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Reconfigurable Computing Research Laboratory

Instantaneous Cylinder Pressure Estimation

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October 30th, 2017

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Outline

- Introduction
- Model for Engine Cylinder Pressure Estimation
  - Description
  - Tests: GM data(3), FCA data(10).
- Hardware implementation
  - Self-Reconfigurable embedded systems.
  - Hardware architecture and embedded interface
- Goals
  - Interpolation of the model.
  - Run-time reconfigurable hardware.

Introduction

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- **Cylinder Pressure Estimation**: This is useful information for engine operation. It can be used to: balance the power given to different cylinders to the engine crankshaft, detect disturbance in the engine operation, compute the optimal spark timing, etc.

- ***Traditional methodology***: Most of today's vehicle engines rely on pre-computed values of cylinder pressure for different operating conditions. This look-up table approach does not scale well with changes in operating conditions or parameters, as the amount of required memory can grow very quickly.

- ***Our method***: We develop a model to compute an estimation of the engine pressure based on specific conditions (e.g.: speed, amount of fuel being used, engine parameters, etc.). This model can then be used to generate meaningful parameters such as instant torque, optimal spark timing, etc.

- For real-time operation, this model is best suited for dedicated hardware implementation for real-time cylinder pressure estimation.

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Procedure

- Relationship among heat release rate, pressure, volume, and heat lost (heat release) for a *closed cylinder engine* (using 1st Law of Thermodynamics):

$$\frac{dQ_{HR}}{d\theta} = \frac{\gamma}{\gamma-1} P \frac{dV}{d\theta} + \frac{1}{\gamma-1} V \frac{dP}{d\theta} + \frac{dQ_{HT}}{d\theta}$$

- Discrete Model:

$$\frac{dQ_{HR}}{d\theta} = \frac{\gamma}{\gamma-1} P(n) \frac{dV}{d\theta} + \frac{1}{\gamma-1} V(n) \left(\frac{P(n+1)-P(n)}{\theta(n+1)-\theta(n)}\right) + \frac{dQ_{HT}}{d\theta}.$$

- Then:

$$P(n+1) = P(n) + \Delta\theta \left[\frac{(\gamma-1)}{V(n)} \frac{dQ_{HR}}{d\theta}\bigg|_n - \gamma \frac{P(n)}{V(n)} \frac{dV}{d\theta}\bigg|_n - \frac{(\gamma-1)}{V(n)} \frac{dQ_{HT}}{d\theta}\bigg|_n \right].$$

- We have an *empirical model* for the Heat Transfer Rate:

$$\frac{dQ_{HT}}{d\theta}\bigg|_n = \frac{dQ_{HT}}{dt} \frac{dt}{d\theta} = h_{corr}(n) A_{ch}(n) \left(T_g(n) - T_w\right) \frac{30}{N\pi}, N = rpm.$$

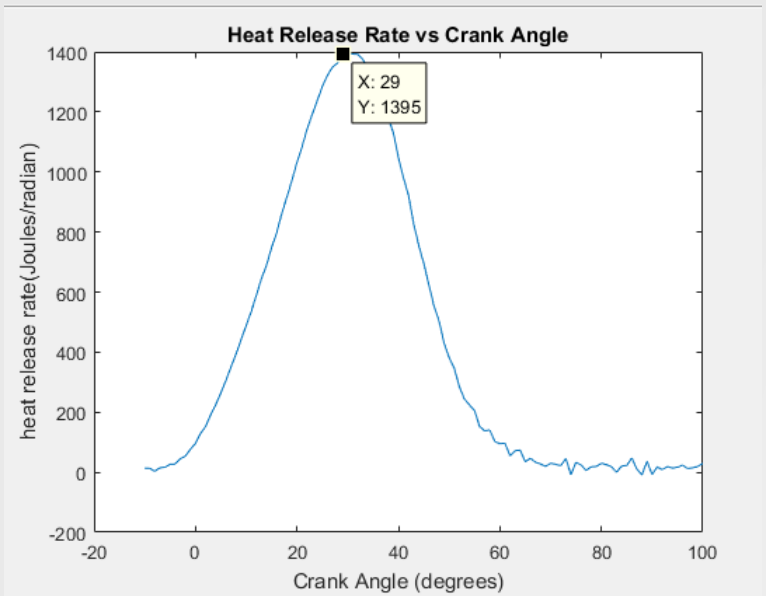
$$h_{corr}(n) = c \times 0.013 \times V(n)^{-0.06} \times P(n)^{0.8} \times T_g(n)^{-0.4} \times \left(v_p + 1.4\right)^{0.8}.$$

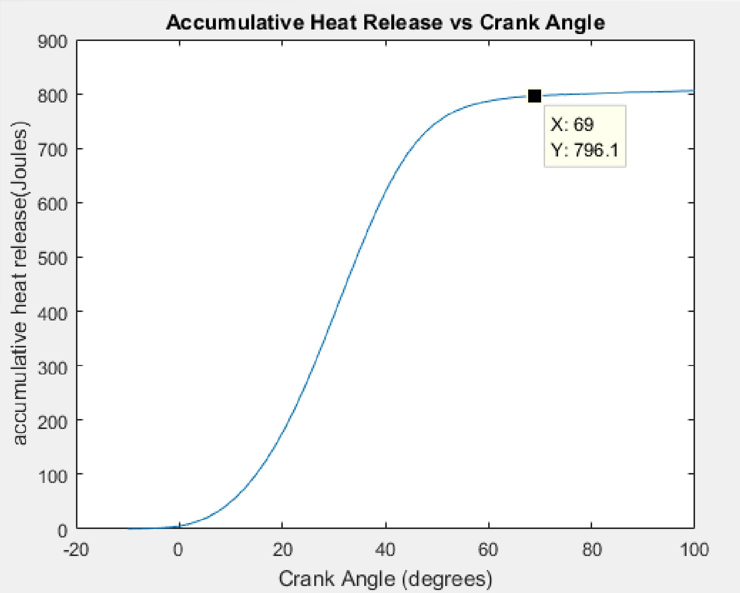
- Heat Release Rate: We approximate the function with:

$$\frac{dQ_{HR}}{d\theta}\bigg|_n = \begin{cases} 0, for\ \theta_n \le \theta_0. \quad \theta_0 : spark\ time \\ \frac{\eta_c m_f LHV \alpha(\beta+1)}{\Delta\theta_B (1-e^{-\alpha})} \left(\frac{\theta_n - \theta_0}{\Delta\theta_B}\right)^{\beta} \times e^{\left[-\alpha\left(\frac{\theta_n-\theta_0}{\Delta\theta_B}\right)^{\beta+1}\right]}, for\ \theta_n > \theta_0 \end{cases}.$$

Procedure

- Many parameters in the model can be directly obtained by the engine data and the operating conditions (rpm, pressure of chamber, etc.). However, there are coefficients and parameters that we cannot get unless we have sensing data at every crank angle (e.g.: pressure).
- Based on Real Pressure Data, we initially assume some constants in the Heat Transfer Rate, and we get the curve for the Heat Release Rate.
- We then plot the cumulative Heat Release in order to get the Total heat release (which is a constant given by $\eta_c m_f LHV$). Most likely, this does not match, so we need to adjust the constants in the Heat Transfer Rate so that the cumulative Heat Release reaches the total heat release.

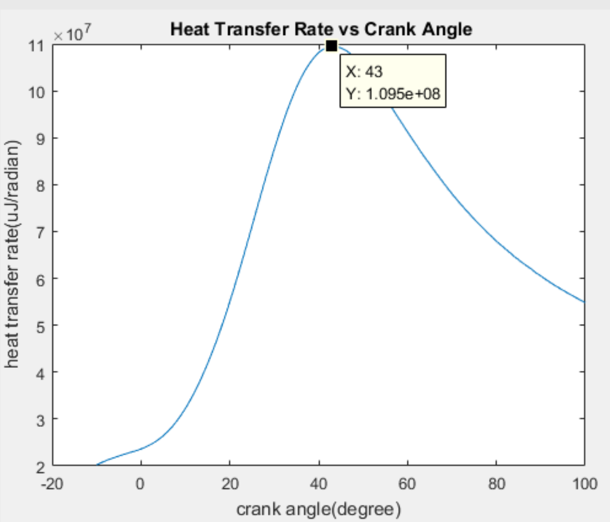


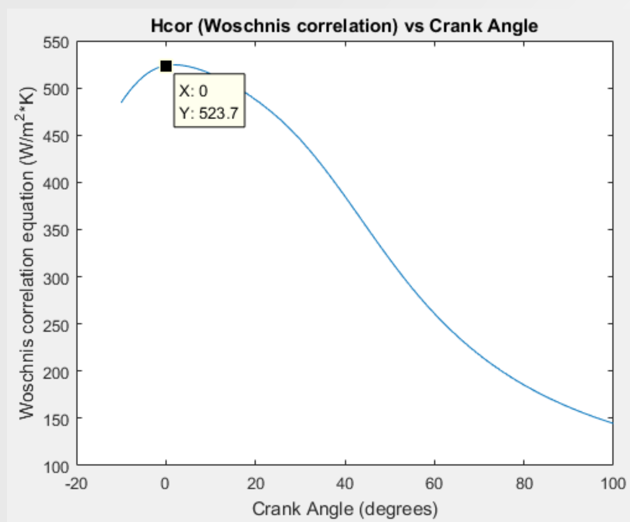


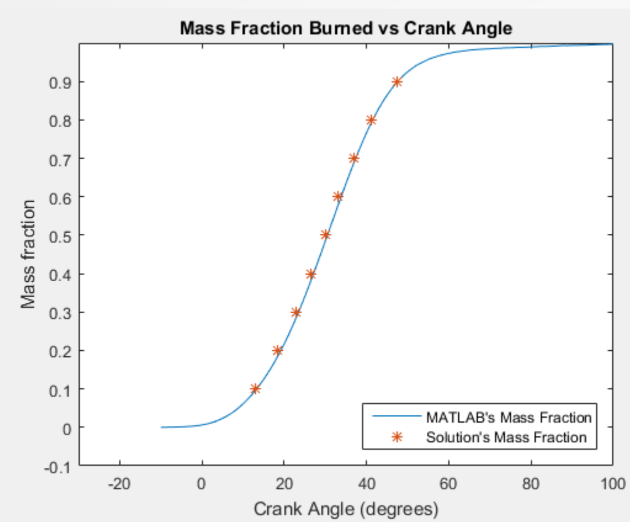
Procedure

- Once this process is completed, we get:
  - The actual Heat Release Rate $\left.\frac{dQ_{HR}}{d\theta}\right|_n$.
  - A complete model for the Heat Transfer Rate. We show this plot along with the Woschni's function (h_{corr}).

- We also show the mass fraction vs. crank angle. This is equal to the cumulative Heat Release Rate divided by $\eta_c m_f LHV$ for every crank angle. When the cumulative HR reaches its maximum ($\eta_c m_f LHV$), the mass fraction reaches 1.







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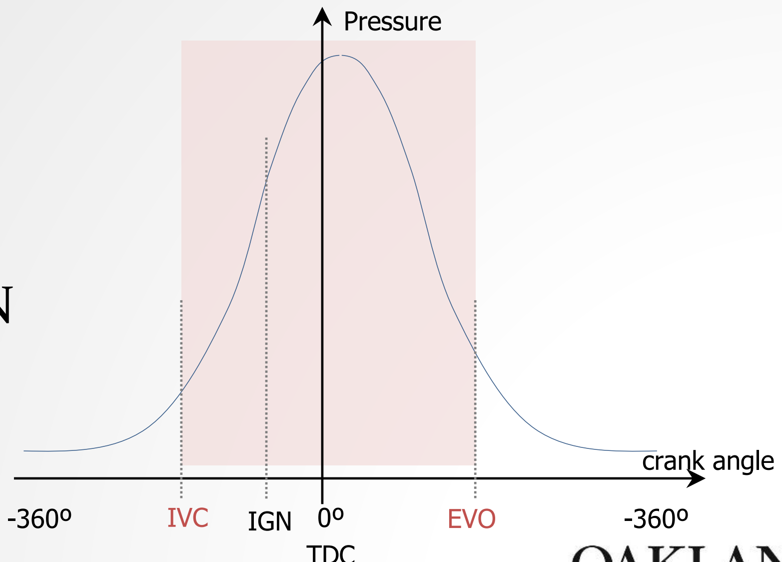
Procedure

- **Approximation of Heat Release Rate:** Since, we have the actual Heat Release Rate, we can now perform ***curve fitting*** to approximate the Heat Release Rate. This step will provide the values α and β.
  - ✓ GM: Curve-fitting for the HR Rate is better.
  - ✓ FCA: Curve-fitting needs improvements. We noted that curve-fitting improved when the spark timing was delayed.
- With the approximated Heat Release Rate and the model for the Heat Transfer completed, we can compute an estimated pressure trace.
- **Reference for the Crank Angles:**
  - ✓ Pressure and Heat Release Rate are estimated from IVC to EVO.
  - ✓ Heat Release Rate is plotted from IGN (spark timing) to EVO. Pressure is plotted from IVC to EVO.



