

MISFIRING CYLINDER DIAGNOSIS THROUGH CRANKSHAFT TORSIONAL VIBRATION
MEASUREMENT

A dissertation submitted to the

Division of Research and Advanced Studies
of the University of Cincinnati

in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

in the Department of Mechanical, Industrial, and Nuclear Engineering
of the College of Engineering

1997

by

Jeremy Williams

B.Sc. M.E., Virginia Polytechnic Institute and State University 1987

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Committee Chair: Dr. David L. Brown

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ABSTRACT

When each cylinder in an internal combustion engine fires, a torque pulse is applied to the crankshaft. These torque pulses contain significant energy for the first twenty four harmonics of engine cycle speed, resulting in dynamic torsional excitation and response of the crankshaft and drivetrain in both rigid body and flexible modes. If a cylinder misfires, the excitation torque for that cylinder is altered, resulting in an altered dynamic torsional system response.

This research presents a new method for diagnosing and identifying misfiring cylinders in an internal combustion engine. A knowledge of the system dynamic model, system boundary conditions, and measured crankshaft torsional response are used to characterize the dynamic input at each engine cylinder. Current methods of misfire diagnosis using crankshaft torsional response as an indicator rely on several key assumptions to form a solvable equation set relating measured response to the system input at each cylinder. Chief among these assumptions are non-overlapping firing pulses and rigid crankshaft behavior. These assumptions limit diagnostic success with current methods to engines with six or fewer cylinders operating at low to moderate engine speeds.

The proposed diagnostic method does not rely on these assumptions. Rather, a set of linear constraint equations are added to the otherwise unsolvable equation set that relates the measured torsional crankshaft response to individual cylinder input. The constraint equations relate the magnitude and phase of the harmonics of the forcing function for each cylinder to the peak pressure and location of peak pressure for each cylinder pressure curve. Thus, the harmonics of the excitation torque for each cylinder are no longer independent. The constraint equations are introduced into the diagnostic equation set through the simultaneous consideration of multiple frequencies of excitation and response.

A series of test cases are presented which show that the diagnostic process should work with engines with overlapping firing pulses operating with significant crankshaft deflection. An error sensitivity analysis shows the process is viable with reasonable levels of noise and error associated with all key assumptions and measurements. In addition, a new signal processing technique is proposed which promises to significantly reduce torsional vibration measurement error compared to current state of the art techniques.

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LIST OF SYMBOLS

f	Input force
n	Number of cylinders
m	Number of engine orders used in the diagnostic system matrix equation
m_{\min}	Minimum number of engine orders needed for a solvable diagnostic equation set
x	Linear displacement
A_r	Piston top area
$ATDC$	After top dead center
F	Parameter characterizing forcing function in proof of concept study
L	Connecting rod length
M	Reciprocating inertia for an engine cylinder
P	Cylinder pressure
PCP	Peak cylinder pressure
R	Crankshaft throw
T	Torque
TDC	Top dead center
T_c	Torque applied to crankshaft by a cylinder
T_{fw}	Boundary condition torque at the flywheel
T_g	Cylinder torque due to gas pressure
T_{in}	Cylinder torque due to inertia effects
TIM	Dynamic timing value
δPCP	Incremental positive increase in peak cylinder pressure
δTIM	Incremental positive increase in dynamic timing
ΔPCP	Peak cylinder pressure correction
ΔTIM	Dynamic timing correction
α	Coefficient for peak pressure in constraint equation
β	Coefficient of dynamic timing in constraint equation
γ	Nominal value of excitation torque in constraint equation
η	Constraint coefficient in proof of concept study
θ	Angular displacement or crankshaft angle
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
ω	Frequency of excitation and response

$[A]$	Matrix of α coefficients
$[B]$	Matrix of β coefficients
$[G]$	Matrix of γ coefficients
$[K_{eq}]$	Equivalent complex system stiffness matrix
$[K^*_{eq}]$	Equivalent real system stiffness matrix
$[H]$	System impedance matrix
$[H_k]$	Portion of system impedance matrix corresponding to known torsional displacements
$[H_u]$	Portion of system impedance matrix corresponding to unknown torsional displacements
$\{f\}$	force vector
$\{F_{eq}\}$	Equivalent complex system force vector
$\{F^*_{eq}\}$	Equivalent real system force vector
$\{S\}$	Coefficient vector for unknown boundary condition torque
$\{TIN\}$	Vector of inertia torque excitations
$\{X\}$	Complex system unknowns vector
$\{X_{eq}\}$	Equivalent complex system unknowns vector
$\{X^*_{eq}\}$	Equivalent real system unknowns vector
$\{\Delta\}$	Vector of unknown peak pressure and dynamic timing parameters
$\{\theta\}$	Vector of torsional displacements
$\{\theta_k\}$	Vector of known torsional displacements
$\{\theta_u\}$	Vector of unknown torsional displacements

