

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

M.Sc. M.E., Virginia Polytechnic Institute and State University 1989

Committee Chair: Dr. David L. Brown

*Randall J. Allemang*

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

M.Sc. M.E., Virginia Polytechnic Institute and State University 1989

Committee Chair: Dr. David L. Brown

## 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.

## ACKNOWLEDGMENTS

I would like to thank my committee chairman, Dr. David Brown, for his advice and support, and for creating an environment in which I could pursue my research goals. I would also like thank my other committee members, Dr. Randall J. Allemang, Dr. Robert W. Rost, Dr. Stuart J. Shelley, and Dr. Robert H. Wynn. I am especially grateful to Dr. Stuart Shelley for his invaluable advice and feedback in the last two years and to Dr. Robert W. Rost for coordinating this project with the University. I would like to thank Dr. Allyn Phillips for his help in developing the new digital torsional vibration measurement techniques.

I would also like to thank Mr. Thomas Reinhart and Mr. Alan Zhao of Cummins Engine Co, Inc. Mr. Reinhart's group at Cummins has sponsored this work in its entirety for which I am very grateful. Tom Reinhart and Alan Zhao have been very supportive throughout the research process. Without the support of Tom and Alan, this work could not have been completed. I look forward to a continuing relationship with each of them.

Last, but by no means least, I would like to thank John Schultze, Walter Lynge, Imtiaz Ali, Ming Yang, Cindy Adelman and all the other members of the Structural Dynamics Research Laboratory for their friendship. Working within the SDRL has been an enriching experience for me on a personal as well as professional level. I have made friendships over the last three years that will last a lifetime.

# TABLE OF CONTENTS

1. INTRODUCTION .....	13
2. LITERATURE REVIEW .....	17
2.1 Introduction .....	17
2.2 Overview And Comparison Of Current Methods .....	17
2.2.1 Introduction.....	17
2.2.2 Engine Torsional Vibration Analysis vs. Engine Diagnostic Analysis.....	19
2.2.3 System Model.....	21
2.2.4 Analysis Methods.....	23
2.2.5 Misfire Detection And Location.....	26
2.2.6 Assumptions.....	28
2.2.7 Remaining Challenges.....	32
2.3 Summary By Author Of Relevant Literature.....	32
2.4 Summary .....	37
3. INTERNAL COMBUSTION ENGINE TORSIONAL VIBRATION ANALYSIS .....	39
3.1 Introduction .....	39
3.2 Forcing Function.....	39
3.3 System Models .....	45
3.4 Boundary Conditions .....	46
3.5 Analysis Techniques .....	47
3.5.1 Overview .....	47
3.5.2 Order Domain Techniques.....	48
3.5.3 Time Domain Techniques .....	56
3.5.4 Summary of Analysis Techniques.....	57
4. TORSIONAL VIBRATION MEASUREMENT .....	58
4.1 Introduction .....	58
4.2 Overview Of Measurement Methods .....	59
4.2.1 Analog Methods .....	59
4.2.2 Digital Methods.....	61
4.3 Analysis Of Digital Measurement Techniques.....	63
4.3.1 Simulation Code.....	63

4.3.2 Aliasing .....	65
4.3.3 Leakage.....	65
4.3.4 Measuring Tooth Pass Times.....	66
4.3.5 Demodulation Techniques .....	69
4.3.6 Tooth Spacing Variation .....	75
4.3.7 Magnetic Pickup Vibration.....	76
4.4 Summary And Conclusions.....	77
5. OVERVIEW OF DIAGNOSTIC TECHNIQUE.....	78
5.1 Problem Definition.....	78
5.2 Solution Procedure.....	79
5.3 Two Degree of Freedom Proof of Concept Study .....	85
6. DIAGNOSTIC ALGORITHM .....	91
6.1 Overview .....	91
6.2 Constraint Equation Formulation.....	93
6.3 System Matrix Equation Formulation.....	96
6.4 Generalization of Equations .....	104
7. ALGORITHM VERIFICATION.....	106
7.1 Overview .....	106
7.2 Forward Simulation .....	106
7.2.1 Forward Simulation Code.....	106
7.2.2 System Model.....	107
7.2.3 Forcing Function.....	108
7.3 Misfire Indicator Function .....	110
7.4 Baseline Diagnostic Case .....	111
8. ERROR SENSITIVITY ANALYSIS.....	114
8.1 Introduction .....	114
8.2 Number And Choice Of Engine Orders.....	114
8.3 Choice Of Solution Parameters.....	117
8.4 Use Of Multiple Engine Speeds.....	119
8.5 Boundary Condition Assumptions.....	120
8.6 Sensitivity To Noise .....	121
8.6.1 Sensitivity to System Model Noise.....	121

