

Virtual Multi-Cylinder Engine Transient Test System

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ABSTRACT

Researchers at the Powertrain Control Research Laboratory (PCRL) at the University of Wisconsin-Madison have developed a transient test system for single-cylinder engines that accurately replicates the dynamics of a multi-cylinder engine. The overall system can perform very rapid transients in excess of 10,000 rpm/second, and also replicates the rotational dynamics, intake gas dynamics, and heat transfer dynamics of a multi-cylinder engine.

Testing results using this system accurately represent what would be found in the multi-cylinder engine counterpart. Therefore, engine developments can be refined to a much greater degree at lower cost, and these changes directly incorporated in the multi-cylinder engine with minimal modification. More importantly, various standardized emission tests such as the cold-start, FTP or ETC, can be run on this single-cylinder engine. These tests are currently only run using multi-cylinder engines, so this moves these important tests more than a year forward in the engine development cycle, and represents a significant competitive advantage. Many other advantages of this new system will be discussed in the paper.

INTRODUCTION

Single-cylinder engines have been used for a number of power applications for over 100 years, and this use continues to this day. They have also been used in laboratories by those involved in engine research and

development as a means for studying physical processes that might occur in multi-cylinder engines. These engines have many advantages in that they are very simple, and relatively inexpensive to set up, modify and operate when compared with multi-cylinder engines. They also have the advantage of being quite accessible and receptive to a host of instrumentation for studying combustion-related processes, such as laser induced fluorescence, particle induced velocimetry, quartz windowed pistons and chambers, etc. Several companies make standardized bases for these research purposes that will accept a variety of engine geometries and types; Ricardo, AVL, and Lotus being some of the most widely used. These attributes make the single-cylinder engine very attractive and widely used in the engine research community.

Conversely, the single-cylinder research engine also has many disadvantages that both prevents its wide use in engine development, as well as discourages direct use of developments into multi-cylinder engines without significant rework. These disadvantages arise from the fact that the single-cylinder is missing the interactive or system dynamic coupling effects that exist between cylinders in a multi-cylinder engine. Further disadvantages arise from components that are typically added to the single-cylinder engine that don't exist in the same form on the multi-cylinder engine, and that also prevent most transient operations of the engine. These components include large flywheels to store kinetic rotational energy between combustion events, as well as very large plenums in the intake and exhaust systems intended to smooth large variations in pressure to some degree between intake events, due to the lack

of additional cylinders and dynamic coupling that exists on multi-cylinder engines. Further disadvantages arise from the fact that the single-cylinder engine draws in only a fraction of the air that would occur in a multi-cylinder engine, and controlling this flow into the engine to simulate the multi-cylinder engine operation is very problematic. In a sentence, the single-cylinder engine operates and behaves quite differently from the multi-cylinder engine it is intended to simulate.

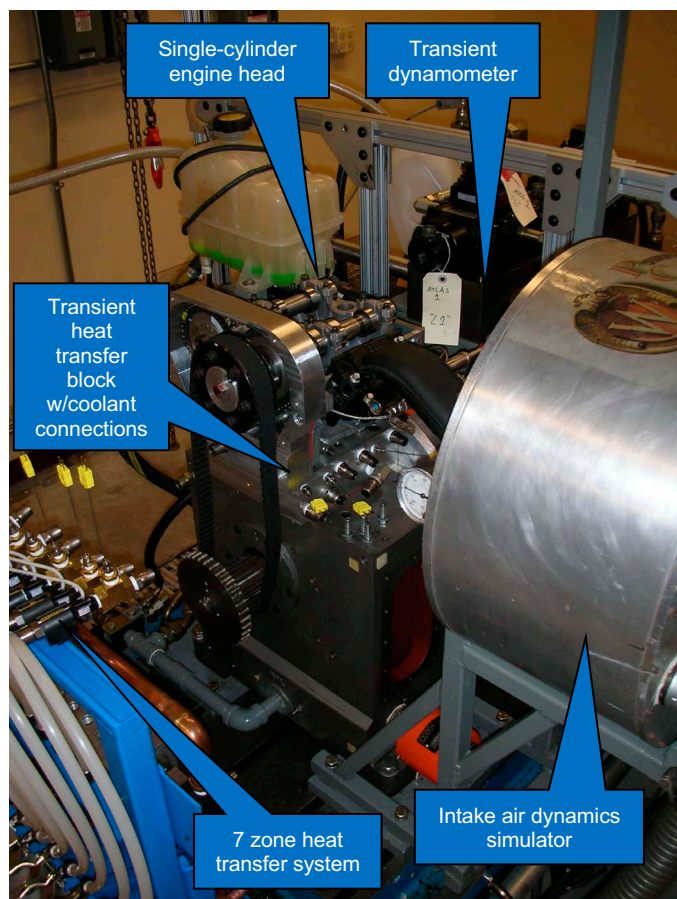


Figure 1 – Single-cylinder engine transient test system in PCRL at the University of Wisconsin-Madison

