Robust control applied to minimize Nox emissions

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Introduction

Motivations

1 – Pollutants emissions standards level (PM, NOx) ↘

2 – Number of actuators ↗

3 – manufacturing tolerances, aging and drift of components ↗

4 – Calibration and validation of control laws ↗

5 – Overall vehicle development cost ↗

→ 1 solution "control strategies on pollutant emission"

Introduction

Motivations

- NOx formation depends on :
  - incomplete combustion of oxygen
  - in-cylinder gas temperature / pressure,
  - availability of oxygen,
  - residence time of fuel/gas mixture.

EGR rate
Start of injection (SOI)

- PM formation depends on :
  - incomplete combustion of the fuel,
  - low air/fuel ratio values,
  - in-cylinder gas temperature,
  - availability of oxygen.

Swirl or Tumble valve

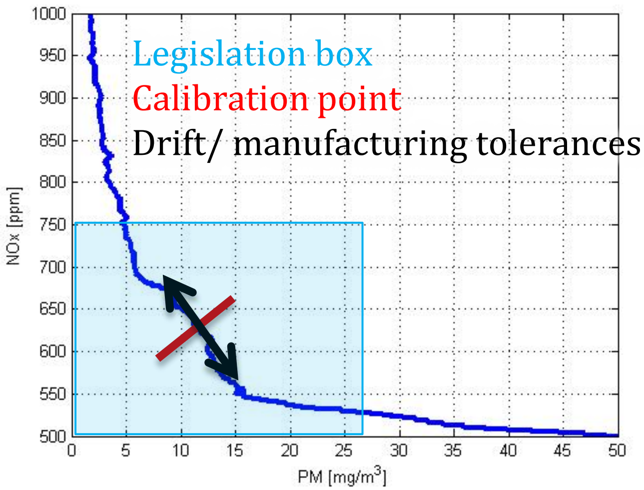
Introduction

Motivations

➢ Engine calibration :

- must work well for all engines and all Operating point
- in spite of manufacturing tolerances, drift.

➩ Time wasting



➢ Engine control:

- EGR and turbine flows (VGT) are driven by exhaust gas
- PM/NOx trade-off depends on in-cylinder temperature (EGR, SOI)

➩ Strong coupling

➔ **Model based robust control that coordinate EGR, VGT, SOI especially during transient operations**

Introduction

How to?

- To solve the pollutant emissions minimization problem using feedback we need :

  ⇨ a virtual sensor (estimator of pollutant quantities)

Extended Zeldovich Mechanism

$O + N_2 \Leftrightarrow NO + N$

$N + O_2 \Leftrightarrow NO + O$

$N + OH \Leftrightarrow NO + H$

$$\frac{d[NO]}{dt} = k_1^+[O]_e[N_2]_e - k_2^+[N]_e[O_2]_e + k_3^+[N]_e[OH]_e$$

$$k_1^-[NO]_e[N]_e + k_2^-[NO]_e[N]_e + k_3^-[NO]_e[H]_e$$

Good results / no real-time

Introduction

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$$k_1^-[NO]_e[N]_e + k_2^-[NO]_e[N]_e + k_3^-[NO]_e[H]_e$$

Not real-time

Methodologies based on :

✓ expensive sensors (Pcyl)

✓ using calibrated model

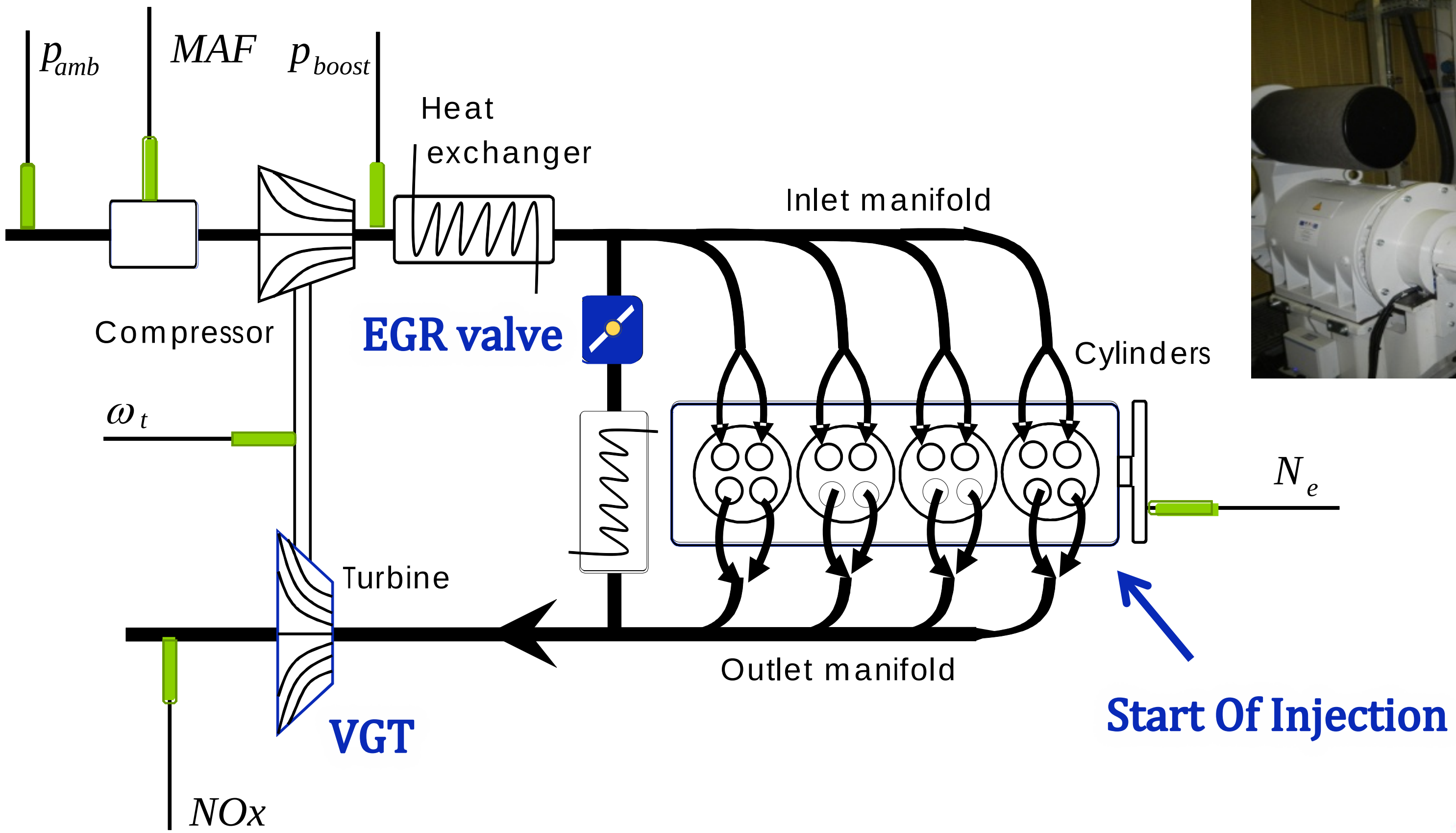
Time consumming / Not precise on transient

