Virtual Camshaft for Solid State Hydraulic Pump

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Products Used:

LabVIEW™ 7.1 FPGA
LabVIEW™ 7.1 for Windows
NI-PXI 1010 Chassis
NI-PXI 8176 Controller
NI PXI-7831R Reconfigurable IO Board
NI-PXI-4472 Data Acquisition Board

The Challenge:

Couple the angular velocity and phase of a rotary valve with the expansion and contraction of a “smart material” to create a solid state hydraulic pump that moves small amounts of hydraulic fluid thousands of times per second.

The Solution:

LabVIEW 7.1 FPGA and the NI-7831R Reconfigurable IO board allowed us to tightly synchronize the high speed valve operation of the pump with the oscillation of the magnetic field generating the motion in the smart material. After previous attempts had failed to create a workable solution due to a long group delay, with LabVIEW for FPGA we created a robust scalable solution in one week.

Abstract

Smaller unmanned military aircraft of the future will require actuators smaller than the hydraulic ones used today. Existing motor-driven pump technology does not scale down well, so DARPA sought alternatives, including the magnetostrictive “smart” material-driven pump. Magnetostrictive materials expand in a magnetic field, but the expansion is very slight so it must be repeated thousands of times per second to produce useful power. Creating a pump from this material required precise synchronization between the valve location and the material expansion. Using LabVIEW for FPGA running on a 7831R, it took us just one week to develop a “virtual camshaft” with precision coupling.

Introduction

Control surfaces on aircraft are typically actuated by hydraulically driven rams. The source of the hydraulic pressure most often comes from an electric motor driven pump. Traditionally the pump would be centrally located powering a network of hydraulic tubes, however in the recently developed “fly-by-wire/power-by-wire” systems the pump is collocated with the actuator at the control surface. This pump-actuator combination has been termed an electrohydrostatic actuator (EHA), and can be fabricated in a suitably compact form for manned aircraft. However, the smaller unmanned military aircraft of the future will require actuators significantly smaller than the current EHA’s.

Recognizing that a new technology would be required, DARPA focused on developing electromechanical actuators that take advantage of the high energy density of smart material transduction elements.

Active Signal Technologies has spent the last two years developing a prototype smart material powered electrohydrostatic actuator that uses the magnetostrictive material Terfenol as the pump driver. The Terfenol is placed within a cylinder that is essentially an electromagnet. When the magnet is on, the Terfenol expands in proportion to the strength of the field. Since the expansion is very small the field must be oscillated thousands of times per second in order to produce useful power. A rotary valve containing multiple orifices needs to be synchronized with the high-frequency excitation of the Terfenol to allow for the input and output of hydraulic fluid thus rectifying the flow. See figure 1.