GLOSSARY OF TERMS

This dissertation presents a method for diagnosing and locating misfiring cylinders in an internal combustion engine using measured crankshaft torsional vibration response as an indicator of the applied torque for each cylinder. The body of the report presupposes that the reader has a working understanding of internal combustion engine dynamics and engine torsional vibration analysis and measurement. An overview of each these topics is included in the body of the report. The following glossary of terms is included for those are not familiar with the field of engine dynamics and torsional vibration analysis and to minimize possible confusion. The terms are grouped by subject matter. The list is not exhaustive, but rather includes the terms most likely to need clarification.

Internal Combustion Engine Terms

Crankshaft A shaft that runs the length of the engine that transmits the engine torque to the flywheel.

Crankshaft Nose The portion of the crankshaft that extends out of the front of the engine. The front of the engine is the end where the radiator fan is located. The rear of the engine is the end where the flywheel is located.

Clutch A device attached to the flywheel that is used to transmit torque to the drivetrain. The clutch usually has a low torsional stiffness, a maximum torque slip device, and a disconnect capability.

Cylinder Pressure Curve The pressure waveform in the combustion chamber .

Driven Inertia The equivalent inertia of the drivetrain components behind the engine flywheel.

Dynamic Timing The crankshaft angle where peak pressure occurs, usually defined in degrees after top dead center (degrees ATDC).

Flywheel A large inertia disk attached to the rear of the crankshaft. The flywheel acts as the attachment point for the clutch.

Flywheel Ring Gear A toothed ring around the circumference of the crankshaft flywheel. The flywheel engine starter motor engages the ring gear to rotate the crankshaft for engine starting. The ring gear also provides a location to measure torsional vibration at the engine flywheel.

Peak Pressure The maximum pressure in the cylinder pressure curve.

TDC Top Dead Center. The crankshaft position where the crankshaft and connecting rod for a given cylinder are aligned in a straight line so that the piston is at the top of its stroke.

Signal Processing Domain Terms

Crankangle Domain Analysis performed with crankshaft angle as the independent variable. Data is sampled at constant increments of crankshaft angle. If the angular velocity of the system is known, time domain data can be converted to the crankangle domain using the relation, $\theta = \omega t$ and then re-sampling the data at constant increments of crankshaft angle.

Frequency Domain Analysis performed with frequency as the independent variable. Analysis is typically performed at discrete, equally spaced frequencies within some frequency band.

Order Frequency referenced to a multiple of the mean shaft speed. For a shaft turning at 1000 rpm, 1st order is 1000 rpm, 2nd order is 2000 rpm, 3rd order is 3000 rpm, etc. For a four stroke engine, one engine cycle corresponds to two complete revolutions of the crankshaft. The fundamental frequency of the excitation and response for the engine, therefore, is one half engine speed, or ½ order.

Order Domain Frequency analysis in which the analysis frequencies are orders. Performing a discrete Fourier transform on crankangle domain data that represents exactly one revolution of data results in harmonic frequency components at integer engine orders.

Time Domain Analysis performed with time as the independent variable. Data is sampled at constant increments of time.

Temporal Filtering Partitioning a time domain waveform into a series of contiguous waveforms. This process is used to partition the applied torque waveform for a crankshaft into waveforms separating the input for individual cylinders.

Engine Torsional Vibration Analysis

Single Cylinder Excitation Torque The torque applied to the crankshaft by a single cylinder during an engine cycle. Single cylinder excitation torque can be expressed in the time, crankangle, frequency, or order domains.

Engine Torsional Vibration Analysis The analytical procedure of predicting the torsional vibration free and forced response of an internal combustion engine and connected drivetrain.

Firing Frequency The frequency of combustion events in an engine. In a four stroke engine, each cylinder fires every two revolutions of the crankshaft, resulting in a firing frequency (in orders) equal to the number of cylinders divided by two. For example, the firing frequency of a four stroke, six cylinder engine is 3rd order.