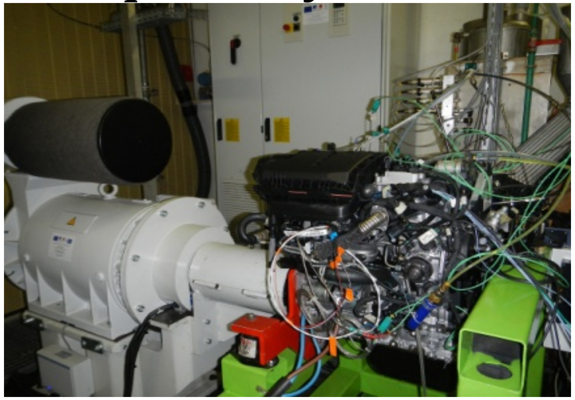
⇨ a fast and accurate sensor (Siemens VD sensor with time response of 0.4 sec and variable time delay)

Introduction

Case of application

- Peugeot DV6: a 1.6 liter diesel engine with 4 cylinders
- Air-path actuators : variable geometry turbine and egr valve
- Fuel-path actuators : Start of injection and fuel quantity

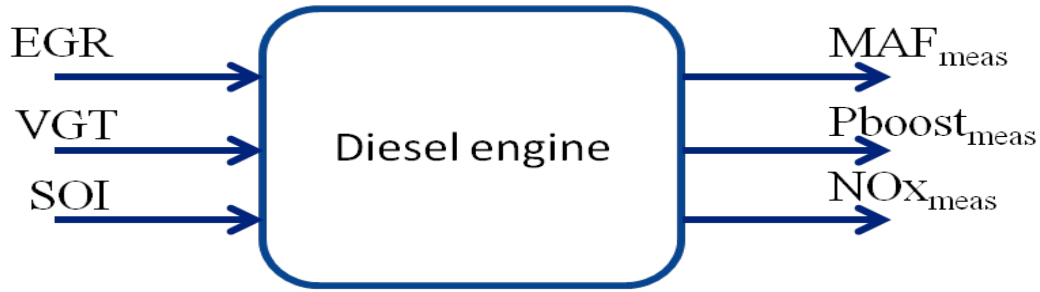




Introduction

Case of application

- System : 3 inputs and 3 outputs



STEP 1 — Identification — Multi-sinus

STEP 2 — Control theory — CRONE methodology

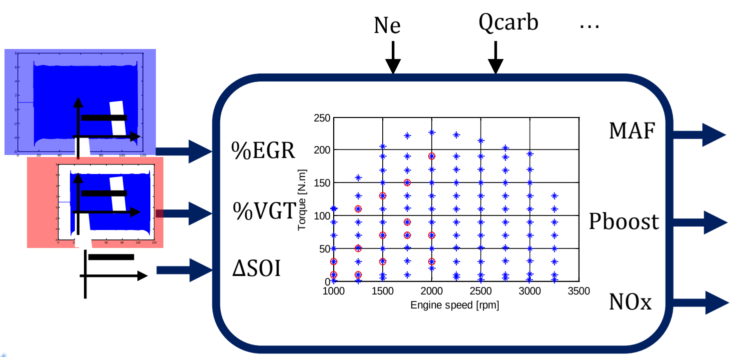
STEP 3 — Test-bed validation — Real-time controller

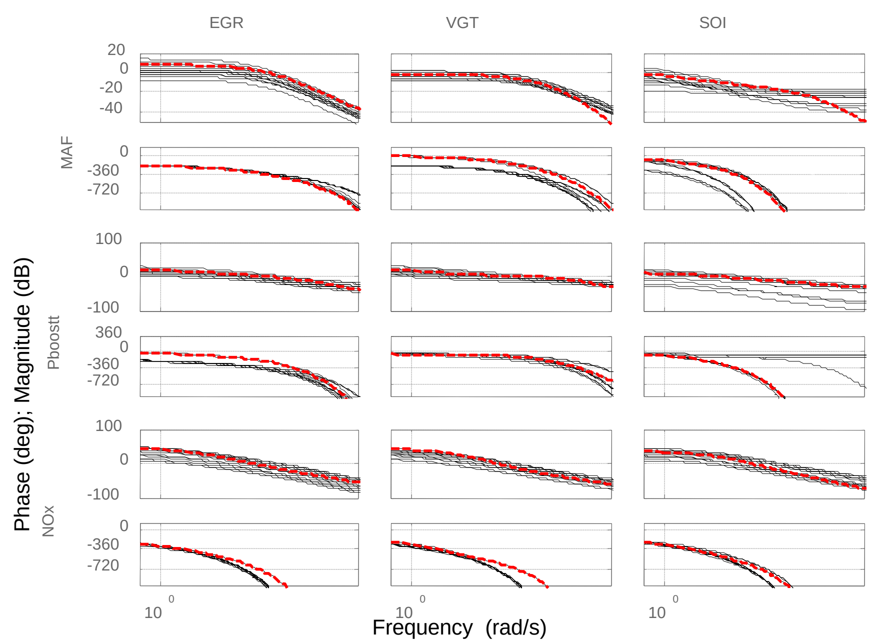
Identification

Multi-sinus

- System : 3 inputs (EGR, VGT, SOI) and 3 outputs (MAF, Pboost and NOx)
  - Exciting each input with a multi-sinus signal
  - obtain frequency response of the system for 1 operating points

➔ Do this for all operating point (14 for my case)





Control theory

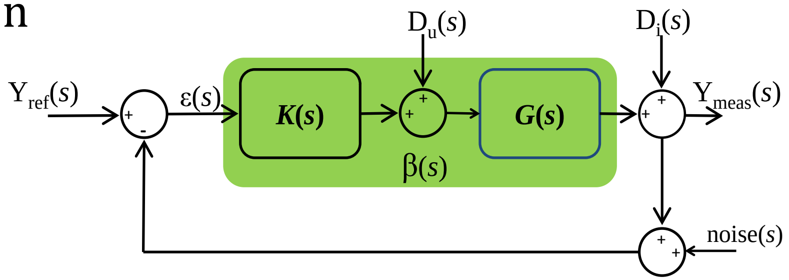
CRONE control

CRONE is a French acronym which means: non integer order robust control

➔ **Design of robust controllers using fractional order transfer functions**

- Frequency-domain and loop-shaping based methodology using fractional differentiation orders as high-level design parameters (since 1975 – 3 generations): $(d/dt)^{a+ib} \rightarrow s^{a+ib}$ (linear operator)

- Use of the common unity-feedback configuration



- Robustness of the stability-degree with respect to the parametric plant perturbation (no over-estimation)

- Control of minimum or time-varying plants, nonlinear plants, unstable plants or plants with time-delay

