

CNN-Based Virtual Sensing of Rate of Heat Release for Fuel-Robust Diesel Engine Control (First Report)

-Rate of Heat Release Estimation and Improvement in Estimation Accuracy-

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KEY WORDS: Heat engine, Compression ignition engine, Combustion analysis, Machine learning [A1]

Variations in fuel properties, including cetane number, affect ignition delay and the rate of heat release (RHR) under the same engine operating and control conditions. To compensate for these effects, a combustion-control concept was proposed in which RHR is estimated from signals obtainable from onboard sensors and engine control parameters are adjusted to reproduce a target RHR profile. As a first step toward implementing this concept, this study evaluated virtual sensing of apparent RHR using a conditional generative adversarial network combined with a convolutional neural network (cGAN-CNN).

Training data were acquired on a production 2.2-L four-cylinder direct-injection diesel engine. In-cylinder pressure was measured in cylinder No. 1, and crank angular acceleration was derived from the pulse intervals of a 720-pulse/rev. rotary encoder. Both in-cylinder pressure and crank angular acceleration were low-pass filtered at 2 kHz. Apparent RHR was calculated from in-cylinder-pressure data based on the first law of thermodynamics. cGAN-CNN models were trained using in-cylinder pressure, rate of pressure rise, or crank angular acceleration as input. Each input waveform and its corresponding RHR profile were converted into 128×128 -pixel images. The models were trained for 70 epochs using 19,800 cycles acquired at 66 steady-state operating points under three start-of-injection (SOI) conditions (the production-calibrated setting and $\pm 3^\circ\text{CA}$). All models were trained exclusively using JIS No. 2 diesel data. The models' ability to reproduce changes in combustion phasing was evaluated at three operating points not used for training by varying the injection timing in 1°CA increments over a range of $\pm 3^\circ\text{CA}$. Small changes associated with the difference in cetane number were evaluated using EPA diesel. Main-combustion start timing (CST), peak RHR (PHR), and peak RHR timing (PHT) were extracted from the calculated and estimated RHR profiles, and estimation accuracy was evaluated using the coefficient of determination (R^2) between the corresponding values.

The model using in-cylinder pressure as input yielded R^2 values of 0.681, 0.989, and 0.963 for CST, PHR, and PHT, respectively. PHR and PHT showed high estimation accuracy, whereas CST estimation remained less accurate. To evaluate the effect of a small difference in cetane number, results obtained with EPA diesel (CN 59.3) were compared with those obtained with JIS No. 2 diesel (CN 56.8). Fig. 1 compares the calculated and estimated RHR profiles for the two fuels at 1800 rpm and 200 Nm. The calculated profiles exhibited a small difference between the fuels. The model using in-cylinder pressure as input did not reproduce this difference sufficiently because the corresponding in-cylinder-pressure difference was equivalent to less than one pixel in the input image. To address this limitation, rate of pressure rise was adopted as the model input to better resolve the fuel-dependent difference at the given image resolution. This change improved the reproduction of the fuel-dependent RHR difference. The resulting R^2 values were 0.943, 0.982, and 0.984 for CST, PHR, and PHT, respectively.

The model using crank angular acceleration as input yielded R^2 values of 0.674, 0.898, and 0.822 for CST, PHR, and PHT, respectively, as shown in Fig. 2. These results demonstrate the feasibility of RHR virtual sensing without an in-cylinder pressure sensor, although CST estimation requires further improvement. Future work will investigate whether augmenting the training set with transient data spanning a wider operating range improves the RHR estimation accuracy of the model using crank angular acceleration under operating conditions not represented in the training set, prior to its application to RHR-based feedback control.

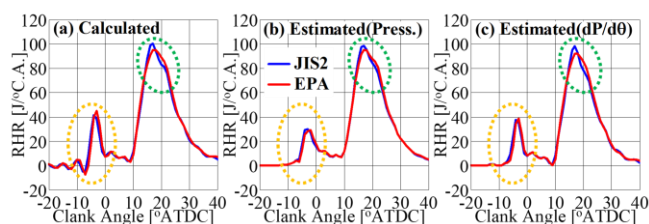


Fig.1 Effect of input-signal resolution on RHR estimation accuracy for cylinder-pressure and rate-of-pressure-rise inputs

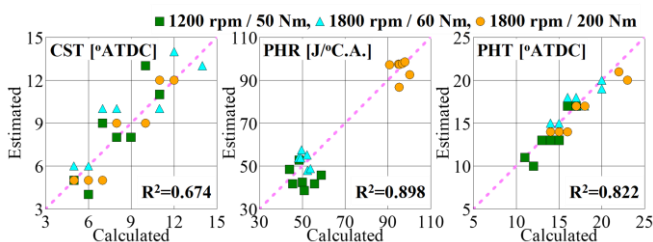


Fig.2 RHR estimation accuracy using crank angular acceleration