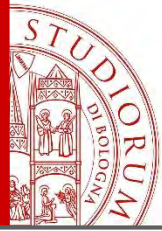


Potenzialità dei sensori microfonici nel controllo motore

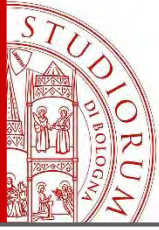
Dipartimento di Ingegneria Industriale
Alma Mater Studiorum – Università di Bologna



La ricerca automotive al DIN

Sono presenti tre gruppi:

- Modellazione, controllo e sperimentazione di motori a combustione interna
- Simulazione termofluidodinamica dei motori a combustione interna e delle macchine a fluido
- Progettazione e scelta dei materiali nel settore automotive



Sperimentazione e controllo

La ricerca verte sullo sviluppo e la validazione di nuovi componenti e di innovative strategie di diagnosi e controllo del motore, con il supporto di 4 banchi prova motore dotati di sistemi di Rapid Control Prototyping.

L'attività comprende:

- modellizzazione per il controllo del motore orientata alla simulazione real-time per implementazione in centralina o in ambienti RCP, SIL e HIL;
- sviluppo di innovative funzioni di controllo e diagnosi del motore;
- modellizzazione e controllo di propulsori ibridi, orientata all'ottimizzazione dei consumi e delle emissioni.

Sperimentazione e controllo

L'attività è distribuita sulle due sedi di Bologna e Forlì e ha collaborazioni in ambito industriale ed accademico.

Sale prova di Forlì

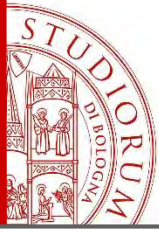


Sala prova di Bologna



Docenti: Nicolò Cavina, Enrico Corti, Davide Moro, Fabrizio Ponti, Vittorio Ravaglioli

Collaboratori: Paolo Bovicelli, Andrea Businaro, Marco Cangini, Filippo Carra, Nahuel Rojo, Michele Taccioli, Lorenzo Zoffoli



Termofluidodinamica degli MCI

Il gruppo di ricerca sviluppa e applica metodologie e modelli di TermoFluidodinamica numerica (CFD) allo studio dei motori a combustione interna e alla macchine a fluido in genere.

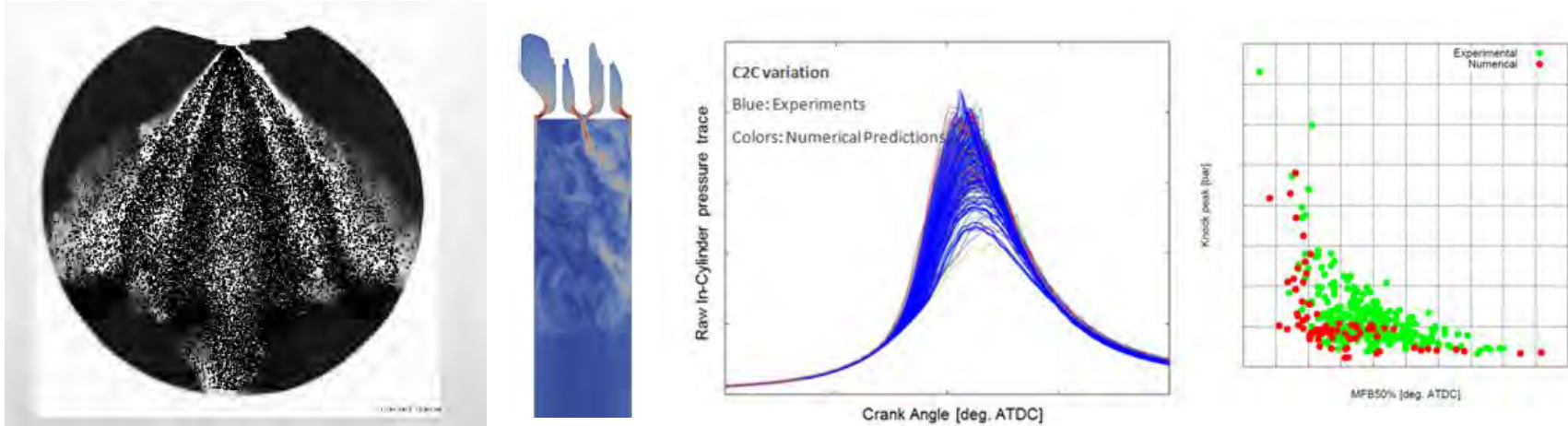
In particolare sono studiati ed ottimizzati i seguenti processi:

- formazione della turbolenza;
- formazione della miscela;
- combustione nei motori alternativi a combustione interna;
- fluidodinamica dei sistemi d'iniezione ad alta e bassa pressione.

-

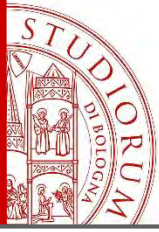
Termofluidodinamica degli MCI

La ricerca, condotta in collaborazione con realtà di riferimento in campo accademico e industriale, viene svolta impiegando codici commerciali e sviluppando ed aggiornando codici open source.



Docenti: Gian Marco Bianchi, Stefania Falfari, Giulio Cazzoli, Claudio Forte


Collaboratori: Giacomo Micci



Potenzialità sensori microfonic

Caratteristiche dei sensori microfonic:

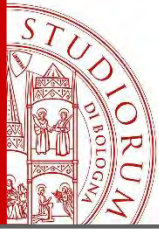
- Costi bassi
- Multi-funzione per applicazioni di controllo e diagnostici.

- 
- ✓ Velocità turbocompressore
 - ✓ Ottimizzazione emissioni inquinanti Diesel in zona ciclo
 - ✓ Knock

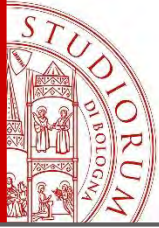
- 
- ✓ Misfire
 - ✓ Determinazione qualità miscela benzina-etanolo

L'attività è sviluppata in collaborazione con la divisione Power-train di Magneti Marelli, coordinata dall'ing. Matteo De Cesare.

Altre funzioni innovative sono in via di sviluppo.

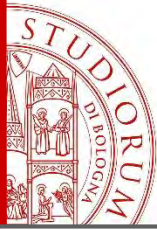


Ottimizzazione delle emissioni Diesel in zona ciclo



Introduzione

- Lo sviluppo del processo di combustione nei motori Diesel ha l'obiettivo di ridurre le emissioni inquinanti e il rumore intervenendo sull'andamento del rilascio del calore.
- Questo risultato viene raggiunto con le iniezioni multiple ed elevati tenori di EGR.
- L'iniezione "singola" permette di ridurre il particolato, con un tollerabile incremento dell'emissione di NOx e di rumore.
- E' stato analizzato il miglior compromesso ottenibile con l'introduzione di alcune iniezioni singole le multiple, mantenendo un livello di rumore controllato



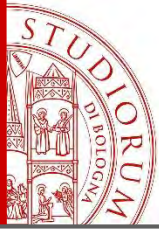
Injection patterns design

- **Engine on test bed: 1.3L Common Rail Diesel engine**

Displaced Volume	1248 cc
Stroke	82 mm
Bore	63.6 mm
Connecting Rod	131.3 mm
Compression Ratio	16.8
Maximum Torque	200 Nm @ 1500 rpm
Maximum Power	70 kW @ 3800 rpm
Number of valves	4 per cylinder
Injection system	Common Rail Multi-Jet

- Injection parameters for **two different engine operating conditions**

	Engine speed [rpm]	BMEP [bar]	pRail [bar]	EGR [%]	AirQ [mg/strk]	Qpil [mm3/strk]	Qpre [mm3/strk]	SoiMain [deg]	ETMain [microsec]
Standard	2000	3	570	15	275	1	1	5	490
Modified						0	0	9	570
Standard	2000	1.5	570	15	195	1	1	4.5	450
Modified						0	0	9.5	515

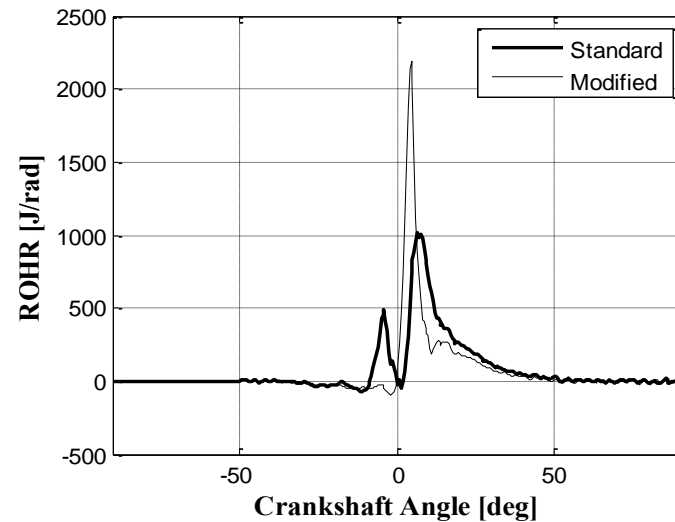
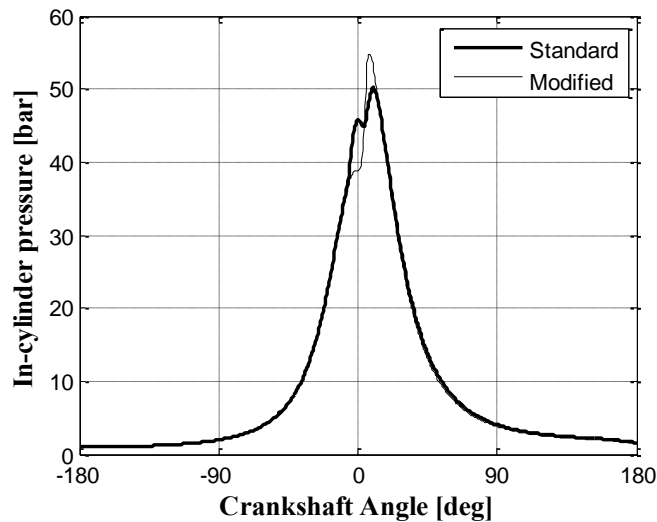


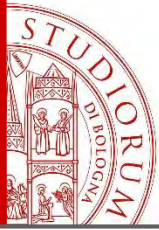
Injection patterns design

	Engine speed [rpm]	BMEP [bar]	pRail [bar]	EGR [%]	AirQ [mg/strk]	Qpil [mm3/strk]	Qpre [mm3/strk]	SoiMain [deg]	ETMain [microsec]
Standard	2000	3	570	15	275	1	1	5	490
Modified						0	0	9	570
Standard	2000	1.5	570	15	195	1	1	4.5	450
Modified						0	0	9.5	515

- In-cylinder pressure and Rate of Heat Release with standard and modified injection pattern**