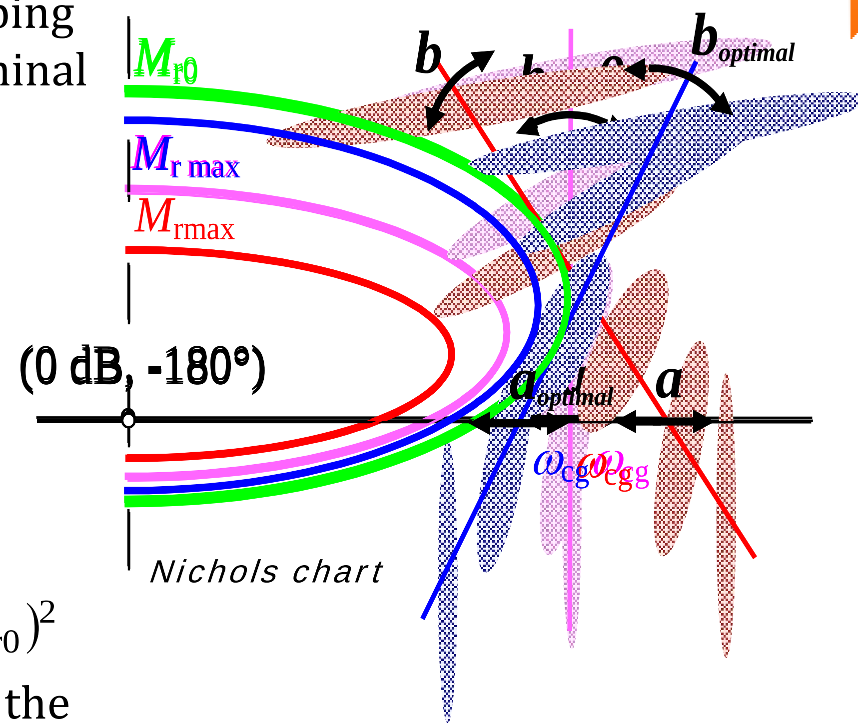
- 3rd generation has been extended to m x n MIMO plant (full MIMO approach or 2 decentralized approaches)

Control theory

CRONE control: SISO system

Using fractional complex integration order as shaping parameters, the aim of the method is to find a nominal open-loop transfer function

$$\beta_0(s) = G_0(s)K(s) \approx \left(\frac{\omega_{cg}}{s}\right)^{a+ib}$$



such that:

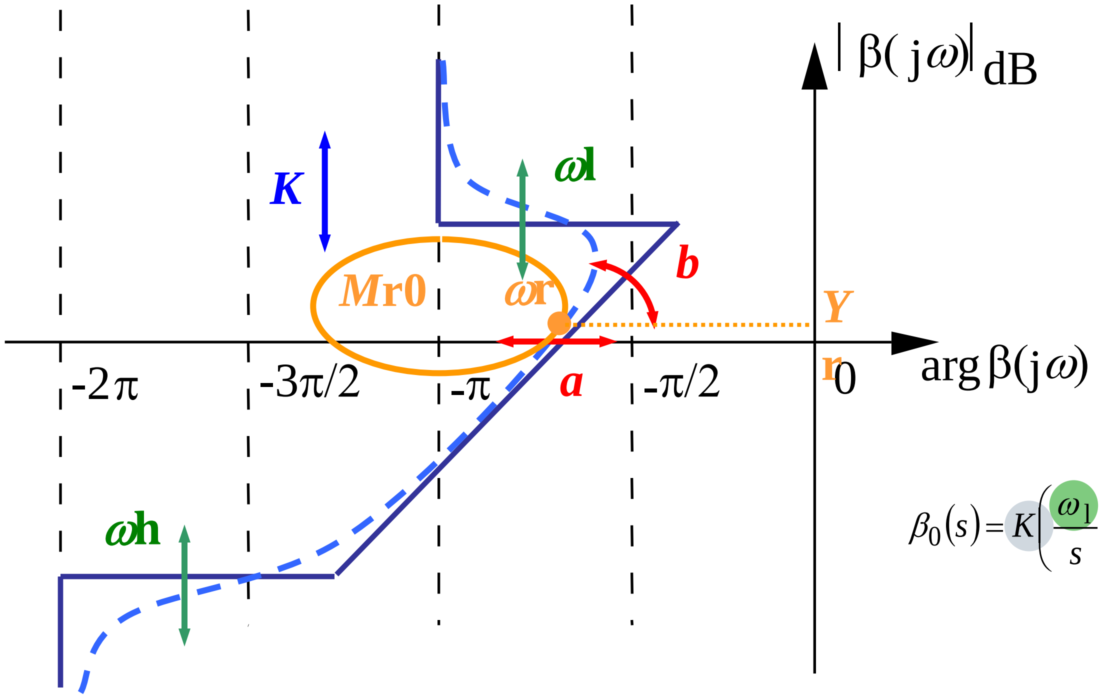
- its Nichols locus tangents a M_{r0} required magnitude contour
- when G differs from G_0, it minimizes a cost function as:

$$J = (M_{r\,max} - M_{r0})^2 + (M_{r\,min} - M_{r0})^2$$

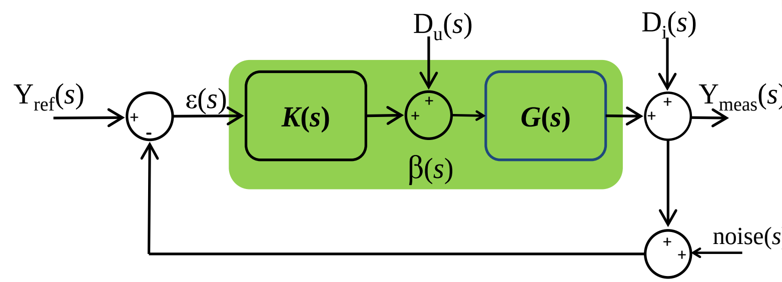
- while respecting the following constraints on the sensitivity functions

$$\begin{cases} \sup\limits_G |T(j\omega)| \leq T_u(\omega) & \sup\limits_G |S(j\omega)| \leq S_u(\omega) \\ \inf\limits_G |T(j\omega)| \geq T_l(\omega) & \sup\limits_G |SG(j\omega)| \leq SG_u(\omega) \\ & \sup\limits_G |CS(j\omega)| \leq CS_u(\omega) \end{cases}$$

CRONE control: SISO system



here nl = 2 *and* nh = 4



$$\beta_0(s)=K\left(\frac{\omega_l}{s}+1\right)^{n_l}\left(\frac{1+\frac{s}{\omega_h}}{1+\frac{s}{\omega_l}}\right)^{a}\left(\Re_{/i}\left[\left(C_0\frac{1+\frac{s}{\omega_h}}{1+\frac{s}{\omega_l}}\right)^{ib}\right]\right)^{-\mathrm{sign}(b)}\frac{1}{\left(1+\frac{s}{\omega_h}\right)^{n_h}}$$

4 independent parameters have to be optimized from high-level parameters n_l, n_h, a, b , ω_l, ω_h , ω_r and K.

Each parameter acts only on one shape feature of nominal (and perturbed) $\beta(j\omega)$, and thus can be easily optimized.