Researchers in the Powertrain Control Research Laboratory (PCRL) at the University of Wisconsin-Madison have developed a single-cylinder engine transient test system with the goals of retaining the advantages of the single-cylinder research engine, while at the same time eliminating the disadvantages that plague this engine and prevent its wider use in engine development. Specifically, systems have been developed in PCRL to replicate the dynamic boundary conditions of the multi-cylinder engine on this single-cylinder test engine. If this can be accomplished then the single-cylinder engine will “think” it is in a multi-cylinder engine, and its performance should be the same as the multi-cylinder engine. Attributes that are retained include its simplicity, its low cost of set-up, maintenance and modification, and its ease of access for a wide range of instrumentation. Attributes that are eliminated include the limitation to steady-state operation, and the lack of dynamic coupling with the

other cylinders that would exist in the multi-cylinder engine.

Accomplishing these goals would yield many advantages and capabilities that do not exist today, and these will be discussed later in the paper. However, the one specific new advantage, which is a goal of the current project using this system, is to move the cold-start test from the multi-cylinder engine to this new single-cylinder engine test system. This test is very important in the engine development process in that it provides critical information on the emissions that result for the engine design, geometry, control strategies and operation, and indicates whether the engine will meet regulatory requirements. Currently this cold-start test is only performed on multi-cylinder engines because the state-of-the-art single-cylinder engine does not operate dynamically similar to the multi-cylinder engine, and does not provide emission results close enough to the multi-cylinder engine to be confident that they are representative. If the cold-start performed on a single-cylinder engine could achieve emission results that are representative of the multi-cylinder engine, then not only would this significantly lower the cost of development to this point, but would also move that important test months to years ahead of where it currently is performed; thus providing a significant competitive advantage.

Other advantages of moving the cold-start test to the single-cylinder engine include the decided reduction of costs in setting up this test, as all of the other systems in the multi-cylinder engine do not have to be developed and operational, machine lines for the manufacture of the multi-cylinder engine do not have to be set up, and large reduction in costs are realized if any modifications need to be made to the combustion chamber or associated hardware. Combustion chamber design and cylinder control hardware can be optimized to a much greater degree at a lower cost on the new single-cylinder test system, and these optimized system designs can be transferred to the multi-cylinder engine with minimal modification.

The specific engine used on the current single-cylinder test system in PCRL is the Ford 3.0L, V-6, SI engine. In addition to the single-cylinder version of this engine, a full multi-cylinder engine is also operational on another transient test cell in PCRL's DynoLab. This allows a direct comparison of test results between the multi- and single-cylinder engine during both steady-state and transient operation.

DISCUSSION OF SUBSYSTEMS

This section will discuss three different subsystems on the single-cylinder transient test system. Each subsystem addresses and eliminates a problem area on current single-cylinder test engines, simulates the dynamic boundary conditions of a multi-cylinder engine, and provides the ability to test under a wide range of conditions. Each of these three subsystems can be

referred to as a hardware-in-the-loop (HIL) system, where dynamic models of processes to be simulated run in real time and are integrated with unique hardware designs that will be discussed. The combination of these dynamic models and the hardware provide the dynamic coupling that exists in multi-cylinder engine operation.

ROTATIONAL DYNAMICS AND TRANSIENTS – In single-cylinder test engines there is a significant time between combustion events, and this causes several problems in trying to run representative tests whose results can be applied to the multi-cylinder engine. In a 4-stroke single-cylinder engine the engine produces only one torque pulse during the cycle's two engine revolutions, and the way this problem is typically addressed is to add a very large flywheel to store kinetic energy between combustion events. Although the flywheel helps to decrease the variation in engine speed during the cycle, such a large flywheel does not exist on the multi-cylinder engine, and it creates additional problems during testing. With the flywheel the speed trajectory of the engine is not the same as a multi-cylinder engine, and the large inertia precludes any rapid transient operation that does occur in multi-cylinder engines. An additional problem in the rotational dynamics is that low speed testing is very difficult because of the elongated period between combustion events, and it is difficult to replicate multi-cylinder engine operation in this regime.