Procedure

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- **Validation**: We compare the Heat Release Model with the actual Heat Release. We also compare the estimated pressure trace against the real one. The metric used is Relative Error:

$$Relative\ Error = \frac{Estimated\ value\ - Actual\ Value}{Actual\ Value}$$

- Then, for a certain engine comes with a set of specific conditions:
  - ✓ We can derive a model for each condition (load, rpm) and obtain the estimated pressure trace for each case.
  - ✓ Eventually, for many load and rpm conditions, we can *interpolate* between this data, and get the estimated pressure.

- **Usefulness of this method**:
  - ✓ The estimated pressure is not stored (otherwise, we better store the actual pressure trace and then interpolate).
  - ✓ Instead, our model only needs to store the parameters of: our model (Heat Transfer, Heat Release Rates), the engine, and the operating conditions (load, rpm), in order to generate the estimated pressure trace.
  - ✓ In order to meet real-time requirements for instantaneous pressure estimation, our method requires a dedicated hardware implementation.

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Results

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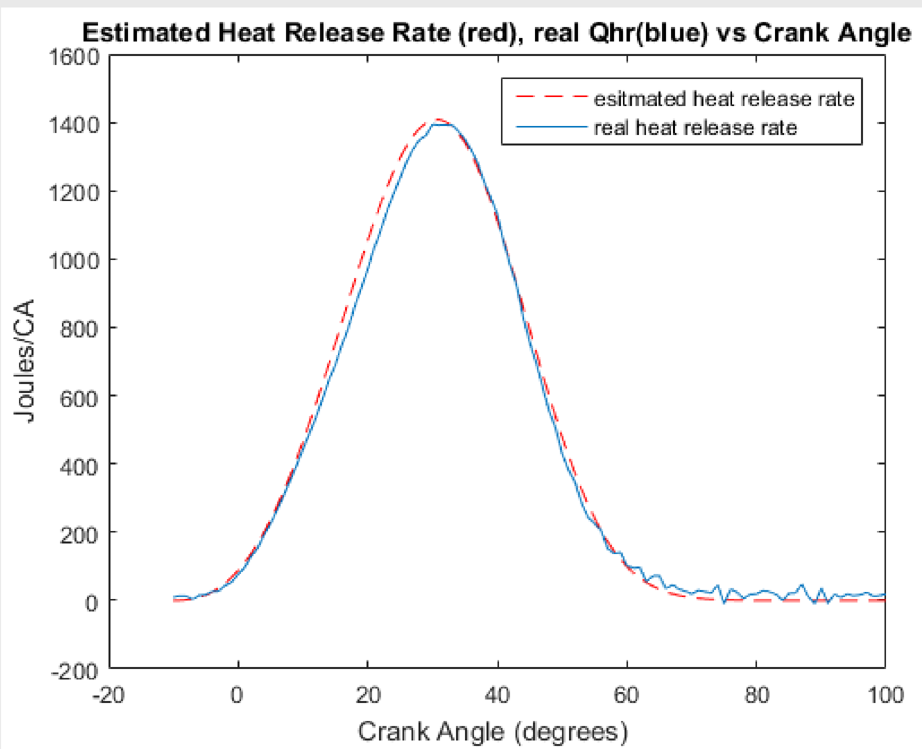
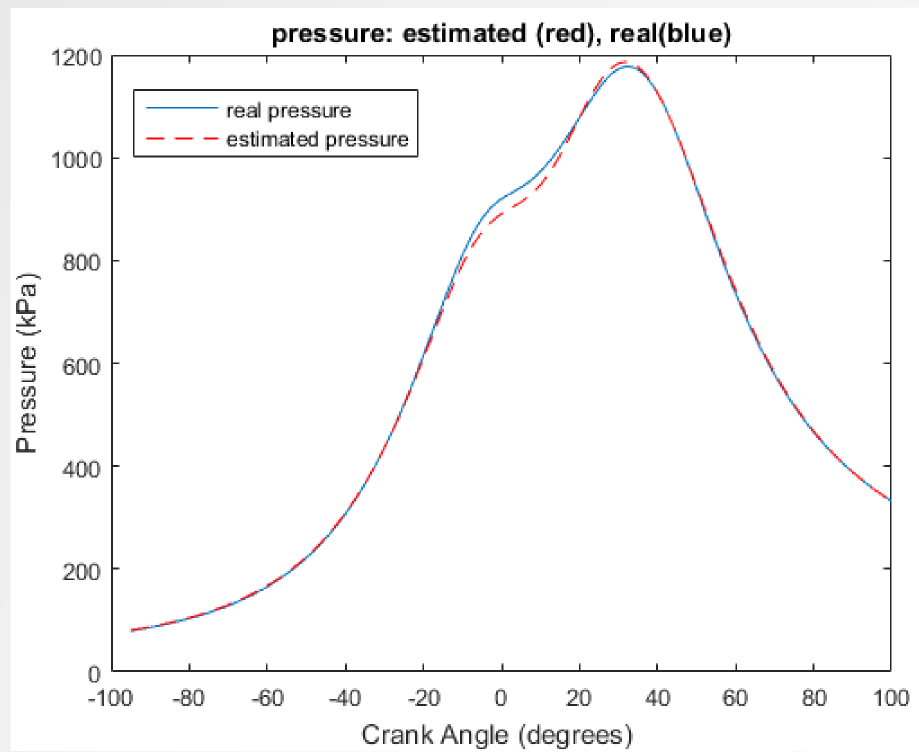
- 3 sets (from a GM engine), and 10 FCA sets.
- We list: data from the engine and operating conditions (e.g.: fuel, IVC, EVO, rpm), and parameters of the Heat Transfer and Heat Release Rates: c, α, β.
- Relative error: We compare estimated and actual pressure traces.

	GM. LHV: 43.5 MJ/kg, η_c: 97%			FCA data. LHV: 41.58 MJ/kg, η_c: 97%									
	Set 1	Set 2	Set 3	1250 2 bar	1250 4 bar	1250 6 bar	2000 2 bar	2000 6 bar	2000 8 bar	3200 4 bar	3200 6 bar	4000 4.5 bar	4000 WOT
θ_0	-10	-26	-40	-14	-14	-10	-17	-15	-10	-20	-13	-15	-8
Rpm	1300			1250	1250	1250	2000	2000	2000	3200	3200	4000	4000
Residual Fraction	0.108	0.1285	0.125	0.135	0.125	0.125	0.125	0.125	0.11	0.125	0.1	0.125	0.125
Fuel	18.58	16.692	17.08	13.66	21.88	29.70	14.01	29.81	38.12	22.65	30.67	25.75	62.58
Air fuel ratio	13.9			13.81	13.82	13.84	13.85	13.9	13.91	13.94	13.88	13.92	11.09
IVC	-95	-95	-95	-88	-87	-87	-87	-87	-95	-87	-91	-91	-109
EVO	100	100	100	123	124	124	124	124	116	124	120	120	102
Burn Duration	64	61	70	43	38	41	103	45	46	42	41	38	43
α	3.45	4.45	10.68	3.243	4.719	4.719	4.782	4.47	4.002	3.347	3.068	3.346	3.125
β	2.48	3.154	4.3	1.947	2.066	2.173	1.961	1.952	1.762	2.69	2.047	2.33	2.327
C	1.45	1.43	1.52	1.35	1.2	1.3	1.45	1.45	1.5	1.25	1.55	1.2	1.45
Relative error -avg	1.0%	1.2%	1.6%	2.2%	2.0%	1.81%	2.49%	3.07%	2.2%	5.4%	4.5%	3.6%	4.34%

Results

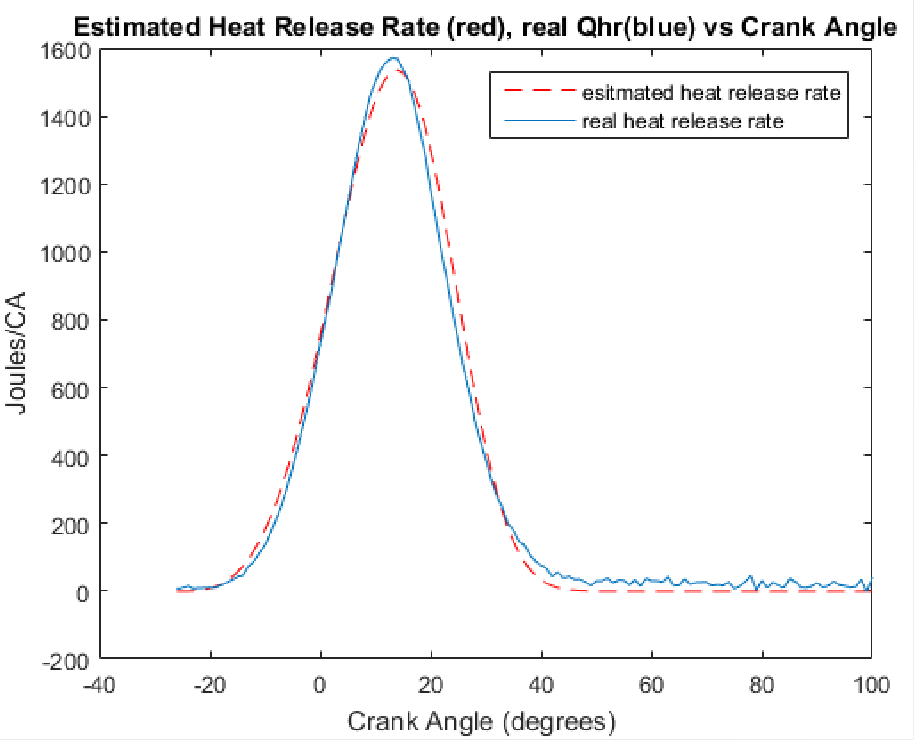
- **1st Data Set (GM engine, 1300 rpm)**
  - Heat Release Rate. From IGN (-10°) to EVO (100°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.45, \beta = 2.48.$
  - Pressure. IVC (-95°) to EVO (100°)
    - Estimated pressure trace (**red**-dotted line).