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CRONE control: MIMO system

- Objective: to get a decoupled (diagonal) closed-loop transfer function matrix for the nominal state of the plant

$$\mathbf{T}_0(s) = \left(\mathrm{I} + \boldsymbol{\beta}_0(s)\right)^{-1}\boldsymbol{\beta}_0(s) = diag\left[\frac{\beta_{0ii}(s)}{1+\beta_{0ii}(s)}\right]_{1\le i\le n} = diag\left[T_{ii}(s)\right]_{1\le i\le n} \quad \begin{bmatrix} T_{0_{11}} & 0 & 0 \\ 0 & T_{0_{22}} & 0 \\ 0 & 0 & T_{0_{33}} \end{bmatrix} \text{ for } n=3$$

- Nominal open-loop matrix β_0 is also diagonal

$$\boldsymbol{\beta}_0(s) = \mathbf{G}_0(s)\mathbf{K}(s) = \mathrm{diag}\left[\beta_{0ii}(s)\right]_{1\le i\le n} \quad \begin{bmatrix} \beta_{0_{11}} & 0 & 0 \\ 0 & \beta_{0_{22}} & 0 \\ 0 & 0 & \beta_{0_{33}} \end{bmatrix} \text{ for } n=3$$

- Cost function $J = \sum_{i=1}^{n}\left(\max_{G}\sup_{\omega}\left|T_{ii}(\mathrm{j}\omega)\right| - \min_{G}\sup_{\omega}\left|T_{ii}(\mathrm{j}\omega)\right|\right)^2$

- Frequency-domain constraints

$$\sup_{G}\left|T_{ij}(\mathrm{j}\omega)\right| \le T_{\mathrm{u}ij}(\omega) \qquad \inf_{G}\left|T_{ij}(\mathrm{j}\omega)\right| \ge T_{\mathrm{l}ij}(\omega)$$

$$\sup_{G}\left|S_{ij}(\mathrm{j}\omega)\right| \le S_{\mathrm{u}ij}(\omega) \qquad \sup_{G}\left|KS_{ij}(\mathrm{j}\omega)\right| \le KS_{\mathrm{u}ij}(\omega)$$

$$\sup_{G}\left|SG_{ij}(\mathrm{j}\omega)\right| \le SG_{\mathrm{u}ij}(\omega)$$

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CRONE control: MIMO system

$$\mathbf{K}(s)=\mathbf{P}(s)\boldsymbol{\beta}_0(s) \text{ with } \mathbf{P}(s)=\mathbf{G}_0^{-1}(s)=\begin{bmatrix} p_{11}(s)e^{\gamma_{11}s} & \cdots & p_{1n}(s)e^{\gamma_{1n}s} \\ \vdots & p_{ij}(s)e^{\gamma_{ij}s} & \vdots \\ p_{n1}(s)e^{\gamma_{n1}s} & \cdots & p_{nn}(s)e^{\gamma_{nn}s} \end{bmatrix}$$

$$K_{ij}(\mathrm{j}\omega)=p_{ij}(\mathrm{j}\omega)e^{\gamma_{ij}\mathrm{j}\omega}\beta_{0\,jj}(\mathrm{j}\omega)$$

- **K** is achievable and the closed-loop system is internally stable and damped if $\beta_{0jj}(s)$ includes:
  - time-delay γ_{ij} of $p_{0ij}(s)$
  - poles defined by RHP or undamped poles of $g_{0ji}(s)$
  - zeros defined RHP or undamped poles of $p_{ij}(s)$

- Rational $K_{\mathrm{R}ij}(s)$ is obtained by identifying the ideal frequency responses $K_{\mathrm{ij}}(\mathrm{j}w)$ by low-order transfer functions:

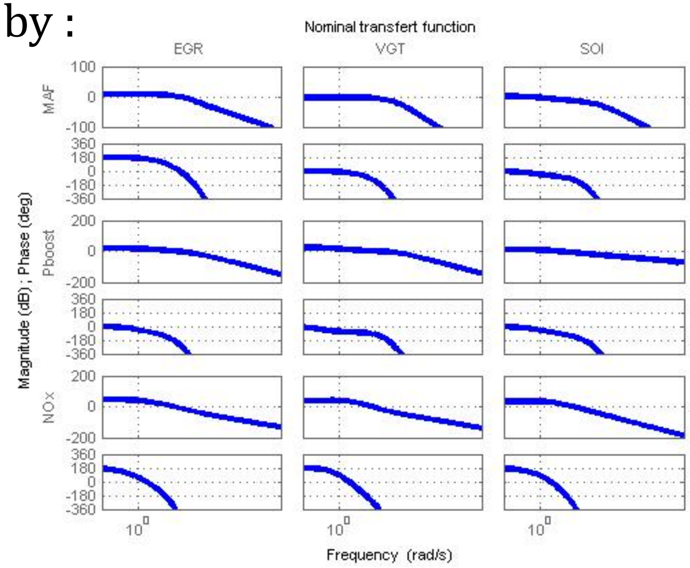
$$K_{\mathrm{R}_{ij}}(s)=\frac{B(s)}{A(s)}$$

Real-time controller

Analysis of the nominal plant

- stabilization of the **CS**(s) : the determinant of $\mathbf{G}_0(s)$ has a right half plane pole (+15.597) that thus needs to be included (as zeros) in $\beta_{011}(s)$, $\beta_{022}(s)$ and $\beta_{033}(s)$.

- Low frequency accuracy specifications are ensured by :
  - $n_l = 1$ for $\beta_{011}(s)$,
  - $n_l = 1$ for $\beta_{022}(s)$,
  - $n_l = 1$ for $\beta_{033}(s)$.



- High-frequency control efforts are limited with :
  - $n_h = 4$ for $\beta_{011}(s)$,
  - $n_h = 3$ for $\beta_{022}(s)$,
  - $n_h = 4$ for $\beta_{033}(s)$.

- The nominal resonant peak for $\beta_{011}(s)$ and $\beta_{022}(s)$ is 2 and $M_{r033} = 1$ for $\beta_{033}(s)$.

- The controller will be achievable if :
  - Time-delay for first loop : 0.09s,
  - Time-delay for second loop 0.1s,
  - Time-delay for third loop 0.44s.