Tests run at **2000 rpm** and **BMEP = 3 bar**

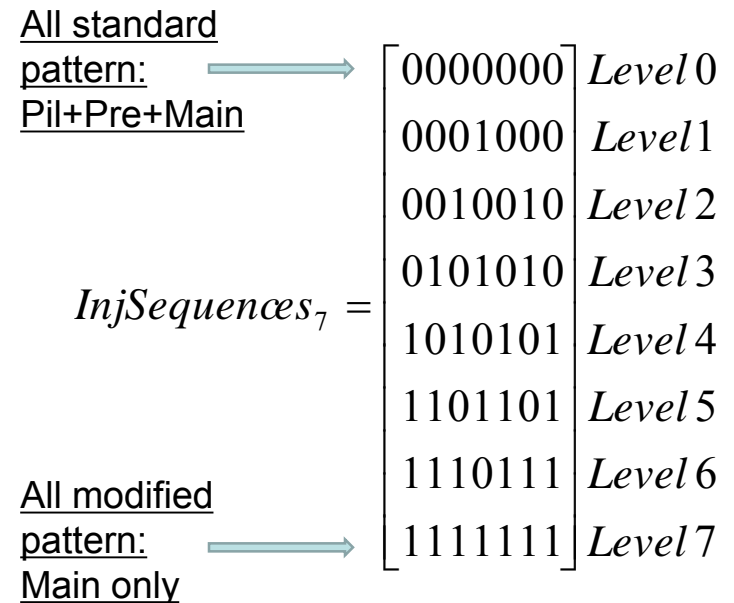




Injection patterns design

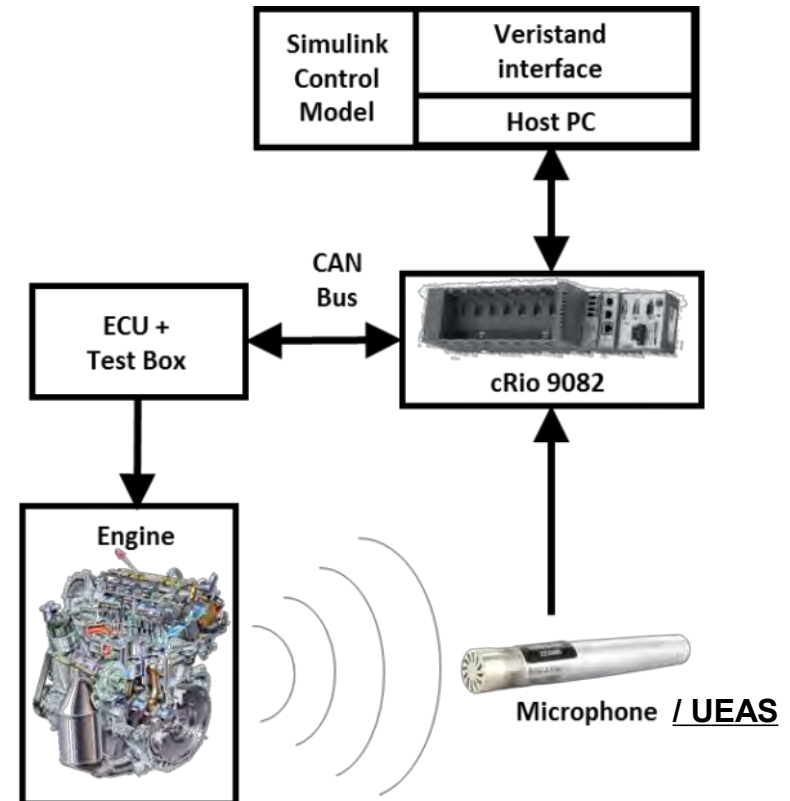
	Engine speed [rpm]	BMEP [bar]	pRail [bar]	EGR [%]	AirQ [mg/strk]	Qpil [mm3/strk]	Qpre [mm3/strk]	SoiMain [deg]	ETMain [microsec]
Standard	2000	3	570	15	275	1	1	5	490
Modified						0	0	9	570
Standard	2000	1.5	570	15	195	1	1	4.5	450
Modified						0	0	9.5	515

- **Intermediate operating mode:** organized sequence of engine cycles run with or without Pilot and Pre
- Main criteria for injection sequence design: **maximize the switching frequency between one operating mode (Standard) and the other (Modified - without Pilot and Pre)**
- Constant torque and CA50 is maintained: no discontinuities in engine operation



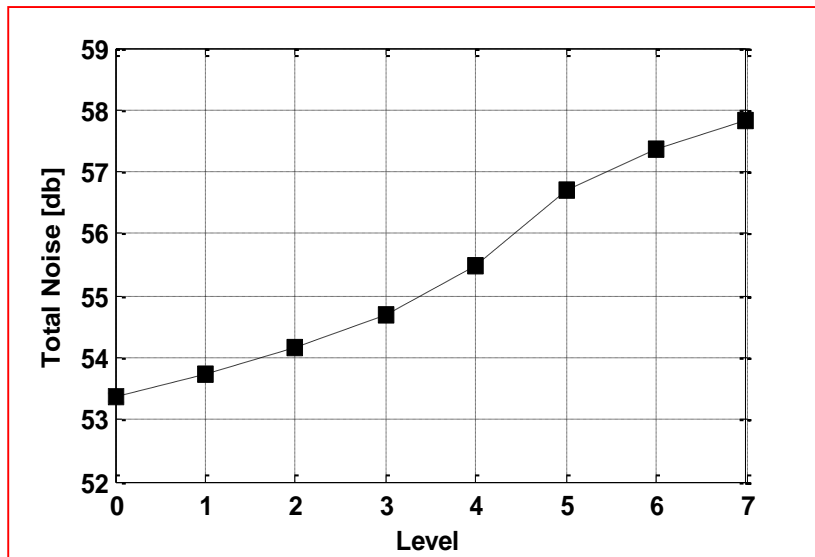
Experimental setup

- **Rapid Control Prototyping system to change injections parameters in real-time**
- Actuation of the **sequence corresponding to the Level set by the engine noise control algorithm**
- **Noise index calculation based on the signal coming from the Magneti Marelli Ultrasonic Engine Acoustic Sensor (UEAS)**



Results

- **Noise is strongly influenced by the number of pre-injections performed over the observed sequence of combustions**
- **As expected, Pilot and Pre deactivation causes a progressive increase in engine noise**



Test run at 2000 rpm and BMEP = 3 bar

All standard
pattern: →

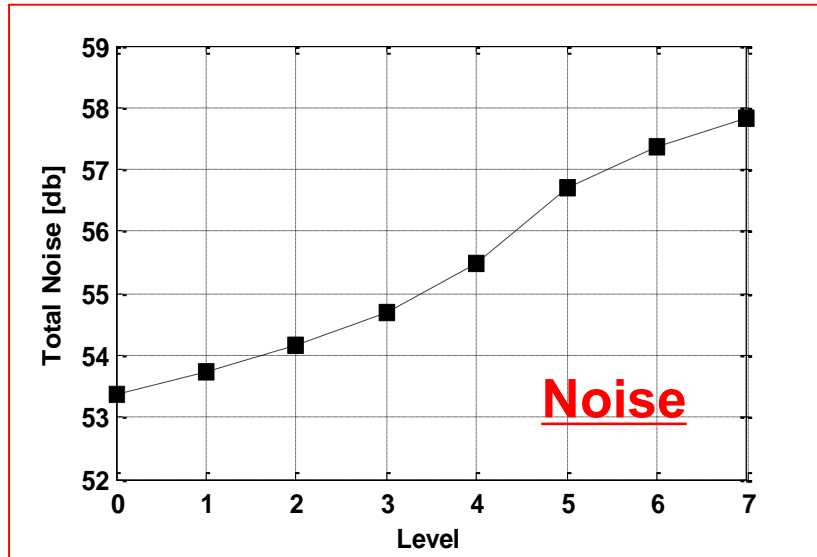
All modified
pattern: →

0000000	Level 0
0001000	Level 1
0010010	Level 2
0101010	Level 3
1010101	Level 4
1101101	Level 5
1110111	Level 6
1111111	Level 7

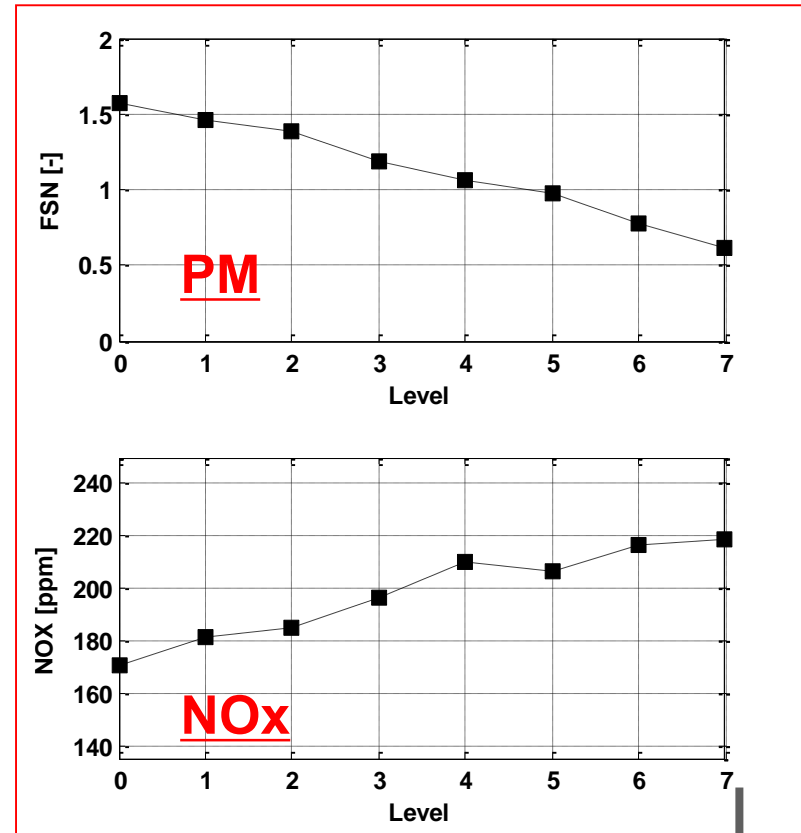
$InjSequences_7 =$

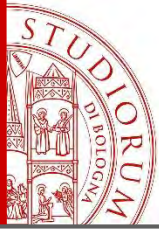
Results

- **Particulate Matter** is significantly **reduced** actuating modified injection patterns
- **NOx** concentration is slightly increased



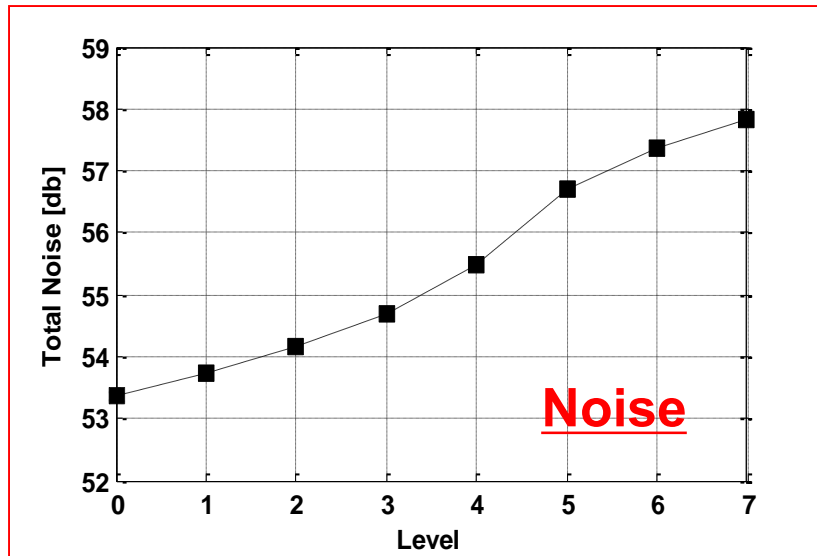
Test run at 2000 rpm and BMEP = 3 bar



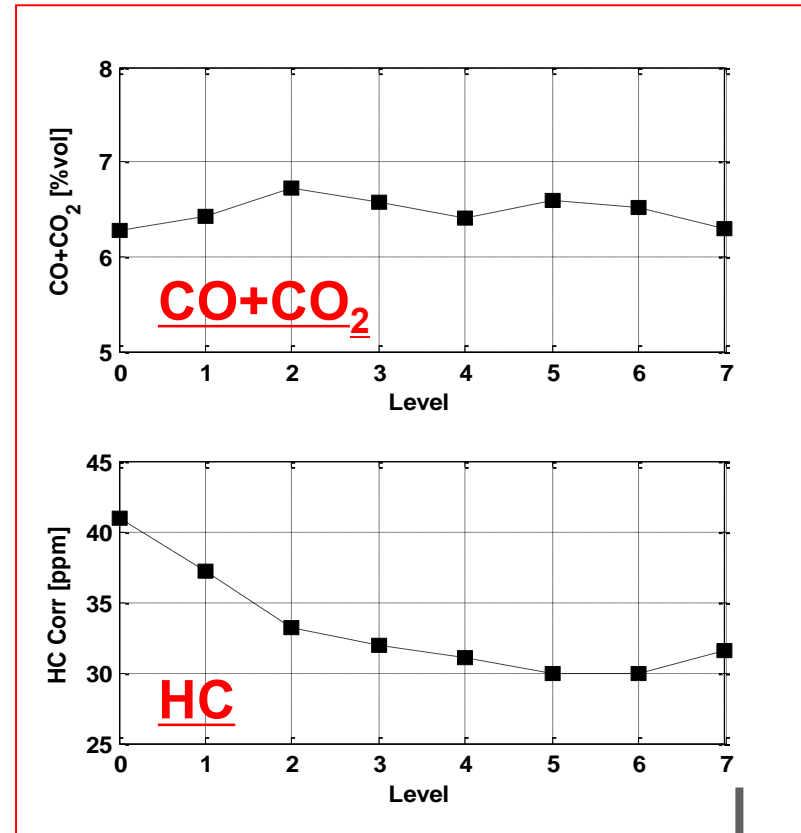


Results

- **Combustion efficiency (fuel consumption)** is kept constant
- **HC/CO emissions** are slightly improved

