Design of a Portable Engine Dynamometer for Multiple Classroom Experiments

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Abstract

Five compact, portable engine dynamometers were designed and built for use by interested Mechanical Engineering Technology locations within the Purdue University School of Technology system. The purpose of the dynamometer is to provide a versatile, compact experimental platform around which numerous laboratory exercises could be designed. Each dynamometer consists of a 14 HP air-cooled gasoline engine providing mechanical shaft power, coupled to a simple hydraulic system acting as the power absorption and measurement system. A compact water/oil heat exchanger is also included to augment energy removal, if needed. Laboratory experiments for Fluid Power, Heat Power, Instrumentation, and Internal Combustion Engine courses are now being implemented using this system.

I. Introduction

Like most universities, the Purdue University School of Technology must balance the need for equipment suitable for laboratory exercises against many other factors, including limitations in funding and space. After initial trials with a smaller prototype unit, it was determined that the fundamental design could be refined and mass-produced to serve multiple classes and locations for a very reasonable cost. Through optimization of performance, design, and project constraints the resulting system proved to be a safe, compact, and versatile experimental platform around which a variety of laboratory exercises could be built.

The goal of the project was creation of an experimental platform that could be used to teach multiple concepts in fluid power, thermodynamics, and instrumentation in a laboratory-type setting to students at the Associates and Bachelors degree levels. To achieve this goal the system needed to demonstrate fluid mechanics concepts such as design elements of portable hydraulic units, and the role of power plants in hydraulic system performance. Relevant thermodynamics concepts would include elementary combustion principles, energy conversion mechanisms and principles, and thermodynamic cycle efficiency. Instrumentation assignments would include dynamic P-V curve measurement, effective real-time speed and fuel flow-rate measurement, and computer data-acquisition equipment and methodologies.

From the engineering perspective this project was segmented into three categories; performance constraints, design constraints, and project constraints. This method of constraint differentiation was later used to introduce project management concepts in another design class.

Performance constraints focused on safely, as well as effectively matching the power generation, absorption, and removal system-performance envelopes against anticipated demands. First, the engine's power generation characteristics must be fully defined as a function of speed. Then the hydraulic system must be engineered to convert, and ultimately absorb that power at a safe pressure and flow-rate across the full system speed range. Recognition of the parabolic versus linear nature of these two competing performance curves as a function of their mutual speed simplified this aspect. Finally, the waste heat generated must ultimately be removed from the entire system through heat-transfer mechanisms. Understanding of the unique nature of the proposed system's heat generation behavior, combined with its removal capabilities greatly simplified this analysis, as well as the resulting design.

Design constraints included aspects such as the ability to transport the completed system between buildings using a compact 6-passenger elevator, while still providing access to all on-board system components. The system must be transportable by a single student safely between its storage and experimentation locations, and operated as a complete stand-alone system without auxiliary equipment or supply lines for starting, data display, or fuel storage and delivery. It was ultimately determined that the complete hydraulic system, the engine with fuel supply, all instrumentation, and the battery and starting/charging system must completely reside within a 36.5 by 26.5 inch footprint to be useful as a classroom test system.

Project constraints included a summer completion schedule, reuse of as much existing hydraulic equipment as possible, and a maximum capital budget of $3000 per completed machine. Of these, the most restrictive turned out to be reuse of available equipment since it significantly impacted all other constraints, especially the budget. The existing equipment also occupied the only space available for storage of the proposed system at the author's location.

II. Equipment Description

Although an engine of lower power was initially selected to better match the performance capacity of existing hydraulic components, contact with the engine manufacturer Kohler yielded a particularly attractive alternative. Kohler offered 14HP engines from its surplus inventory at a price of $10 per horsepower. These brand new engines included an on-board starter/ignition switch, solid-state charging system, counterbalance shaft, integral fuel pump, and 2-gallon fuel tank. Prototype work earlier in the year revealed that all of these additional features were worthy of serious consideration. The integral fuel pump, in particular, was necessary for inclusion of a rotometer-type instantaneous fuel consumption display. It was installed after the fuel pump using automotive fuel lines, and placed next to the tachometer display. Additionally, the starting and counterbalance features made the overall system much less intimidating to some students, particularly women in the program.

The hydraulic system was directly coupled to the engine output shaft using Lovejoy couplings and consisted of a Vickers 101P4 vane pump, a 2000-psi pressure relief valve, and a 10-gallon reservoir that also served as the engine-mounting platform. With the exception of the P4 pump ring purchased to accommodate the larger engine, all hydraulic components were already in the New Albany inventory.

