

Misfire Detection in a Dynamic Skip Fire Engine

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ABSTRACT

Misfire detection and monitoring on US passenger vehicles are required to comply with detailed and specific requirements contained in the OBD-II regulations. Numerous technical papers and patents discuss various methods and metrics for detecting misfire in conventional all-cylinder firing engines. However, the current methods are generally not suitable for detecting misfires in a dynamic skip fire engine. For example, a detection approach based on peak crankshaft angular acceleration may work well in conventional, all-cylinder firing engine operation, since it is expected that crankshaft acceleration will remain generally consistent for a given operating condition. In a skip fire engine, any cylinder or cycle may be skipped. As a result, the crankshaft acceleration peaks and profiles may change abruptly as the firing sequence changes. This paper presents two approaches for detecting misfires in a dynamic skip fire engine.

The first method utilizes crankshaft angular acceleration with the addition of cylinder skip or fire status, which is used to recognize a firing sequence in order to ignore skips and apply a separate threshold to various sequences. For the second approach, a torque model based on multi-cylinder pressure modeling is employed. The paper describes the details in modeling cylinder pressure, indicated torque and crankshaft angular acceleration, and proposes a new metric for misfire detection. Validation tests are carried out both on an engine dynamometer and a vehicle under steady state and transient conditions. The results indicate a very promising approach for detecting misfires in a dynamic skip fire engine.

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INTRODUCTION

A dynamic skip fire engine has the ability to selectively deactivate cylinders, in which any cylinder or cycle may be skipped to match the torque demand. This strategy improves fuel economy significantly by minimizing pumping losses while only a few cylinders operate at their peak efficiency to deliver torque. To illustrate this concept, [Figure 1](#) shows firing density versus torque demand. As the torque demand increases, the density of firing cylinders also increases. Design considerations and benefits of dynamic skip fire engines are presented in SAE papers [1] and [2].

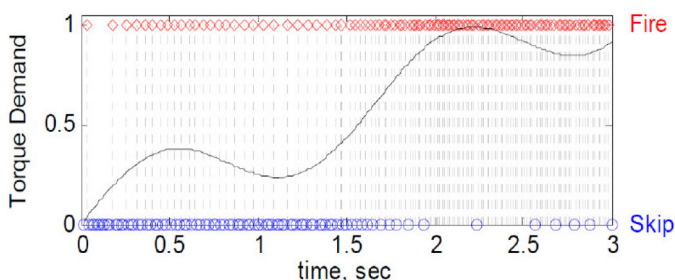


Figure 1. Dynamic skip fire concept

Integrating dynamic skip fire into an engine control strategy greatly impacts on-board diagnostic systems, particularly on misfire detection. There have been a number of methods available to detect misfires on conventional all-cylinder firing spark-ignition engines [3]. A recent SAE paper compares various misfire detection technologies for such engines [4]. Crankshaft angular acceleration has long been used for misfire detection for internal combustion engines [5]. Other methods using the signal of a knock sensor [6] or a torque model [7, 8], have also been proposed. For conventional all-cylinder firing engines, these approaches provide a reasonably accurate means for misfire detection. The methods rely on the fact that angular acceleration is proportional to torque and that neighboring cylinders produce similar torque for a given engine operating condition. Misfire of a particular cylinder results in reduced torque for that cylinder. In a conventional engine, this reduced torque and corresponding reduced angular acceleration can be used to determine a misfire.

In a skip fire engine, a particular cylinder may be skipped instead of fired, which results in a missing torque pulse or low angular acceleration. Since the lack of torque production is equivalent to a misfire, this makes it difficult to discern a misfire from a skip when looking only at angular acceleration. Thus information on whether a cylinder is fired or skipped needs to be explicitly considered. When a cylinder is skipped, no effort is made to detect a misfire event with respect to that specific cylinder. In this way, the lack of acceleration

peaks during the time period or crank angle window associated with the skipped firing opportunities will not be interpreted as misfires of the associated cylinders.

Additionally, the firing sequence needs to be identified in order to apply a different threshold to different firing sequences due to the effects of fire/skip operation of neighboring cylinders. In a more sophisticated implementation the acceleration threshold is determined dynamically by the output of a torque model based on the known sequence of fires and skips, and cylinder loading, via their resulting modeled torque waveform.

EXPERIMENTAL SETUP

The development of misfire detection on a skip fire engine was carried out on two GMC Yukon Denali full-size sport utility vehicles, each equipped with a 6.2L port fuel injected V8 engine, and with an engine on an eddy-current dynamometer. The Dynamic Skip Fire (DSF) engine was based on a production engine with GM's Active Fuel Management (AFM) system, which deactivates four out of the eight cylinders. The valvetrain of the engine and the engine controller were modified so that the test engine is capable of deactivating all eight cylinders. The specifics of this engine are listed in Table 1. Additional information on engine modifications performed can be found in [1].

