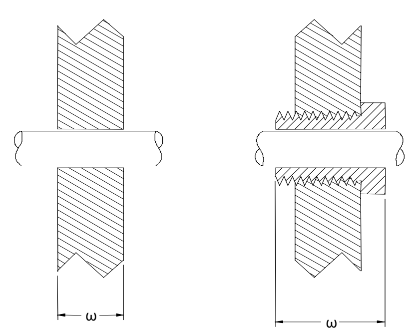

Figure 3 Typical Explosion Proof Entry joints. (ω denote the controlled length)

Threaded joints are considered the best as, in addition to controlled length and width, threads force the explosive gases to make several turns thereby removing energy.

The enclosure must also contain an explosion. The CSA Standard 22.2-30 [5] requires an enclosure test where the maximum explosive pressure is empirically measured. The enclosure must not yield when a hydrostatic pressure five times greater than the maximum explosive pressure is applied.

TEMPERATURE

Industrial gas turbines employing DLE technology maintain around 1000 °C (2800 °F) combustion flame temperature [2] [4]. With proper insulation and ventilation, a gas turbine package enclosure air temperature can be brought within 14°C (25°F) of ambient. Therefore, assuming a maximum 52°C (125°F) ambient temperature, the actuator must operate in a minimum of 66°C (150°F) enclosure temperature. In addition, some industrial gas turbines operate in cold environments around the Alaskan oil fields. Nighttime temperatures can hover around -40°C (-40°F).

In order to operate controllers in this environment, keeping electronic component temperatures within their respective operating envelopes is very difficult. Given the high enclosure temperature, all selected electronics components meet 125°C (257°F) minimum case operating temperature. The low temperature requires -40°C (-40°F) maximum case operating temperature. Automotive and military temperature range electronic components meet these stringent requirements.

Typical explosive gases in a turbine environment include methane. The AIT of methane is 537 °C (999°F) [6]. To remain compliant with hazardous location design standards, the electronics enclosure surface temperature must remain significantly below the explosive gas AIT. Controller efficiency must be high to limit the IR (current times resistance) losses thereby reducing thermal heating. Controller motor drive circuit configuration is critical to reducing the electronics self-heating. Careful attention to component selection and heat sinking is also important. Active cooling fans are not allowed in an explosion proof enclosures. Therefore, thermal conduction is the dominant heat transfer mechanism requiring large heat sinks.

Selected mechanical components should withstand the defined temperature range and more. Care should be used in lubricant selection. Whereas there are many types of lubricant currently available on the market today, not many will perform well over the wide -40°C (-40°F) to 125°C (257°F) operating temperature range. Fluro-silicon lubricants are now available that meet and exceed these temperature ranges.

ACTUATOR DEVELOPMENT RESULTS

A new all-electric actuator was developed for mid-size gas turbine use. This new all-electric actuator meets the challenges documented above. US Patent No. 6,392,322, was granted for this rugged, explosion proof actuator with integral electronics [7].

The all-electric actuator pictured in Figure 4 contains integrated electronics and actuator has been thermally tested at 93 °C (200 °F) external ambient temperature. Maximum enclosure surface temperature measured below 115 deg C (at 93 °C external ambient). The actuator enclosure housing has been explosion tested to meet CSA requirements [4] [5].

Figure 4 All Electric Linear Actuator 150 mm Stroke

ACCURACY

Starting with a specification of, ± 1% full-scale positional accuracy with an axial load of at 4,448 N (1000 lbf). Several electro-mechanical components were identified that would limit all-electric positional accuracy.

The electrical components include circuit tolerance, analog to digital conversion (A/D) and digital to analog conversion (D/A) error In addition, A/D resolution is typically 16 bit or 65,536 counts. These counts are resolved across a command span of 0-20mA. By design, the actuator operates from 4-20 mA. 20mA/65,536 counts = 3.05 x 10^{-4}mA/count.

The mechanical components include screw mechanism lead accuracy, backlash and deflection. Precision ball or inverted roller screw mechanisms are available with lead accuracies, including backlash under 0.005 mm (.0002 inch)

The all-electric actuator shown in Figure 4 achieves the required accuracy, ± 1,5 mm (± 0.059 in) through the use of precision circuits and direct driven screw shaft mechanism. The above all-electric actuator accuracy under 4,448 N (1000 lbf) load is shown in Figure 5.

