Flexplate Torque Sensor for Engine and Gearbox Control

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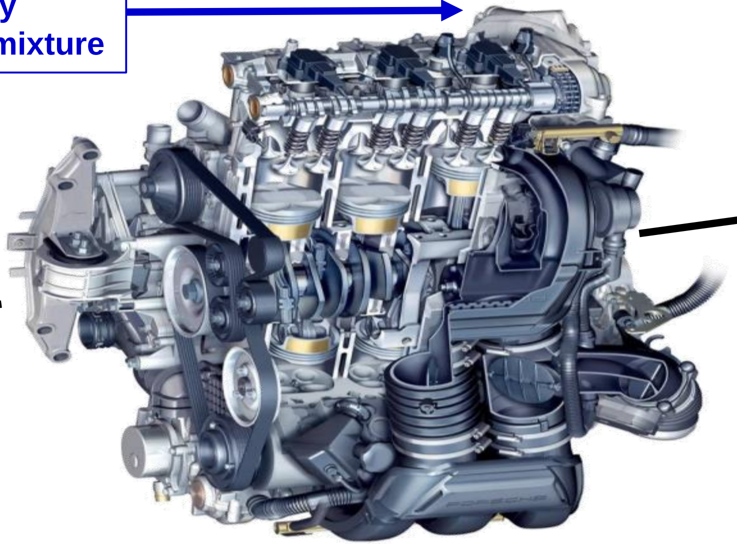
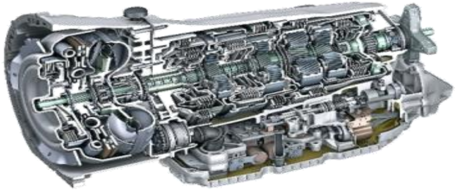
Flexplate Torque Sensing

This presentation concerns the important future role for flexplate torque sensing

Introduced energy created by the air-fuel mixture

Ancillary components: generator, servo pump, oil pump, compressor etc





Output to the drive train (Flexplate torque)

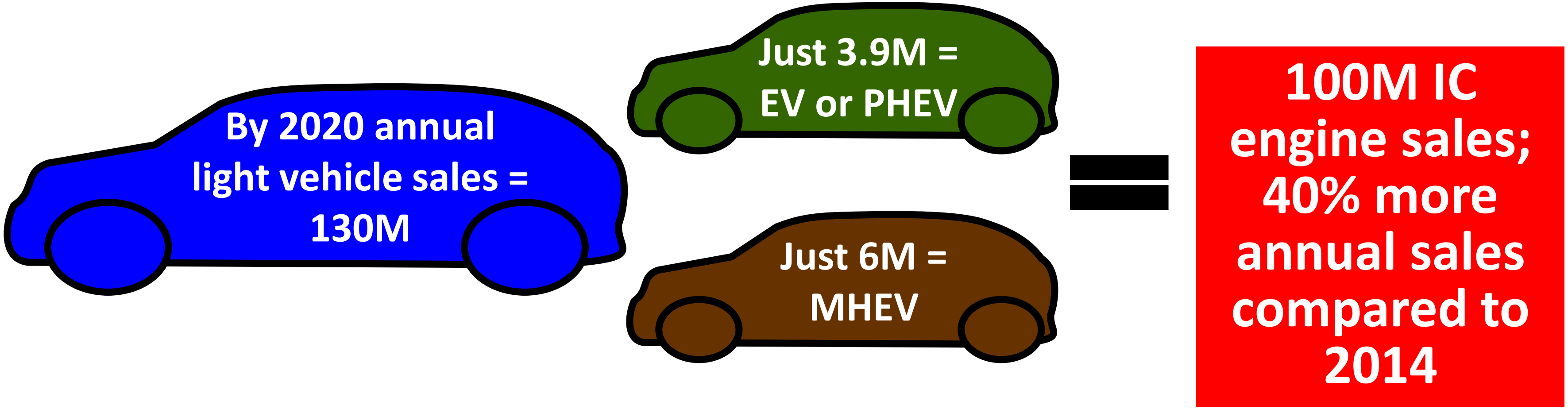
Flexplate torque = Introduced energy - Required energy of ancillary components

Flexplate torque ≠ Engine Torque (Inaccurate calculation)

$C0_2$ Emissions are reducing?