Of most immediate concern was the proper matching of the engine and hydraulic performance envelopes. Engine performance data came from the supplied Kohler data sheet, while hydraulic pump performance data was derived from published Vickers literature. An Excel spreadsheet was used to verify proper matching of the power performance envelopes of the hydraulic and engine systems over the entire speed range required. This analysis served to reinforce the previously mentioned observation that, in fact, published pump performance curves are linear in nature, with hydraulic power directly related to increasing speed for a given setpoint pressure. Engine power versus speed, on the other hand, is parabolic in nature and decreases exponentially after reaching a peak at approximately 3600 rpm, for the Kohler engine selected. By matching peak engine power at its rated speed to pump hydraulic power produced at the relief valve's maximum spring pressure, a preliminary performance envelope match can be verified prior to a more detailed spreadsheet analysis. The Excel spreadsheet provided a more complete pictorial representation of this relationship for students. Iso-horsepower lines were also added to verify safe hydraulic system performance at intermediate speeds. Refer to Figure 1.

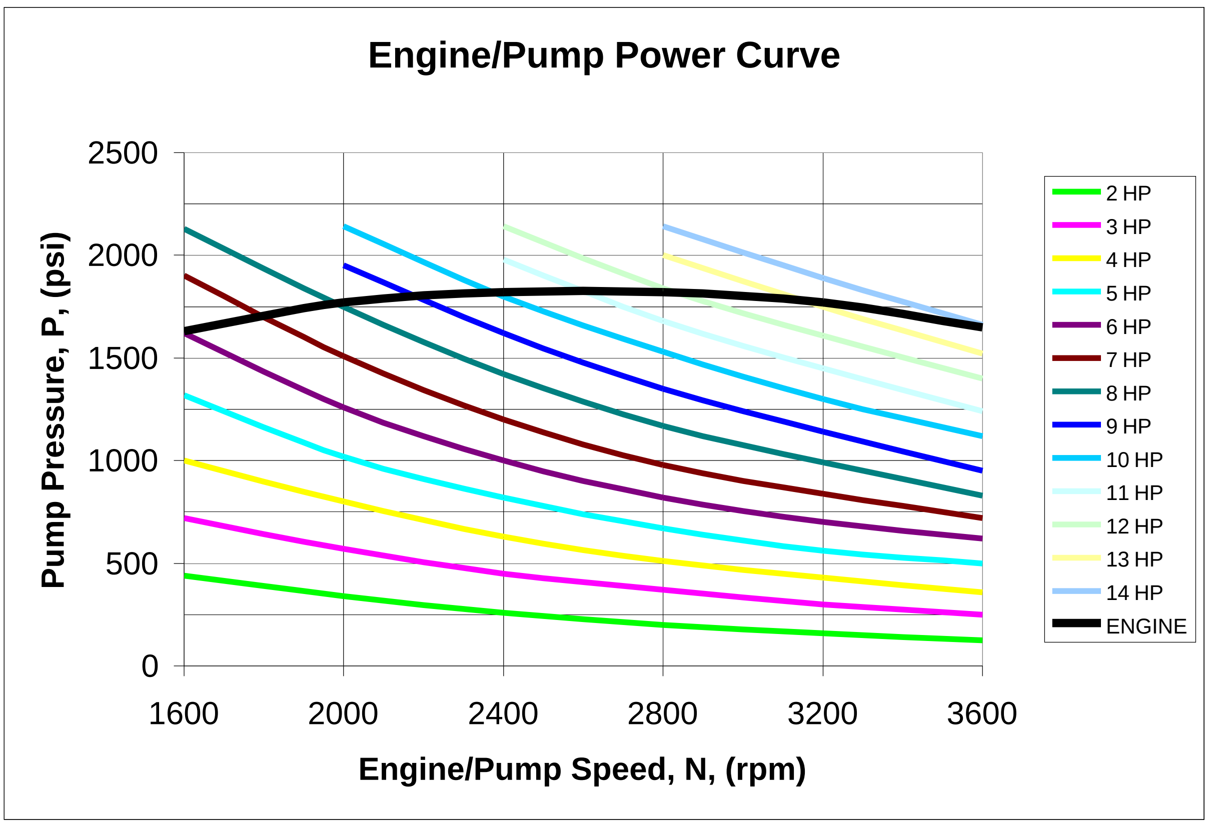

Figure 1 – Engine/Pump Performance Matching

Ultimately the engine power is converted to heat, which must be removed from the system. With a 14 HP engine supplying energy to a 10 gallon reservoir with a published removal capacity of only 0.3 HP, it was deemed prudent to include at least a 5 HP compact heat exchanger to provide assistance, if necessary. Higher capacity exchangers were not seriously considered for two reasons. First, their larger size made accommodation within the specified footprint difficult. Secondly, preliminary testing using the prototype unit revealed that a typical laboratory assignment utilized the equipment under full load less than 10 percent of the time. By taking advantage of this fact, as well as beginning the assignment with the system at room temperature and operating within published guidelines for maximum operating temperature (145 degrees Fahrenheit), it was determined that the system could be operated safely with a steady-state removal capacity of only 5 HP.

