Control of a Water Brake Engine Dynamometer System

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ABSTRACT

It was the objective of the team to design a control system for a water brake engine dynamometer. The system will supply and control water flow, measure temperature through the dynamometer absorber plates, and provide data characterization feedback for the dynamometer through a dynamic user interface. The SAE standard, J1349, was used in the control system software to ensure that an accurate horsepower reading would be calculated.

I. INTRODUCTION

Greenspeed Research, a non-profit renewable energy research organization, has an existing absorber system, seen in Fig. 1, to be incorporated into a water brake engine dynamometer. A single absorber unit is made of two stators on either side of a rotor, as seen in Fig. 2. The existing system uses two individual absorbers. Each side of the stator is supplied one fluid inlet and outlet, totaling four inlets and outlets for the system. To complete the water dynamometer, a control system consisting of a plumbing system, sensor management system, as well as a feedback system, will be required.

II. BACKGROUND

The purpose of a water brake engine dynamometer is to absorb the mechanical energy produced by an engine and directly measure its horsepower output. Horsepower can be calculated using Eq. 1.

$$H = \frac{s * T}{5252} \qquad \textit{Equation 1}$$

In this equation, *s* is speed of the engine in revolutions per minute and *T* is the torque in foot-pounds. The speed of the engine is measured with a tachometer and a load cell attached to the absorber system measures the torque.

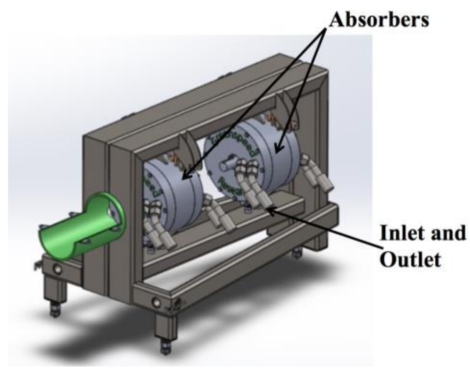

Figure 1 Labeled Existing Absorber System

Water flows in a toroidal motion as it is forced through the veins of the rotor and stator, absorbing energy in the form of heat transfer before exiting the system. In a closed system, the water will continue to rise in temperature as an engine is tested to reach its maximum horsepower. If the temperature of the water in the stator reaches too high of a temperature or pressure, the water could cavitate, causing the water to become steam instantaneously, resulting in the loss of load to the engine. This could mean catastrophic failure of the engine and a significant loss of time and money for its owners. The control system will incorporate temperature sensors as well as a pressure sensor to ensure this critical system parameter is monitored.

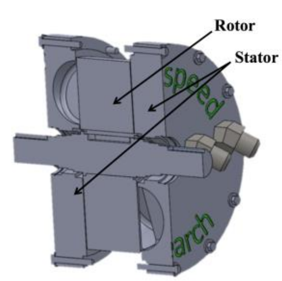

Figure 2 Labeled Absorber Unit

III. SPECIFICATIONS

After analyzing the existing absorber system and discussing the goals and objectives of the project with Greenspeed Research, various requirements were determined to be design-driving features.

The dynamometer operator is not to be in the same room as that of the engine being tested to prevent injury in case of engine failure. To adhere to this, the control system and pumping system will all be regulated and controlled remotely via a computer and user interface.

The dynamometer will be located in a small room with dimensions anywhere from 8x10 feet to 10x20 feet, therefore keeping the system compact and mobile is desirable. Mobility will be obtained by mounting the pumping system to a stand-alone cart and utilizing quick-disconnect plumbing attachments.

The customer also desired that at least 10 gallons per minute must be maintained through the absorber plates for every 100 horsepower being tested. Greenspeed Research would like to test engines of up to 2500 horsepower, requiring the pumping source to be able to supply a volumetric flow rate of at least 250 gallons per minute.

The absorber system defines the maximum allowable inlet temperature during operation to be 100°F. Thermodynamic analysis was done at various inlet temperatures to determine what inlet temperature, water would be at or above the vapor pressure at the outlet, causing the water to cavitate within the absorber.

The analysis was done by considering the whole dynamometer as a control volume. Then applying an energy balance to the control volume and simplifying it, the energy equation, Eq. 2, becomes:

$$\dot{W}_{in} = \dot{m} C_p \Delta T \qquad \textit{Equation 2}$$

Where $\dot{W}_{in}$ is the work put into the system by the engine, $\dot{m}$ is the mass flow rate of the water, C_p is the specific heat capacity of water, and ΔT is the temperature difference between the inlet and the outlet. A spreadsheet was then created to look at the effects over a range of inlet temperatures and power inputs. Also, the vapor pressures at the outlet temperatures were calculated using the Antoine equation, which was derived from the Clausius–Clapeyron relations in 1888 by Louis Charles Antoine.

$$\log_{10} P = A - \frac{B}{C+T} \qquad \textit{Equation 3}$$

Where P is the pressure, T is the temperature, A, B, and C are temperature dependent Antoine constants for water. This determined an inlet temperature of 100°F or less will keep the system safe when operating at the maximum horsepower of 2500 and the maximum flow rate of 250 gallons per minute.