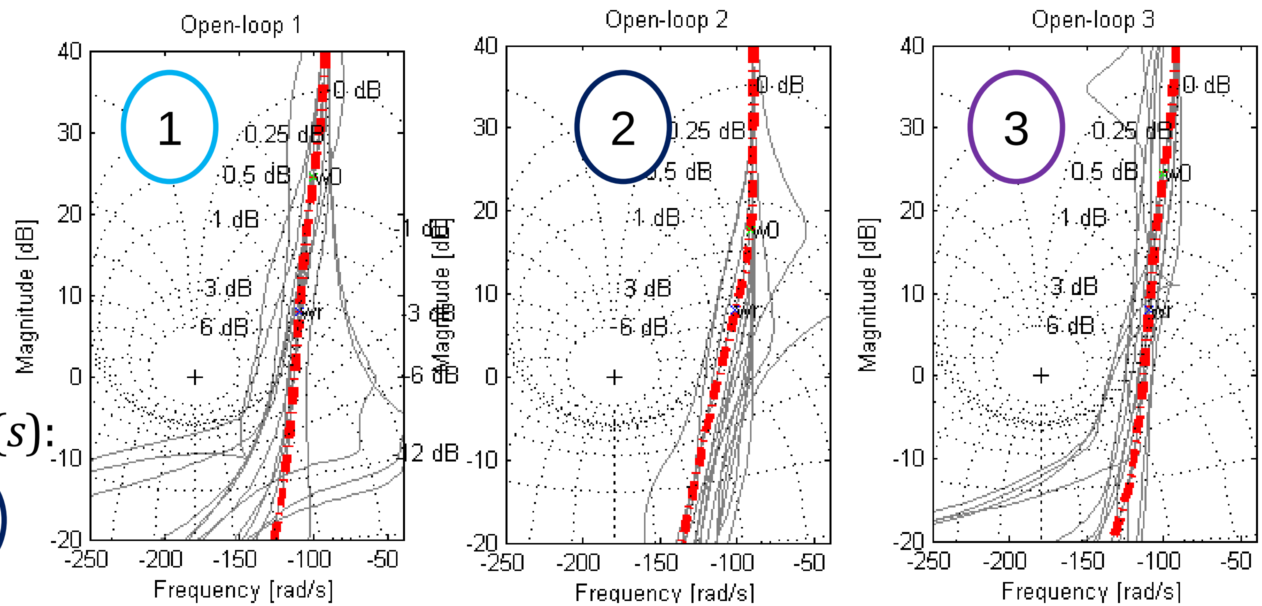
Real-time controller

Optimization of open-loop parameters

- Optimal parameters of $\beta_{011}(s)$:
$Mr0$=2dB, Yr = 5dB, 1
ωr = 0.1rad/s,
ω-1 = 0.01rad/s,
ω l= 10rad/s, ωh = 100rad/s,
a+1 = -1, and b+1 = 0
Thus $a0$ = 1.1, $b0$ = -0.51.

- Optimal parameters of $\beta_{022}(s)$:
$Mr0$=2dB, Yr = 3dB, 2
ωr = 0.01rad/s,
ωl = 0.005rad/s, ωh = 5rad/s.
Thus $a0$ = 1.32, $b0$ = -0.60.

- Optimal parameters of $\beta_{033}(s)$:
$Mr0$ = 1dB, Yr = 8dB, 3
ωr = 0.05rad/s,
ωl = 0.01rad/s, ωh = 100rad/s.
Thus $a0$ = 1.22, $b0$ = -0.08.

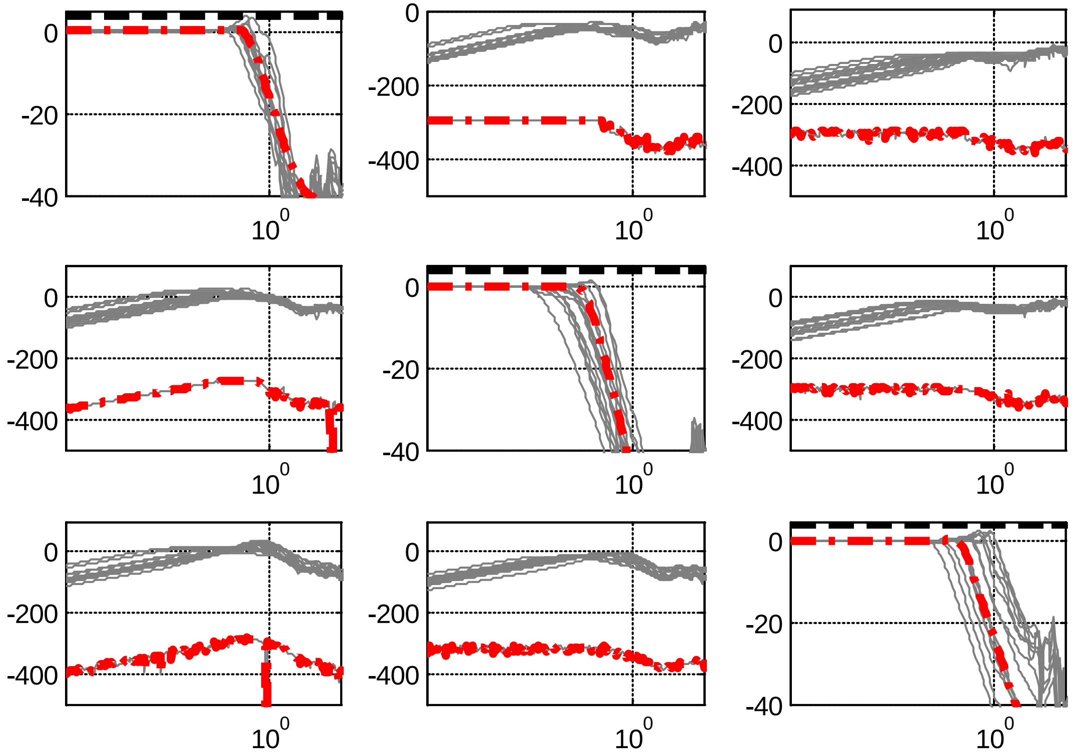


Nominal open-loop β_{0ii} and (perturbed) equivalent open-loop

$$\beta_{ii}(j\omega) = \frac{T_{ii}(j\omega)}{1 - T_{ii}(j\omega)}$$

Complementary Sensitivity function

- Decoupling for the nominal plant (gain around -250dB for off-diagonal of $\mathbf{T}_0$
- Decoupling specification also satisfied for the perturbed plant.
- Frequency-domain constraints are reached or slightly exceeded; the bandwidths cannot be increased more.