The Internal Combustion engine will remain a dominant power source

Future projections for passenger vehicle fleets suggest that the combustion engine will remain the main source of power. With this being the case more optimisation will be necessary to impact the EPA estimate that 20% of global emissions stem from light vehicle transportation.



Targeted emission reductions

Emission and fuel economy targets demand new control strategies

Following the recent VW "diesel-gate" saga there will be a renewed focus on emissions testing and the test cycle. From 2016 to 2025 the Automotive industry faces unparalleled demands to reduce emissions and improve fuel economy:

Region	Year	Type	Target	Method	Test Cycle	Penalty
United States	2016	Fuel economy + other GHGs + CO_2	36.2 mpg or 225g $CO_{2/mi}$	FP-based corporate avg.	US combined	Economic Fines
	2025		56.2 mpg or 143g $CO_{2/mi}$			Sales restrictions
Canada	2016	CO_2 + other GHGs	217g $CO_{2/mi}$	FP-based corporate avg.	US combined	Economic Fines
	2025		TBC			Sales restrictions
Europe	2015	CO_2	130g $CO_{2/Km}$	Weight-based corporate avg.	NECD	Economic Fines
	2021		95g $CO_{2/Km}$			
China	2015	Fuel consumption	6.9L/100km	Weight-class based corporate avg.	NEDC	Economical Fines
	2020		5L/100 km			Publically published
Japan	2015	Fuel Economy	16.8 km/L	Weight-based corporate avg.	JCOB	Economic Fines
	2020		20.3 km/L			Publically published

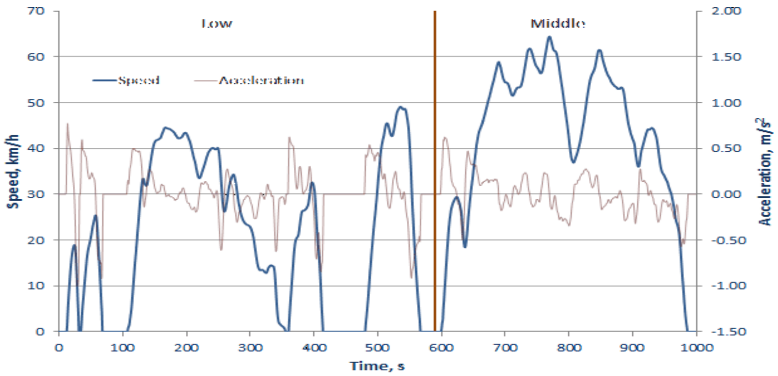
Emission tests are becoming harder

EU National Emission Ceilings Directive is already planning tougher tests.

To address the exploitation of loopholes and tolerances in the official laboratory-based NEDC test to produce flattering results, the European authorities have been developing a test based on real-world conditions rather than lab emission and consumption testing. This new test is called the World harmonized Light vehicle Test Procedure (WLTP).

Three different driving cycles are proposed developed for three different vehicle classes, based upon a vehicle's power-to-mass ratio and its maximum speed.

The graph on the right shows the speed pattern for a Class 3 vehicle, which is the highest power and speed class. This class is likely to cover the largest share of the world light-duty vehicle market.



Whilst this test looms there is no certainty around the proposed 2017 implementation date, nor how the 2021 fleet average CO_2 target of 95 g/km will be translated into the WLTP figures.