IV. DESIGN

The design incorporates a three horsepower pump mounted to a square tube framed cart on swivel casters as shown in Fig. 3. The pump will be bolted to a steel plate which is welded to the cart frame. Incorporating the cart allows the pump subassembly to be mobile and independent of the engine cart and absorber system. Custom bolt flanges were machined to incorporate v-band clamps for easy removal and installation.

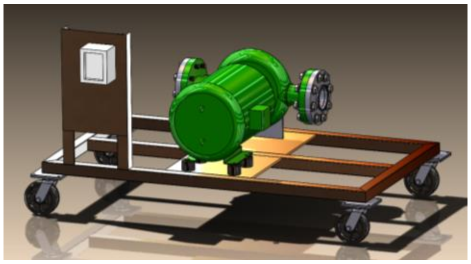

Figure 3 Design of Pump Cart

The cart originally was designed to have a panel to mount the variable frequency drive (VFD) and disconnect switch for the pump. This was improved by installing a full enclosure to contain all of the system control components. Control of the system was achieved with National Instruments and Automation Direct components. These components include: a tachometer sensor, thermocouples attached to the stator, a load cell, a VFD, and a pressure transducer.

The VFD controls the flow to the absorber unit by varying the frequency to the motor and thereby controlling the speed of the pump. This is an efficient design that eliminates the need for any valves and allows for precise control of the flow and therefore the load being put on the engine.

A custom distribution manifold will be attached to the outlet of the pump to divide the 4” pump outlet into two 2” outlets. Braided vinyl hoses will be used to connect the outlets of the manifold to a dividing tee to further divide the flow for each stator. This hose was specifically selected because of its reasonable price and flexibility. Silicone hose will be used on the outlet of the stator to plumb to the collection tank due to the possibility of higher temperatures at the outlet. A cradle mounted to the cart will support the manifold.

The Bell & Gossett (B&G) Series 80, 4x4x9.5 pump, chosen for the water system, meets the volumetric flow rate requirement. The maximum build pressure of this pump at full speed is given by the manufacturer to be 20 psi. The B&G pump curve can be found in Fig. 4. All of the manifold, piping, plumbing attachment mechanisms were chosen to exceed this pressure rating.

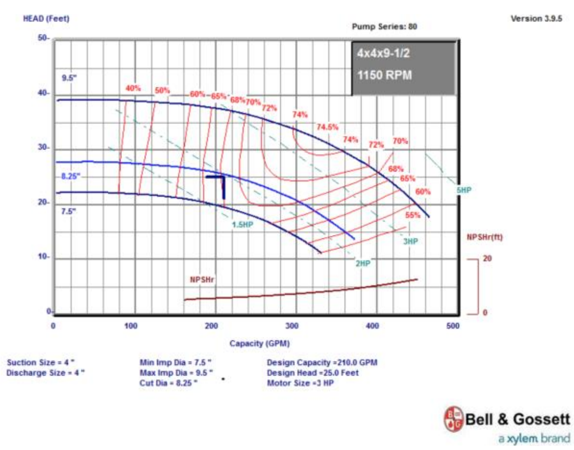

Figure 4 Bell and Gossett Pump Curve for Series 80, 4x4x9.5

It was also important to implement a standard into the project. Standards are important considerations, creating repeatability and safety in a product. SAE J1349 was chosen for its relevance to the project. The customer did not request this application, but was very appreciative of it. They are aware of the importance of this standard in a project of this nature due to uncorrected horsepower values being up to 20% greater than actual values in some instances. Greenspeed Research races vehicles in different locales around the United States and now will have the ability to tune an engine based on relative conditions where the vehicle will be operated. This gives the ability to predict more closely how the vehicle will perform.

V. STANDARD APPLIED

SAE standard, J1349, was incorporated in the LabVIEW program to correct the horsepower output for humidity and temperature during testing. A toggle switch was included on the user interface to give the user the ability to turn on or off the correction factor. The following equations were taking directly form the standard. They allow one to get an accurate horsepower reading based on relative conditions. The importance of this is recognized in the fact that repeatable results can be obtained. Outside of Greenspeed’s use, in a manufacturing environment for instance, consistency is paramount for safety, customer satisfaction, and product uniformity.