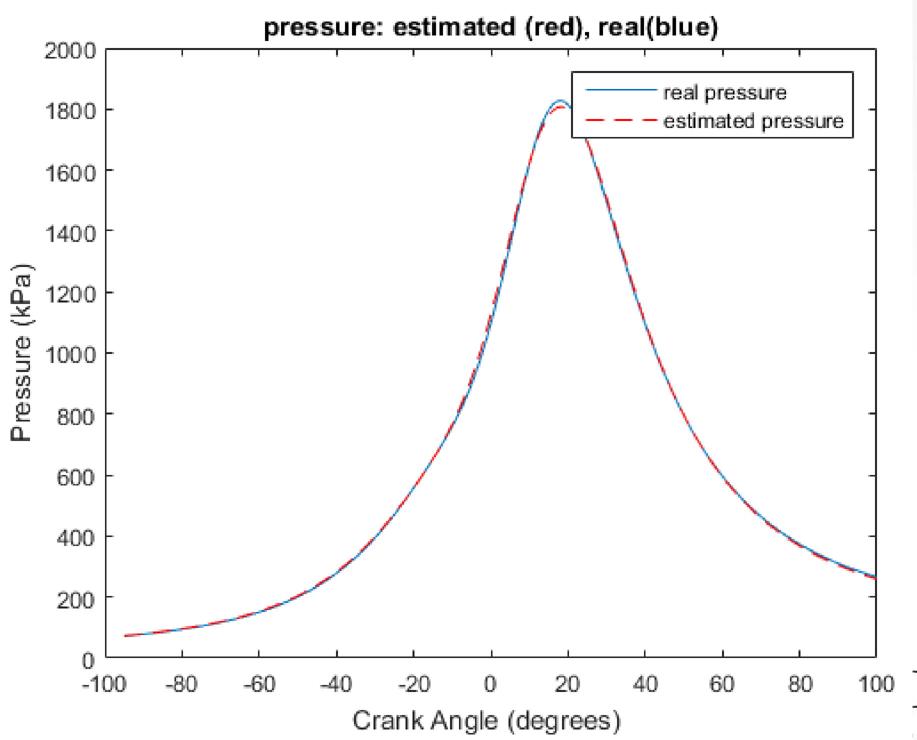




Results

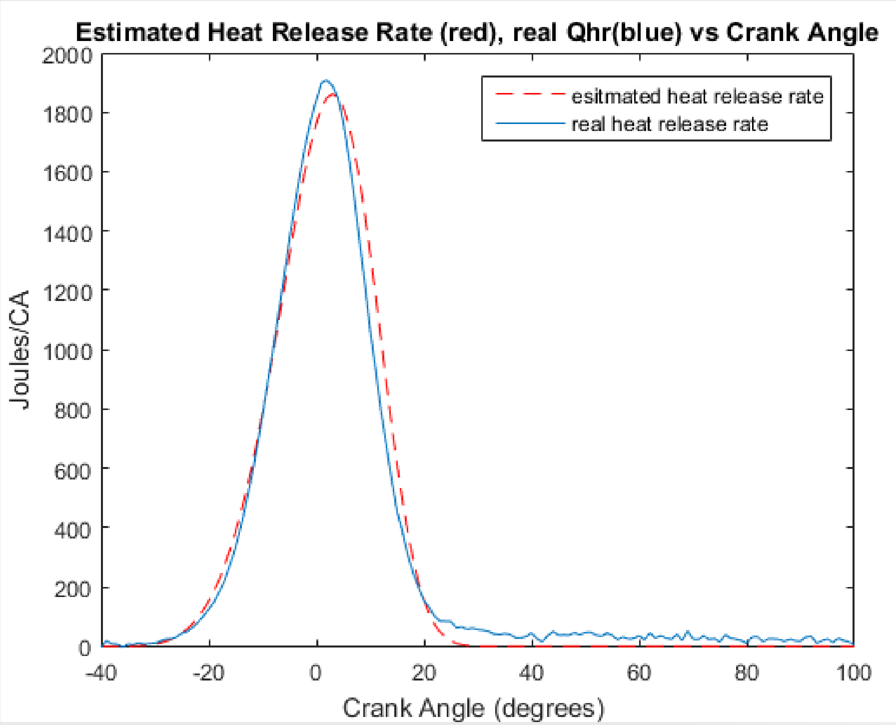
- **2nd Data Set (GM engine, 1300 rpm)**
  - Heat Release Rate. From IGN (-26°) to EVO (100°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.45, \beta = 2.48.$
  - Pressure. IVC (-95°) to EVO (100°)
    - Estimated pressure trace (**red**-dotted line).

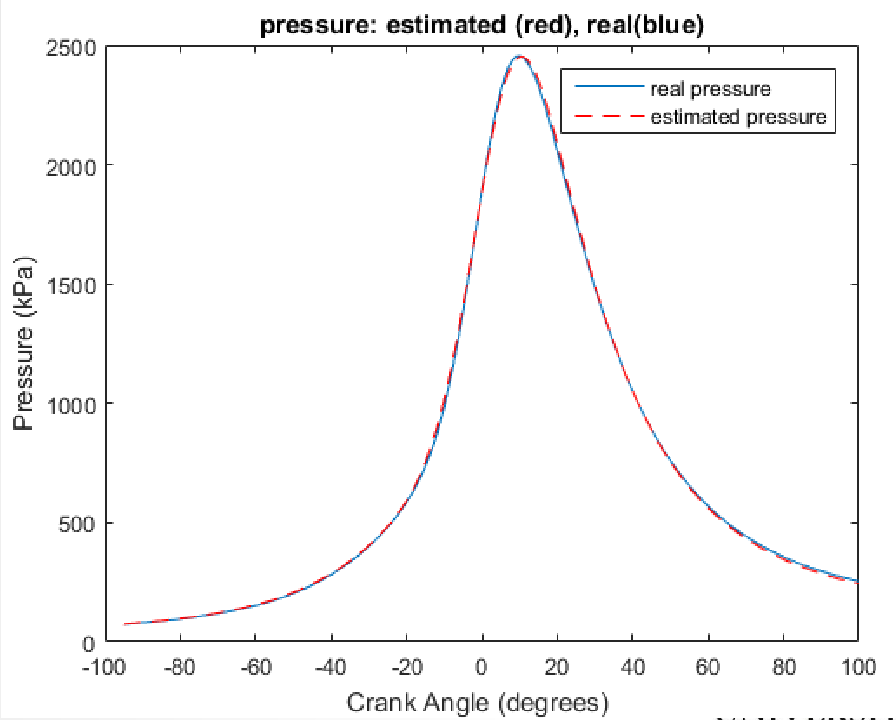




Results

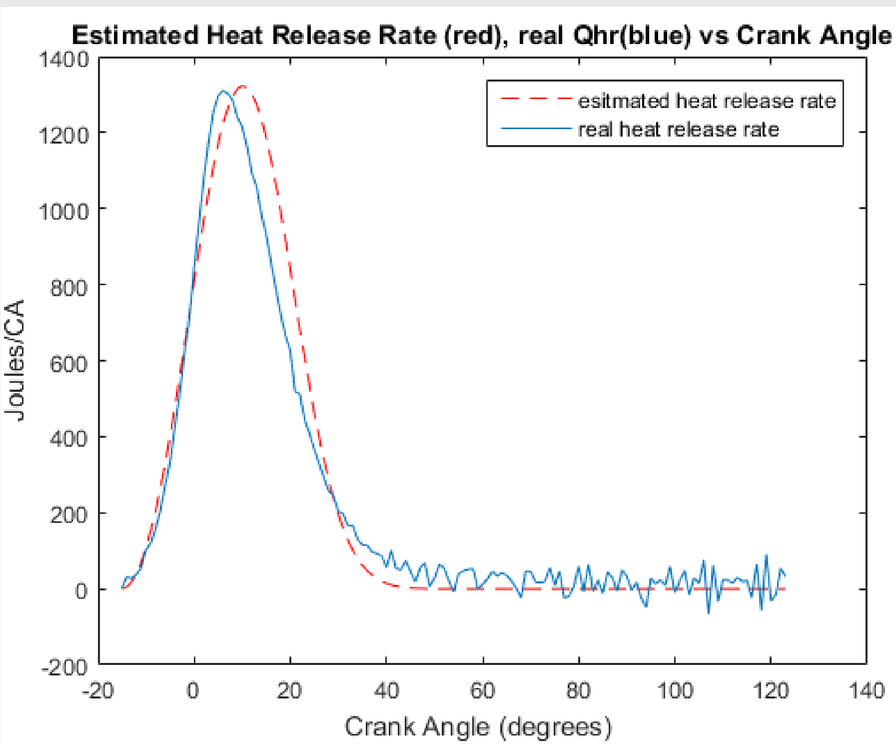
- **3rd Data Set (GM engine, 1300 rpm)**
  - Heat Release Rate. From IGN (-40°) to EVO (100°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 10.68$, $\beta = 4.3$.
  - Pressure. IVC (-95°) to EVO (100°)
    - Estimated pressure trace (**red**-dotted line).

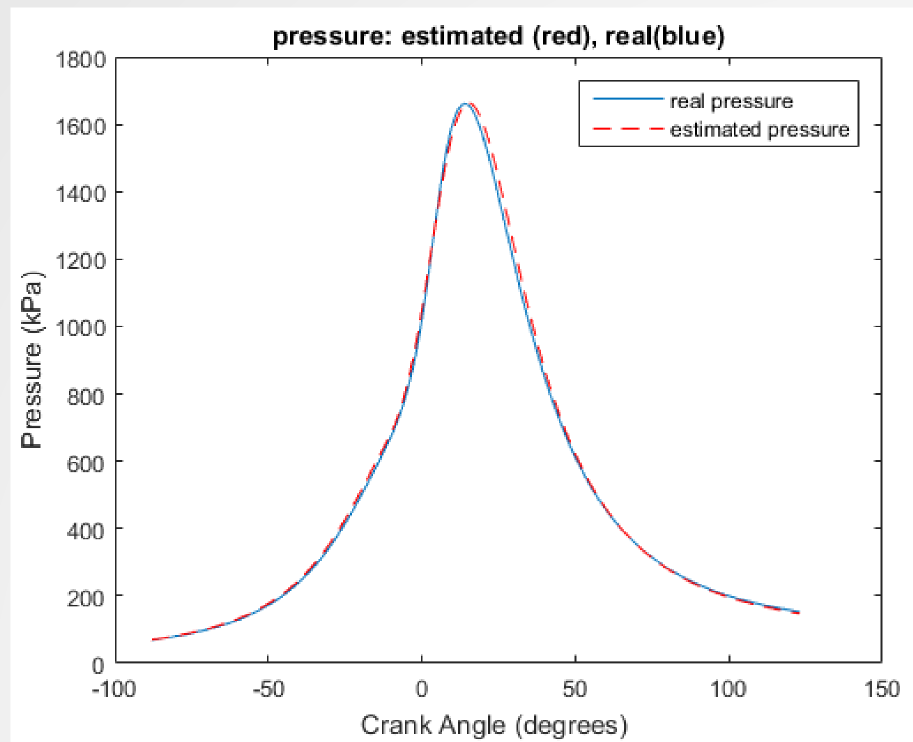




Results

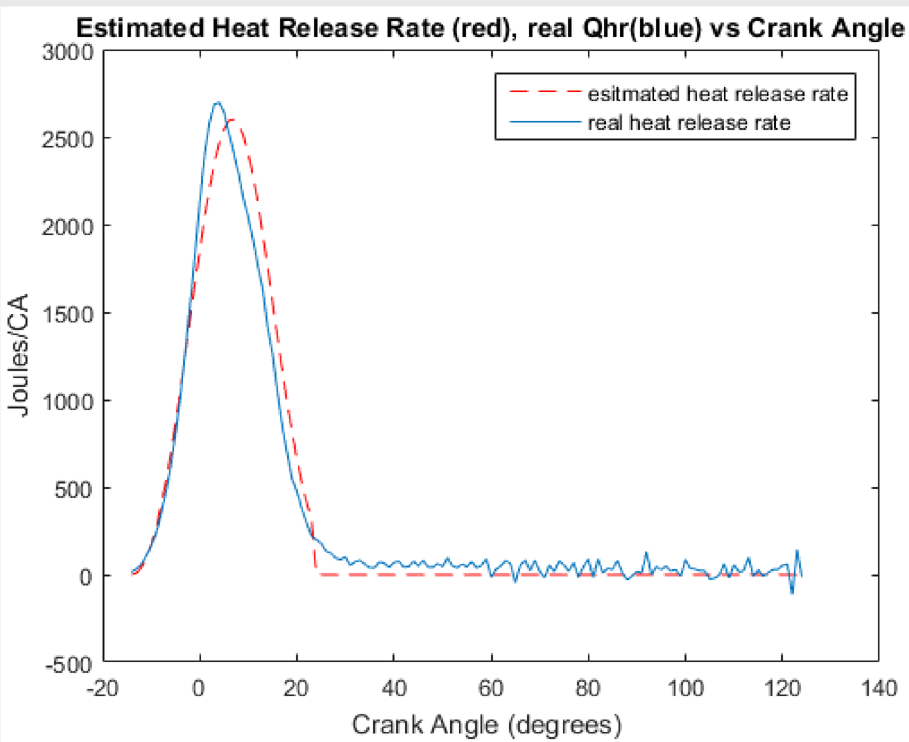
- **1st FCA Data Set (1250 rpm, 2 bar).** IGN delayed. Original IGN: -23°
  - Heat Release Rate. From IGN (-14°) to EVO (123°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.243, \beta = 1.947$.
  - Pressure. IVC (-88°) to EVO (123°)
    - Estimated pressure trace (red-dotted line).