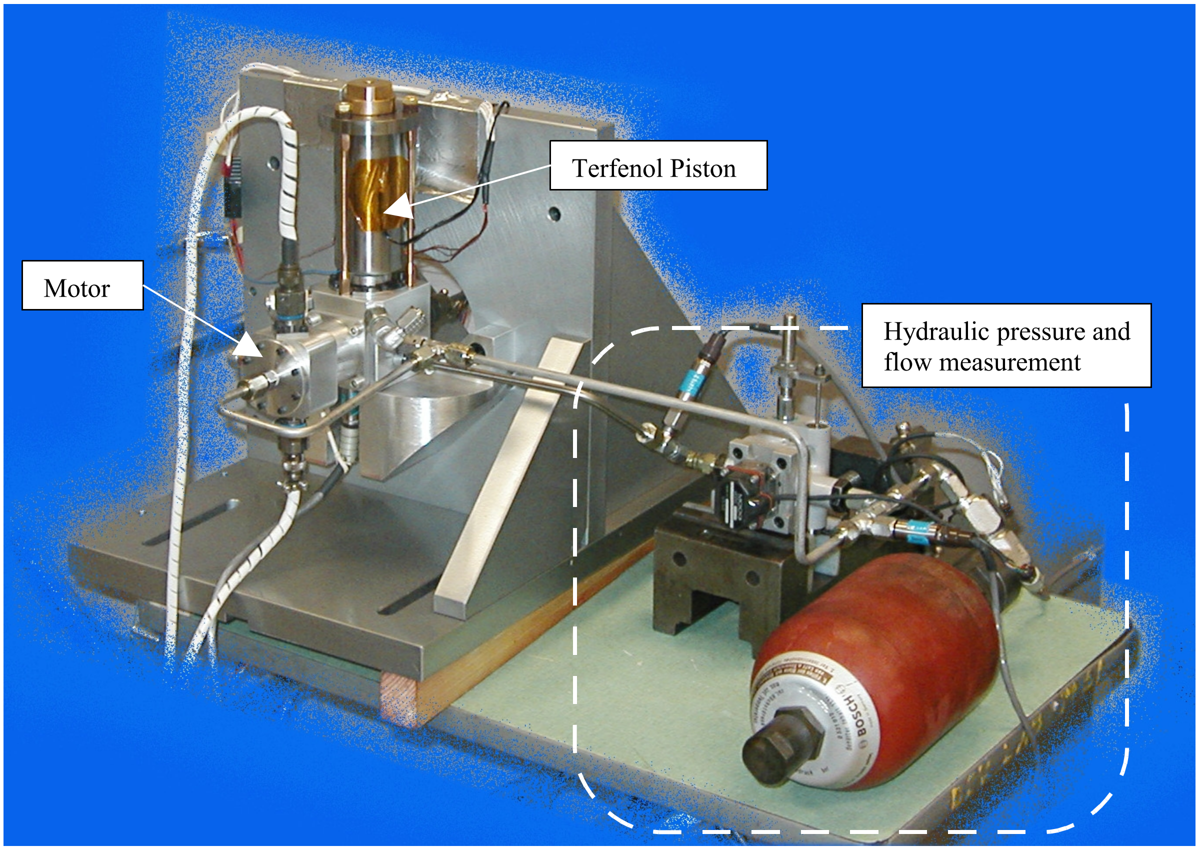

Figure 1. The Solid State Hydraulic Pump

To accomplish the tight coupling required, Mink Hollow recommended the NI PXI-7831R Reconfigurable I/O Board using LabVIEW for FPGA. The high speed and deterministic behavior of LabVIEW FPGA running on this board allowed us to read all nine bits of the encoder and provide an analog output waveform directly linked to the absolute position of the rotary valve. Further, should the encoder connection be temporarily interrupted, the system would immediately resume correct operation when the connection re-established.

Closing the Loop

For the pump to function, control hardware needed tight synchronization between the valve location and the waveform sent to the Terfenol piston. A motor rotates a rotary valve with six evenly spaced openings at about

30,000 rpm. Each time a valve is aligned with the piston, the piston must be at or near full expansion or flow will be inefficient or nonexistent. The feedback from the motor comes from a 9-bit absolute encoder with 0.7 degrees of resolution per step. The speed of the motor is controlled by a GPIB-based power supply. To close this loop, the 7831R FPGA board was used. See Figure 2.