Instrumentation to achieve maximum versatility within the declared budget meant measurement of the following variables was undertaken; fuel flow-rate, engine/pump speed, in-cylinder combustion pressure, hydraulic pump outlet pressure, and hydraulic reservoir temperature. Components to accomplish this included a fuel rotometer (10 to 120 ccm range), an optical (reflective) engine tachometer with digital display, an analog hydraulic pressure gage (2000 psi), a PCB brand in-cylinder pressure probe (model P112A05) with an in-line signal conditioner and amplifier, and a traditional reservoir temperature indicator. The addition of real-time, in-cylinder pressure measurement was pursued after careful examination of both the cylinder head and the pressure transducer specification sheet revealed a single suitable port location was, indeed, available. To maintain the project timetable and minimize risk, implementation of this feature included the purchase and modification of a second engine cylinder head. Thermocouples for the heat exchanger were also contemplated prior to compilation of the final project cost summary.

The final cost for this system came to $2998.34 per dynamometer, including outside parts and labor for fabrication of the frame and mounting plate, and second cylinder head. Miscellaneous features and components needed to complete the design included; heavy-duty wheels, an automotive battery, a remote throttle cable, paint and miscellaneous hardware items. It was initiated in May and completed by August 15th with delivery of 4 units (using the 6-passenger elevator) to locations within the Purdue University School of Technology system.

The completed design is shown below. Refer to figure 2.

III. Sample Results

Upon completion each unit was started and run under load, as part of the checkout portion of the project. The unit destined to remain at the New Albany location was also tested over its entire designed performance range. Results, shown below in Figure 3, revealed the actual delivered hydraulic power to be less than the manufacturer's published data. Instead of 14 horsepower at 3600 rpm, the author only achieved 11.7 HP. This trend was evident through the entire speed range, beginning at 1600 rpm. Refer to Figure 3, below.

Several factors are thought to account for this discrepancy. First, the engine was supplied with an integral 15 amp solid-state charging system, supplying current to the starting battery at 14.7 volts. This reduces shaft power by approximately 0.3 HP. Additionally, vane pumps typically have an overall efficiency of approximately 90 percent, meaning 1.4 horsepower is typically lost to friction. Together these losses account for 1.7 of the missing 2.3 horsepower.