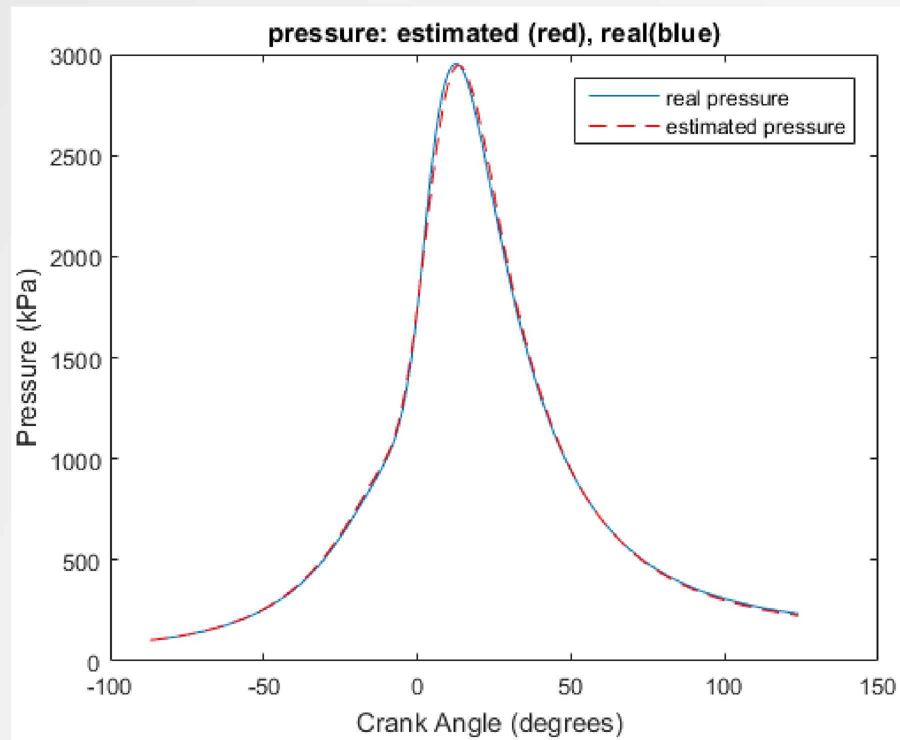




Results

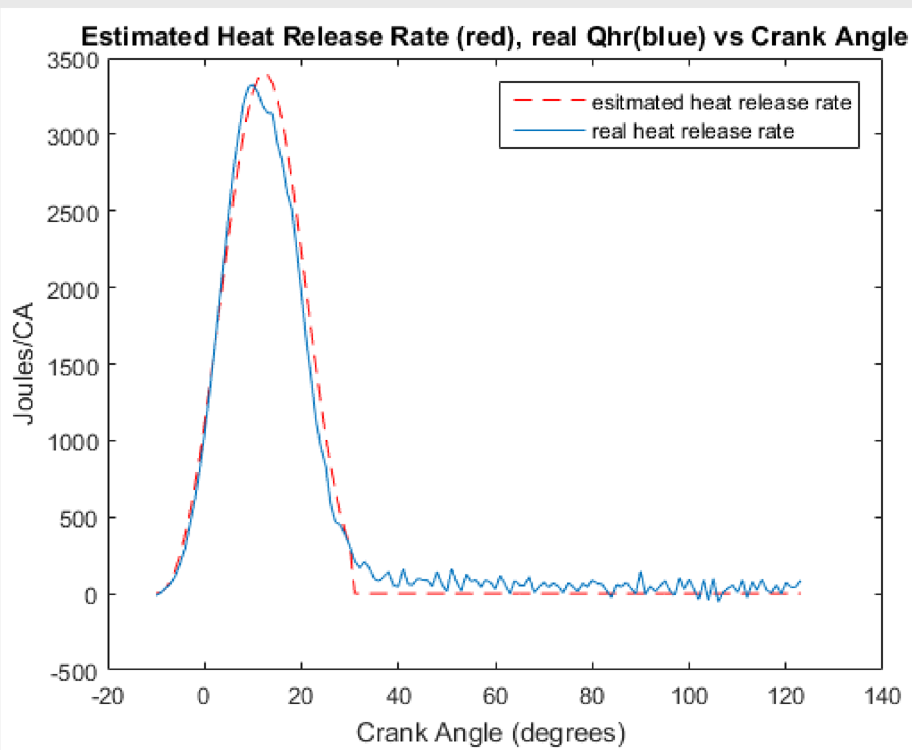
- **2nd FCA Data Set (1250 rpm, 4 bar).** IGN delayed. Original IGN: -19°
  - Heat Release Rate. From IGN (-14°) to EVO (124°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 4.719, \beta = 2.066.$
  - Pressure. IVC (-87°) to EVO (124°)
    - Estimated pressure trace (**red**-dotted line).

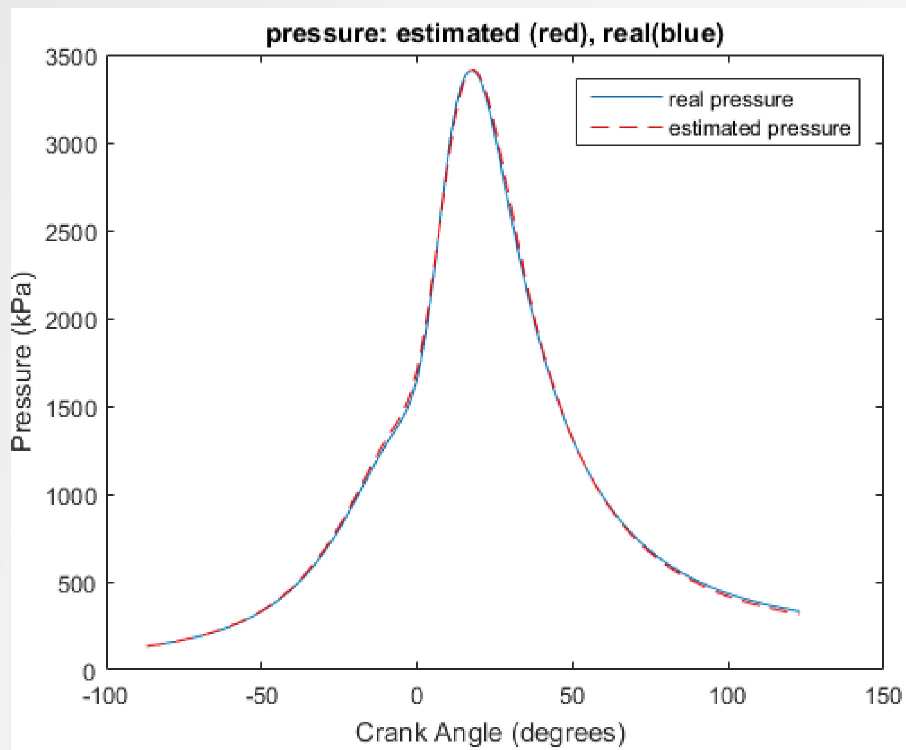




Results

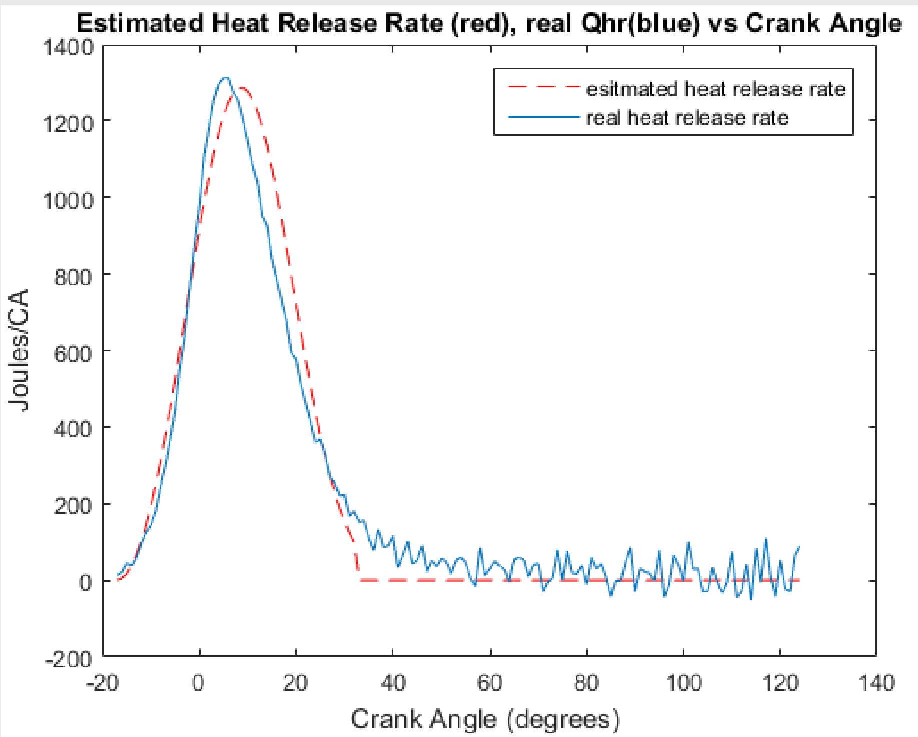
- **3rd FCA Data Set (1250 rpm, 6 bar).** IGN delayed. Original IGN: -13°
  - Heat Release Rate. From IGN (-10°) to EVO (124°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 4.719, \beta = 2.173.$
  - Pressure. IVC (-87°) to EVO (124°)
    - Estimated pressure trace (**red**-dotted line).

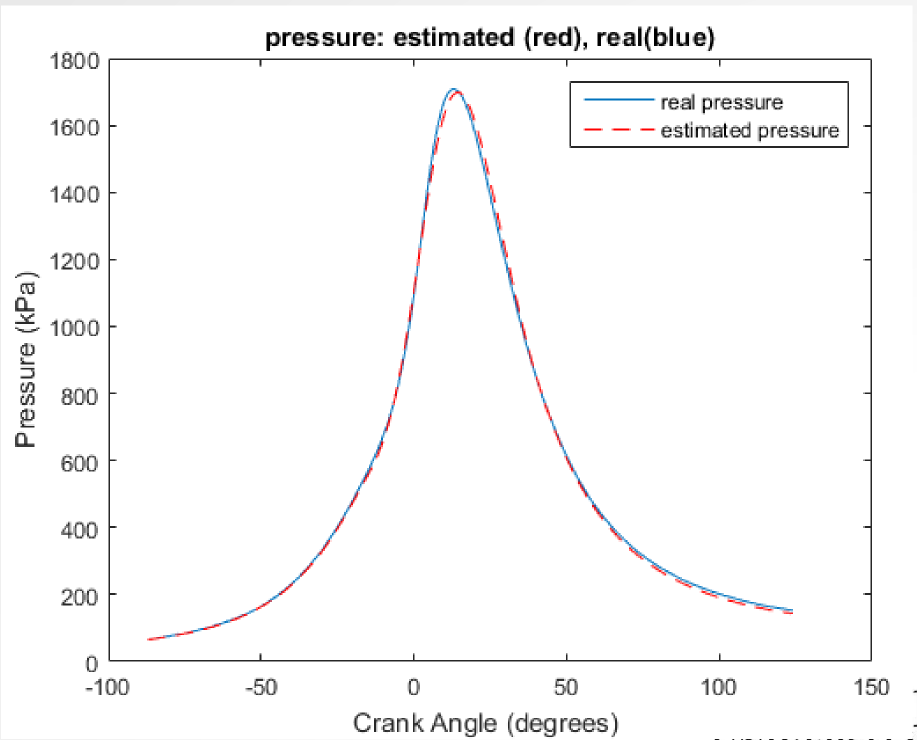




Results

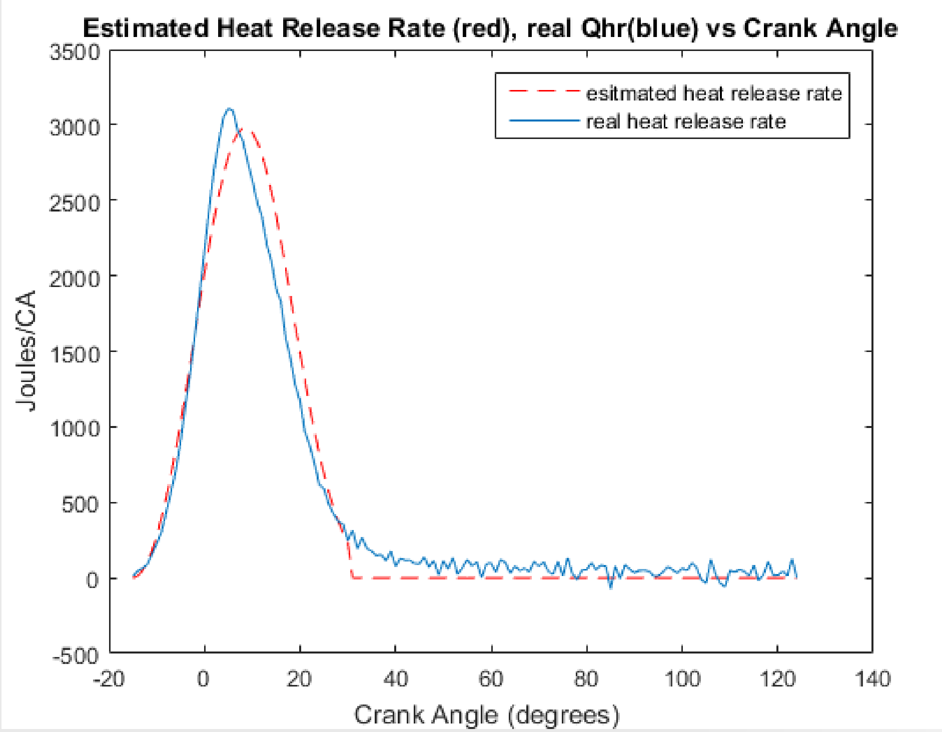
- **4th FCA Data Set (2000 rpm, 2 bar).** IGN delayed. Original IGN: -29°
  - Heat Release Rate. From IGN (-17°) to EVO (124°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 4.782, \beta = 1.961$.
  - Pressure. IVC (-87°) to EVO (124°)
    - Estimated pressure trace (**red**-dotted line).