Table 1. Engine and transmission specifications

Engine Designation	GM L94
Displacement	6.2 Liters
Engine Configuration	V8
Power	406 hp
Transmission	6 Speed Automatic
Valvetrain	2 Valve per cylinder, Single Cam
Cylinder Deactivation	8 cylinders, individually controlled

The engine is controlled by a dSPACE engine control unit comprised of a RapidPro and MicroAutobox. This controller allows the engine to be operated in a normal mode of pedal torque request to produce vehicle acceleration or cruise accordingly. The engine controller also has the ability to specify any firing density or firing sequence under steady state or transient conditions. This allows test data to be collected at all engine operating conditions for model development and validation.

Misfire generation code was developed for the controller to allow simulated misfires to be induced at any specified frequency at any given cylinder, two sequential cylinders, or two opposing cylinders. Misfires are simulated by not injecting fuel for a cylinder that is otherwise scheduled to fire. This approximates misfire from a torque and valve state standpoint. By programming misfires this way, the catalyst is protected from potential damage by avoiding large amounts of unburnt hydrocarbons flowing into the converter.

In initial experiments the engine is operated on an eddy current dynamometer test cell which has extensive instrumentation including piezoelectric in-cylinder pressure transducers, intake runner pressure

transducers, and a high resolution crankshaft encoder used by a combustion analysis system to analyze peak cylinder pressures and indicated mean effective pressure (IMEP). The transducers and piezo amplifiers are made by AVL, Kistler and Kulite, and the data acquisition system is from A&D. The data collected on the dynamometer can be correlated with results from the cylinder pressure model and torque model for validation.

Due to the possibility of programmed misfires producing resonance on the engine dyno driveshaft not indicative of those on the vehicle, as well as the lack of a slipping torque converter and torque converter clutch, further development and validation of misfire detection is carried out using test vehicles on the road. These are production vehicles with only engine and the engine controller modifications to be able to deactivate all eight cylinders, as described earlier. Spark plug pressure transducers and combustion analysis system were fitted in the vehicle to validate the cylinder pressure model when needed. The engine speed signals, based on which the crankshaft angular acceleration is calculated, are generated from the production 60-2 tooth crank trigger wheel. The vehicles were driven at steady state or on transient cycles for functionality validation. The data is saved as Matlab files and processed using in-house developed scripts.

RESULTS AND DISCUSSION

A number of misfire detection techniques were explored during development. This paper describes the two most promising methods. Both methods use the production vehicle sensor set and thus do not add cost.

A. Angular Acceleration with 3-Cylinder Firing/Skip Status

In general, engines having multiple cylinders are designed with their cylinders working out of phase with one another at consistent intervals, such that the power stroke of one cylinder occurs during the compression stroke of the next cylinder. Figure 2 illustrates torque signatures for three sequential cylinders with relative phasing corresponding to an 8-cylinder engine. Fired, skipped, and misfire torque signatures are depicted, with the skipped cylinder operating as with low-pressure exhaust trapping strategy.

The shaded area between 270 and 360 crank angle degrees indicates that Cylinder N is in the first half of power stroke, the previous cylinder (Cyl N-1) is in the second half of power stroke while the next cylinder (Cyl N+1) is in the second half of compression stroke. This illustrates that crank acceleration or torque in the shaded window where misfire detection occurs for the cylinder of interest (Cyl N), can be significantly affected by the events occurring in the adjacent cylinders. Although the other cylinders have a small torque effect executing their intake or exhaust processes, the influences from the immediately adjacent cylinders in the firing order are most significant and account for majority of the torque effects.

Figure 2 also shows that the commanded firing status (fire or skip) in the cylinder before (Cyl N-1) and the cylinder after (Cyl N+1) the cylinder of interest has a different effect on the crank acceleration and torque during the detection window than a conventional, all-cylinder

firing engine, the cylinders N-1 and N+1 are always firing, therefore the effect on torque is consistent. In a fixed pattern cylinder deactivation engine, such as four out of eight cylinders deactivated, Cylinders N-1 and N+1 are both normally skips. Therefore, the effect on torque signature from Cylinders N-1 and N+1 is also consistent from cycle to cycle under quasi-steady state conditions. However, in a dynamic skip fire engine, the fire/skip status of the cylinders N-1 and N+1 are changing dynamically. Therefore, it is important that the fire/skip status of both Cylinders N-1 and N+1 are taken into consideration in the misfire detection algorithm design. This is why a 3-cylinder pattern was chosen for this method.

