

Replicating Instantaneous Cylinder Mass Flow Rate with Parallel Continuously and Discretely Actuating Intake Plenum Valves

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ABSTRACT

The focus of this paper is to discuss the modeling and control of intake plenum pressure on the Powertrain Control Research Laboratory's (PCRL) Single-Cylinder Engine (SCE) transient test system using a patented device known as the Intake Air Simulator (IAS), which dynamically controls the intake plenum pressure, and, subsequently, the instantaneous airflow into the cylinder. The IAS exists as just one of many devices that the PCRL uses to control the dynamic boundary conditions of its SCE transient test system to make it "think" and operate as though it were part of a Multi-Cylinder Engine (MCE) test system. The model described in this paper will be used to design a second generation of this device that utilizes both continuously and discretely actuating valves working in parallel. Throughout this paper it is possible to find a description of the operation and performance of the current IAS system, the goals for the second generation IAS system, and the means by which the authors are pursuing these goals. Iterations of the dynamic model will be described and results from these iterations will be shown and discussed. These results will then be used to shape the continuing research into the construction of the second generation IAS.

CITATION: Gander, A. and Moskwa, J., "Replicating Instantaneous Cylinder Mass Flow Rate with Parallel Continuously and Discretely Actuating Intake Plenum Valves," *SAE Int. J. Engines* 5(2):2012, doi:10.4271/2012-01-0417.

INTRODUCTION

For the past decade, members of the PCRL have been developing SCE transient test systems whose dynamic boundary conditions replicate those of a MCE. These boundary conditions include instantaneous crankshaft speed and torque, gas transport into and out of the cylinder, and heat transfer surrounding the cylinder. The goal of controlling these boundary conditions in this test system is to sufficiently control the SCE system so that it may "think" it is operating in a MCE system, which in turn will lead it to perform as such. The motivation behind this research is to create a hardware-in-the-loop system that allows very rapid transients to be tested, and for the operator to dynamically control normally internal variables. The practical benefits of such a test system are to maintain all of the desirable attributes of the SCE, while eliminating the undesirable characteristics, and broadly expand the range of testing.

Expanding the range of testing allows for the potential benefits of decreasing the time spent researching and

improving prospective internal combustion engine designs, which in turn could reduce the time from idea conception to practical production. The system created by the PCRL is a transient test platform that performs dynamically as a MCE but with extraordinary in-cylinder access for instrumentation, dynamic control of the internal variables, the ability to explore both steady-state and transient operation, and the ability to run standardized emission tests such as the Federal Test Procedure (FTP), or European Transient Cycle (ETC). Currently, the PCRL makes use of the first generation IAS to simulate the intake air gas dynamics of an MCE, but the use of proprietary hardware and software with this device has resulted in it being considered overly complicated and slightly daunting to replicate. Thus, in order to make the IAS more industrially friendly efforts have been taken to streamline the device through a second generation design.

BODY

BACKGROUND

The IAS currently used by the PCRL has worked wonderfully with SCE transient test system for many years. Its concept is novel, and its method is simplistic and elegant, but its practical application leaves room for streamlining. Whenever developing a SCE test system it is desirable to try to recreate the gas dynamics in the intake runner that would be seen with a MCE. This is typically done by introducing a large intake plenum between the throttle and the intake runner in an attempt to replicate the intake plenum that would feed the intake runners of a MCE. Though, this method often misrepresents the Manifold Absolute Pressure (MAP) that would be seen from a comparable MCE system, which is commonly used to represent the load at which an engine is operating. This makes it difficult to easily compare and transfer results obtained on a SCE system to those found on a MCE system. This misrepresentation of MAP results quite simply from the fact that the other intake runners that would normally be drawing air from the plenum are nonexistent and not replicated. Thus, the concept of the IAS was born in the idea of creating a device that would replicate the air being drawn out of the plenum by the missing intake runners [7].