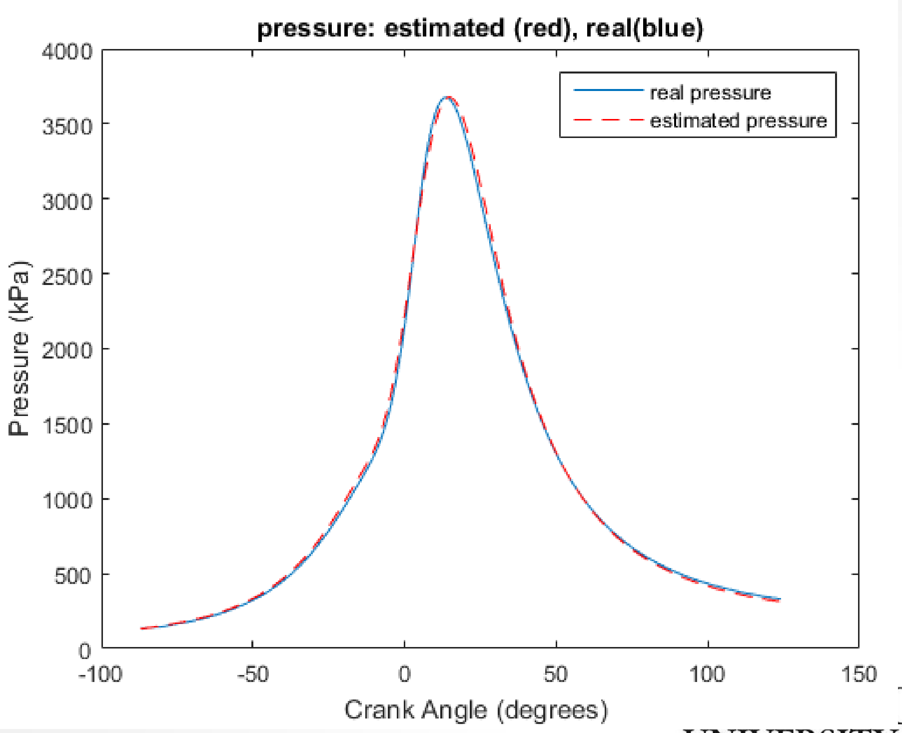




Results

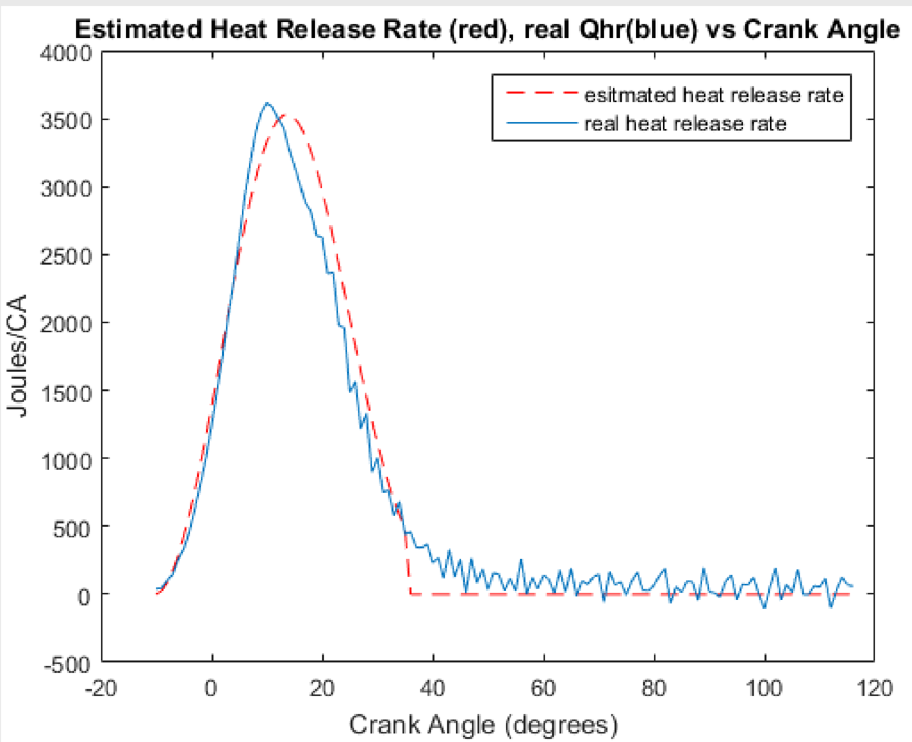
- **5th FCA Data Set (2000 rpm, 6 bar).** IGN delayed. Original IGN: -22°
  - Heat Release Rate. From IGN (-15°) to EVO (124°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 4.47, \beta = 1.952.$
  - Pressure. IVC (-87°) to EVO (124°)
    - Estimated pressure trace (**red**-dotted line).

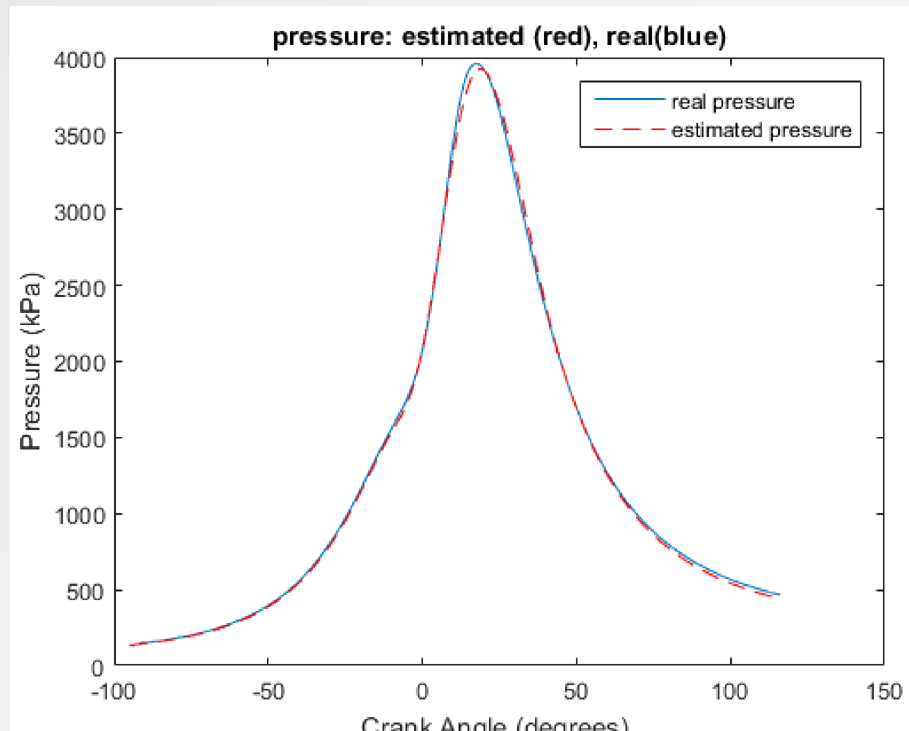




Results

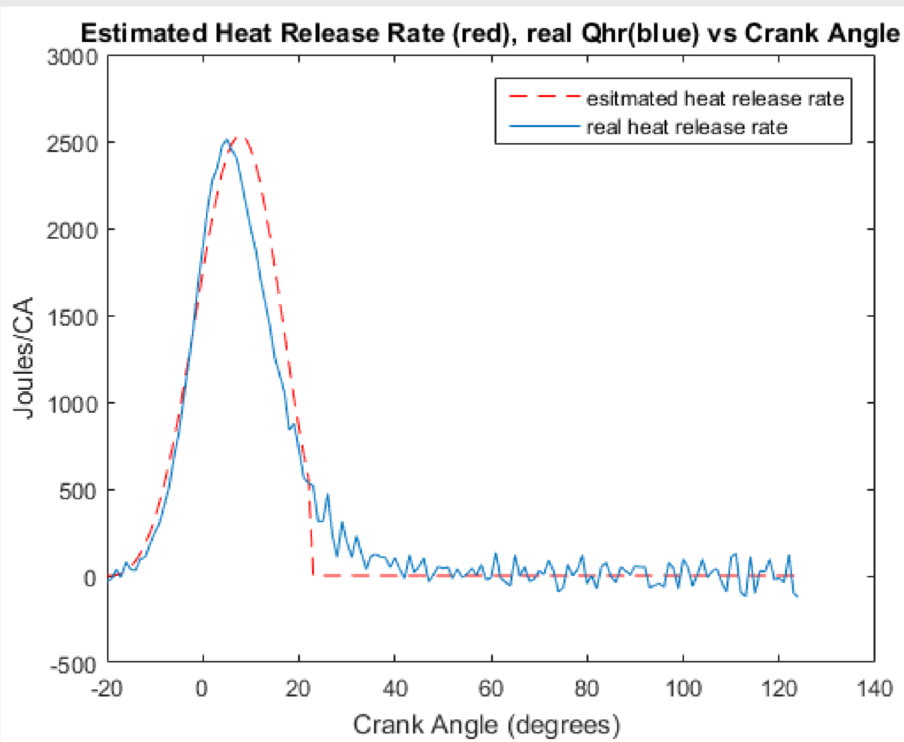
- **6th FCA Data Set (2000 rpm, 8 bar).** IGN delayed. Original IGN: -16°
  - Heat Release Rate. From IGN (-10°) to EVO (116°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.243, \beta = 1.947.$
  - Pressure. IVC (-95°) to EVO (116°)
    - Estimated pressure trace (**red**-dotted line).

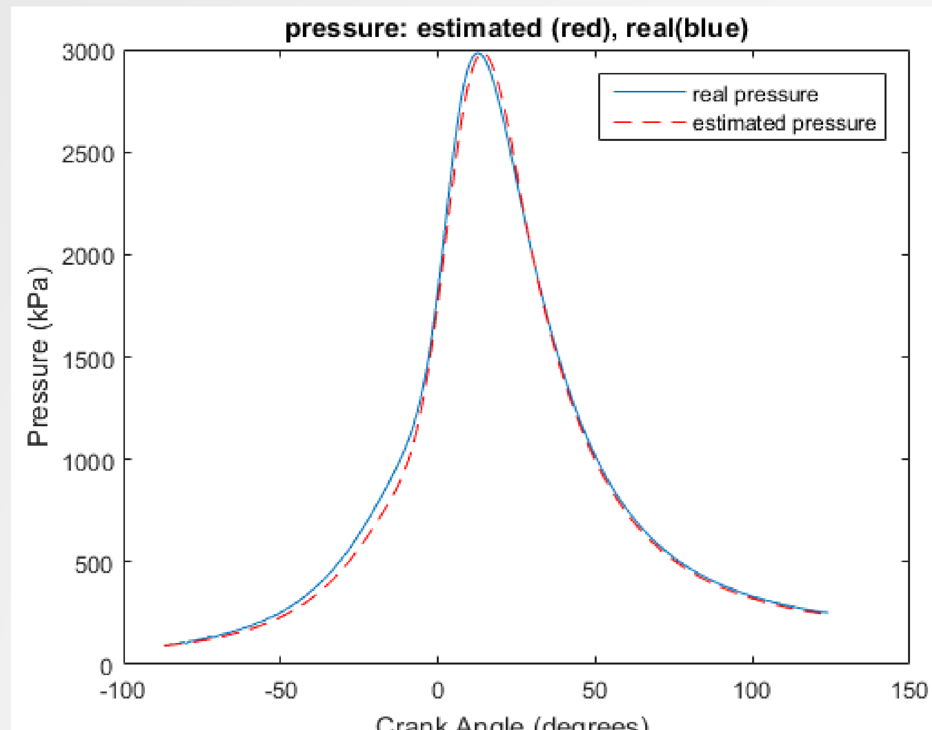




Results

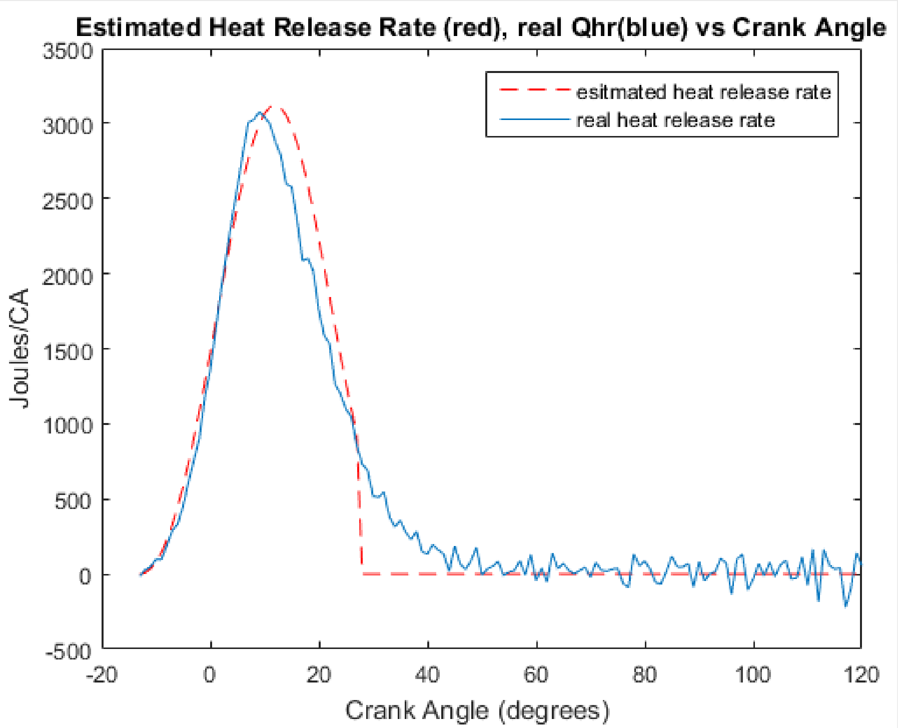
❖ **7th FCA Data Set (3200 rpm, 4 bar).** IGN delayed. Original IGN: -24°
- Heat Release Rate. From IGN (-20°) to EVO (124°):
  - The red-dotted line is the estimated HR rate.
  - Curve fitting parameters: $\alpha = 3.347, \beta = 2.69.$
- Pressure. IVC (-87°) to EVO (124°)
  - Estimated pressure trace (**red**-dotted line).