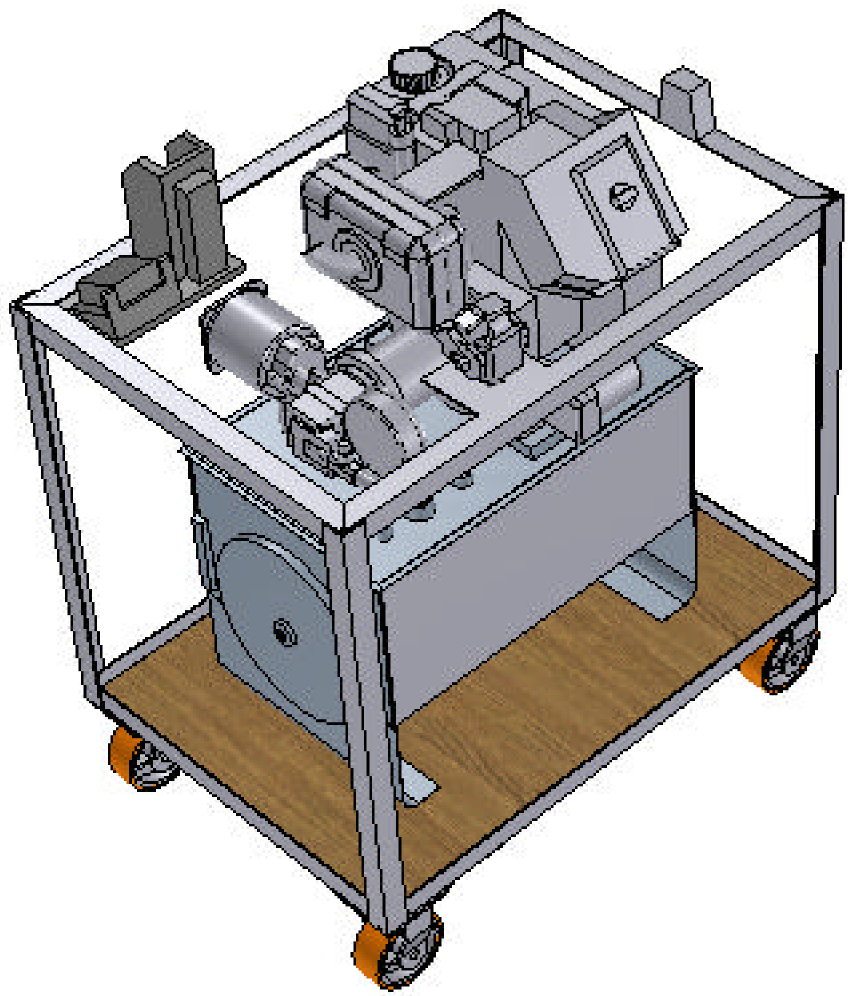

Figure 2 – System Design

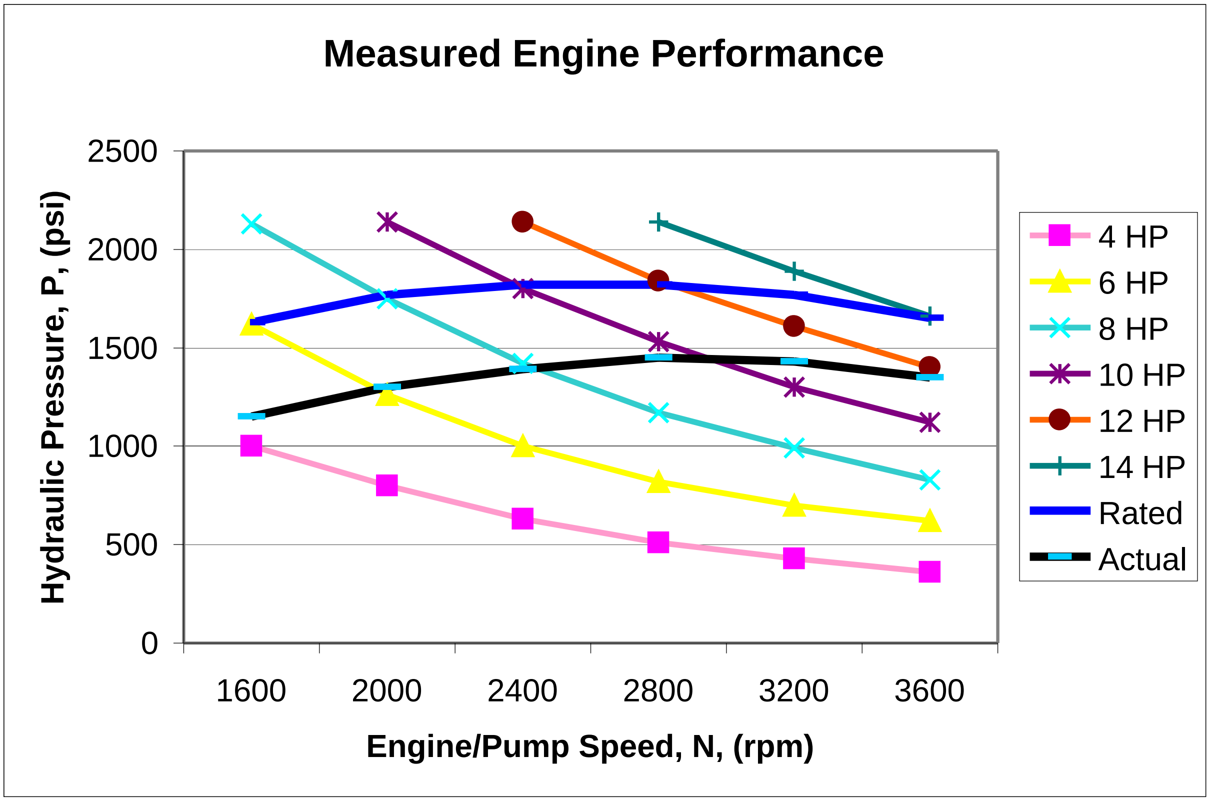

Figure 3 – Actual Measured Performance

IV. Instructional Applications

The units were designed to provide laboratory exercises for several Mechanical Engineering Technology classes including MET 230 (Fluid Power), MET 220 (Heat Power); MET 382 (Instrumentation & Control); and MET 462 (Internal Combustion Engines). Of these, the author currently teaches MET 230 and MET 220 so these experiments are discussed.

1. MET 230, Fluid Power

One application of particular importance to hydraulic systems designers is the portability of units, inaccessible to electrical power supplies. In cases such as this is it important to know the behavior of hydraulic systems driven by internal combustion engines, and how they differ from their electric-driven counterparts. To simulate this design environment a laboratory exercise was undertaken in which students were required to determine the hydraulic horsepower available in a hydraulic system powered by a small gasoline engine. The exercise proceeded in the following manner:

A. The student researched the horsepower demands of hydraulic pumps as a function of speed and pressure. This was compared to published data on the Kohler engine to be used in the experiment. Results were compiled in Excel format to simplify visualization and subsequent analysis.

B. The laboratory exercise consisting of operation of the dynamometer at regular intervals over its functional speed range (1600 to 3600 rpm), although it was pointed out that in field applications, the engine would typically be operated only at its performance setpoint of 3600 rpm. At each setpoint speed, pressure was increased in regular increments until the maximum available engine power was reached and the engine governor could no longer maintain setpoint speed. (Manual manipulation of the throttle plate at lower speed settings was required, due to design limitations of the engine's governor.)

C. Analysis of recorded pressure and speed data was done to determine the actual hydraulic horsepower generated. Chart data was used to convert speed measurements into equivalent pump flow rates, thereby allowing students to use the equation: hydraulic horsepower *equals* pressure (in pounds per square inch) *times* flow-rate (in gallons per minute) *divided* by 1714. [HHP = P * Q / 1714].

D. Final reports included comparisons of actual versus published engine performance, including a graphical presentation similar to section III of this paper, followed by explanation of possible causes of any discrepancies uncovered. The relationship between engine speed and maximum system pressure was particularly emphasized, as it governs field performance of hydraulic systems; the primary objective of the assignment.