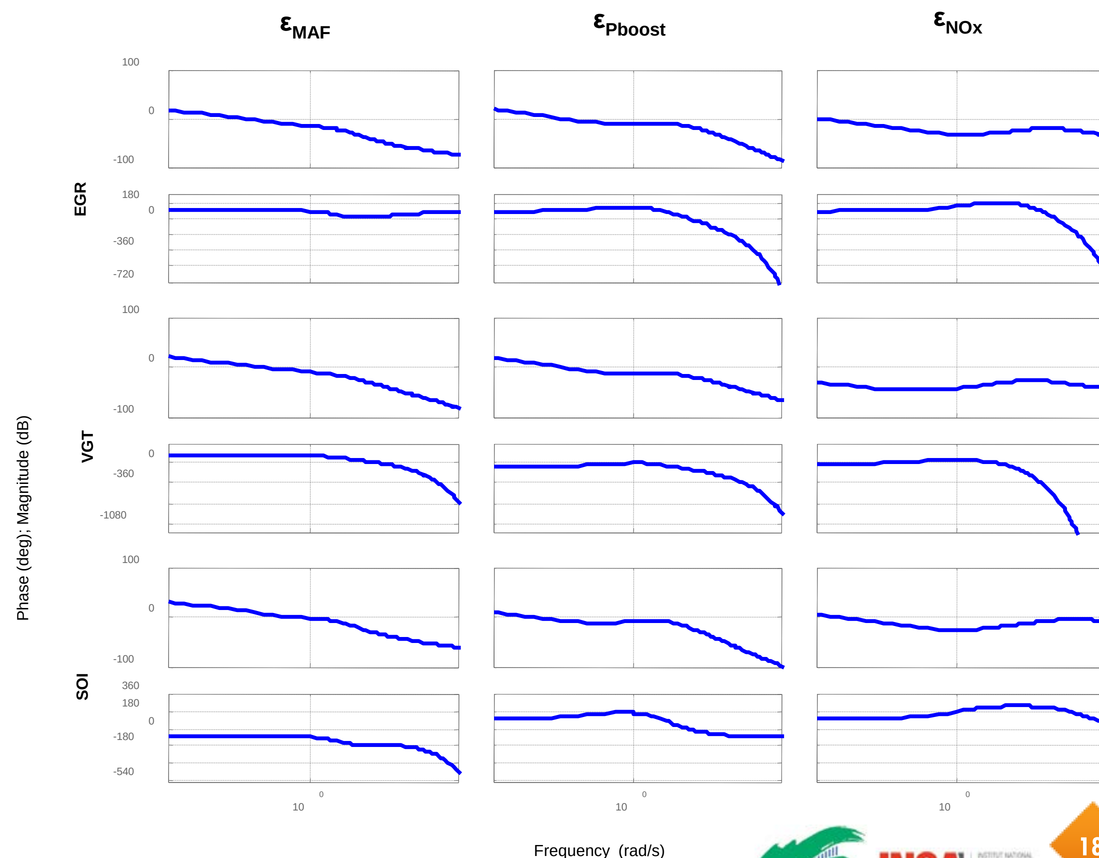
Real-time controller

Rational controler synthesis

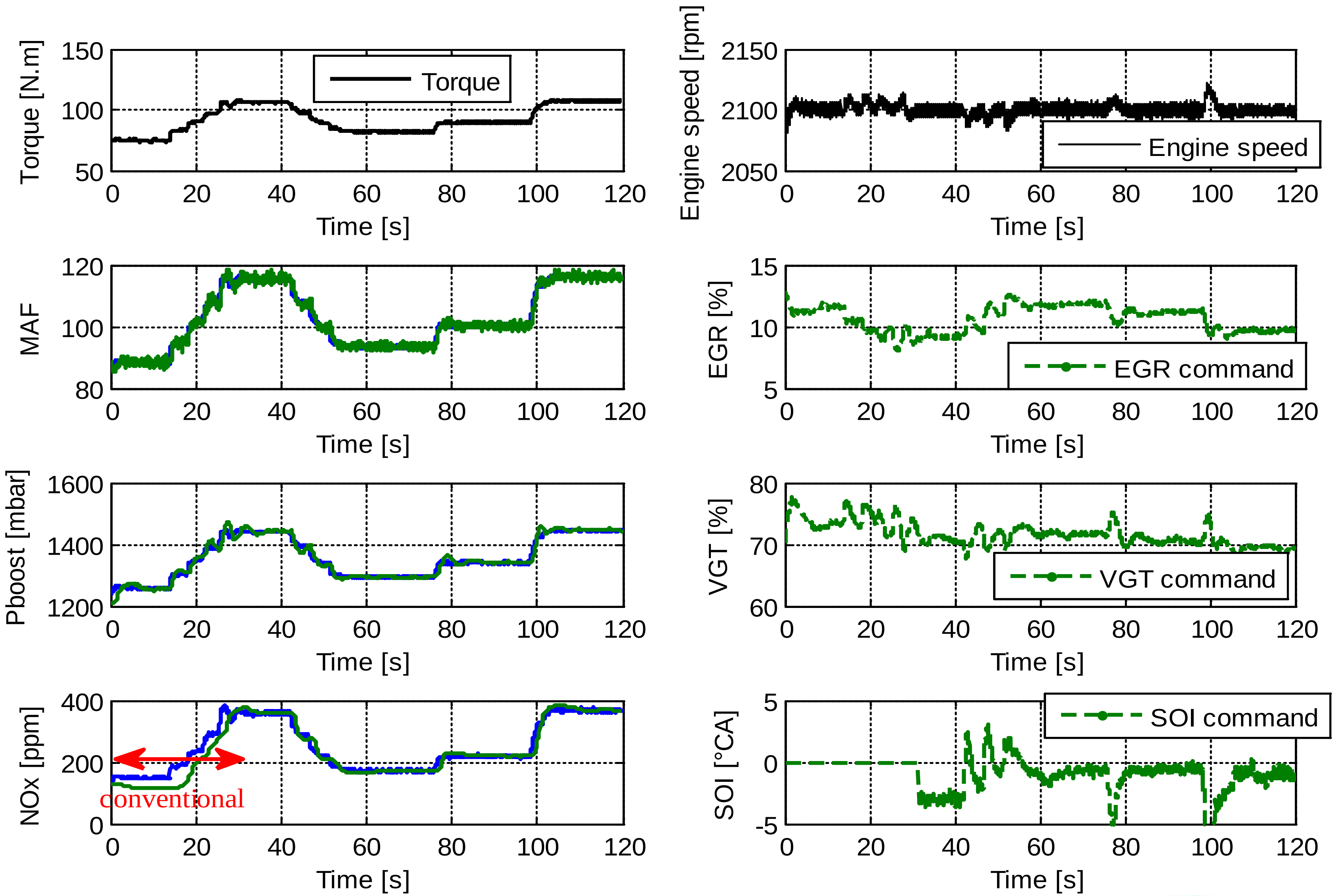
- The frequency response of the controller is also given by :

$$\mathbf{K}(j\omega)=\mathbf{G}_0^{-1}(j\omega)\boldsymbol{\beta}_0(j\omega)$$

- Using identification toolbox of Matlab/Simulink we approximate this frequency response by a **rational and linear matrix transfer function.**



