	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	2008 - 9 - 4	Final Report 22 Sep 2003 - 21 Jun 2008

4. TITLE AND SUBTITLE	5. FUNDING NUMBERS
Computer Based Adaptation Tool for Advanced Diesel Engines Used in Military Applications	DAAD19-03-1-0338
6. AUTHOR(S) Naeim A. Henein, Dinu Taraza, Nabil Chalhoub	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Wayne State University, 656 Kirby, Room 4002 FAB, ORSPS Detroit Mi 48202	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	10. SPONSORING / MONITORING AGENCY REPORT NUMBER 45615.4-EG

11. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

14. SUBJECT TERMS	15. NUMBER OF PAGES
Diesel Engine Simulation, Engine Combustion, Engine tribology, Engine Controls	
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	UU

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

FINAL REPORT

Project: COMPUTER-BASED ADAPTATION TOOL FOR ADVANCED DIESEL ENGINES USED IN MILITARY APPLICATIONS

Funding Number: DAAD19-03-1-0338

Performing Organization: Wayne State University, Office of Sponsored programs 656 West Kirby 4001Faculty Admin. Bldg., Detroit MI 48202

Sponsoring Agency: U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

Authors: Naeim A. Henein, Dinu Taraza, Nabil Chalhoub

Abstract

The main goal of the project was the development a computer code capable to simulate the operation of a multi-cylinder common rail diesel engine.The code should be used in investigating the possibilities of a commercial engine to be adapted for miltary applications by increasing the engine output whhile reducing fuel consumption and assure safe operation of the engine.
In the process of developing the simulation model and the corresponding computer code, the critical loading of the engine bearings and the piston assembly were determined by developing detailed models for loading and stresses in the bearings and the piston. Experimental setups were developed to validate the models.
To correctly estimate the fuel consumption, a detailed friction simulation model has been developed.
Both experimental and analytical investigations were conducted to allow better estimation of the ignition delay, combustion and emissions.
The Computer based Adaptation Tool has been built in a modular form in the Matlab-SIMULINK platform. The advantage of this configuration resides in the fact that modules could be replaced as new modules are developed, for example the ignition delay and the combustion modules for different fuels that could be used by the diesel engine.

Finally the Computer Based Adaptation Tool has been validated by experiments conducted on a 2.5 liters common rail diesel engine both for steady state operation and for engine transients.

The main achievments obtained during the period of operation (2003-08) are the following:

- Development of detailed models and simulation codes for the loading and lubrication of multi-cylinder main engine bearings
- Development of a detailed model and simulation code for the total engine friction losses
- Development of a tribology test rig that allows for the direct measurement of the instantaneous piston-assembly friction force under motoring conditions
- Development of a dynamic model to examine the piston secondary motions and the relationships with which they interact with the lubricating oil film.
- Development an experimental single cylinder diesel engine equipped with telemetric system to measure piston secondary motion
- Development the **Computer Based Adaptation Tool** consisting of the complex simulation model, developed in Matlab-Simulink for a multi-cylinder high power density military engine including a new total engine friction model and a model of the common rail injection system.
- Development of a model to reconstruct cylinder pressure variation from the measure instantaneous crankshaft speed.
- Development of control strategies for Cold Starting of diesel engines with common-rail injection system
- Development of a 3D CFD model to compute the non steady state heat transfer in the EGR cooler of a diesel engine and experimental model validation
- Experimental research of the effect of replacing diesel fuel by biodiesel on autoignition, combustion and emissions to adapt military engines to the use of biodiesel
- Experimental research in the optical accessible engine to determine the effects of different fuel properties on autoignition, combustion and emissions necessary to adaptation of military engines to the use of different fuels.
- Enhancement of the accuracy of the $(P-\omega)$ method by relying on estimated rather than measured state variables of the piston/connecting-rod/crankshaft mechanism.