2. MET 220, Heat Power

Many of the laboratory exercises for this class focus on the processes of energy transformation, and their associated efficiencies. Analysis often consists of identification of the specific energy available from different sources of energy, and quantification of losses in available energy as it is progressively transformed into waste heat. Because of size, space, and time constraints laboratory exercises at New Albany are typically segmented as described below, with students completing individual portions in successive weeks.

A. Power as a function of speed: Analysis of available engine power (as measured by hydraulic horsepower) versus speed is performed in a manner similar to the laboratory exercise described above.

B. Specific fuel consumption: Measurement of actual versus published values for fuel consumption versus horsepower produced provides an indication of conversion efficiency from gasoline into hydraulic power. Knowing this is the inverse of thermodynamic efficiency, students compare the measured efficiency of the dynamometer to manufacturer’s data, as well as to theoretical values for Otto Cycle engines of comparable compression ratio and cylinder volume.

C. Indicated horsepower: Following installation of the pressure transducer / cylinder head assembly, New Albany students will conduct experiments to measure the pressure-volume (P-V) relationship inside the engine cylinder. This information will be used to determine indicated horsepower, a measure of the theoretical horsepower available directly from combustion pressure, for comparison with actual hydraulic horsepower developed.

V. Summary

A portable engine dynamometer was built and used by students in multiple classes to provide exposure to interesting, multifaceted laboratory exercises across multiple disciplines. The project balanced numerous performance, design, and project constraints to achieve a versatile system costing less than $3000 per unit for 5 units. Three laboratory exercises at the New Albany site have been delivered to students, with additional exercises planned at this and other Purdue University School of Technology sites across the state of Indiana.

Other colleges and universities could easily duplicate or modify this design to introduce undergraduate students to practical applications in machine design, basic project management, hydraulics, and internal combustion engines.

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