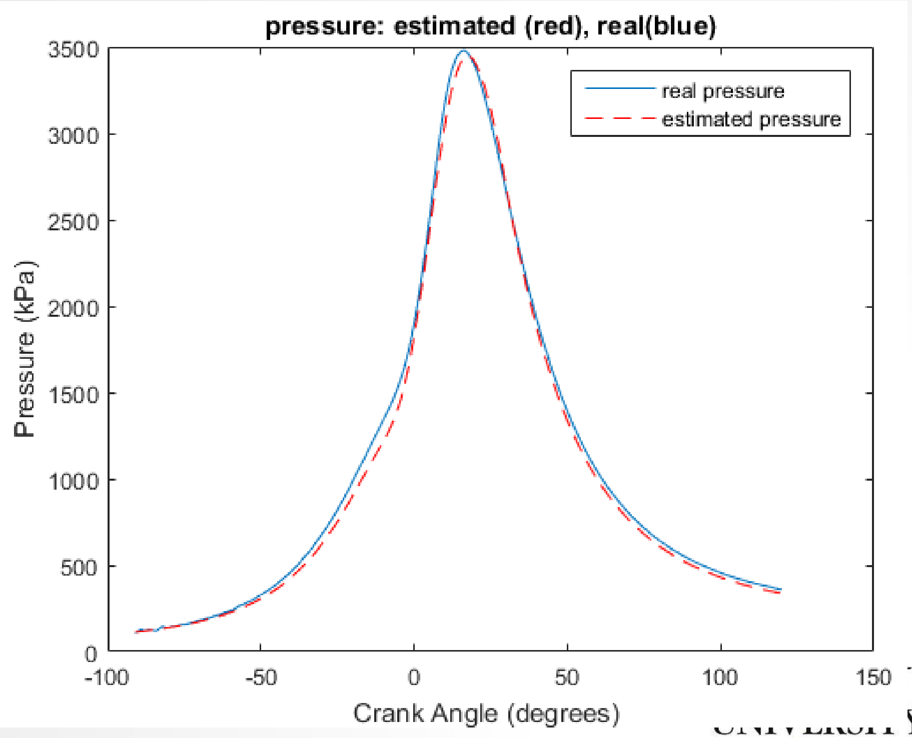




Results

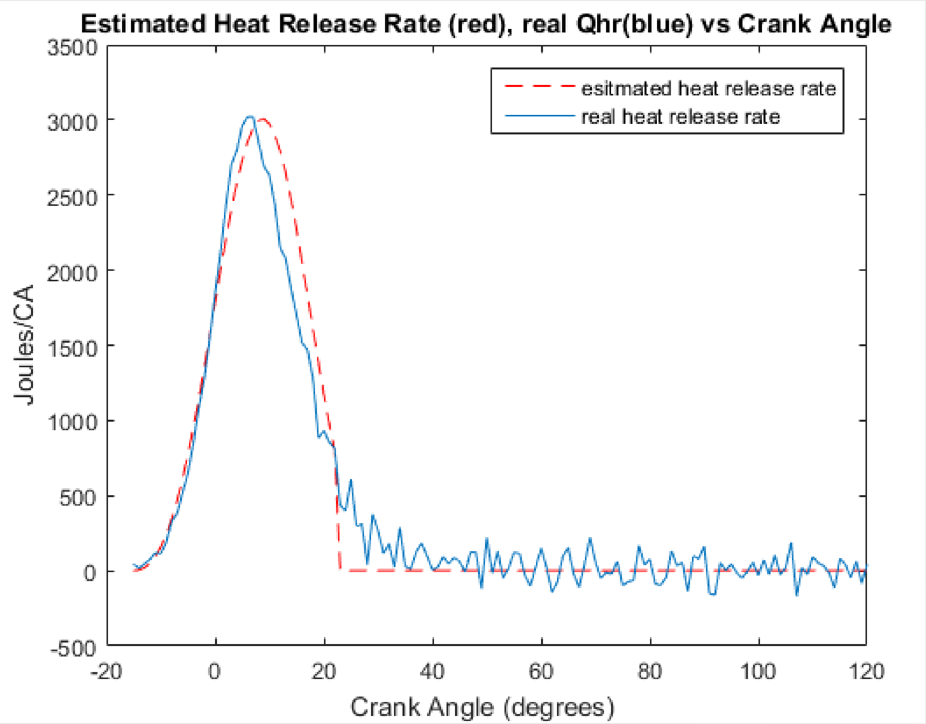
- **8^{th} FCA Data Set (3200 rpm, 6 bar).** IGN delayed. Original IGN: -19°
  - Heat Release Rate. From IGN (-13°) to EVO (120°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.068, \beta = 2.047.$
  - Pressure. IVC (-91°) to EVO (120°)
    - Estimated pressure trace (**red**-dotted line).

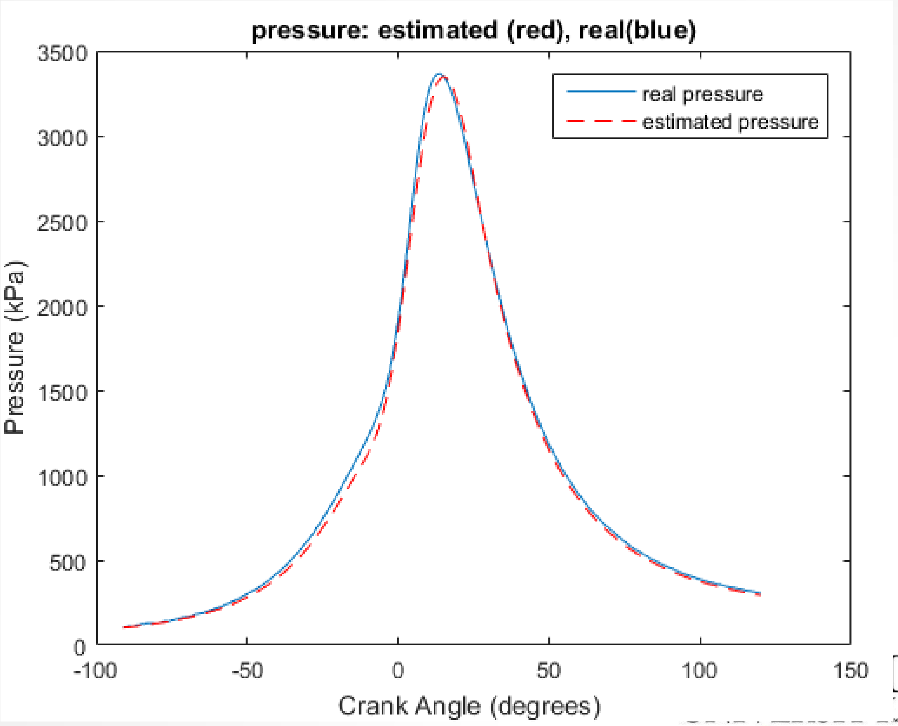




Results

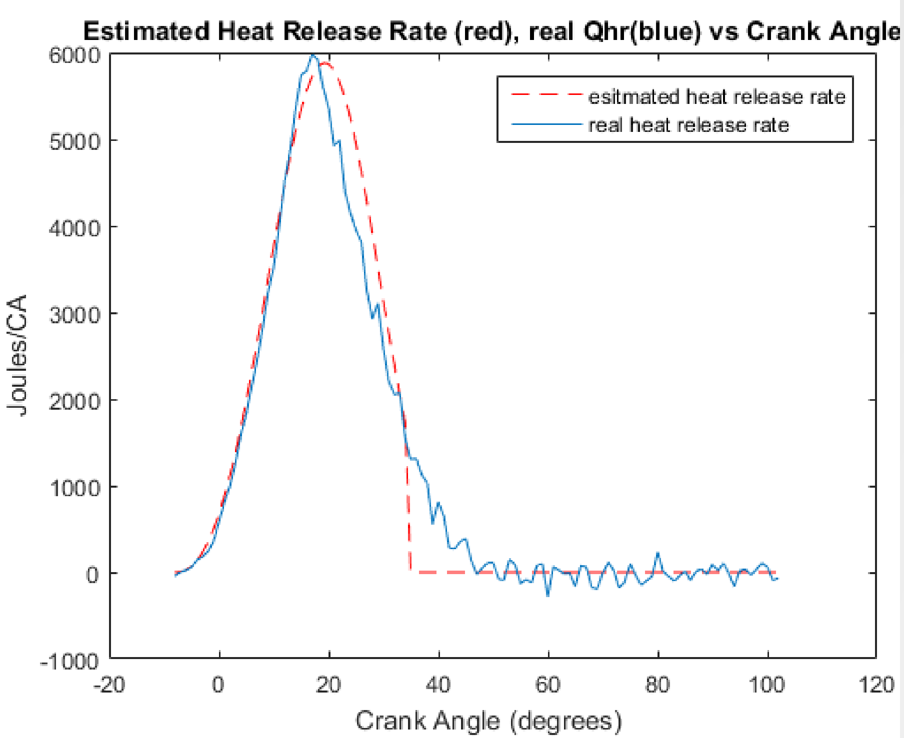
- **9th FCA Data Set (4000 rpm, 4.5 bar).** IGN delayed. Original IGN:-21°
  - Heat Release Rate. From IGN (-15°) to EVO (120°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.346, \beta = 2.33$.
  - Pressure. IVC (-91°) to EVO (120°)
    - Estimated pressure trace (red-dotted line).

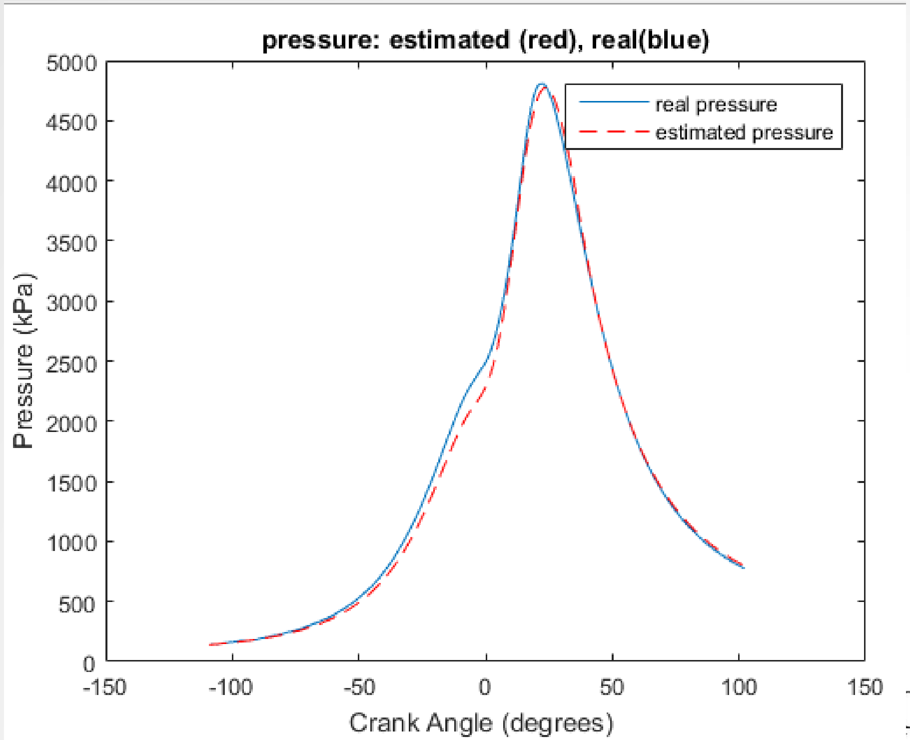




Results

- **10th FCA Data Set (4000 rpm, WOT).** IGN delayed. Original IGN: -11°
  - Heat Release Rate. From IGN (-8°) to EVO (102°):
    - The red-dotted line is the estimated HR rate.
    - Curve fitting parameters: $\alpha = 3.125, \beta = 2.327.$
  - Pressure. IVC (-109°) to EVO (102°)
    - Estimated pressure trace (red-dotted line).