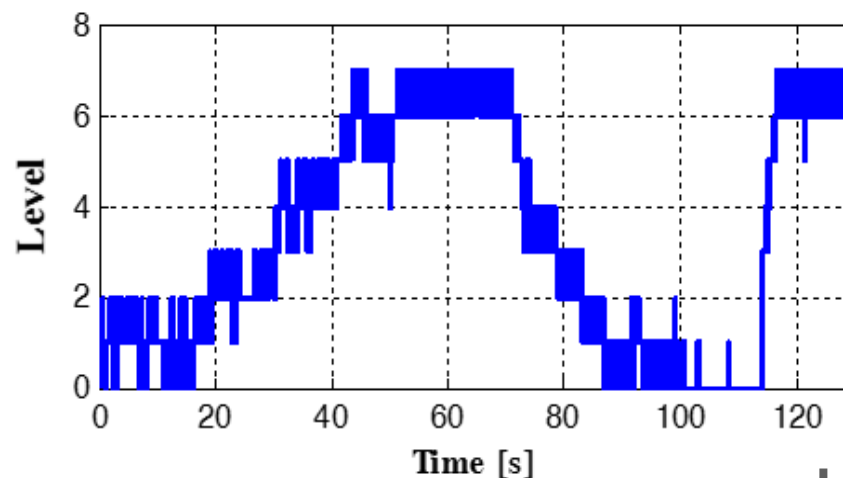
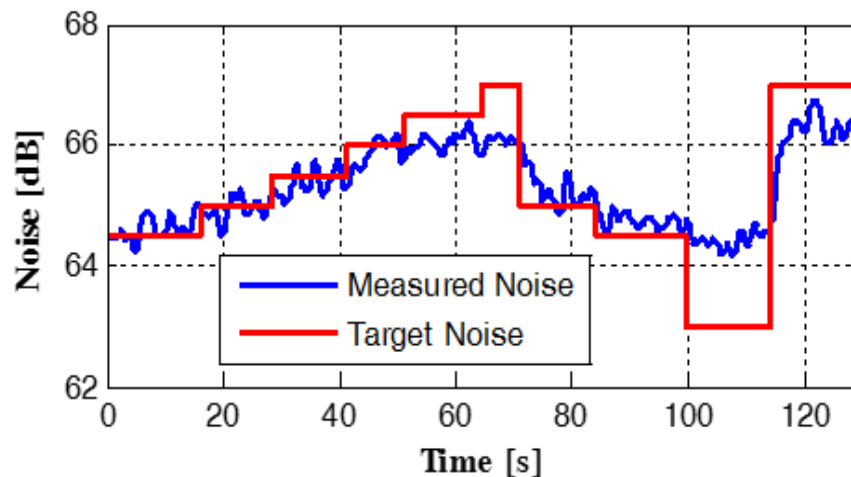


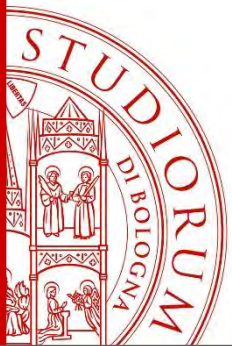
Test run at 2000 rpm and BMEP = 3 bar



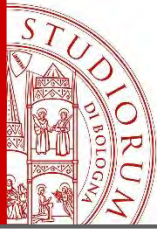
Results

- Noise control algorithm: **Target noise is achieved changing the Level used to select the Injection Sequence.**
- **Engine noise can be set to intermediate values between those obtained running stationary injection patterns**
- **Injection Pattern can be controlled in real-time to achieve the best compromise in term of noise and emissions**





Knock



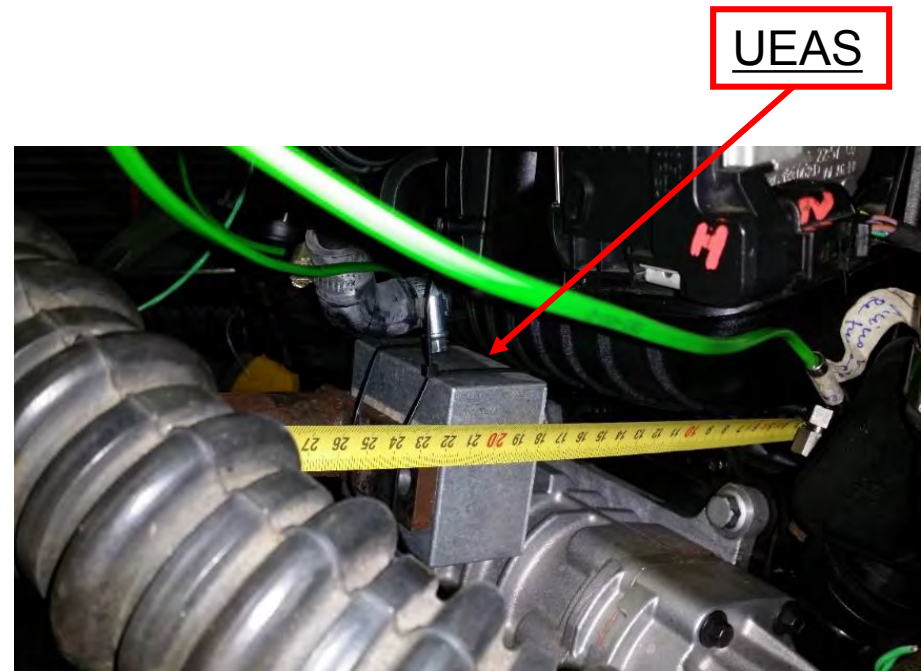
Optimal Microphone Position

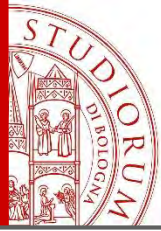
During the tests knock has been externally induced acting on the spark advance. Three steady-state engine operating conditions have been tested:

Op. Point #	Engine Speed	Intake Manifold Pressure
1	2000 rpm	1300 mbar
2	2500 rpm	1500 mbar
3	3000 rpm	1500 mbar

500 subsequent engine cycles have been acquired and processed.

Intake engine side, with the microphone placed very close to the cylinders (~200 mm) has been identified as the location with the highest Signal-to-Noise Ratio.



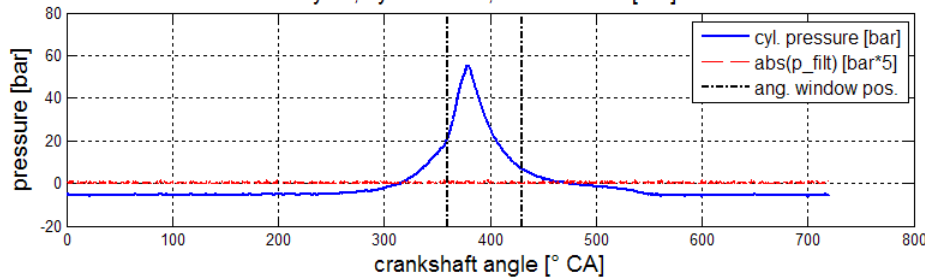


Sound and pressure signals pre-processing

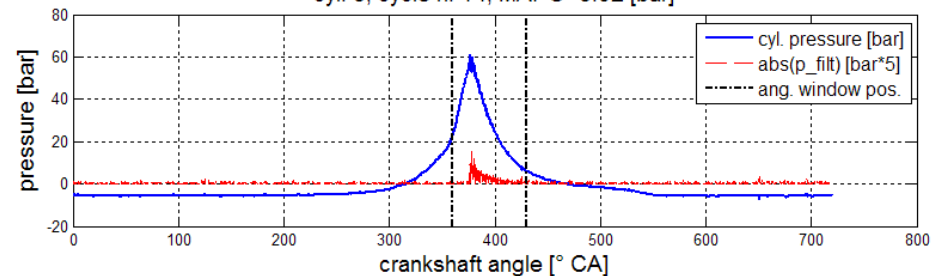
- It is interesting to compare in-cylinder pressure, vibration and sound emission signals in the time and frequency domain, both for non-knocking and light/medium-knocking combustions
- The lower plot of each of the following figures represents the frequency spectrum of the upper plot signal windowed around the combustion phase (i.e., in the angular interval between the vertical dashed lines of the upper plot).

in-cylinder pressure signal, 2000 rpm, full load, $\Delta SA = +7^\circ CA$

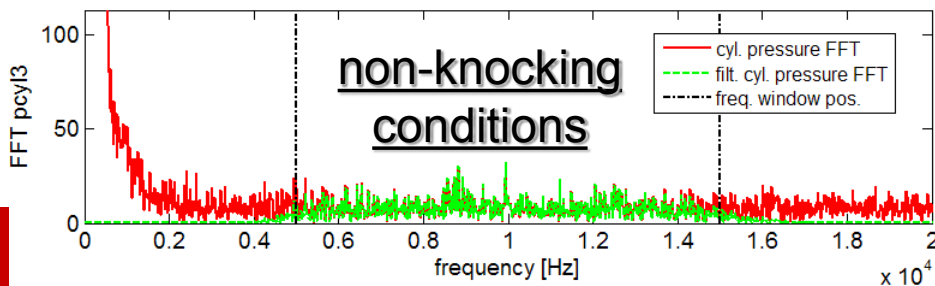
cyl. 3; cycle n. 210; MAPO=0.39 [bar]



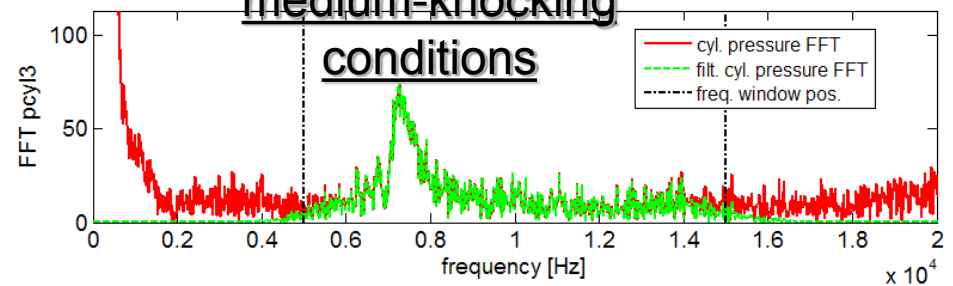
cyl. 3; cycle n. 14; MAPO=3.02 [bar]



non-knocking conditions



medium-knocking conditions

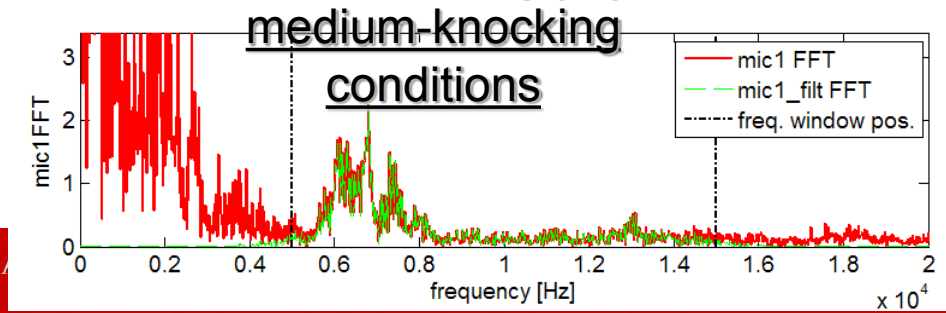
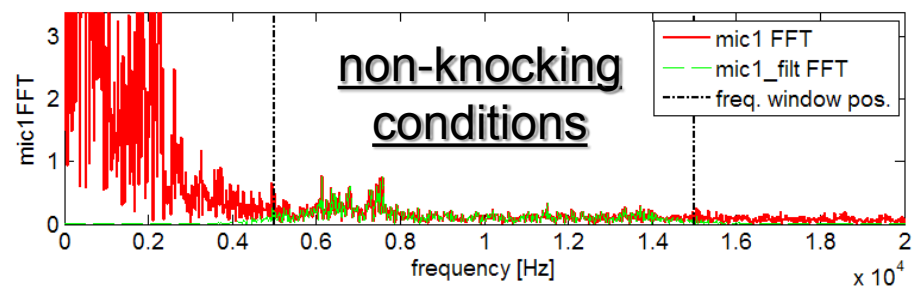
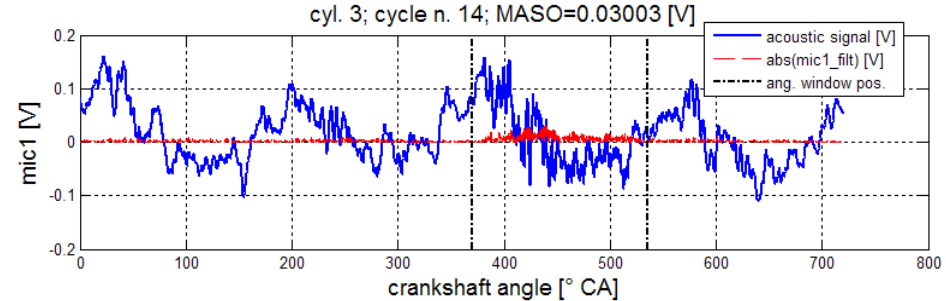
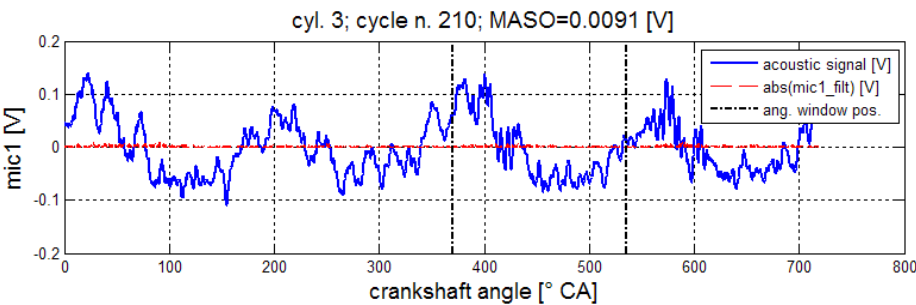