The following publications have resulted from the work performed for this project:

1. “Effect of Smoothing the Pressure trace on the Interpretation of Experimental Data for Combustion in Diesel Engines”, Lurun Zhong, N.A. Henein, W. Bryzik, SAE Paper 2004-01-0931 and SAE Transactions, Journal of Engines,Vol.115, pp. 2006

2. “A Generic, Transient Model of a Turbocharged, Multi-Cylinder, Common-rail Diesel Engine”, Radu Ceausu, Dinu Taraza, Naeim A. Henein, Walter Bryzik, Paper ICES 2005-1021, Proceedings of ICES2005 ASME Internal Combustion Engine Division 2005 Spring Technical Conference April 5-7, 2005, Chicago, IL.

3. “Cylinder Pressure Reconstruction from Crankshaft Speed Measurement in a Four-stroke Single Cylinder Diesel Engine”,Dinu Taraza, Naeim A. Henein, Magesh Gade, Walter Bryzik, Paper ICES 2005-1023, Proceedings of ICES2005 ASME Internal Combustion Engine Division 2005 Spring Technical Conference April 5-7, 2005, Chicago, IL.

4. “Enhancement of the Accuracy of the Modified $(P-\omega)$ Method Through the Implementation of a Nonlinear Robust Observer,” Kfoury, G.A., Chalhoub, N.G., Henein, N.A. and Bryzik, W., 2005, *Proceedings of the 2005 ASME International Mechanical Engineering Congress and Exposition (IMECE),* Orlando, Florida, November, 2005, Dynamic Systems and Control, Modeling and Identification, Paper No. IMECE2005-80115, 1-10.

5. “Enhancement of the accuracy of the $(P-\omega)$ method through the implementation of a nonlinear robust observer, ”Kfoury, G.A., Chalhoub, N.G., Henein, N.A. and Bryzik, W., 2006, Journal of Sound and Vibration, 291(3-5), 1080-1103.

6. “OPERAS” in Advanced Diesel Engines for Commercial and Military Applications”, N.A. Henein, A. Kasturi, K. Natti, W. Bryzik, SAE Paper 2006-01-0927.

7. “Engine Friction Model for Transient Operation of Turbocharged, Common Rail Diesel Engines”, Dinu Taraza, Naeim A. Henein, Radu Ceausu, Walter Bryzik, SAE Paper 2007-01-1460, SAE 2007 World Congress, Detroit, Michigan, April 16 – 19, 2007

8. “Advanced low temperature Combustion (ALTC): Diesel Engine Performance, Fuel Economy and Emissions”, N.A. Henein, A. Kasturi, K. Natti, W. Bryzik, SAE Paper 2008-01-0652.

9. “Lower Temperature Limits for Cold Starting of Diesel Engine with a Common Rail Fuel Injection System,” by Zhong, L., Gruenewald, S., Henein, N. A. and Bryzik, W., SAE 2007-01-0934, 2007

10. "PM Characterization in an HSDI Diesel Engine under Conventional and LTC Regimes," Natti, K., Henein, N. A., Poonawala, Y., Bryzik, W., SAE 2008 World Congress, paper number 2008-01-1086, SP 2185 (2008).

11. “Chemiluminescence Imaging of Pre-Injection Reactions During Engine Starting”, Marcis Jansons, Fadi Estefanous, Radu Florea, Dinu Taraza, Naeim Henein, Walter Bryzik, accepted for publication in the International Journal of Vehicle Design (Inderscience).

12. “Piston secondary motions and hydrodynamic lubrication regime in a single cylinder internal combustion engine”, Chalhoub, N.G. and Edelby, W., 2008, accepted for presentation and publication in the Proceedings of the 2008 ASME Dynamic Systems and Control Conference, October 20-22, Ann Arbor, Michigan, USA.

13. “Development of a robust observer for constrained nonlinear systems,” Kfoury, G.A. and Chalhoub, N.G.*, 2007,* accepted for presentation and publication in the Proceedings of the 2007 ASME International Mechanical Engineering Congress and Exposition, IMECE2007-43680, November 11-15, Seattle, Washington, USA.

14. “Direct measurement of the piston-assembly friction force in a single cylinder engine under motoring conditions,” Fadel, C., Chalhoub, N.G., Kfoury, G.A. and Henein, N.A., 2008, *Proceedings of the 2008 ASME Dynamic Systems and Control Conference,* October 20-22, Ann Arbor, Michigan, USA.