Hardware Implementation

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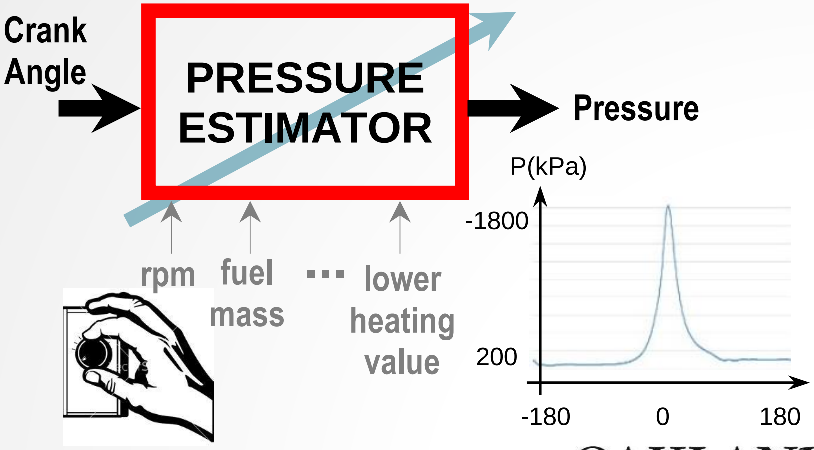
- **Hardware**: The nature of the calculations in the model suggests that a dedicated hardware implementation inside an embedded system can deliver real-time performance for computing the estimated pressure at every crank angle.

- Closed Cylinder Engine: Based on input parameters, the hardware should compute estimated pressure at every crank angle. Moreover, the hardware can adapt (statically or dynamically) to different operating conditions.

- ***Static Approach***: the parameters are inputs to our circuit. If we need to update the parameters, we just upload them into input registers in order to update the estimated pressure trace.

- ***Dynamic Approach***: the parameters are constants to our circuit, leading to a *significant reduction in hardware resources*. However, the hardware is fixed and cannot be modified. Here, we use Dynamic Partial Reconfiguration Technology to load (on-the-fly) a new hardware configuration (in order to update parameters).



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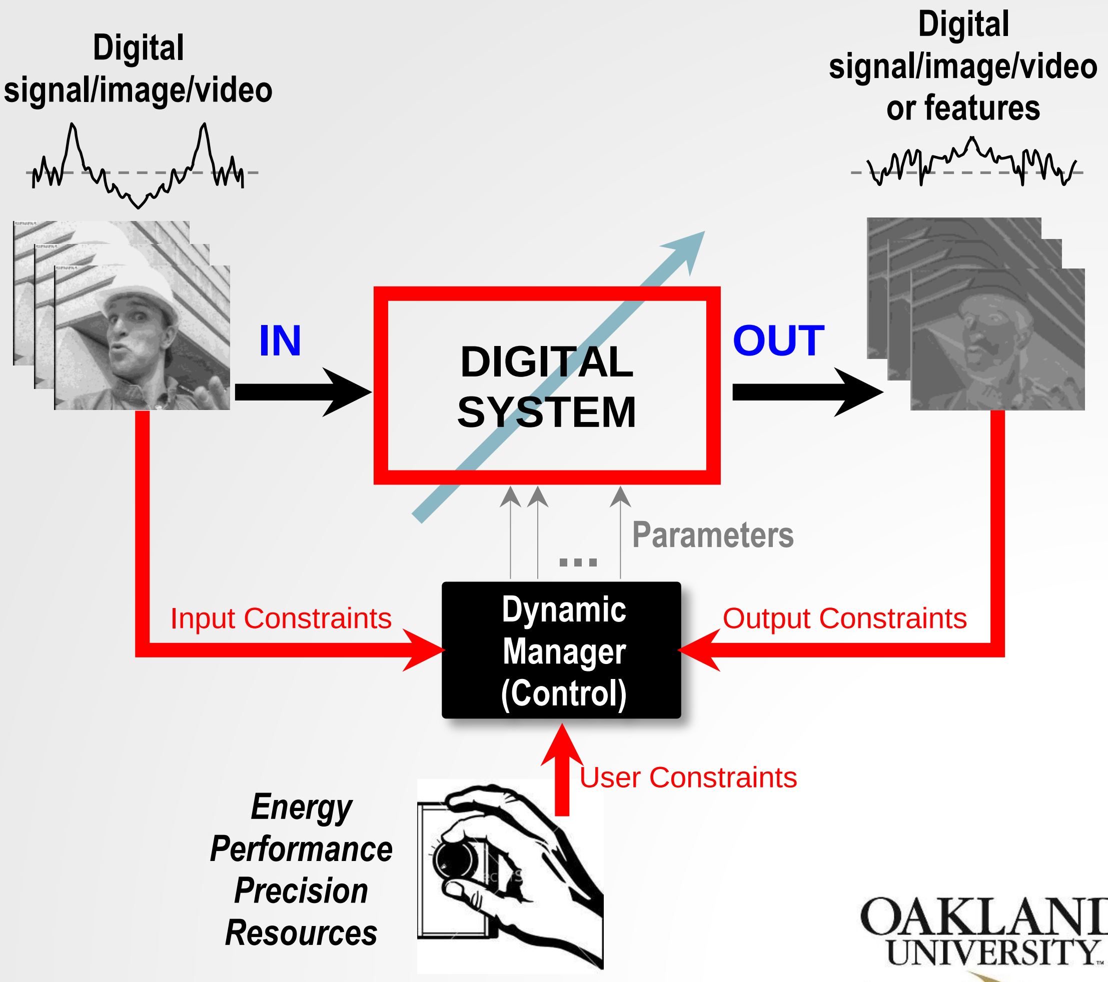
Self-Reconfigurable Embedded Systems

Digital systems can be characterized by a series of properties:

- *Energy*
- *Performance*
- *Precision,*
- *Bandwidth, Quality, etc.*

***Self-Reconfigurable Embedded Systems** are self-adaptive systems that can satisfy time-varying requirements, optimizing resources and energy.*



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Self Reconfigurable Embedded Systems

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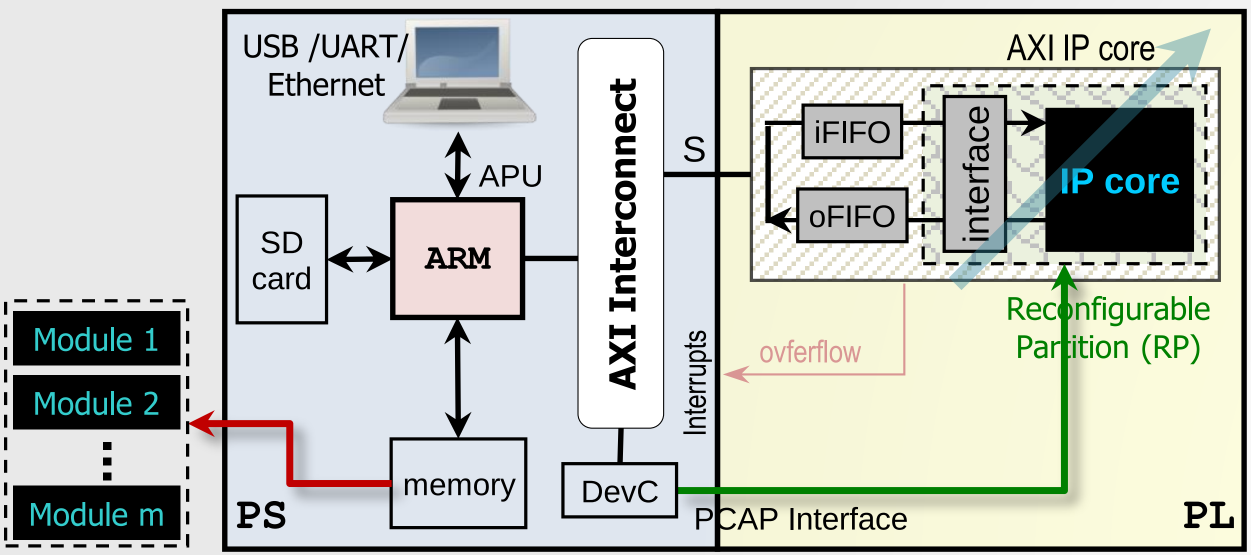
- ***Technology***: *Programmable System-on-Chip (SoC): They integrate:*
  - *Processing System (PS): A dual-core ARM® CortexTM-A9 processor and common peripherals (USB, SD, etc.)*
  - *Programmable Logic (PL): Reconfigurable fabric (also known as FPGA) that can be reconfigured at run-time.*

Xilinx Zynq-7000 All-Programmable SoC:



Embedded system with common peripherals, interrupts, and run-time alterable custom hardware.

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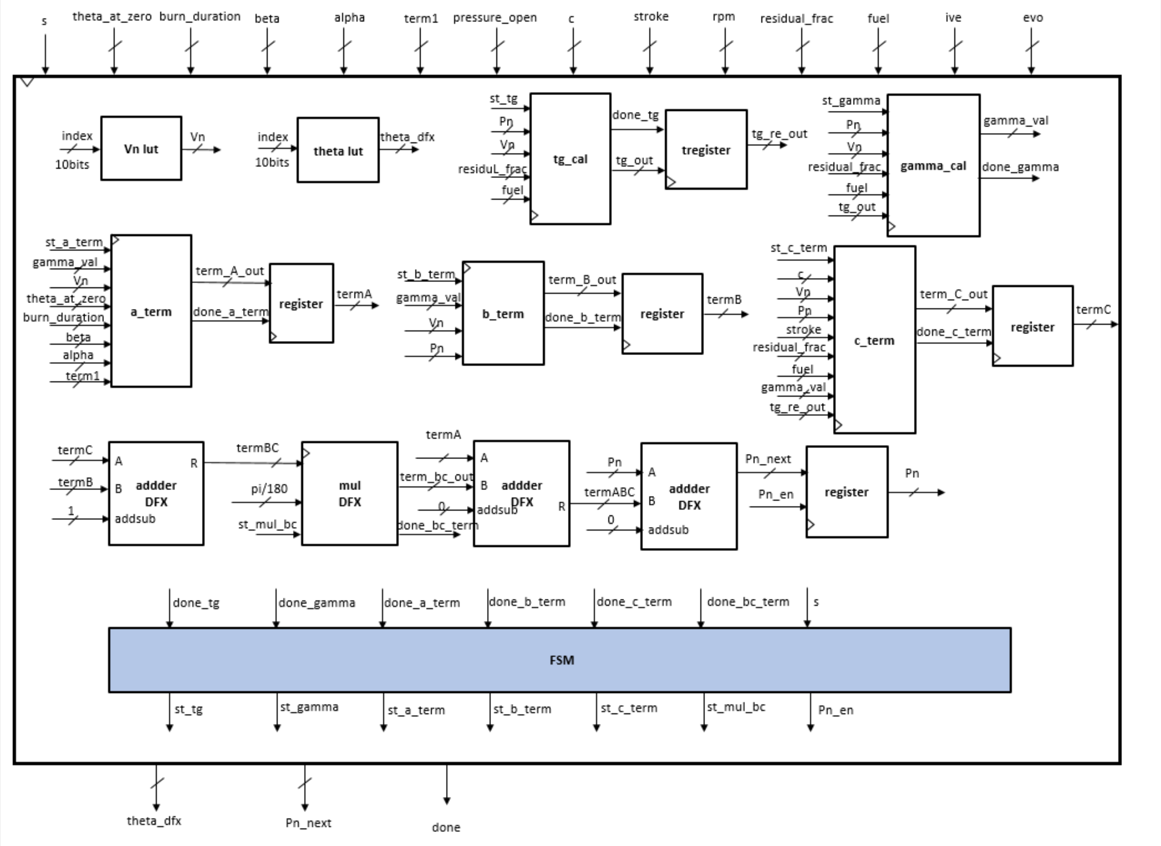
Hardware Implementation