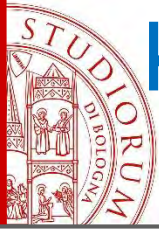


Sound and pressure signals pre-processing

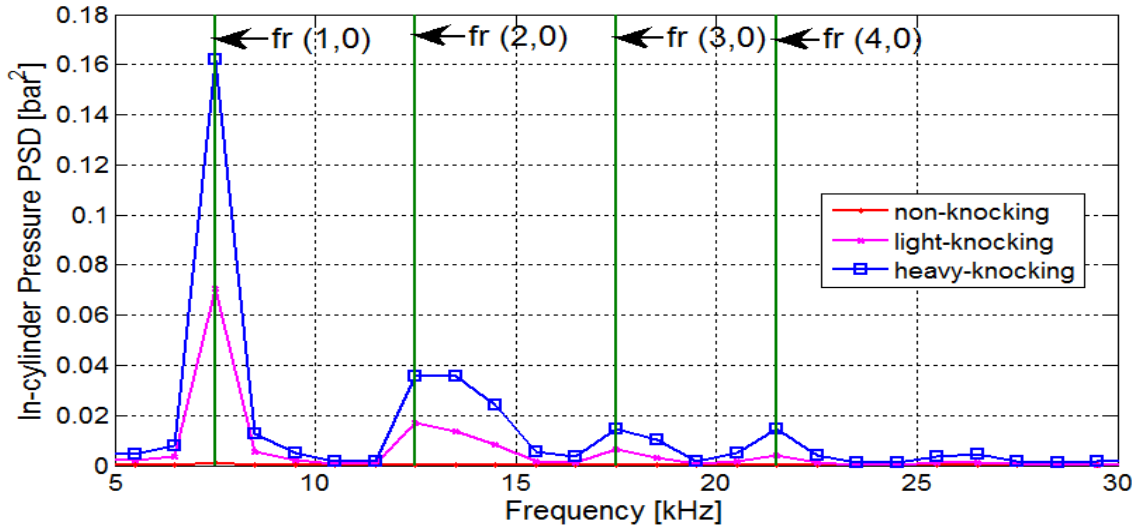
- It is interesting to compare in-cylinder pressure, vibration and sound emission signals in the time and frequency domain, both for non-knocking and light/medium-knocking combustions
- The lower plot of each of the following figures represents the frequency spectrum of the upper plot signal windowed around the combustion phase (i.e., in the angular interval between the vertical dashed lines of the upper plot).

MIC # 1 sound signal, 2000 rpm, full load, $\Delta SA = +7^\circ CA$

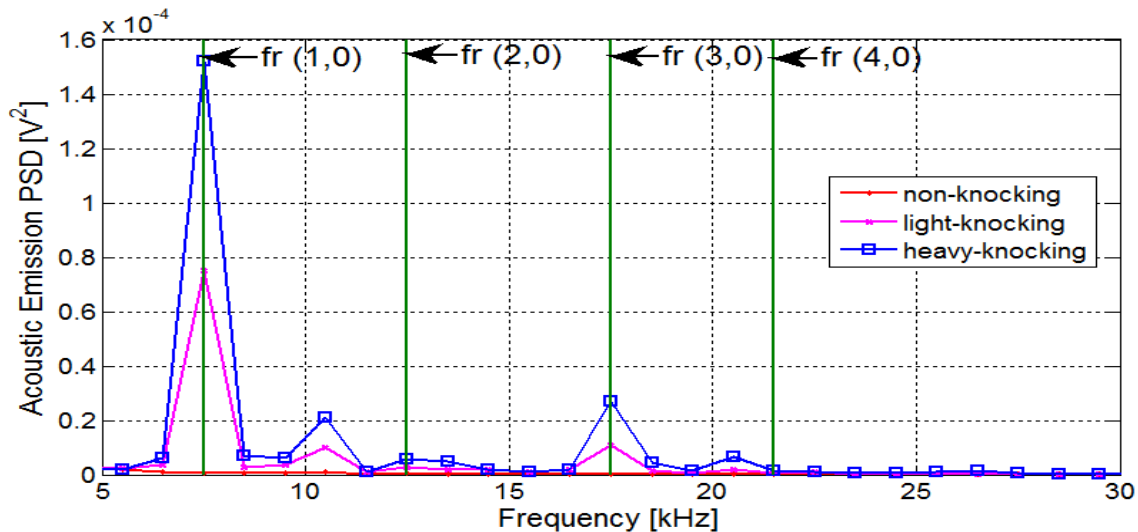




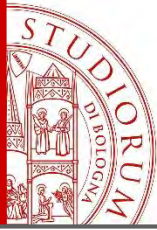
Knock Detection - Combustion chamber vibration modes



The same frequencies are excited during knocking combustions. Further, the intensity of the energy in the acoustic emission spectrum increases in the same way as for the in-cylinder pressure signal.



Sound speed delay has been compensated in order to obtain an accurate cycle and cylinder identification considering speed of sound ($C_s = \sqrt{KRT}$)



Optimal Microphone Position

- Different knock indexes have been tested in order to identify the best solution for acoustic-based application.
- Correlation levels between audio-based knock and in-cylinder pressure based indexes (MAPO) have been taken as a measure of the acoustic index performance.

$$Int = \frac{1}{\theta_2 - \theta_1} \int_{\theta_1}^{\theta_2} |Sound_{filt}| d\theta$$

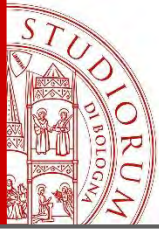
Band-pass filter 7-8kHz

$$SDBP = \max(|Sound_{filt1}|) + \max(|Sound_{filt2}|) + \max(|Sound_{filt3}|)$$

Band-pass filter
7-8kHz + 12-13kHz+17-18kHz

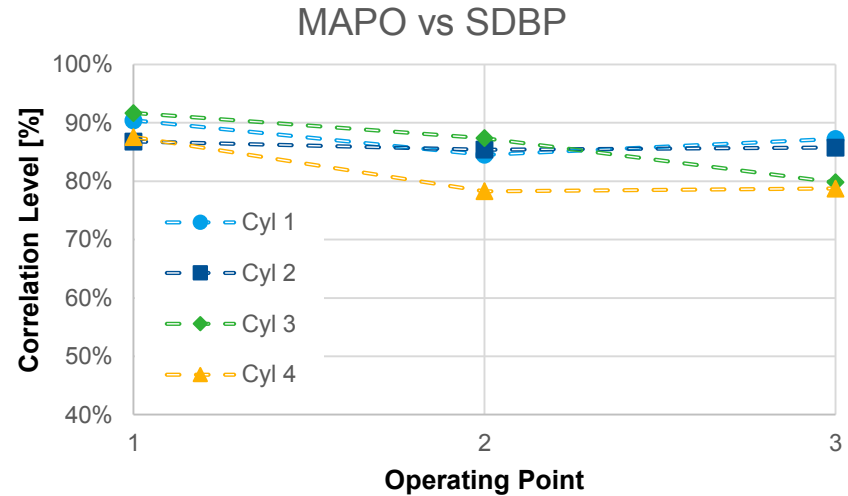
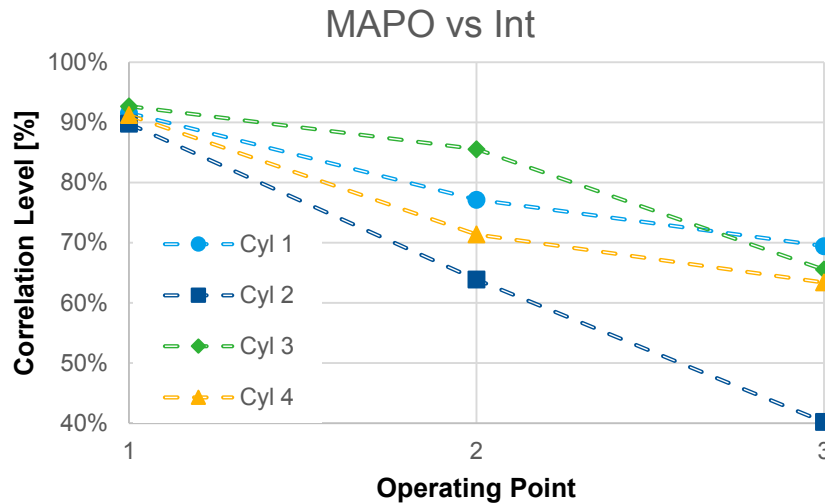
$$MAPO = \max(|Pcyl_{filt}|)$$

High pass filter 5kHz



Optimal Microphone Position

Ultrasonic Engine Acoustic Sensor (UEAS) – MAPO correlation levels



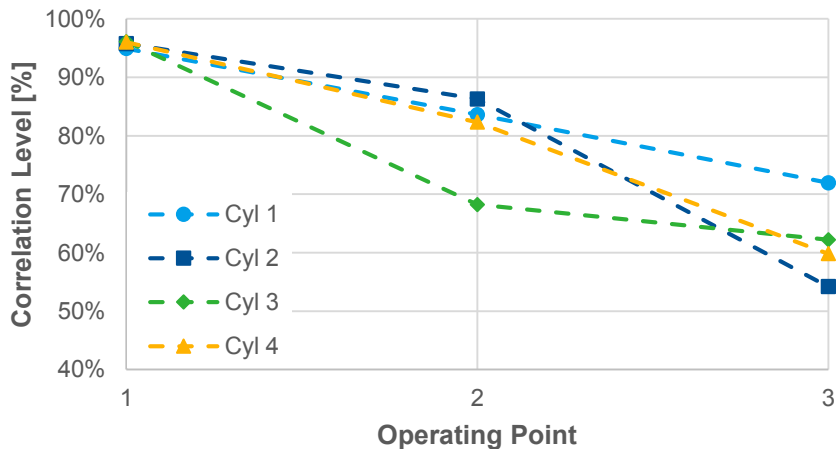
Point #	rpm-mbar	Cyl. 1	Cyl. 2	Cyl. 3	Cyl. 4
1	2000-1300	91.54%	89.74%	92.66%	91.19%
2	2500-1500	77.12%	63.84%	85.52%	71.35%
3	3000-1500	69.41%	40.17%	65.49%	63.36%

Point #	rpm-mbar	Cyl. 1	Cyl. 2	Cyl. 3	Cyl. 4
1	2000-1300	90.43%	86.79%	91.69%	87.56%
2	2500-1500	84.52%	85.40%	87.37%	78.27%
3	3000-1500	87.24%	85.77%	79.81%	78.75%