The following students working in this program have graduated during this period:

Ph. D. Theses

1. Lurun Zhong, “A Control Strategy for Cold Starting of a Diesel Engine with Common rail Fuel Injection System,” 2006.

2. Radu Ceausu, Ph.D. in Mechanical Engineering, “Improvement of Transient Response of Turbocharged Multi-cylinder Diesel Engines.” June 2006

3. Bogdan Nitu, Ph. D. in mechanical Engineering, “A multi-zone quasi three-dimensional model for a single cylinder high power density diesel engine,” 2006

4. Kfoury, G.A., Ph.D. in Mechanical Engineering, “Computation of the instantaneous frictional losses in internal combustion engines using estimated variables,” August 2008.

MS Theses

1. Vadiraj Kulkarni, MS in Mechanical Engineering, “Oil Film Thickness Calculation in Variable Loaded Bearings Considering the Elastic Deformations”. November 2004.

2. Mangesh J. Gade, MS in Mechanical Engineering, “ Cylinder pressure Reconstruction from Crankshaft Speed measurement in a Four-Stroke Single Cylinder Diesel Engine”. June 2005.

3. Sivaramakriishnan Muthusubramaniyan, MS in Mechanical Engineering, “Simulation of Cavitation in Engine bearings”, December 2005. For his work, Sivaramakriishnan won one of the 2005 STLE Detroit Section Scholarships.

4. Rupinder Kumar Sharma, MS in Mechanical Engineering, “Performance of EGR Cooling Device”, May 2006.

5. Rajesh Patel, MS in mechanical Engineering, “Telemetric Measurement of Secondary Motion of Piston”, October 2006.

6. Sudharsan Srinivasan, MS in Mechanical Engineering, “Simulation model of piston secondary motion”. December 2007.

7. Fadel, C., 2007,MS in Mechanical Engineering, “An experimental study for a direct measurement of the piston-assembly frictional losses in a single cylinder test”.

8. Edelby, W., 2007, MS in Mechanical Engineering, “Piston secondary motions and hydrodynamic lubrication regime in a single cylinder internal combustion engine”.

9. Vijay K. Venugopal, MS in Mechanical Engineering, “Feasibility Study of Using Piezoelectric Devices in Diesel Injection Applications,” 2004.

10. Jasmeet Singh, MS in Mechanical Engineering, “An Investigation of

Low Temperature Combustion Concept in a Small-Bore High Speed Direct Injection Diesel Engine," June, 2006.

11. Anamitra Bhattacharyya, MS in Mechanical Engineering, "A Quasi Dimensional Model for Droplet Evaporation and Spray Impingement on Combustion Chamber Wall, for a two-Component Fuel," 2006.
12. Mukul Girotra, MS in Mechanical Engineering "Cold Start of Diesel Engine and Analysis of Injection Strategy for Prompt Cold Start," Oct 2000.
13. Yusuf M. Poonawala, MS in Mechanical Engineering, "Effect of EGR, Injection Pressure and Swirl Ratio on Engine-out Emissions for a HSDI Diesel engine at Low Load and Medium Speed Condition," 2007.
14. Krishna Natti, "An Analysis of Sources of Regulated and Unregulated Emissions from a Single Cylinder HSDI Engine in the Low Temperature Combustion Regime" 2007.
15. Ashish Gupta, MS in mechanical Engineering, "Ionization in Diesel Engines, "March 2008.
16. Vinay Nagaraju, MS. in Mechanical Engineering, "Effect Of Injection Pressure, Exhaust Gas Recirculation And Swirl Ratio On Autoignition, Combustion And Engine Out Emissions In An HSDI Engine Fueled By Soybean Biodiesel Blend (B-20)," 2008.
17. Steve Gruenewald, M.S."Effect Of Hydrocarbon Recirculation (Hcr) On Cold Starting of A Direct Injection Common Rail Diesel Engine In Low Ambient Temperature," April 2008.
18. Donghong Jia, M.S.,"Diesel Engine Cycle Simulation During Cold Start Cranking Considering Instantaneous blowby and Heat Transfer", April, 2008.