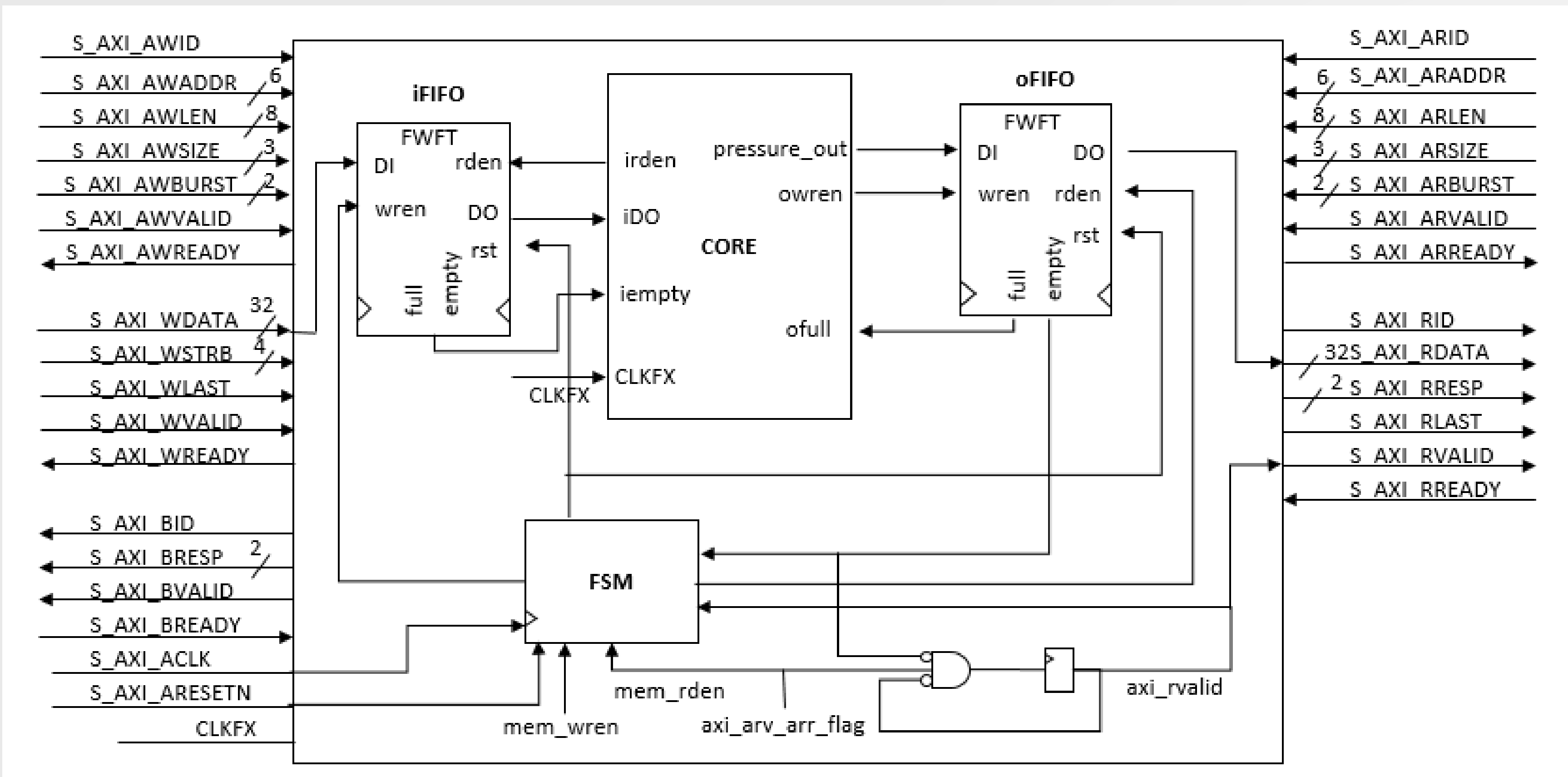
- Hardware implementation: It uses ***Dual Fixed-Point Arithmetic*** that provides a compromise between Floating Point Arithmetic (high hardware usage) and Fixed Point (reduced range of numerical values).
- Inputs: engine data, conditions, and model parameters.
- Output: Estimated pressure trace for every crank angle.

- A dedicated hardware was designed for each term in the discrete equation for $P(n)$. This included common arithmetic operations as well as trigonometric, exponential, and power functions. These were implemented in dedicated hardware (CORDIC algorithm for Dual-Fixed Point).



Hardware Implementation

- Once the hardware is designed and verified via simulation, we place it into an embedded interface. Then, using custom software drivers, we can perform data write and data retrieval.
- Platform: ZED Board, containing a Xilinx® Zynq-7000 All-Programmable System on Chip.
- The figure shows the connection of our hardware to the microprocessor bus.



Hardware Implementation

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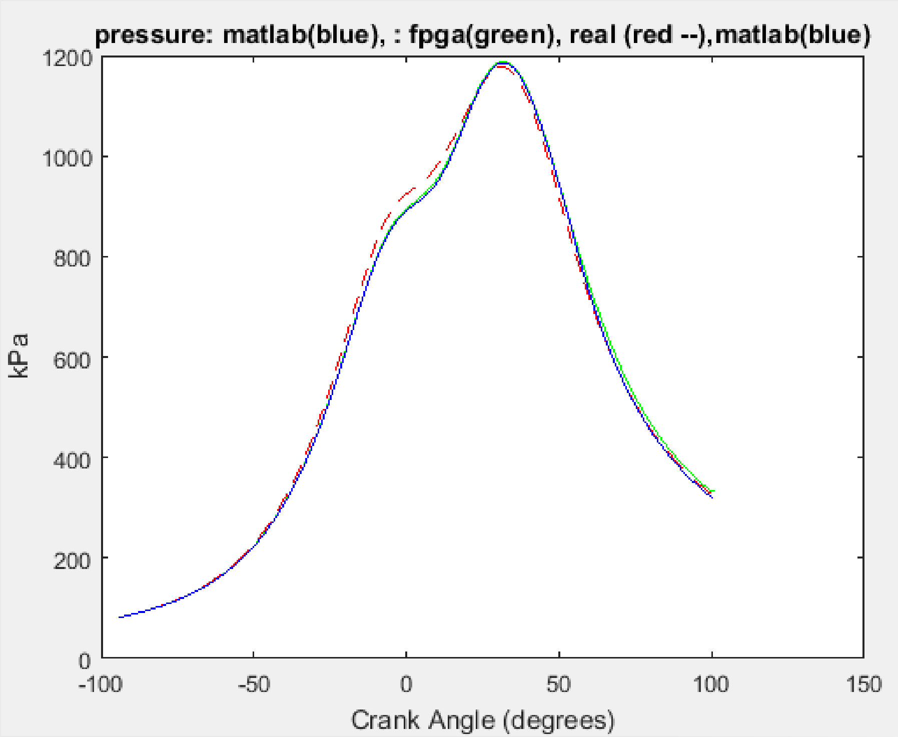
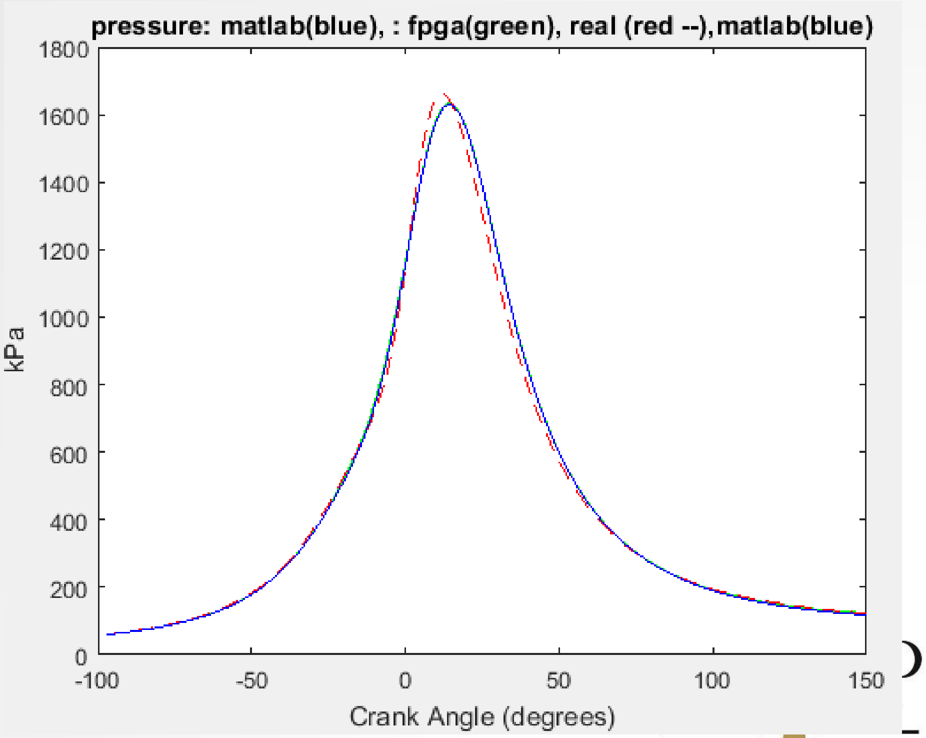
- Once the hardware is implemented inside an embedded system, we perform extensive testing to compare our results with those of the MATLAB model:
  - Example: (left) GM pressure trace (1300 rpm), 1st set
  - Example: (right) FCA pressure trace (1250rpm, 2 bar load), 1 set
- We can see how the FPGA results approximate the ones of the model in MATLAB. The difference is due to the fact that our hardware is implemented in Dual Fixed Point Arithmetic (DFX) with 32 bits (in order to save resources) as oppose to the MATLAB implementation using 64 bit in floating point arithmetic. A significant amount of resources is saved by using DFX.





Hardware Implementation

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- Hardware Time: (IVC to EVO): 3.288 ms (GM engine), 3.556 ms (FCA engine)

N (RPM)	Time for 1 revolution (ms)	Time for IVC-EVO (ms)	
		GM engine: 196°	FCA Engine: 212°
1500	40.00	21.77	23.55
2000	30.00	16.33	17.66
2500	24.00	13.06	14.13
3000	20.00	10.89	11.78
3500	17.14	9.33	10.09
4000	15.00	8.16	8.83
4500	13.33	7.26	7.85
5000	12.00	6.53	7.06
5500	10.90	5.93	6.42
6000	10.00	5.44	5.8
6500	9.23	5.02	5.43
7000	8.57	4.66	5.04
7500	8.00	4.35	4.71
8000	7.50	4.08	4.41
9000	6.67	3.63	3.92

- Thus, the hardware can estimate pressure at every crank angle up to 9000 rpm. Higher rpms result in smaller IVC to EVO times.

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Conclusion

- We implemented an instantaneous Pressure estimation using a self-reconfigurable embedded system.

- **Model completed.**
  - Better tweaking of the parameters of the Heat Transfer Rate might be required. GM gives better results than FCA data, as it seems that the parameters have been calibrated for the GM engine.

- **Embedded system with dedicated hardware completed**
  - We use a nonstandard numerical representation (DFX)
  - We use a modern embedded interface (AXI).

- **Results are very encouraging**. The estimated pressure results match very closely those of the model in MATLAB. The hardware processing time allows the system to run at up to 9000 rpm while computing the estimated pressure for every crank angle (1 degree resolution).

Future work

- **Interpolation of the model:**
  - This would be piece-wise interpolation based on actual pressure traces and conditions. ***We need more data!***

- **Model outside the valve closed:**
  - Do we need to implement it?

- **Static Approach vs. Dynamic Approach?**
  - So far, we only implemented the static approach.
  - A static approach can support a very fine interpolation mechanism.
  - A dynamic approach requires us to pre-compute every hardware configuration. This might not be appealing if we want to do very fine interpolation as we may incur in a large memory overhead (we might be able to identify a small area that needs to be run-time alterable, reducing the memory overhead). ***This is an open research question.***

Future work

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❖ **Run-time Reconfiguration and dynamic management:**

- Even if the dynamic approach results not to be a good solution, we should still use dynamic partial reconfiguration to alter the hardware so that we can trade-off performance, power, and crank angle resolution.

  For example: we can create hardware profiles that run at a slower pace, but utilize fewer resources (less power).

- This dynamic approach requires the development of a software dynamic manager that can determine which hardware configuration should be loaded next based on user input, input-based constraints, or output-based constraints.