Time domain validation



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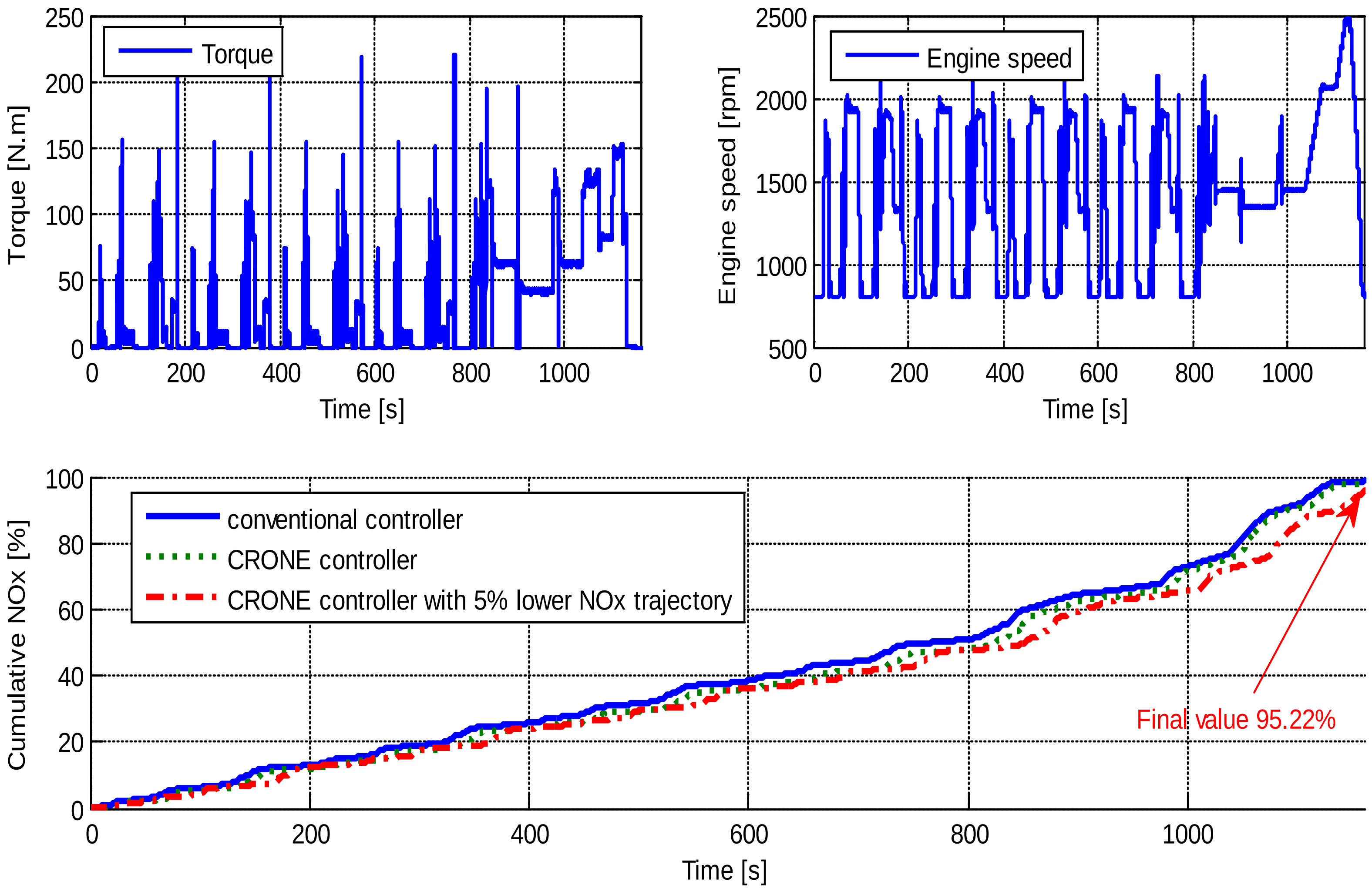
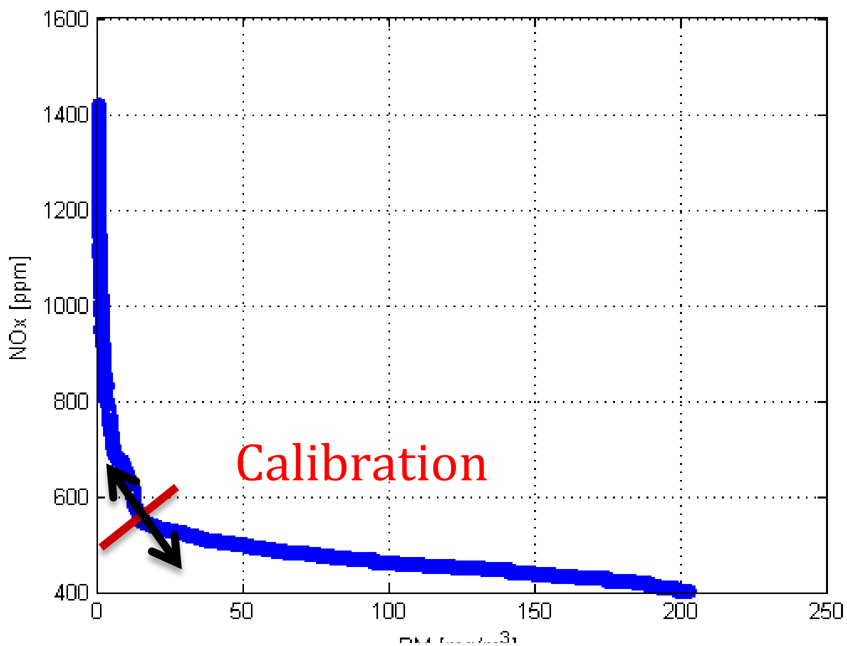


Conclusion

How about PM?



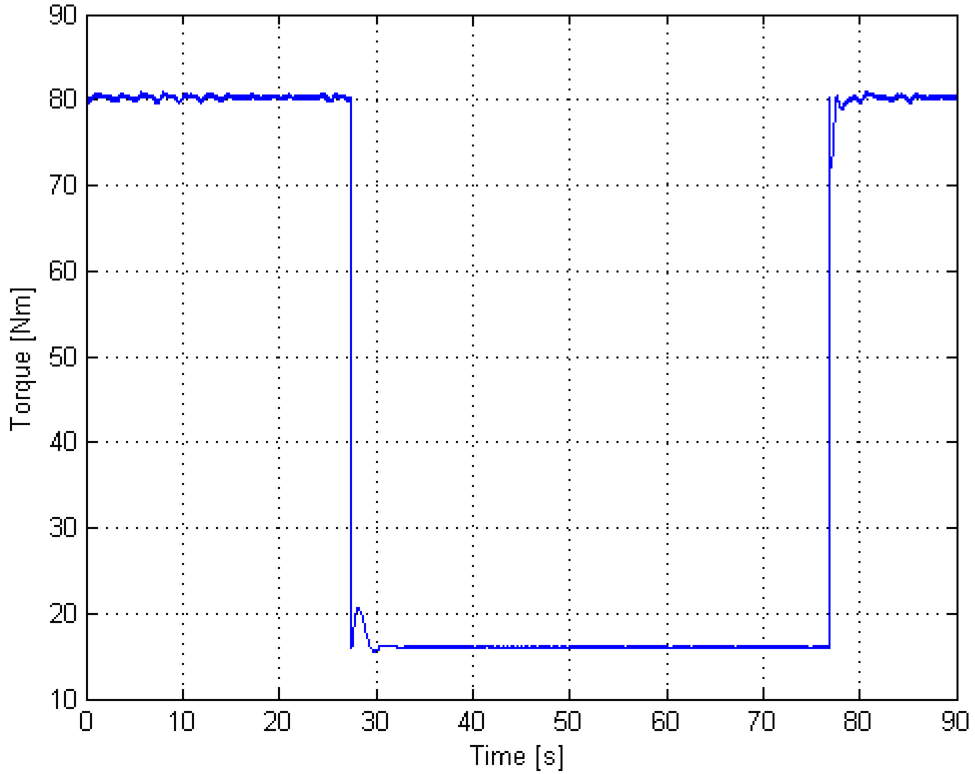
- Using a cheap sensor we can control NOx emissions
- With this control design we can also :
  - Adjust the engines behaviour,
  - Moved the calibration point.
- It can handle larger manufacturing tolerances
  - compensation of deviation and on-line calibration
  - Allows changing conditions such as environmental changes and ageing

- But there is a trade-off between PM emissions and NOx emissions
  ➔ Lower NOx level increasing PM level!

Conclusion

How about PM?

- But there is a compromise between PM emissions and NOx emissions
  ➔ Lower Nox level increasing PM level!