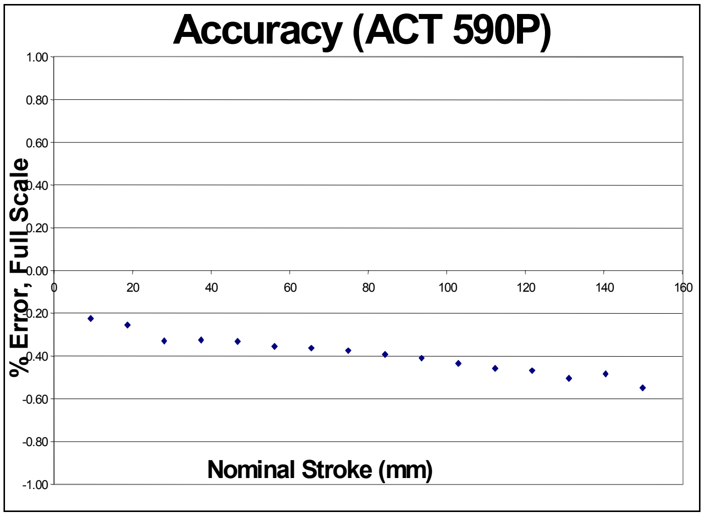

Figure 5 All-Electric Actuator Accuracy

Figure 5 shows a bias towards the negative position. For specific, well defined load profiles, this offset could be reduced.

PERFORMANCE

The performance requirements of the actuator depend on the application. The fuel valve would be different than a bleed valve.

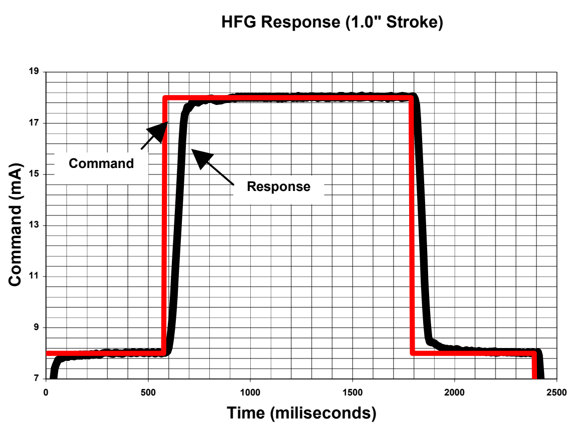

Figure 6 Command Response Curve All Electric Actuator (test data)

Figure 6 shows a 10% to 90% command response plot for the 150 mm linear actuator. The velocity setting for this actuator was set at 152.4 mm per second. The same actuator can be set for stroke velocity of 254 mm per second without detectable overshooting or ringing.

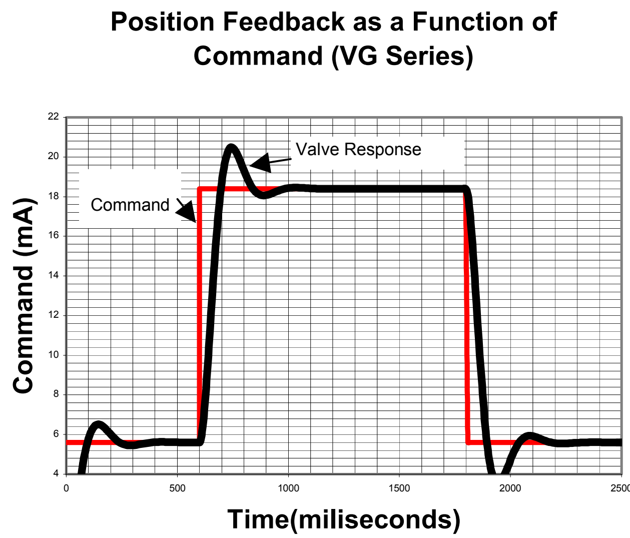

Figure 7 Command Response Curve Electro Mechanical Solenoid (test data)

Figure 7 shows a comparable electro-mechanical solenoid 10% to 90% command response plot. The electro mechanical solenoid actuator operates by pulse width modulating voltage to the solenoid coil. This will cause the shaft to move in response to the magnetic field. A spring is used to return the shaft when the voltage is removed.

When comparing Figure 6 to Figure 7 the time required to respond to the command is similar. Each actuator required approximately 350 milliseconds to respond to the step command and stabilize. Figure 7 shows a response that overshoots the command initially then stabilizes on the command signal. This would indicate that any attempt to increase response rate would cause a corresponding increase in overshooting and the time to reach a stable response. This would tend to limit the maximum response rate of the system.

SUMMARY

The electric actuator development described in this paper did not result in a quantum leap in actuator performance. It did, however, represent the integration of motor control electronics into the actuator assembly. This eliminated the requirement for a separate controller and the issues associated with that configuration.

A patent was granted for the actuator's integral electronic controller [7]. Specifically, the patent was granted for the explosion proof design, which makes the actuator suitable for hazardous location applications.

The all-electric actuator with integrated electronics has been installed on more than 750 mid-size industrial gas turbine engines. Applications range from a single fuel valve to a complete all-electric mid-size gas turbine package.

Field experience has provided real world conditions not found in the development lab. A design that employs an onboard integral controller, demands increased attention in a number of areas. These considerations include attention to proper wiring, shielding, power conditioning and grounding. Each can have a negative impact on reliable operation. Field experience has to be used to point out opportunities to further improve the reliability and robustness.

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