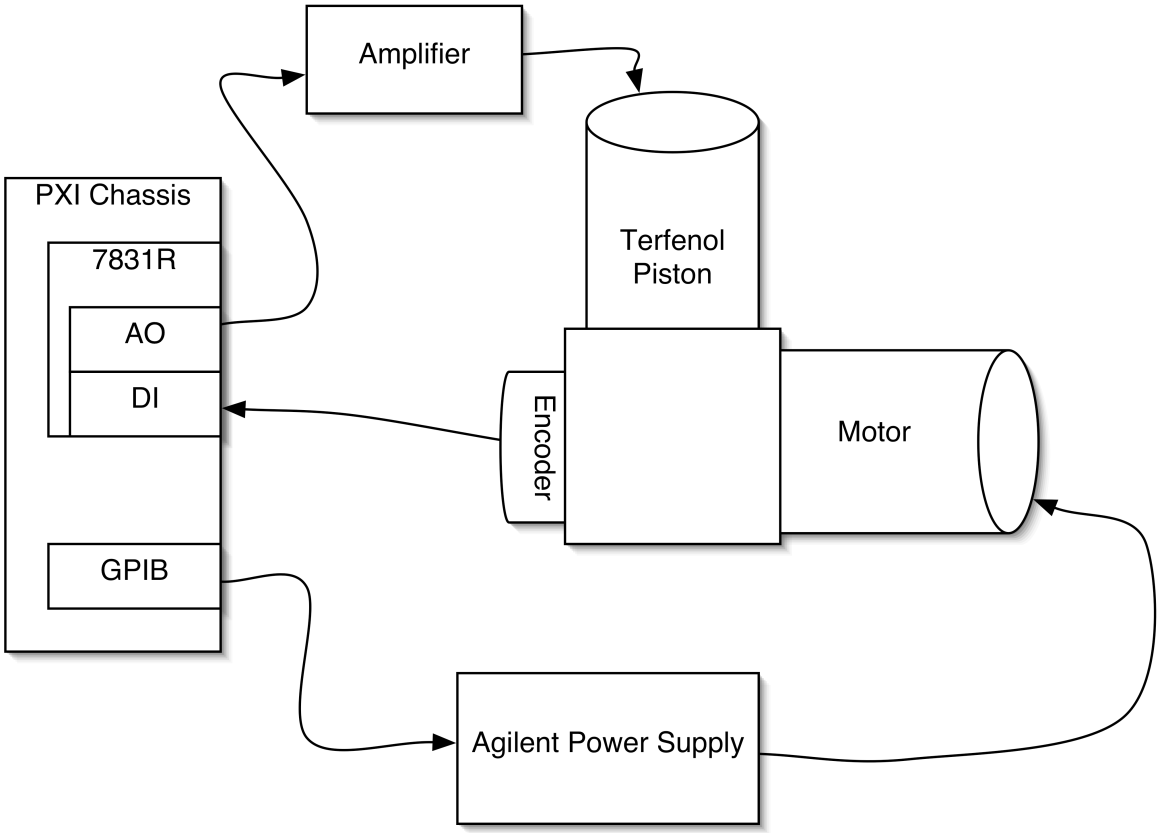

Figure 2. Simplified Control Schematic of Active Signal's Terfenol-Driven Pump

The FPGA feedback works by reading the absolute encoder position, and thus the location of the rotary valve, and outputting the corresponding voltage to the Terfenol piston. In essence, we had to create a virtual "camshaft" to couple the rotation of the motor with the excitation of the Terfenol – outputting sinusoidal waveforms at 3,000 Hz. At this rate, FPGA was the only viable option. Additionally, like the spark advance of a car engine, we also needed to be able to tune the system such that each opening aligns before, after or right at the peak expansion ("top dead center") of the Terfenol piston.

Creating Virtual Resolution

The software consists of two components: a host module and an FPGA module. The host module provides a user interface for operators to set the phase offset, amplitude and attributes of the output waveform. As much as possible, the host also performs floating-point calculations for the FPGA. The FPGA module performs the I/O to implement the virtual camshaft.

The FPGA module brought challenges that required a new way of thinking.

The FPGA does not allow floating point math so it cannot perform a simple sine function. It can use a lookup table, but this introduces a new problem affecting phase resolution. The 512 steps of the encoder provide angular resolution of 0.7 degrees per step. However, since the output waveform cycles 6 times per revolution, this provided only 4.2 degrees of phase resolution per cycle. A resolution of about one degree per cycle was desired for pump efficiency.

The 44 MHz loop rate of the FPGA provided a robust means to create virtual resolution using a technique similar to a sigma-delta ADC. By oversampling the encoder and timing bit transitions, we were able to increase the feedback resolution from 4.2 degrees to 1.05 degrees. Physically at the top speed of 30,000 rpm, the 9-bit encoder changes from one step to the next every 3.9 microseconds. A single cycle loop running at 44 MHz on the FPGA iterates 171 times in 3.9 microseconds. By counting the cycles between encoder steps, the software interpolates the angular position of the motor during the *very next* step of the encoder.

For instance, if the software counts 200 cycles between steps, it calculates that on the next step the position will be approximately 1.05 degrees every 50 cycles. Since the angular rotation between any two steps of the encoder is very small, the interpolation is relatively accurate even as the motor accelerates.

Conclusions

We were able use the FPGA camshaft module within a larger data acquisition application in order to perform crucial experiments on the pump. We automated a sweep across a range of phase offsets and frequencies to find the optimal performance characteristics.

Two years of effort in developing the solid-state pump depended on creating software that could control it. Using LabVIEW for FPGA we created a reliable “virtual camshaft” in just one week at minimal cost, allowing Active Signal to conduct tests culminating years of effort spent researching, designing and building the pump.