Extensive research was then done into the method that would be best to replicate the flows of the missing intake runners. From this research and investigation, it was decided to create a double-walled plenum where the internal volume of the plenum would connect the throttle to the intake runner of the SCE, and the external volume would have a pressure sufficiently low enough to induce choked air flow from the internal volume to the external volume by way valves placed between the two volumes. This allows for a simple control strategy where the pressure in the internal volume is compared to a desired MAP, and, if the measured pressure is greater than the desired pressure, more valves are opened, and vice versa [5,8]. After the method of control was decided upon, it was necessary to implement this method on the SCE engine.

Due to the availability and price of certain valves and controllers, the hardware of the first generation was compiled as follows. Between the internal and external volume of the double-walled plenum, it was decided to install 143 discretely actuating air injection valves that, when connected to the proper Engine Control Modules (ECM), are able to fully open in as little as 1.7 milliseconds. This reaction time is more than quick enough to keep up with the rapidly changing dynamics of the intake plenum. Though, each ECM only has the output ability to support 12 air valves. Thus, 12 ECM's are needed in order to completely actuate all of the air valves. The control signal that tells each ECM how many valves to open comes from three 0-5 volt analog outputs from a Digital-to-Analog Converter (DAC), which receives its control from a Digital Signal Processor (DSP). The ECM's read in the analog signal and converts it to a digital count. This count is then compared

to each valve's individual "turn-on" count, which must be programmed into the memory of each ECM. Thus, if the digital count is higher than a valve's "turn-on" count, the valve is energized and opens, and, if the count is lower than the valve's "turn-on" count, the valve is not energized and remains closed. The control signal is manipulated by way of a Proportional plus Integral (PI) controller that allows the control signal to correct for instantaneous errors between the measured and commanded pressures within the manifold, and the integral of the error between the two pressures over time [5,6,8]. It can once again be seen that the concept and method of the device are quite ingenious, but the implementation still has the potential to be improved.

INVESTIGATION OF NEW METHOD

The main thought process behind streamlining the IAS was to decrease the number of valves and actuating hardware by a factor of at least two. The simple solution to this problem was to replace the current valves with valves capable of twice the flow area. Though, when investigated it was found that commercially available valves with these flow areas had a response time that was anywhere between 2 and 15 times slower than the valves currently being used on the IAS, which was a significant disadvantage due to the fact that the quick response of the current IAS was highly favorable. This created the contradiction that in order to reduce the number of valves, and, in turn, actuating hardware, it was necessary to find large valves that acted with quickness comparable to that of the current IAS valves. Also, it was thought that by finding valves that responded proportionally to the analog signal currently being input to the ECM's, it would be possible to further reduce the amount of hardware necessary to actuate the new valves and reduce the quantization error that inherently came about through the use of discretely actuating valves. Investigation yielded a continuously actuating valve with a response time of 2 milliseconds and a maximum effective flow area four times that of the existing discretely actuating valves, but the valves price was over \$600 which meant that in order to completely replace the existing discretely actuating valves of the current IAS, about 40 valves would need to be purchased, which would cost more than \$24,000. This cost proved great enough that the lab made the decision to pursue alternative options.

In order to more cost effectively reduce the number of valves within the IAS, and the amount of hardware necessary to actuate those valves, yet retain the quickness of the first generation IAS, it was decided that a parallel actuation system would be used. In this system, the large continuously actuating valves would contribute most of the flow area that would be necessary to replicate the flow of the missing intake runners, and a smaller amount of the quick discretely actuating valves already in the system would be used to make-up the flow area missed by the larger valves when the intake plenum was experiencing rapid transients. With the methodology of the second generation IAS in place, it was determined that a model of the intake system would be

developed in order to better determine what type of valves would work well with this parallel system.

MODEL DEVELOPMENT

In order to accurately model the intake system, each element of the intake system would need to be modeled. A block diagram of the interaction between elements of the model can be seen in [Figure 1](#).