Torsional Vibration Variation in shaft speed about some mean speed. Torsional vibration includes both rigid body speed fluctuation and dynamic torsional deformation.

Torsional Vibration Measurement

Magnetic Pickup A variable reluctance sensor (VRS) used to generate a periodic waveform whose frequency is equal to the tooth passing frequency of a magnetic gear.

Shaft Encoder An optical disk used to produce a periodic waveform whose frequency is proportional to the angular velocity of the attached shaft.

Misfiring Cylinder Diagnostic Terms

Misfiring Cylinder A cylinder with a cylinder pressure curve peak pressure that is significantly lower than normal. Common causes of misfiring cylinders include faulty fuel injectors, faulty valves, and faulty piston rings.

Misfire Detection The detection of the presence of a misfiring cylinder.

Misfire Identification/Location The identification of the misfiring cylinder(s).

1. INTRODUCTION

A misfiring cylinder in an internal combustion engine results in decreased engine performance, increased exhaust emissions, and increased powertrain noise and vibration. Also, a misfiring cylinder is often symptomatic of a more serious engine problem that can lead to catastrophic engine or drivetrain failure if not corrected. For engines with high cylinder counts such as sixteen cylinder engines used in locomotives and off road mining trucks, the overall power drop associated with a misfiring cylinder is small and the problem is often not apparent to the operator until a catastrophic failure occurs. With such engines, once a misfire is diagnosed, the identification of the offending cylinder is often a long process involving the removal of individual cylinder heads (these engines have a separate cylinder head for each cylinder) in succession until the offending cylinder is found. Current and proposed legislation requiring on-board detection of engine misfire in automotive passenger vehicles has created an immediate industry need for reliable engine diagnostic systems. Existing angular velocity based diagnostic systems only work with engines with six or fewer cylinders operating at low to moderate engine speeds.

When each cylinder in an internal combustion engine fires, a torque pulse is applied to the crankshaft throw. This torque contains significant energy for the first 24 harmonics of cycle speed (see Section 3.2). The resulting periodic excitation causes the engine and driveline angular velocity to fluctuate in both rigid body and flexible modes. When a cylinder misfires, the applied torque to the crankshaft is altered, resulting in an altered engine and driveline angular velocity response. The objective of this doctoral research is to develop a novel and improved technique to use the measured angular velocity response of the system to diagnose and locate misfiring cylinders.

Current angular velocity based misfire diagnostic techniques include threshold criteria, pattern recognition, and model based deconvolution. All current techniques require the assumption of non-overlapping firing pulses and a rigid crankshaft. These assumptions have limited misfire diagnostic success so far to engines with six or fewer cylinders operating at low to moderate engine speeds.

The goal of the doctoral research is to develop a diagnostic system which will work for engines with overlapping firing pulses and with significant crankshaft deflection. The proposed diagnostic method will, for the first time, enable 100% detection of misfire in passenger vehicles, and also allow misfire detection and faulty cylinder identification in engines with high cylinder counts and significant crankshaft deflection. The fundamental process in the diagnostic method is to deconvolve measured angular velocity at the crankshaft nose and flywheel through a dynamic model for the engine and powertrain to arrive at the unmeasured cylinder pressure input for each cylinder. Additional equations required to solve the otherwise indeterminate equation set are generated by forming constraint equations between the harmonic components of the forcing function at each cylinder. The research results in several improvements in state of the art techniques:

1. A new diagnostic method allowing misfire detection and location for engines with flexible crankshaft behavior and overlapping firing pulses.
2. A new, more accurate method of measuring rotating shaft angular velocity fluctuation.
3. A new method of input force reconstruction by forming constraint equations between harmonics.

Chapter Two reviews the literature on angular velocity based misfire diagnostic methods. The relative merit of each of the existing diagnostics methods are presented. The choice and consequences of the underlying assumptions in the various methods are reviewed in detail. The remaining challenges for a comprehensive, accurate and reliable diagnostic system are explained. A summary of relevant literature is then listed by author. Finally, the current state of the art is summarized.

Chapter Three provides an overview of engine torsional vibration analysis techniques. Engine torsional vibration analysis refers to the process of using a dynamic system model, system boundary conditions, and an applied forcing function to calculate the dynamic torsional response of an engine and powertrain system. There are many assumptions in this process that limit the accuracy and applicability of the results. The consequences of each of these assumptions is explained in detail. A thorough understanding of torsional vibration analysis techniques, assumptions, capabilities, and limitations is