The general equation for the compressive ignition engine formula can be seen in Eq. 4.

$$Bp_c = (CA \times CF) \times Bp_o \qquad \textit{Equation 4}$$

In Eq. 4. Bp_o is the observed brake power, CA is the atmospheric correction factor, and CF is the fuel correction factor. The atmospheric correction factor can be calculated using Eq. 5 and 6. The fuel correction factor can be calculated using Eq. 7, 8, and 9.

$$CA = (Fa)^{Fm} \qquad \textit{Equation 5}$$

$$Fa = \left(\frac{99}{Pa_{do}}\right)^{\alpha}\left(\frac{t_o + 273}{298}\right)^{\beta} \qquad \textit{Equation 6}$$

For 4 stroke Cummins 5.9L turbo-charged diesel engine operating in Boise Idaho using air-air intercooler the engine factor, Fm, is 1.2, the pressure sensibility exponent, α, is 0.7, the temperature sensibility exponent, β, is 1.2, and the inlet air supply total pressure, Pa_{do}, is 101.998 kPa. The inlet air supply observed temperature, t_o, is a parameter which is input by the user via the LabVIEW user interface.

$$CF = Fd \times Fv \qquad \textit{Equation 7}$$

$$Fd = 1 + 0.70\left(\frac{0.850 - SG_o}{SG_o}\right) \qquad \textit{Equation 8}$$

$$Fv = \frac{1 + \frac{S}{V_o}}{1 + \frac{S}{2.6}} \qquad \textit{Equation 9}$$

For pump diesel no. 2 at 15°C, the fuel density, SG_o, is 0.832 kg/L and the viscosity sensitivity coefficient, S, is 0.15. For pump diesel no. 2 at 40°C, the observed fuel viscosity is 2.98 mm^2/s.

As before mentioned, uncorrected values can be up to 20% higher, giving a false reading as to power of the engine being tested.

VI. TESTING

Testing and calibration of the system was performed in phases. The first phase was to verify the VFD as a valid design. The goal of this test was to get a rough estimate of the ramp time of a pump ran by a VFD would look like in a load situation. This was done by testing the ramp time of the VFD from zero to 100% at various frequencies in a load situation. The testing apparatus can be seen in Fig. 5. The pump was connected to a water supply and the VFD was connected to the pump. The plumbing was configured so that the pump had to lift water, simulating a load situation. Data was then collected by setting the VFD to the desired frequency and measuring the time it took the drive shaft of the pump to reach a stable RPM speed of the drive shaft, measured with a tachometer. The data collected during this testing can be found in Fig. 5. The tachometer used is not a precise device and did not update quickly. This would make the data we collected a high estimate for the 0 – 100% response time of a VFD.

Figure 5 VFD Verification Testing Set Up

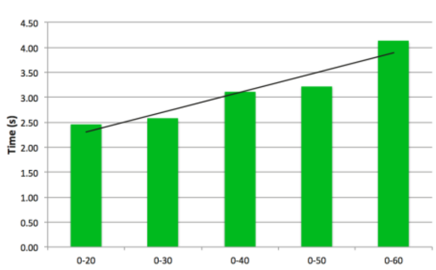

Figure 6 VFD Testing Results

The next phase of testing involved DAQ programing to control the VFD to increase and decrease flow. Sensor data acquisition was also tested using the developed LabVIEW program. This testing proved the VFD controls and all sensors worked completely and as expected.

Full system tests could not be completed due to a lack of time and the rest of the absorber system not containing the necessary components to make it a functional system; however final test plans were outlined for the customer.

VII. RESULTS

Greenspeed Research has been given an expandable system to complete their water brake engine dynamometer project. The control system and pumping solution that were created, meet all of the original design specifications while allowing for future improvements. The completed pumping solution cart and attached control box can be seen in Fig. 7. By incorporating the SAE standard, J1349, Greenspeed will have the ability to accurately measure the horsepower output of a test engine in any environment. As mentioned earlier, the implementation of this standard was not requested, but much appreciated, by the customer.

Further testing and characterization of the full system will allow the dynamometer to meet its potential as a very valuable addition to Greenspeed's capabilities.

Figure 7 Completed Pumping Solution Cart and Control Box

ACKNOLEDGEMENTS

Our team would like to thank IEEE for accepting our project proposal and contributing to the sponsorship of our project. We also thank Greenspeed Research for being dedicated to providing renewable energy education in an open source environment. Thank you to Automation Direct for the donation of the Variable Frequency Drive as well as the many sensors and wiring. The team would also like to thank Lynn Catlin, P.E., for assisting with the project.

REFERENCES

[1] Engine Power Test Code—Spark Ignition and Compression Ignition—Net Power Rating, SAE Standard J1349, AUG2004.