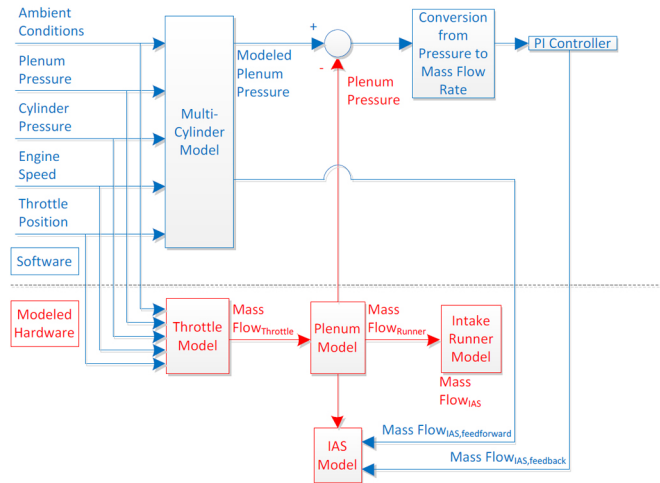


Figure 1. Block Diagram of Intake System Model

It can be seen from the block diagram how the model was split into the two main categories of modeled hardware and software. On the software side, important physical parameters are fed into an ideal gas plenum filling model that simply consists of an intake plenum that gets air fed to it from a throttle and air pulled from it by six intake runners that feed the six cylinders of the MCE system that will eventually be used to validate the model, and performance of the second generation IAS on the SCE system. From this plenum model, a model plenum pressure of the MCE system is obtained. This pressure is compared with the measure plenum pressure which comes from the plenum model of the modeled hardware. A pressure error is produced, which is converted into a mass flow rate of air. This calculated mass flow rate is then fed into a PI controller that produces the commanded mass flow rate, which the modeled IAS is to pull from the modeled intake plenum in order to correct for the error between measured and modeled plenum pressure.

On the hardware side, it can be seen that a throttle model is given ambient conditions and outputs a mass flow rate into the intake plenum model. Attached to the plenum model is the modeled intake runner and modeled cylinder elements, which will typically be pulling air out of the plenum to feed the SCE system. Finally, there exists the IAS model, which has a control strategy that can be visually represented by [Figure 2](#).

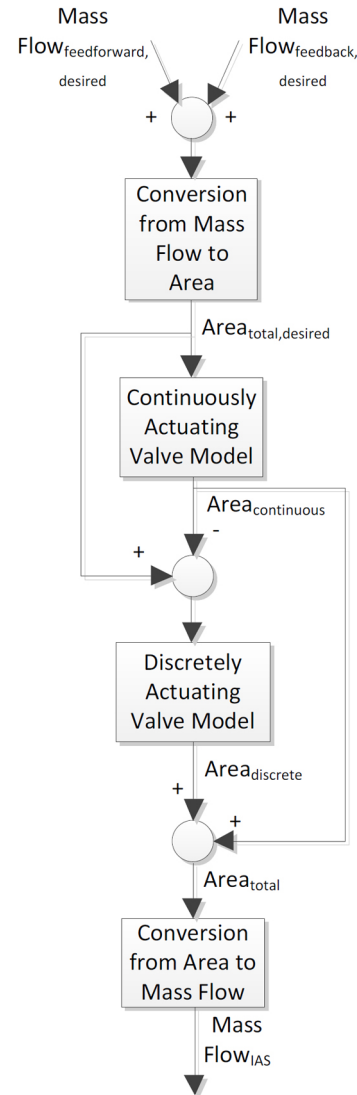


Figure 2. Block Diagram of Modeled IAS

It can be seen through this block diagram that the commanded mass flow rate from the PI controller is summed with the assumed mass flow rate that would go to the missing cylinders of the MCE, which acts as a feed-forward term. This summed mass flow rate is then converted into the flow area necessary to have the desired mass flow from the interior to exterior volume of the double-walled plenum. At this point, the desired flow area is first fed into the continuously actuating valve model to allow these valves to get the first attempt at achieving the necessary flow area. Whatever area the continuously actuating valves do not produce is then sent to the discretely actuating valves, so that they can attempt to achieve the remainder of the desired flow area. The flow areas achieved by the continuously actuating valves and the discretely actuating valves is then summed and converted back into a mass flow rate to produce the modeled mass flow the IAS removes from the intake plenum.