Multi-objective optimization of the performance-emission trade-off characteristics of a CRDI coupled CNG diesel dual-fuel operation: A GEP meta-model assisted MOGA endeavour

Sumit Roy, Rahul Banerjee

A meta-model based multi-objective optimization endeavor was undertaken in the present work to investigate the potential of the off-line model based calibration technique to extend the actual CRDI-CNG dual-fuel experimental investigations in determining the possibility of unearthing viable potential trade-off domains hitherto unexplored by the constraints of resources, cost and time warranted by an experimental investigation. For the ensuing optimization study, CNG energy share, fuel injection pressure and load have been used as the decision variables while PM, NHC and BSFC were chosen as the output variables to be optimized. In absence of a closed form correlation between the participating variables under study, the explicit characterization capability of the Gene Expression Programming technique was harnessed. The appropriate GEP based meta-models were adopted from a previous study correlating the identical system output responses for the same set of decision variables of interest in the present study. Genetic algorithm was chosen as the optimization routine in the present study in view of its promising potential of extremely fast convergent speed, diversity of optimal solutions and simplicity of operation. Experimental validation of the obtained solutions pertaining to the desired objectives were carried out by actual experimentation. The present optimization endeavor was able to better the best vantage in category of the desired objective of minimum fuel consumption and exhaust emissions, obtained not only as compared to baseline diesel operation comprehensively but also was superior than the actual CRDI-CNG strategy during actual dual-fuel operation corresponding to actual experimentation.

1. Introduction

In order to meet the upcoming global emissions standards in the near future, research studies concur that the impending impasse of the PM-NOx-BSFC trade-off of diesel engines is to be met by deploying non-conventional measures of exhaust after treatment such as SCR, DPF, LNT technology in unison with state-of the art conventional engine designs deemed most appropriate for a given engine application. However, such additional after treatment systems are easier contemplated than implemented, as they pose a considerable operational challenge for ready adaptability to conventional diesel combustion paradigms [1–4]. The significantly higher capital and running costs, increased maintenance chores which stand as additional constraints that inevitably stand to challenge the very notion of scalability of present day after-treatment systems to the new as well as the vast repository of existing diesel engines in a time frame within which the upcoming emission norms go into effect.

CRDI systems with its characteristic ability to simultaneously provide a significantly reduced PM-TUHC-BSFC footprint as compared to conventional diesel operation [5–9], have been aptly considered to be a pivotal technical breakthrough to grace the diesel engines of today. However, the very ability of the CRDI systems to decrease PM emissions has been found to be a penalizing precursor for NOx formation [10–13].

Considering the context of the present day insecurities of conventional fossil fuel based energy resources, air pollution, and climate change that are collectively calling into question the fundamental sustainability of the current fossil fuel based energy system, alternative fuels, are destined to be a dominant stake holder [14] in the transition of the

Abbreviations: BDO, Baseline Diesel Operation; BSFC, Brake Specific Fuel Consumption; CES, CNG Energy Share; CI, Compression Ignition; CRDI, Common Rail Diesel Injection; CNG, Compressed Natural Gas; DI, Direct Injection; GA, Genetic Algorithm; GEP, Gene Expression Programming; HC, Hydrocarbon; IC, Internal Combustion; NHC, NOx + HC; NOx, Oxides of Nitrogen; PM, Particulate Matter; SIT, System Identification Tool

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energy sector in the immediate future. It is in this context that CNG with its inherent synergy of its cheap availability [15,16] and its established potential of reducing the emission footprint of conventional diesel operation [17–23]; has recently found itself as a suitable alternative vector of addressing the imposing performance-emission trade-off challenges in diesel engine paradigms and has consequently been explored as a dual fuel in many studies on the diesel platform. Thus, a potential scope of investigation unfolds wherein the synergistic opportunities of CRDI and CNG in reducing the NHC-PM-BSFC footprint of conventional diesel operation.

To this end, a comprehensive experimental CNG dual fuel investigation was carried out on an existing single cylinder diesel engine at pre-determined load steps (0–100% full load in 25% increments) and varying CNG induction durations on the CRDI strategies which produced the lowest PM-BSFC footprint as compared to BDO at the corresponding load steps respectively. The experimental methodology and the test cases of the CNG-CRDI strategies investigated have been detailed in the previous study of the authors [24].

As per the experimental observations, it was evident that CNG-diesel dual-fuel under CRDI operation yielded commendable PM-NHC-BSFC trade-off incentives to be perused as compared to baseline diesel operation. However, such incentives were observed to be sensitive to the parametric variation of the load, CRDI Fuel Injection Pressure (FIP) and CNG Energy Share (CES). During the experimental endeavour, the decision variables could, but, only be varied on a one-factor-at-time (OFAT) univariate methodology at the discrete load steps under investigation. A-priori full factorial design based recourse to actual experimentation was obviated by the impractical consequences of a prohibitive involvement of the cost of resources and time.

To this end, Approximate meta-model based calibration has been seen here as a viable solution [25–36]. Meta-model based calibration involves the relevant engine or vehicle behaviour being simulated on a PC through a plant model within acceptable levels of accuracy but without compromising the physics of the problem under study, so that the main calibration task of parametric optimization can be done virtually [37–39].