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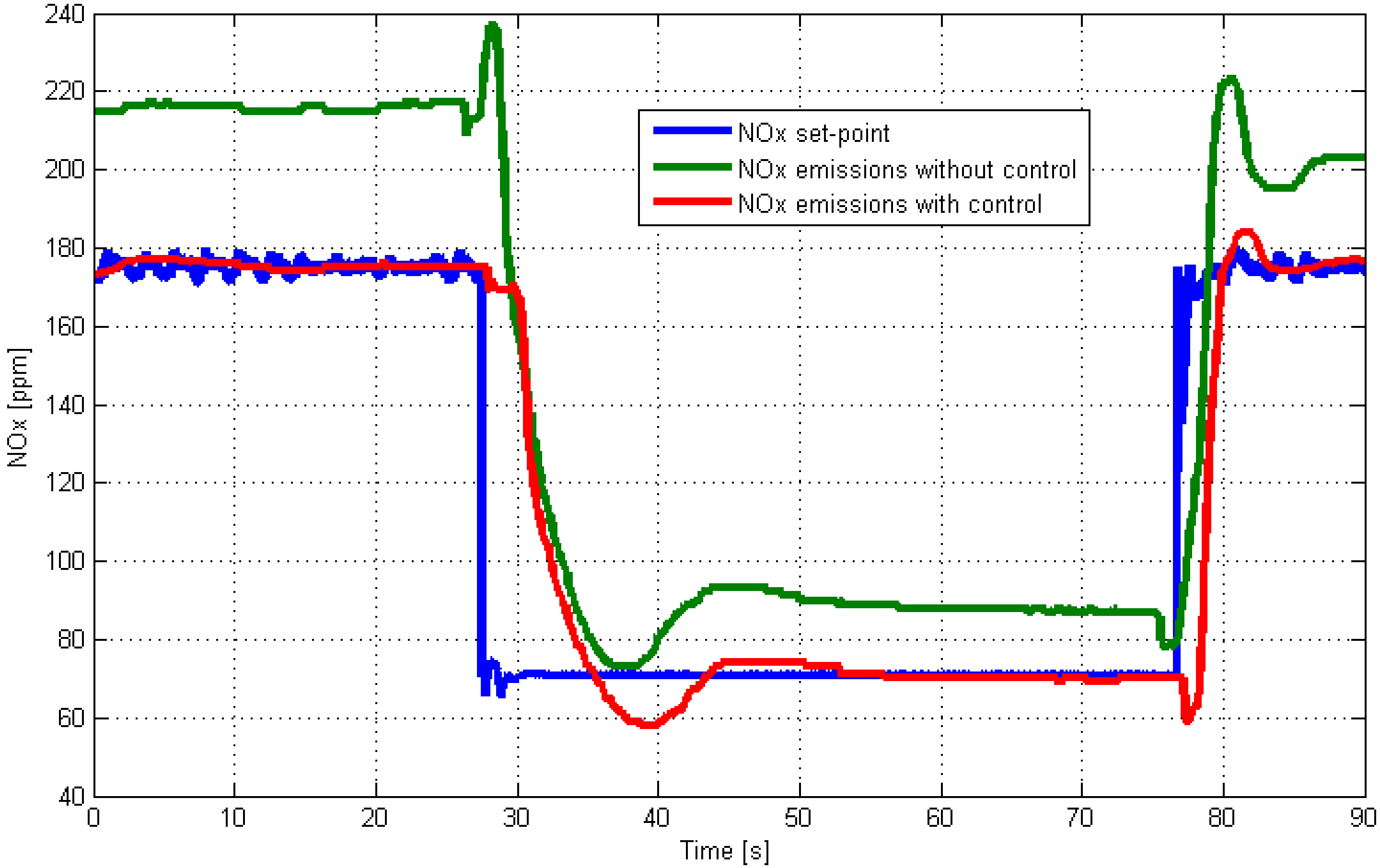

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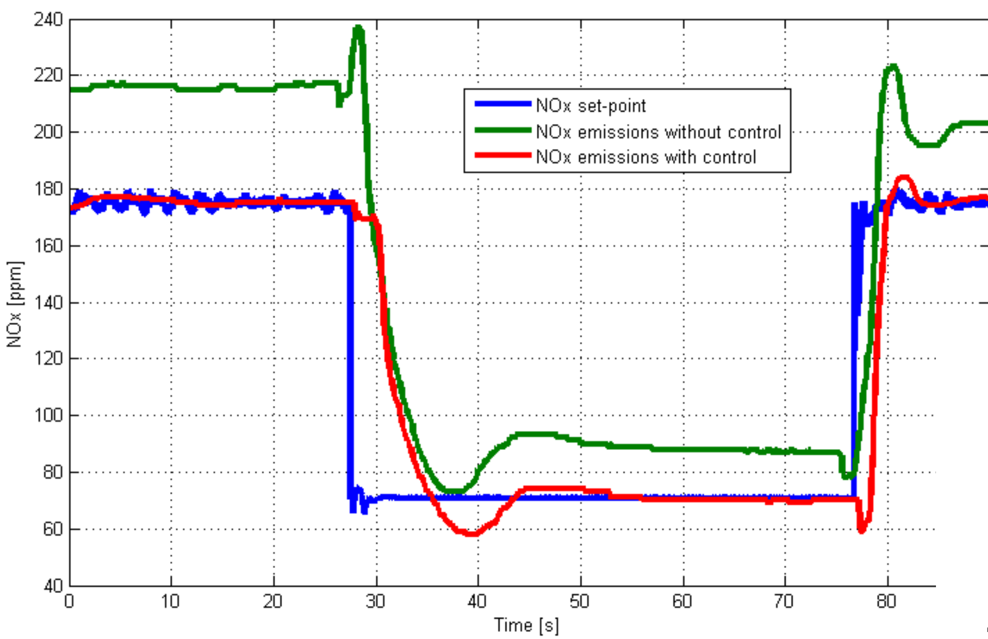
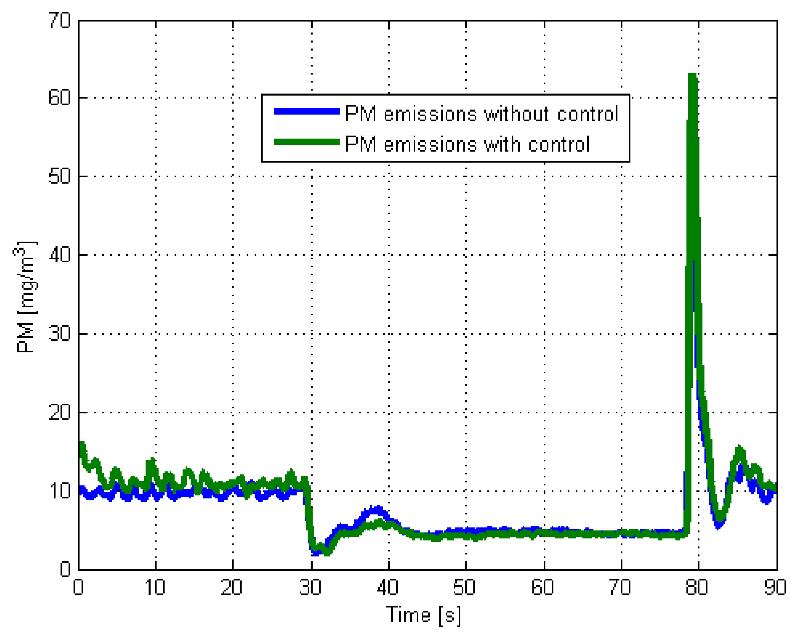


-30% NOx emissions

+5% PM emissions



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Thank you

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