Fuel Use and CO2 Reducers

There is demand for new emission and fuel economy enablers

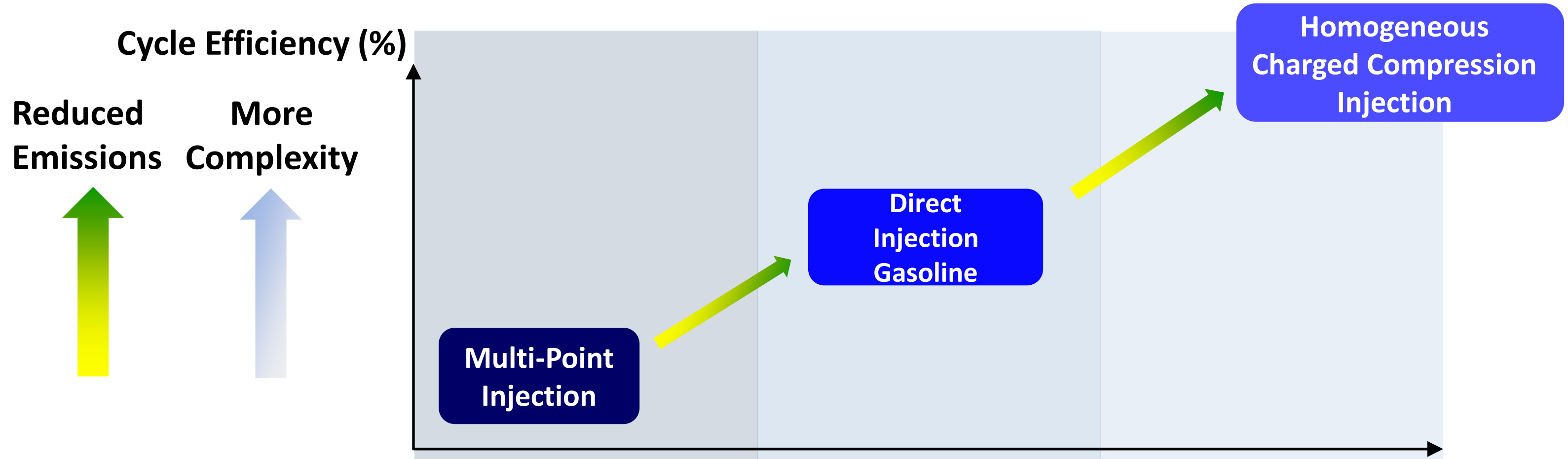
There are numerous external factors governing emission and fuel economy such as vehicle weight, climatic conditions, driving style and terrain amongst others. These external factors can be improved some what with driver education. In addition there are the internal factors that contribute to poor emission control and fuel economy. These include:

- Air-fuel ratio
- Compression ratio
- Spark ignition timing
- Exhaust gas recirculation
- Engine and transmission load factor.
- Individual engine optimisation

Whilst all of these parameters can be controlled today it is not possibly to measure or calculate all of them in real time and this is the focus of this presentation.

$C0_2$ Reducing Technologies

More improvement is necessary to offset the increase in IC engine sales.



Items in green influenced by torque

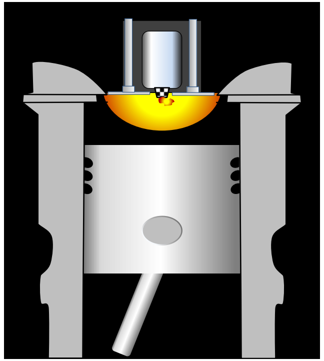
Multi-Point Injection	Direct Injection Gasoline	Homogeneous Charged Compression Injection
Knocking Prediction	Fuel to Air Mixture	Chemical complexity
In-Cylinder flow motion	Cooling Effect of DI	Ignition timing
Coolant Flow	Combustion Stability	PN/PM Exhaust
Flow Coefficient	Cold start HC emissions	Exhaust emissions
Cylinder to Cylinder Performance	Exhaust Temperature	E-10 Bio-Fuel / Fuel Quality

Nissan, Future Technology, Reducing CO2 Emissions From Internal Combustion Engines, May 2016

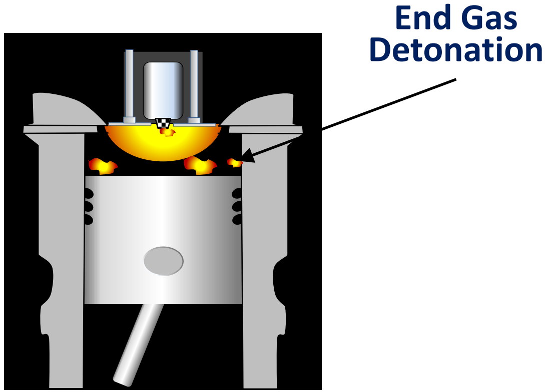
Knock Detection

Knock Detection

Engine knock is a phenomenon that limits how efficiently an engine can operate. ECUs are designed to operate engines at an averaged fuel efficiency operating point, but the demand to limit knocking impacts the amount of charge in the cylinder and the ignition angle that can be chosen. It is therefore not always possible for an individual engine to operate at its most efficient operating point.