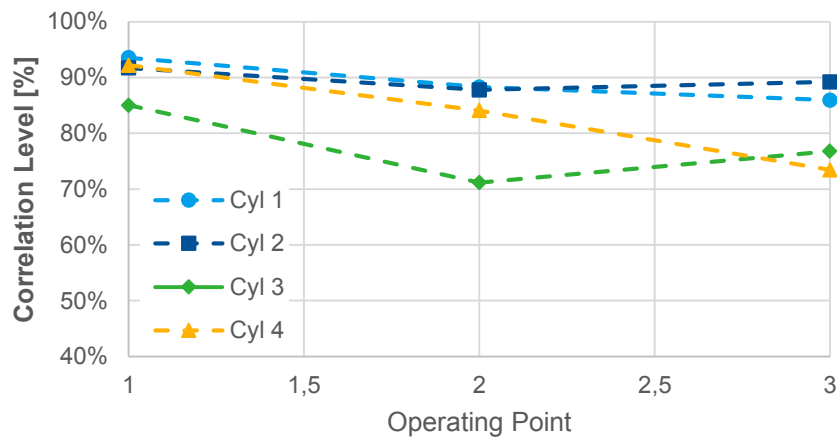
Accelerometer Results

Accelerometer – MAPO correlation levels

MAPO vs Int

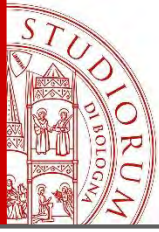


MAPO vs SDBP



Point #	rpm-mbar	Cyl. 1	Cyl. 2	Cyl. 3	Cyl. 4
1	2000-1300	94.91%	95.76%	96.10%	96.01%
2	2500-1500	83.62%	86.29%	68.23%	82.33%
3	3000-1500	71.96%	54.19%	62.20%	59.82%

Point #	rpm-mbar	Cyl. 1	Cyl. 2	Cyl. 3	Cyl. 4
1	2000-1300	93.54%	91.71%	85.01%	92.19%
2	2500-1500	88.28%	87.77%	71.15%	84.07%
3	3000-1500	85.94%	89.21%	76.77%	73.42%

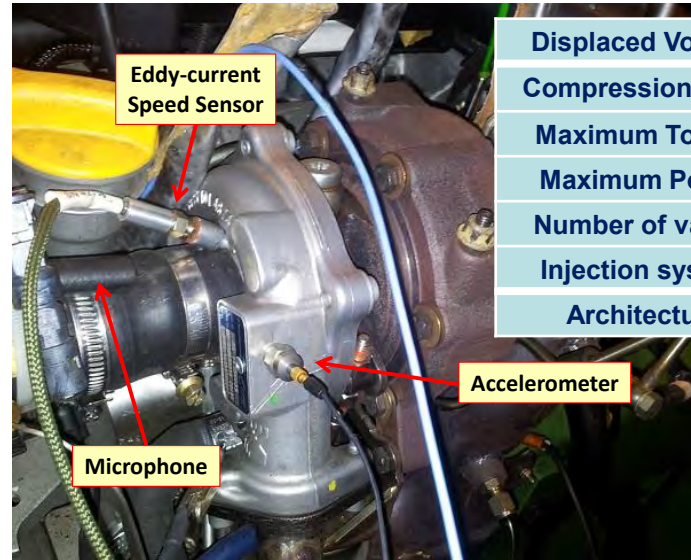


Velocità turbocompressore

Experimental Setup

- The whole estimation algorithm has been developed and validated through specifically designed tests carried out running a **1.3L Common-Rail Diesel engine**

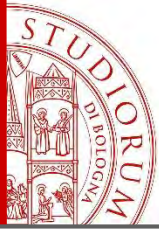
- Steady – State Tests:** In order to investigate a wide engine operating range, 16 tests have been carried out at different speed and load levels



Displaced Volume	1248 cm ³
Compression Ratio	16.8
Maximum Torque	200 Nm @ 1500 rpm
Maximum Power	70 kW @ 3800 rpm
Number of valves	4 per cylinder
Injection system	Common Rail Multi-Jet
Architecture	L4, firing order 1-3-4-2

Borg Warner's BV35 turbocharger

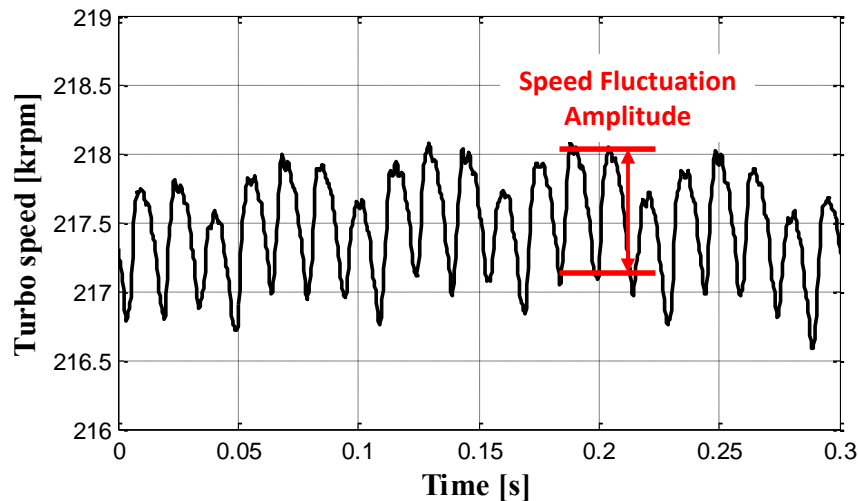
Engine Speed	BMEP			
	3 bar	8 bar	14 bar	20 bar
1500 rpm	1	2	3	4
2000 rpm	5	6	7	8
2500 rpm	9	10	11	12
3000 rpm	13	14	15	16

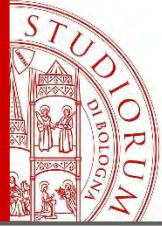


Speed Fluctuations

Relationship with Turbine Power

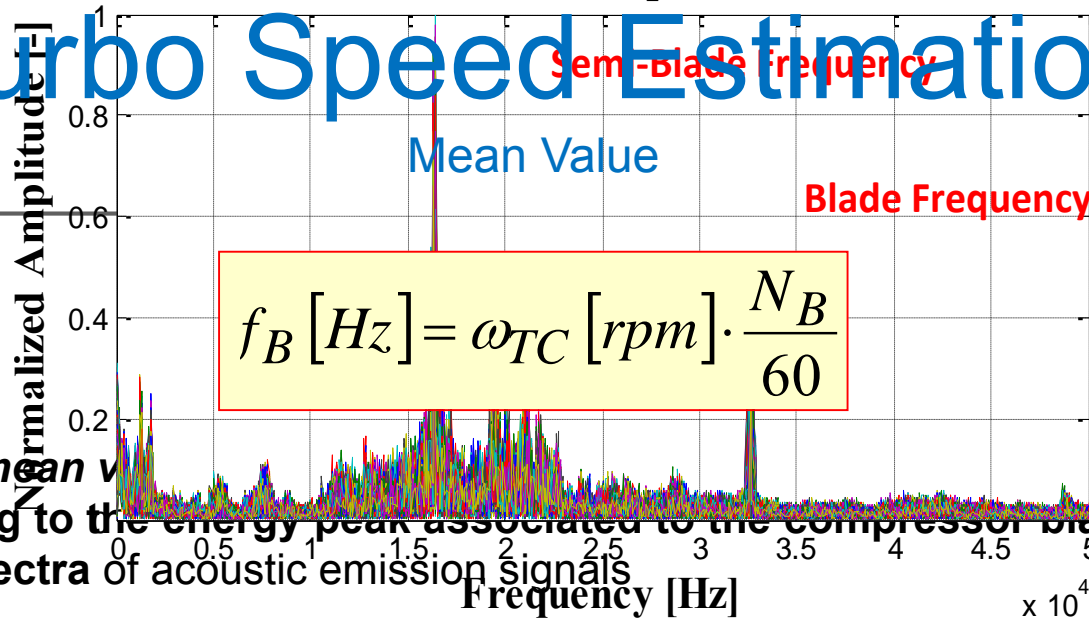
- **Turbocharger Control** – *both Compressor and Turbine maps depend on Turbocharger Speed, therefore this quantity is necessary to quantify turbocharger performance.*
- **Turbocharger Diagnostic** – *an accurate knowledge of rotational speed allows extending turbocharger operating range avoiding mechanical damages. This is very important for engine power increase and fuel consumption reduction.*





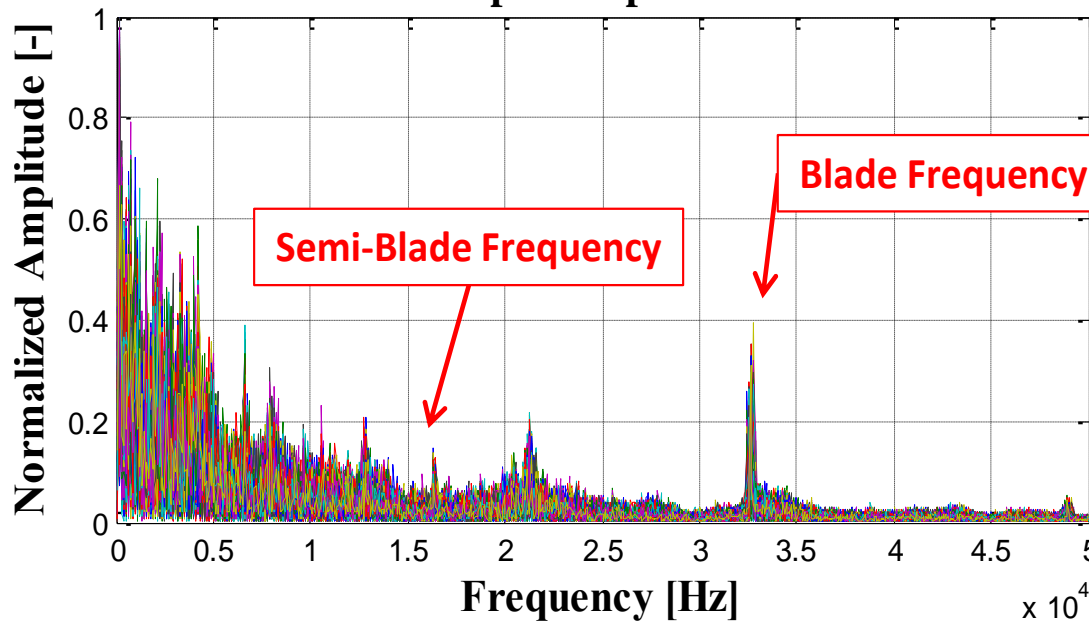
Turbo Speed Estimation

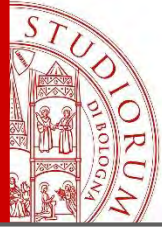
Accelerometer spectrum



Turbo speed *mean value* corresponding to the energy peak associated to the compressor blade in the frequency spectra of acoustic emission signals