8.6.2 Sensitivity to Cylinder Pressure Shape Noise .....	122
8.6.3 Sensitivity to Angular Velocity Measurement Error.....	130
8.6.4 Test Cases with Random Noise.....	131
8.7 Summary .....	134
9. SUMMARY AND CONCLUSIONS .....	135
10. RECOMMENDATIONS FOR FURTHER RESEARCH.....	137
10.1 Misfiring Cylinder Diagnostics .....	137
10.2 Torsional Measurement Methods .....	138
10.3 Force Reconstruction with Constraint Equations .....	138
11. BIBLIOGRAPHY .....	139
APPENDIX A: DIAGNOSTIC TEST CASES .....	142

## LIST OF FIGURES

Figure 1. Diagnostic Process.....	20
Figure 2. Diagnostic System Models.....	22
Figure 3. Order Domain vs. State Space Deconvolution.....	25
Figure 4. Illustration of Diagnostic Equation Indeterminacy.....	29
Figure 5. Rigid Crankshaft and Constant Load Torque Assumptions.....	31
Figure 6. Slider Crank Mechanism Model.....	40
Figure 7. Single Cylinder Excitation Torque.....	44
Figure 8. Typical Torsional Mass Elastic Model.....	45
Figure 9. Torsional Vibration Analysis Techniques.....	47
Figure 10. Holzer Analysis Forced Response.....	51
Figure 11. Transfer Matrix Analysis.....	53
Figure 12. Impedance Model Analysis.....	55
Figure 13. Standard Digital Measurement Method.....	62
Figure 14. Effect of Counter/Timer Sample Rate on Measurement Noise Floor.....	67
Figure 15. Digital Data Acquisition of Magnetic Pickup Signal.....	68
Figure 16. Effect of A/D Sample Rate on Measurement Noise Floor.....	69
Figure 17. Frequency Response of Standard Demodulation Method.....	71
Figure 18. Frequency Response Function Correction Window.....	73
Figure 19. Corrected Frequency Response Function.....	74
Figure 20. Effect of Gear Tooth Spacing Errors on Measurement Noise Floor.....	76
Figure 21. Cylinder Pressure Curve Parameterization Scheme.....	81
Figure 22. Diagnostic Solution Procedure.....	84
Figure 23. Two Degree of Freedom System.....	86
Figure 24. Two Mass Diagnostic Algorithm.....	90
Figure 25. Diagnostic Algorithm Flowchart.....	92
Figure 26. Misfire Indicator: Baseline Case.....	113
Figure 27. Iteration Time vs. Number of Engine Orders.....	115
Figure 28. Engine Order Selection.....	117
Figure 29. Sensitivity to System Model Noise.....	122
Figure 30. Peak Pressure Balance Sensitivity to Cylinder Pressure Shape Random Noise.....	124
Figure 31. Excitation Using Different Cylinder Pressure Curves.....	126



Figure 32. Diagnostic Sensitivity to Cylinder Pressure Shape Bias Errors .....	128
Figure 33. Diagnostic Results Solving for Peak Pressure Alone.....	129
Figure 34. Sensitivity to Angular Velocity Measurement Noise.....	130

## LIST OF TABLES

Table 1. System Model Complexity.....	21
Table 2. Diagnostic Analysis Methods .....	24
Table 3. Misfire Detection and Location Methods .....	27
Table 4. Common Assumptions .....	30
Table 5. Comparison of Torsional Analysis Methods .....	57
Table 6. Analog Torsional Measurement Methods .....	60
Table 7. Digital Measurement Errors .....	63
Table 8. Six liter Engine Mass Elastic Model.....	108
Table 9. Six liter Engine Forcing Function .....	109
Table 10. Diagnostic Test Cases .....	132

## 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
$\delta PCP$	Incremental positive increase in peak cylinder pressure
$\delta TIM$	Incremental positive increase in dynamic timing
$\Delta PCP$	Peak cylinder pressure correction
$\Delta TIM$	Dynamic timing correction
$\alpha$	Coefficient for peak pressure in constraint equation
$\beta$	Coefficient of dynamic timing in constraint equation
$\gamma$	Nominal value of excitation torque in constraint equation
$\eta$	Constraint coefficient in proof of concept study
$\theta$	Angular displacement or crankshaft angle
$\dot{\theta}$	Angular velocity
$\ddot{\theta}$	Angular acceleration
$\omega$	Frequency of excitation and response

$[A]$	Matrix of $\alpha$ coefficients
$[B]$	Matrix of $\beta$ coefficients
$[G]$	Matrix of $\gamma$ 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, 1<sup>st</sup> order is 1000 rpm, 2<sup>nd</sup> order is 2000 rpm, 3<sup>rd</sup> 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 3<sup>rd</sup> 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