Constructing such approximation models essentially entail a data-based model identification process where parameters of a model relate input variables to the desired responses, through adaptation of actual experimental data [40–42]. Polynomial Regression Models [43], Kriging [44], Radial Basis Function [45,46] and Artificial Neural Networks (ANN) [47,48], Gene Expression Programming [49] and their respective variants represent the major classes [50] of meta-modelling approaches among many others. Their robustness and success as alternative SIT in various engineering disciplines as per their individual scope of appropriateness to a given problem at hand, have seen an unprecedented proliferation of their applications into the model based calibration paradigms of the day.

Of these, GEP strategies in SIT techniques have registered an increasing interest in several engineering disciplines; though its proliferation in IC engine domains, especially in diesel dual fuel domains are yet to mature. Considering the reported proficiency of such GEP strategies to emulate non-linear characteristics in system identification endeavours with indices of commendable accuracy, robustness and more specifically, a unique ability in establishing explicit closed form analytical relationships with the involved decision parameters, a detailed study was undertaken in the previous work [51]. Based on the results of the correlation and statistical metrics evaluation, it was established that the individual GEP metamodels of NHC, PM and BSFCeq could effectively emulate the engine response characteristics with a reliable degree of credibility within the experimental range investigated in [24] corresponding to the chosen decision variables of Load, CNG Energy Share and Fuel Injection Pressure. Thus, in line with the multi-objective optimization endeavour intended in the present study, the GEP models were adopted as an appropriate system identification platform to explore the parametric engine design space as provided by the experimental range of the involved decision variables through the Multi objective Genetic Algorithm search routine. Multi objective Genetic Algorithms bearing its genesis from the fundamentals of evolutionary algorithms (EA) are essentially a class of stochastic optimization routines that emulate the metaphor of natural biological evolution or the social behaviour of species.

Considering the discussions enumerated above, a first-of-its-kind GEP meta-model assisted multiobjective optimization endeavour was envisaged with a quest to determine the optimal NHC-PM-BSFCeq trade-off points of operation in an existing diesel engine under a CRDI-CNG dual fuel approach with a distinct perspective of meeting the applicable EPA Tier 4 final NHC-PM emission mandates.

2. Experimental investigation

2.1. Experimental setup

The experiment was conducted on an existing single cylinder four-stroke CI engine coupled to a Common Rail Direct Fuel Injection system as detailed in Table 1. The engine was coupled to an air-cooled eddy current dynamometer of PowerMag® make. The CRDI setup is an attachment to the experimental engine. The description of the fuel injection system is given in Table 2. The CNG was stored in a 25 lit cylinder compressed at 210 bar. The CNG was inducted into the Vidhata make VL-8 single cylinder four stroke diesel engine through the manifold of the engine intake. Technical Specification CNG Injector Rail is given in Table 3. The CNG energy share was calculated as per Eq. (1) [51,52]. The exhaust gases were experimented by a “5 Gas analyzer” and an “AVL smoke meter (415S)” was used to measure the soot content, present in the exhaust. The specifications of the emission measuring apparatus are detailed in Tables 4 and 5 [9].

\[
\text{CES} = \frac{[\text{PM}] \times \text{LHV}_{\text{PM}} - [\text{NHC}] \times \text{LHV}_{\text{NHC}}]}{[\text{BSFC}] \times \text{LHV}_{\text{PM}}}
\]

(1)

2.2. Experimental methodology

In the present experimental work, the fuel injection methodology

Table 1

<table>
<thead>
<tr>
<th>Specification</th>
<th>Resources</th>
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<tbody>
<tr>
<td>Make</td>
<td>Vidhata</td>
</tr>
<tr>
<td>No of Cylinder</td>
<td>One (1)</td>
</tr>
<tr>
<td>Bore</td>
<td>120 mm</td>
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<tr>
<td>Stroke</td>
<td>139.7 mm</td>
</tr>
<tr>
<td>Displacement</td>
<td>1580 cc</td>
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<tr>
<td>Cooling</td>
<td>Water</td>
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<tr>
<td>Compression Ratio</td>
<td>18:1</td>
</tr>
<tr>
<td>Valve Timing</td>
<td></td>
</tr>
<tr>
<td>Exhaust valve opening</td>
<td>35 deg before BDC</td>
</tr>
<tr>
<td>Exhaust valve closing</td>
<td>4 deg after TDC</td>
</tr>
<tr>
<td>Inlet valve opening</td>
<td>4 deg before TDC</td>
</tr>
<tr>
<td>Inlet valve closing</td>
<td>35 deg after BDC</td>
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</tbody>
</table>

Table 2

<table>
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<tr>
<td>Make</td>
<td>Bosch</td>
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<tr>
<td>Injection Pressure</td>
<td>10–120 MPa</td>
</tr>
<tr>
<td>Number of Holes</td>
<td>5 (Symmetric)</td>
</tr>
<tr>
<td>Nozzle Diameter</td>
<td>0.15 mm</td>
</tr>
<tr>
<td>Injection Angle</td>
<td>120°</td>
</tr>
</tbody>
</table>

Table 3

<table>
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<th>Specification</th>
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<tr>
<td>Make</td>
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