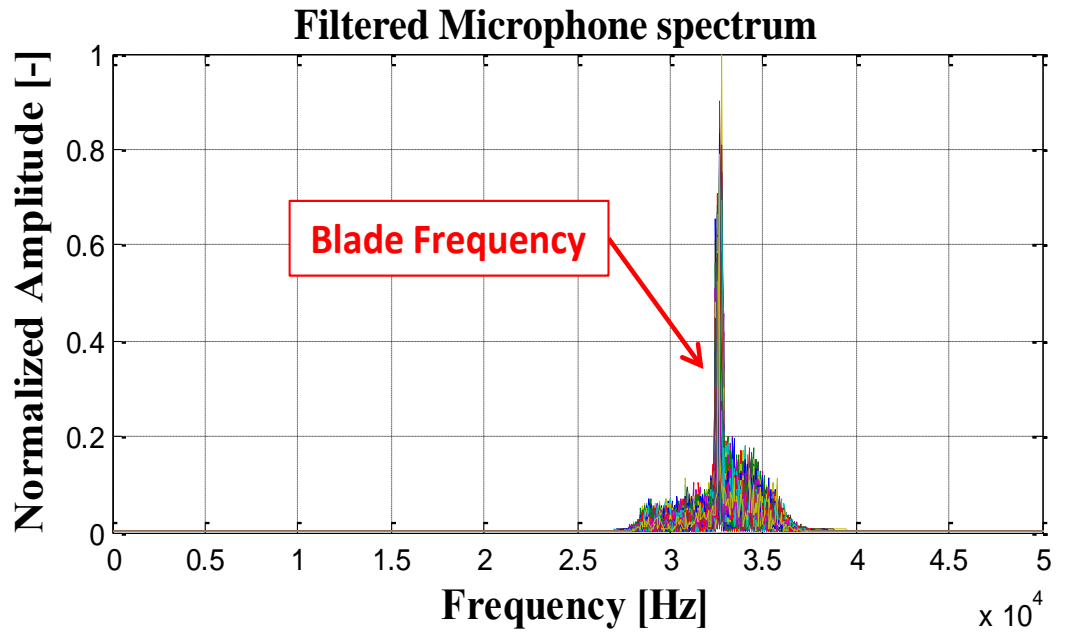
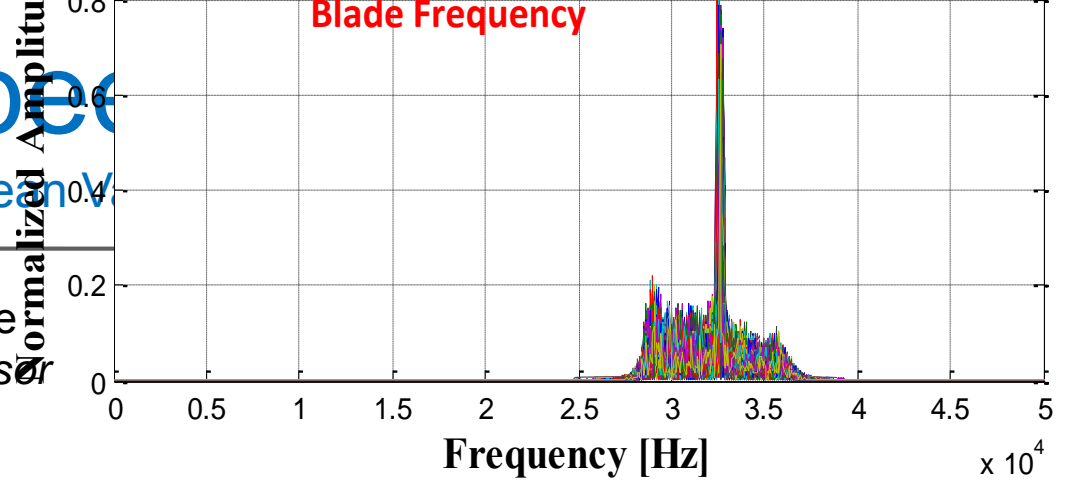
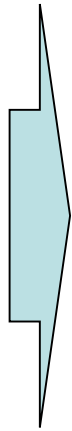
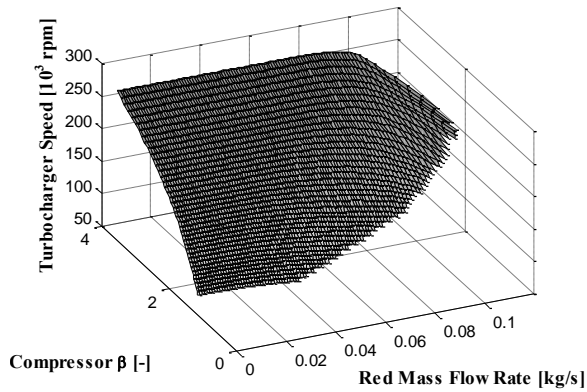
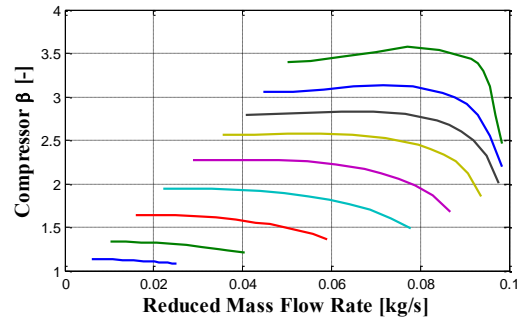
Microphone spectrum

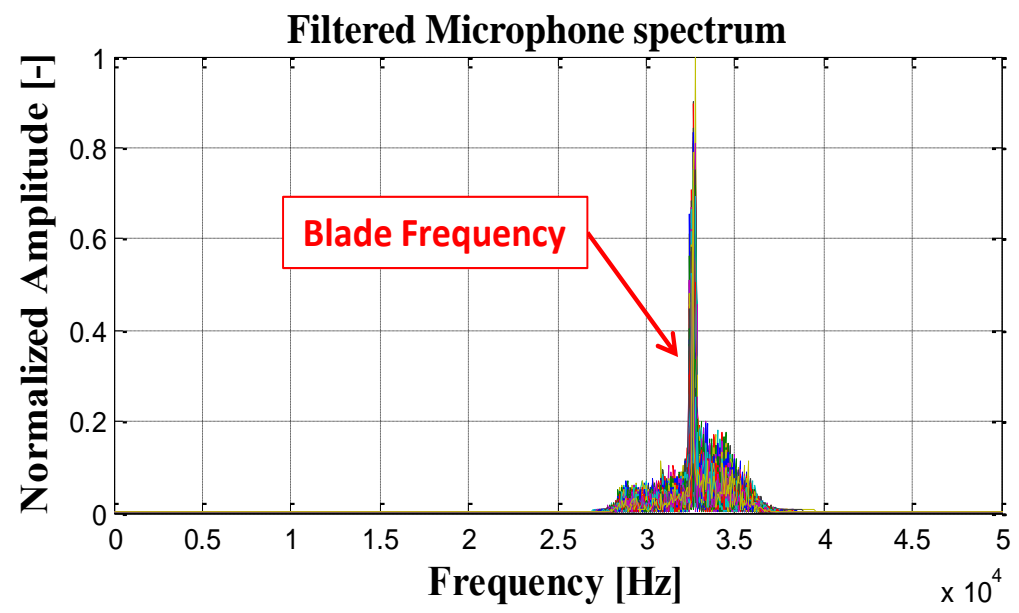
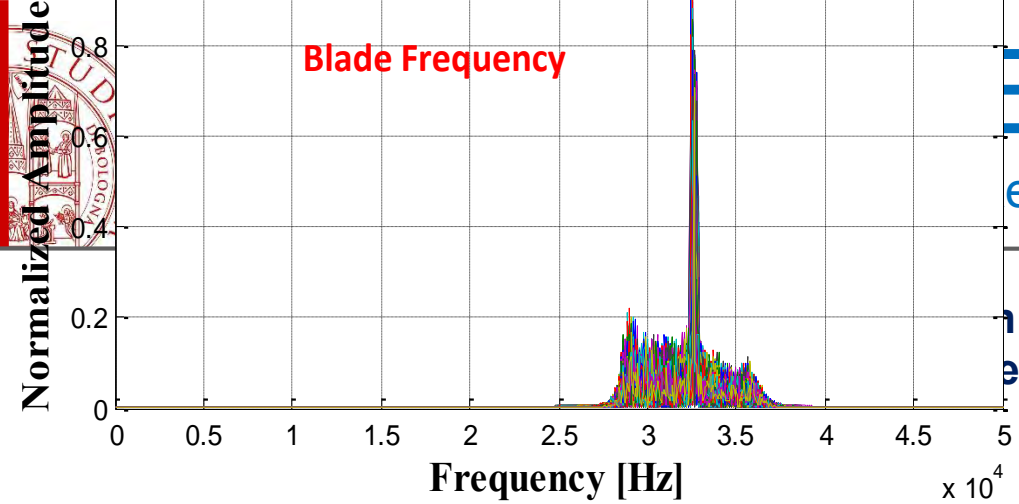




Turbo Speed

- **Signal Filtering** based on the compressor model (*compressor map*)

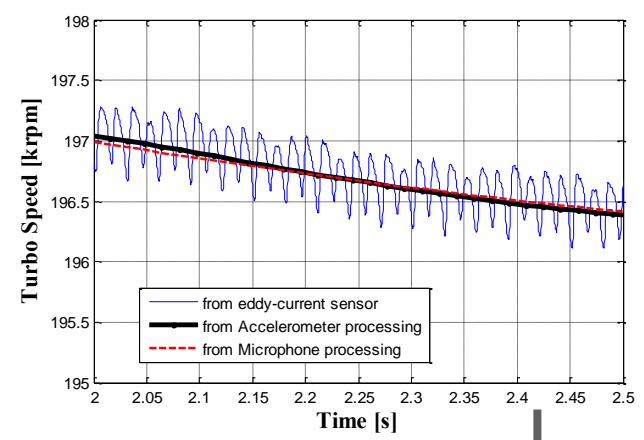
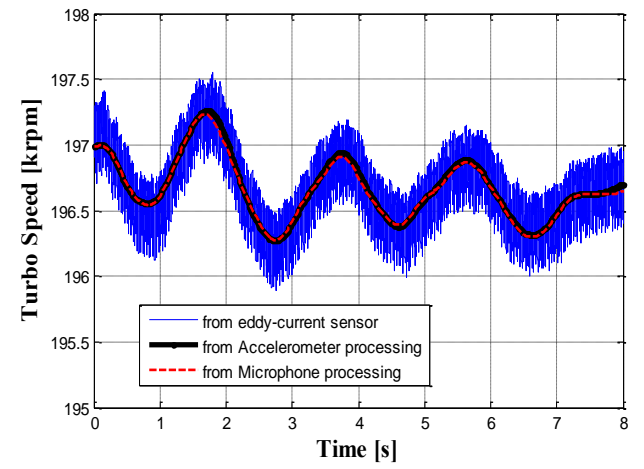
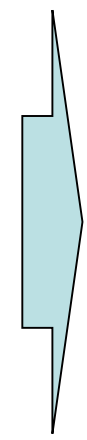


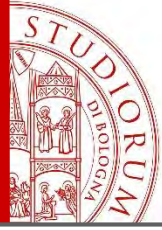


Estimation

result

can be used to
 speed mean value.