The PCRL transient test system solves these problems by eliminating the flywheel, and by actively providing the dynamic torque trajectory that would be applied to a single cylinder in a multi-cylinder engine. This is accomplished by coupling the engine through a very rigid and compact driveline to a high-bandwidth dynamometer that can produce this dynamic torque trajectory.

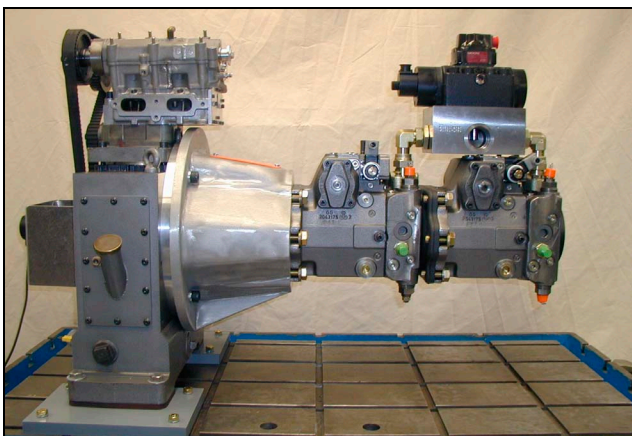


Figure 2 – Transient dynamometer system early in its development, showing the single-cylinder engine (left) and the basic dynamometer hardware (right) [1, 2]

The test system includes a dynamic model of the entire multi-cylinder engine that runs in real time. That model computes the instantaneous torque trajectory, and the

dynamometer applies that trajectory to the single-cylinder engine. The single-cylinder then “thinks” it is in a multi-cylinder engine because it received a torque trajectory that replicates the torque from other cylinder's compression, combustion, inertial, and ancillary torques. This approach also allows testing that includes very rapid speed transients. In the current system slew rates in excess of 10,000 rpm/sec have been tested. The following figures show comparisons of a typical multi-cylinder engine speed trajectory with speed trajectories from a typical single-cylinder engine with a constant load (Figure 3) and the speed trajectory from the single-cylinder engine transient test system (Figure 5).

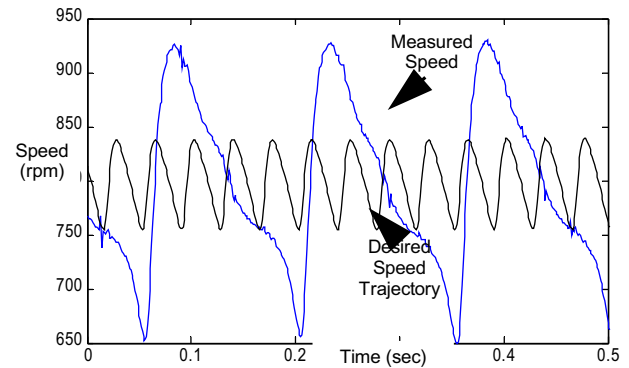


Figure 3 – Comparison of desired (multi-cylinder engine) and actual speed trajectories with typical single-cylinder engine test stand [1, 2]

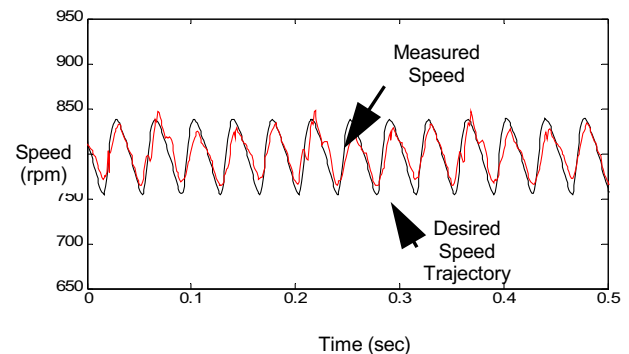


Figure 4 – Comparison of desired (multi-cylinder engine) and actual speed trajectories with the transient test system [1, 2]

By providing all of the external torques that would normally be applied to a cylinder in a multi-cylinder engine, the resulting speed trajectory on the single-cylinder engine transient test system closely approximates the multi-cylinder engine. A significant additional benefit is the ability to now perform very rapid speed transients, as it is now a fully transient system.

AIR INTAKE DYNAMICS AND TRANSIENTS - In single-cylinder test engines there are many air handling problems that arise because of the long time between intake events, because this engine is drawing in only a small fraction of what the multi-cylinder engine draws in, and because this engine is completely without the dynamic coupling between other cylinders that exists in