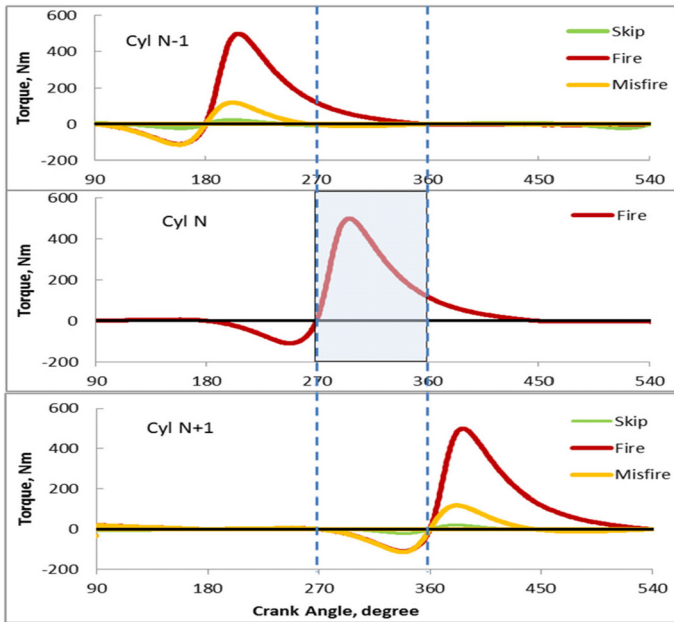


Figure 2. Effect of adjacent cylinders on crankshaft torque

Figure 3 below depicts a flow diagram of the 3-cylinder status based misfire detection algorithm in a DSF engine. It should be noted that if the previous cylinder was commanded to fire, but a misfire has been detected in that cylinder, then both misfire flag and the fire status should be taken into account since the torque contribution from that cylinder during the detection window is greatly reduced, as illustrated in Figure 2 above. It should also be pointed out that the algorithm performs rationality checks on input signals to ensure robustness of the strategy.

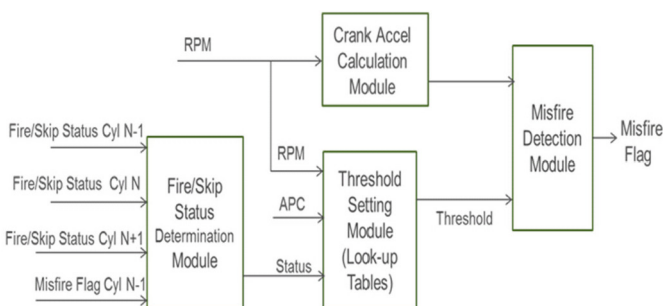


Figure 3. A flow diagram illustrating misfire detection algorithm based on 3-cylinder fire/skip status

Crank Acceleration Calculation Module

The angular crank acceleration is calculated in the Crank Accel Calculation module. The calculation is performed over a 90-degree moving window and is updated every 6 degrees (every crank tooth), as depicted in Figure 4A. The 90-degree window is further divided into two segments, each of 42 degrees and separated by a 6-degree gap. The purpose in doing so is to frequency band-limit the detection area to exclude noise sources outside of the frequency of where the bulk of the combustion event is located. This is important since angular acceleration is the derivative of the angular velocity and a derivative function is essentially a high pass filter that would otherwise pass high frequency noise that might confound the detection of misfire. The calculated angular acceleration is then latched for each cylinder in a 90-degree interval for an 8-cylinder engine, as illustrated in Figures 4B and 4C. It should be pointed out that this 90-degree latching interval derives from the 720 crank angle degrees per cycle divided by the number of cylinders of the engine and does not necessarily have to be the same as 90-degree filtering window.

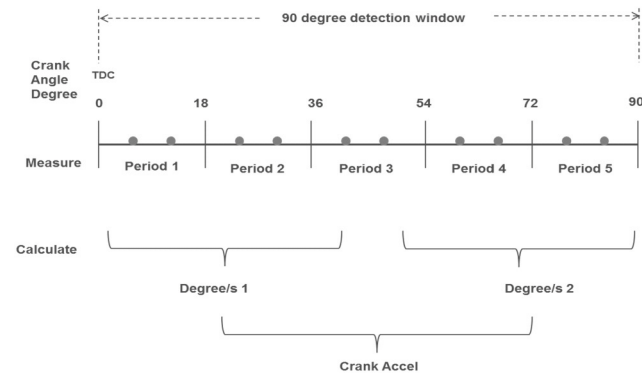


Figure 4A. Method of calculating crankshaft angular acceleration

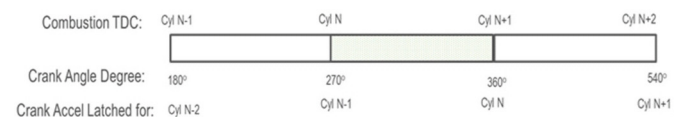


Figure 4B. A diagram illustrating location for latching crankshaft angular acceleration

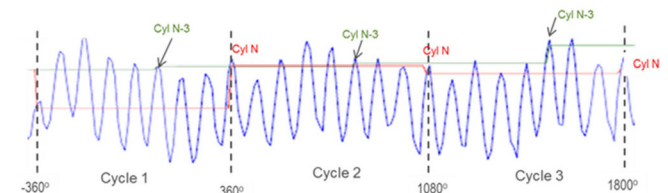


Figure 4C. Example of results of calculated crankshaft angular acceleration

Fire/Skip Status Determination Module

As discussed earlier, the fire/skip status of the two cylinders immediately adjacent to the cylinder of interest (Cyl N) has significant impact on crank acceleration in the detection window. To categorize the eight different possible combinations of fire/skip statuses of Cylinders N-1, N and N+1, the following definition is employed and the results are summarized in Table 2.