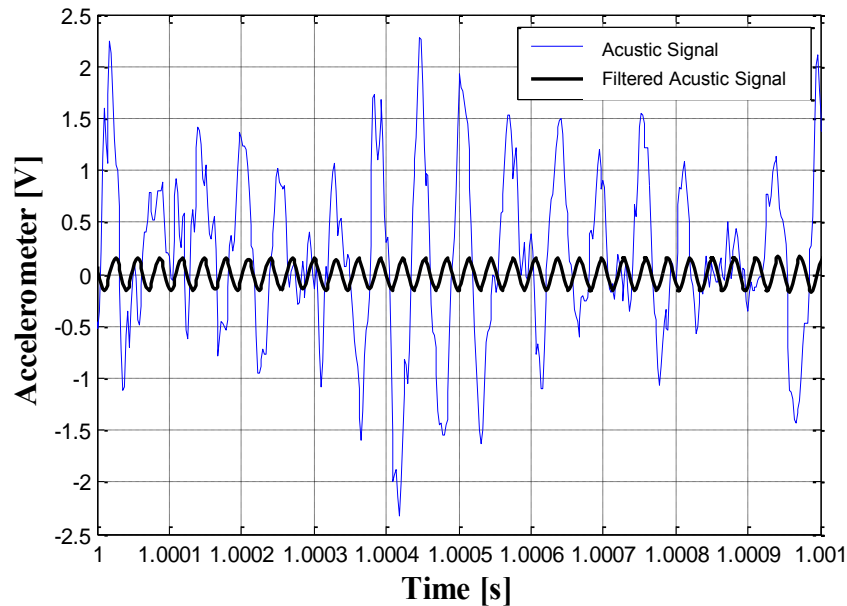




Turbo Speed Estimation

Fluctuation – Filter 2

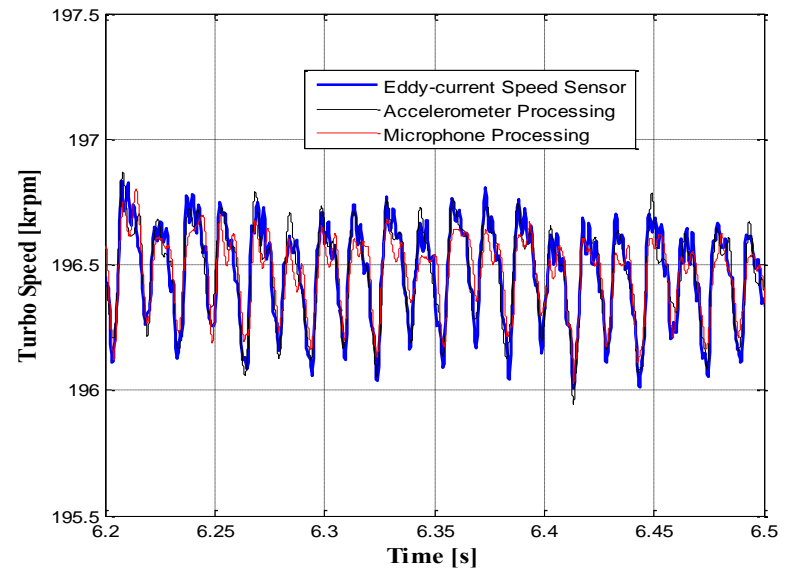
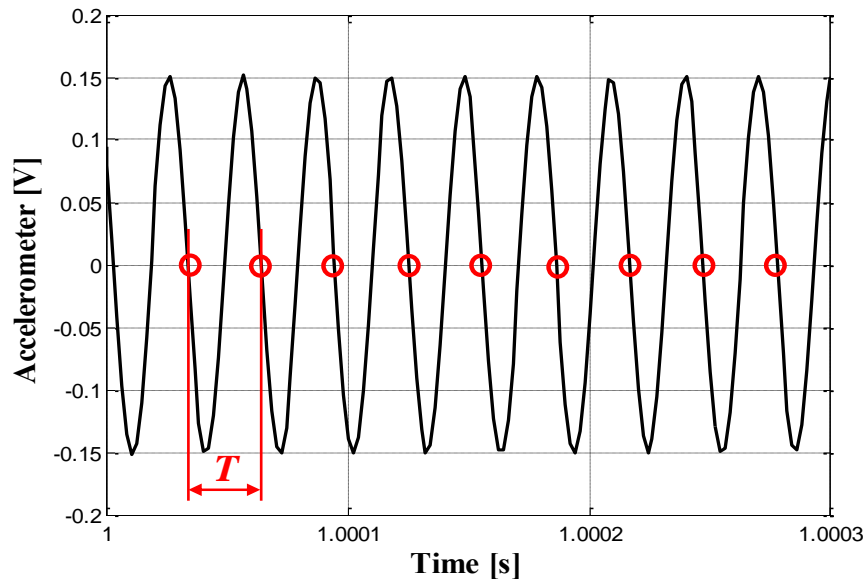
- the information about compressor **blade frequency**, accurately determined using the approach based on spectral analysis, **can be used to set up a new band-pass filter for acceleration and audio signals**.
- **This filter can be more selective**, since the actual value of compressor blade frequency has been accurately determined.



Turbo Speed Estimation

Fluctuation – Calculation

- Once the proper filter has been applied to acceleration or acoustic emission signals, the **period T** (variable over time) of the filtered waveform **can be identified simply by measuring the time interval between two corresponding zero-crossings** (rising or falling).

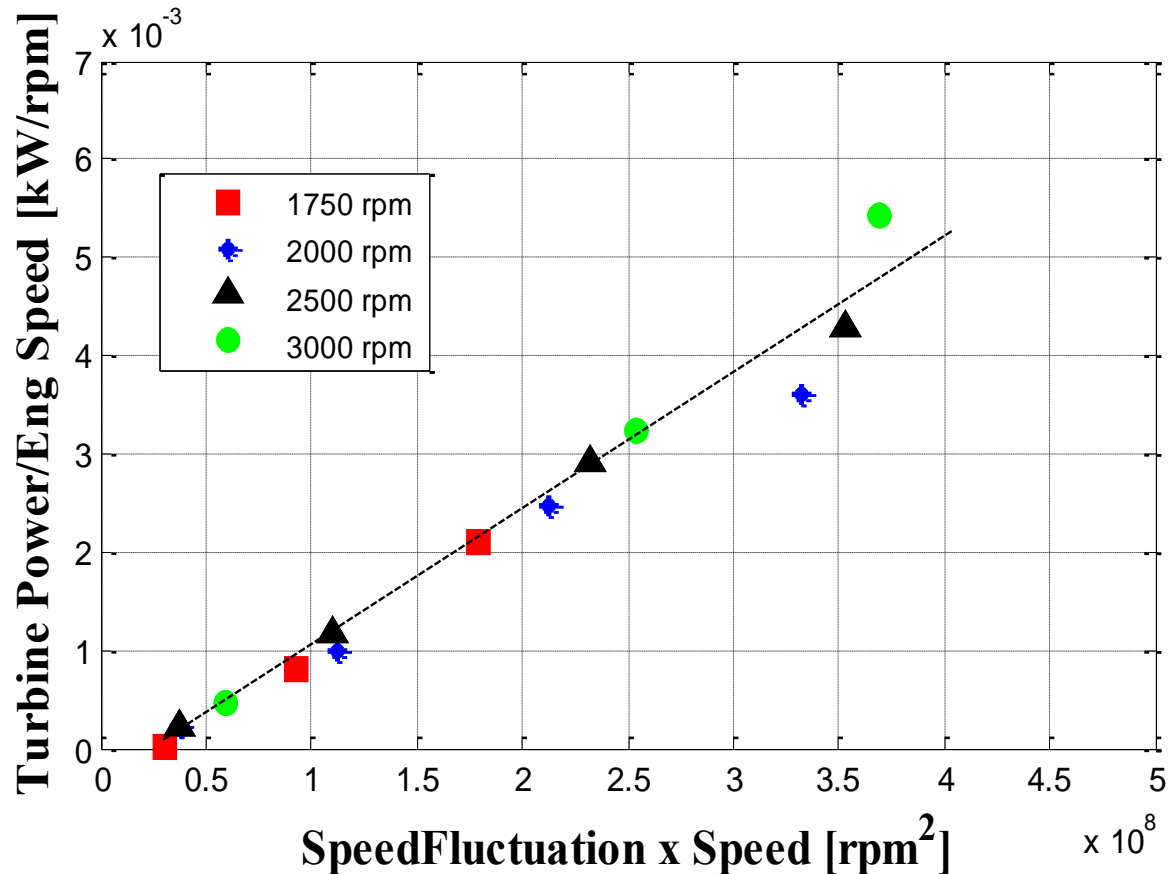


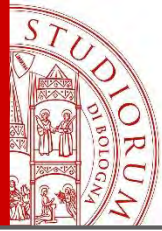


Speed Fluctuations

Relationship with Turbine Power

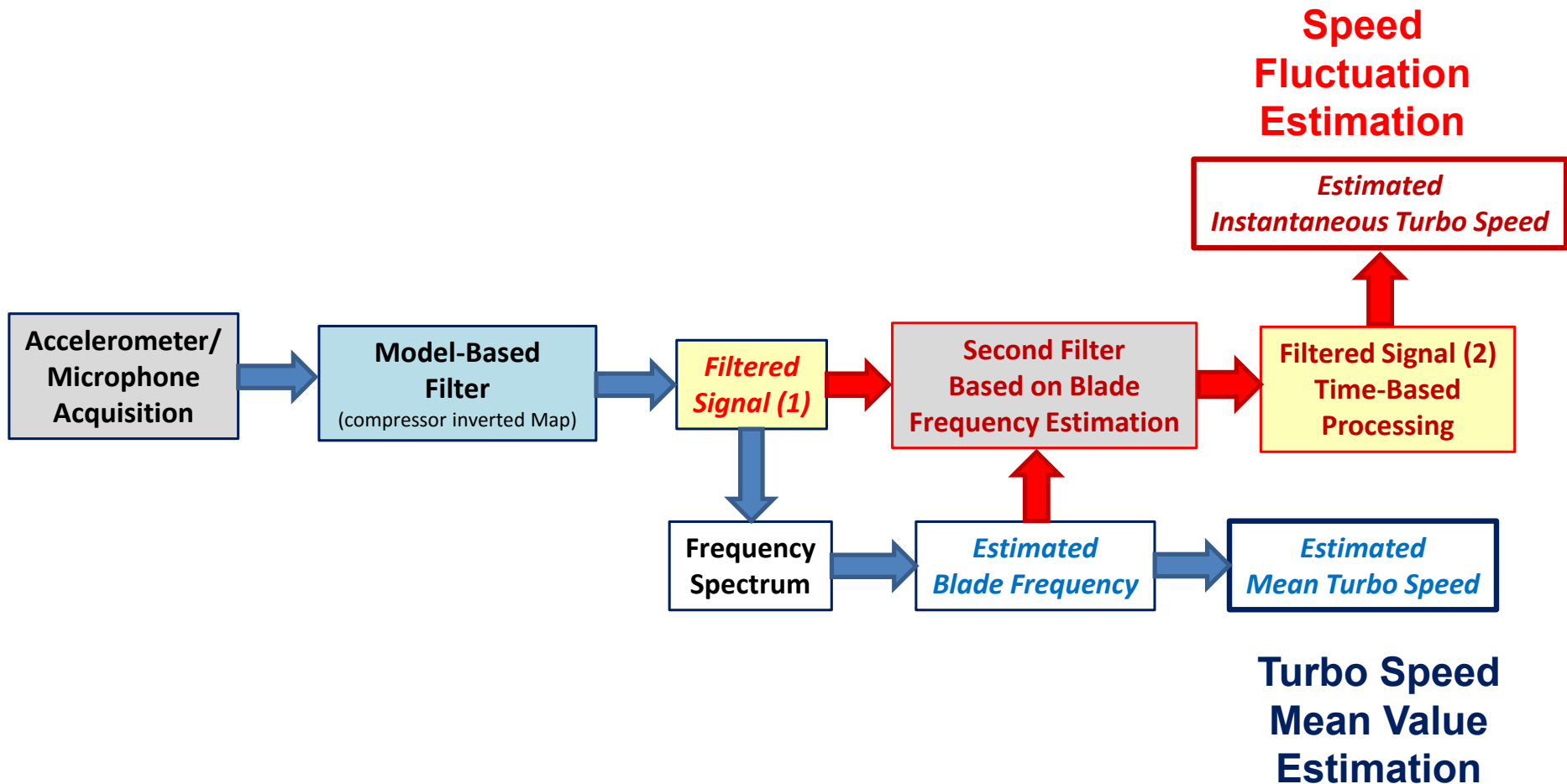
- K represents the linear correlation existing between normalized turbine power (with respect engine speed) and the product between the amplitude of turbo speed fluctuation and its mean value**





Turbo Speed Estimation

Algorithm





Misfire



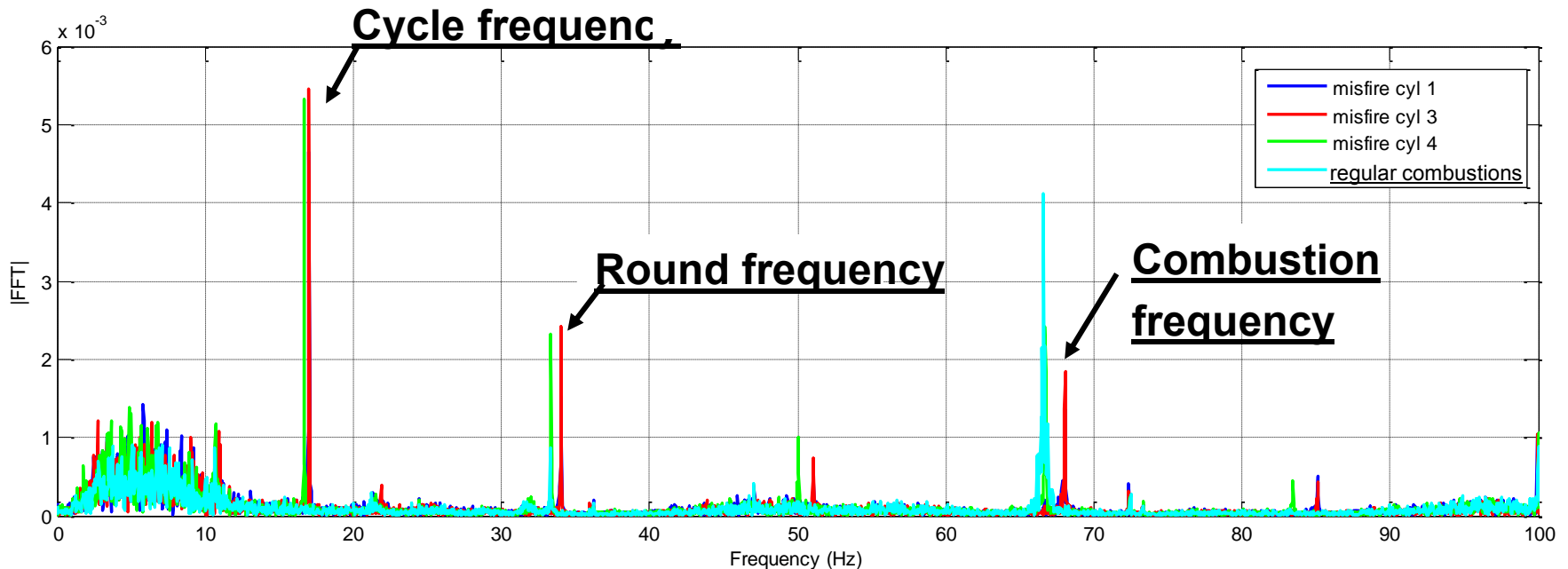
Misfiring diagnosis via audio signal analysis

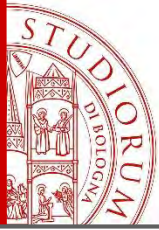
- During an **engine cycle with a misfiring cylinder**, the frequency spectrum of the sound emission is characterized by an **energy shift towards lower frequencies**.
 - During engine cycles with **all cylinders normally firing**, the **frequency spectrum is concentrated around engine round and combustion frequency values** (respectively, engine orders 1 and 2, or harmonic number 2 and 4 of the engine cycle frequency).
 - During **engine cycles with one misfiring cylinder**, **cycle frequency** (order 0.5 or harmonic number 1) and its harmonics **become instead prevalent**.



Misfiring diagnosis via audio signal analysis

- An index based on the **sound signal amplitude of the cycle frequency** could be used to isolate engine cycles with misfiring cylinders, and **the phase of the very same frequency component would allow identifying the faulty cylinder.**
- Example: **2000 rpm, full load**



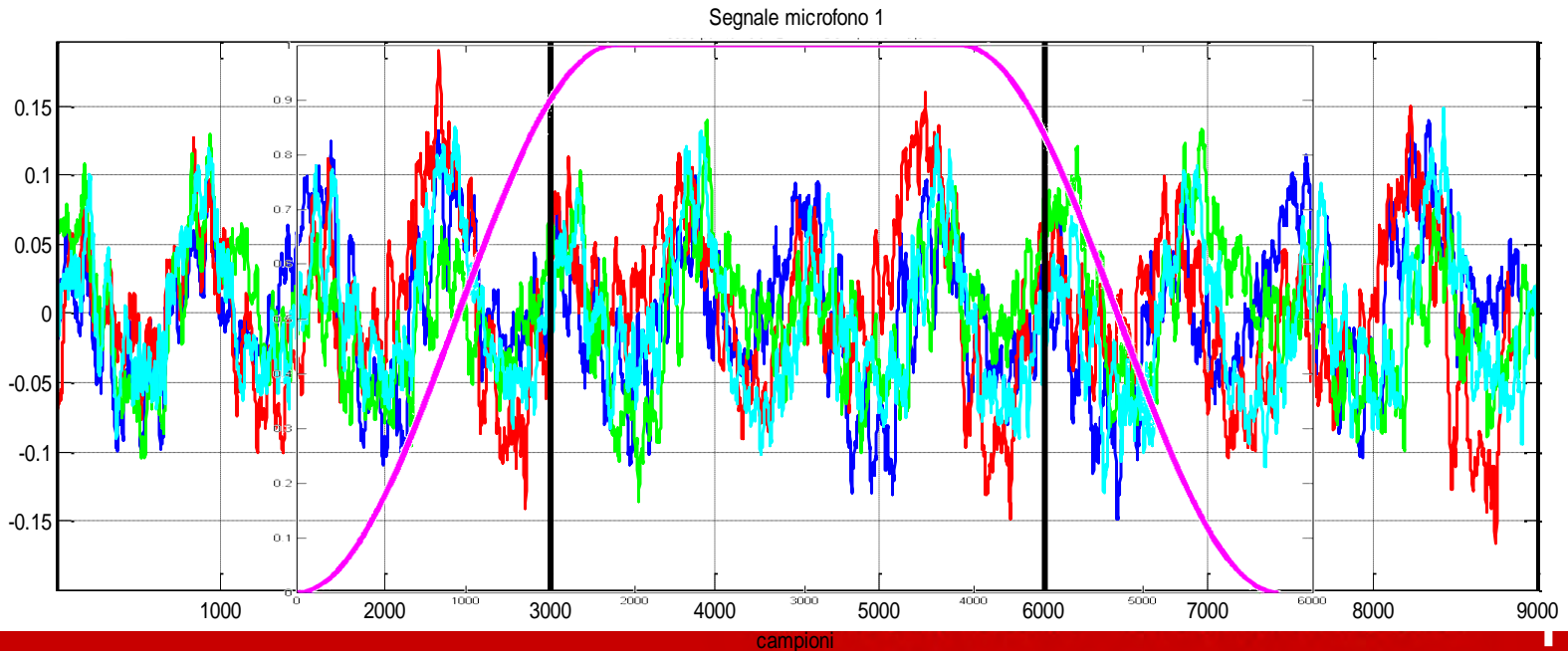


Misfiring diagnosis via audio signal analysis

misfire cyl 1
misfire cyl 3
misfire cyl 4
combustione normale

- In order to perform misfiring diagnosis on a cycle-by-cycle basis, **the frequency resolution should be increased**, thus increasing the signal-to-noise ratio
- The sound emission signal can be **windowed**, over two or more engine cycles, as shown in the plot (*Tukey Window, ratio = 0,65*)

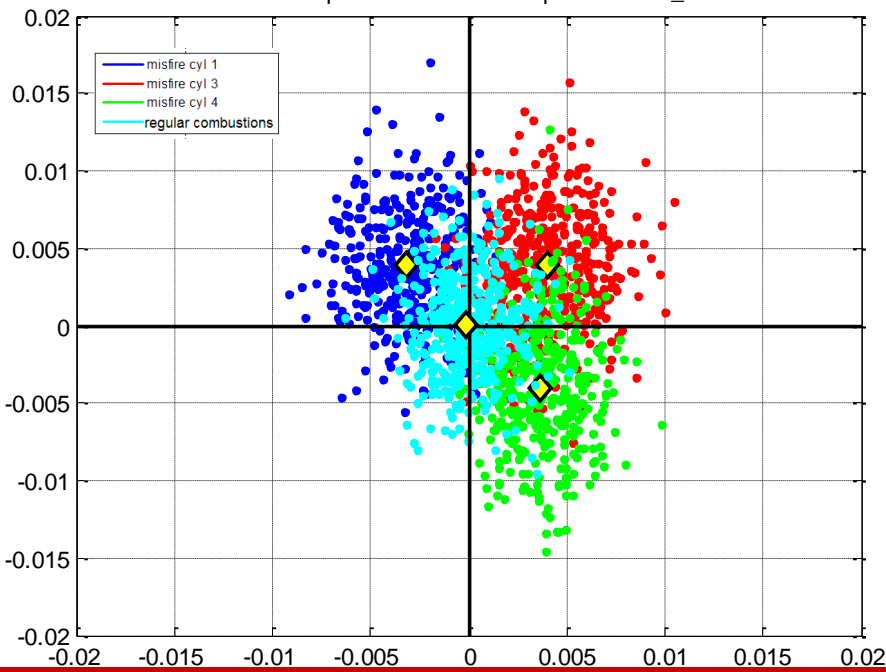
0 20 40 60 80 100
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
campioni



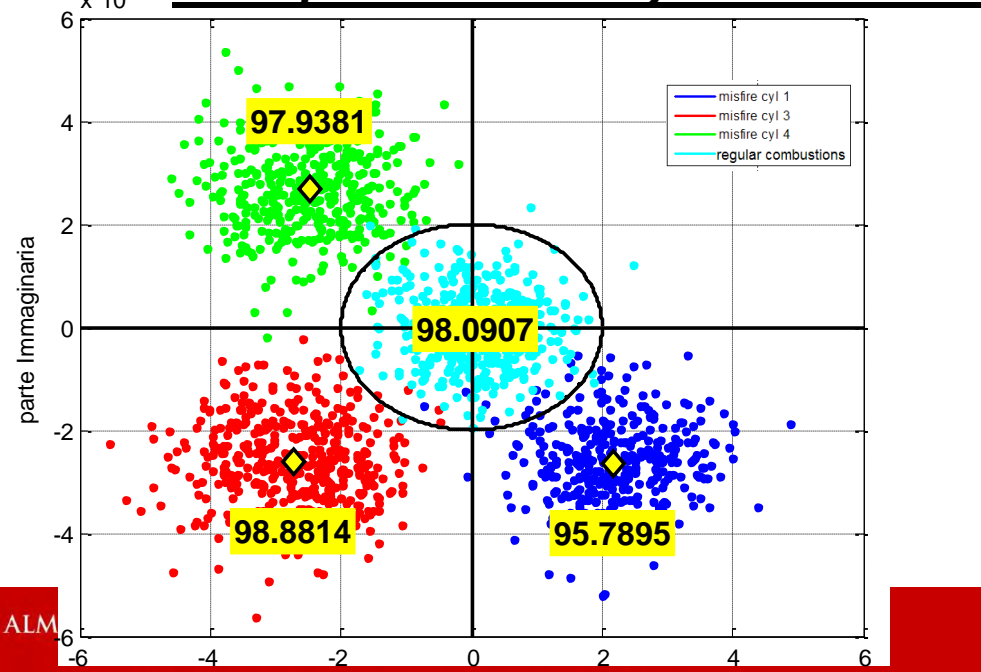
Misfiring diagnosis: cycle-by-cycle application

- The engine cycle harmonic frequency component can be plotted, cycle by cycle, on the Gauss plane
- The application of the window increases the SNR, and it allows isolating the faulty cylinder, on a cycle-by-cycle basis
- The misfiring cycles can be robustly isolated by setting a threshold in terms of frequency component amplitude, while the faulty cylinder can be identified by analysing the corresponding phase

Microphone # 2 - no window

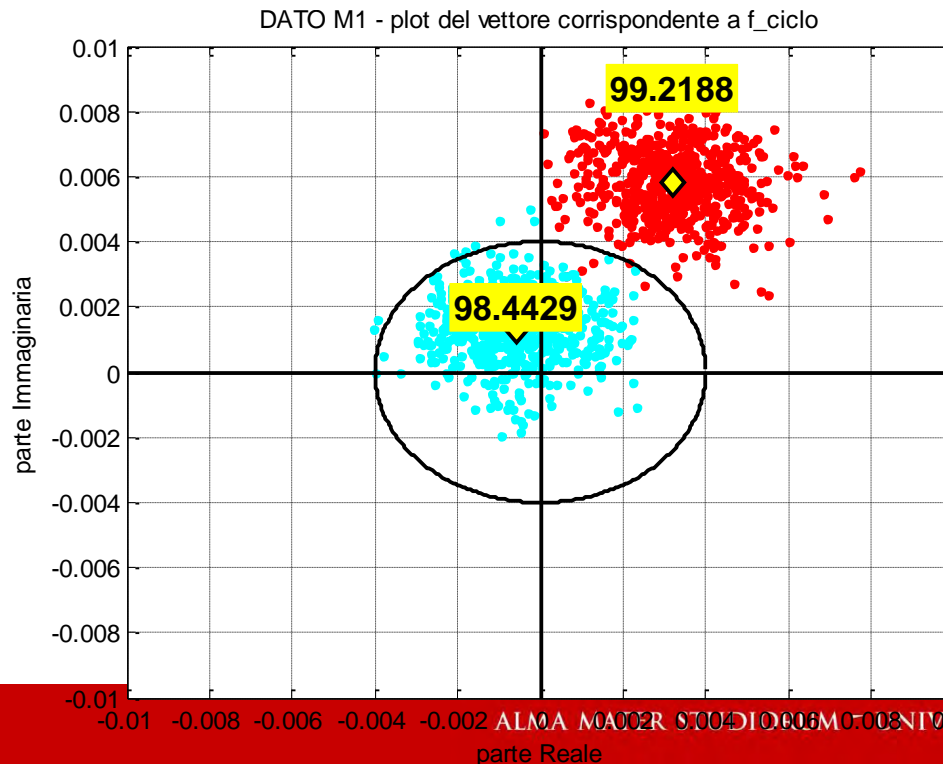


Microphone # 2 - 2 cycles wide window



Misfiring diagnosis: cycle-by-cycle application

- The same type of results have been obtained for all the investigated engine operating conditions
- Example: **5000 rpm, low load (microphone # 2)** →
→ comparison between test with regular combustions and test with continuous misfire in cylinder # 3





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