Clean Combustion



Detonation (Knock)

Pre-Ignition Piston Damage

Knock Detection

Knock Detection

- Controlling knock intensity is complicated by cycle to cycle variation.

- This phenomenon causes the knock to vary even when an engine runs at steady state.

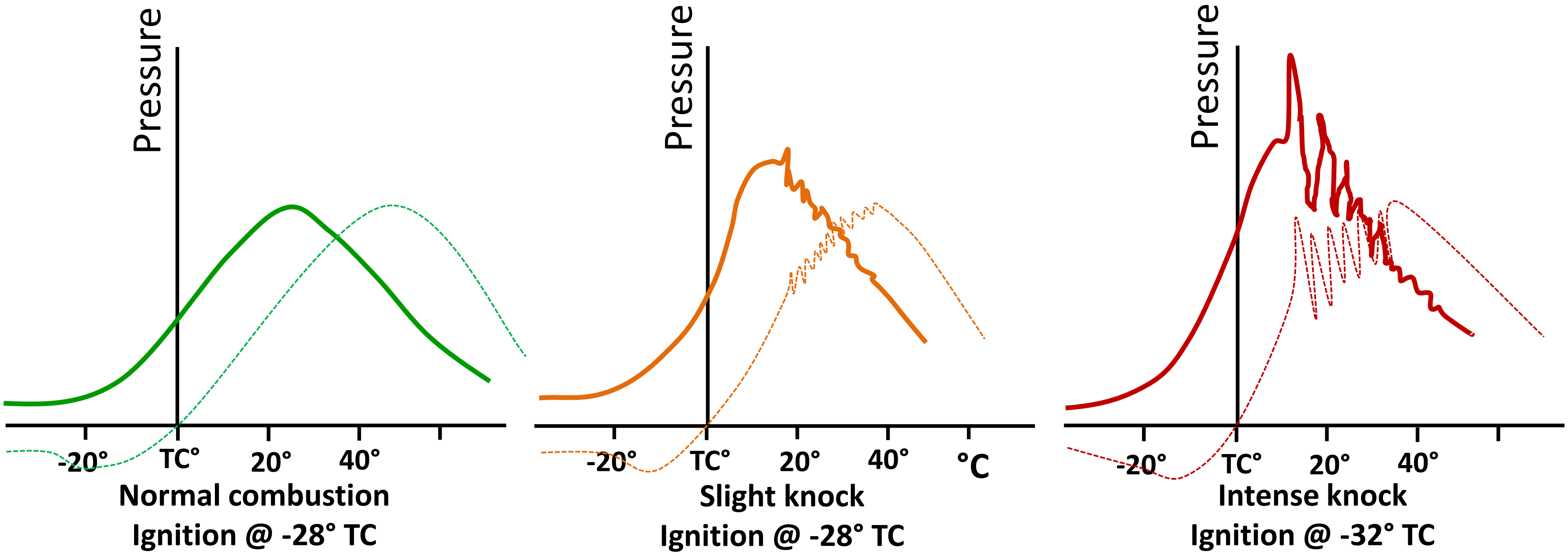
- Knock has to be treated therefore as a stochastic variable, and control carried out using a mean value from a number of cycles.

- It takes a relatively long-time to measure cylinder pressure, filter out a knock and calculate the mean value, control cannot be made in real time with current sensing methods.

Torque measured through a flexplate will produce a unique pattern for each cylinder once knocking occurs, allowing easy detection in real-time.

Knock Detection

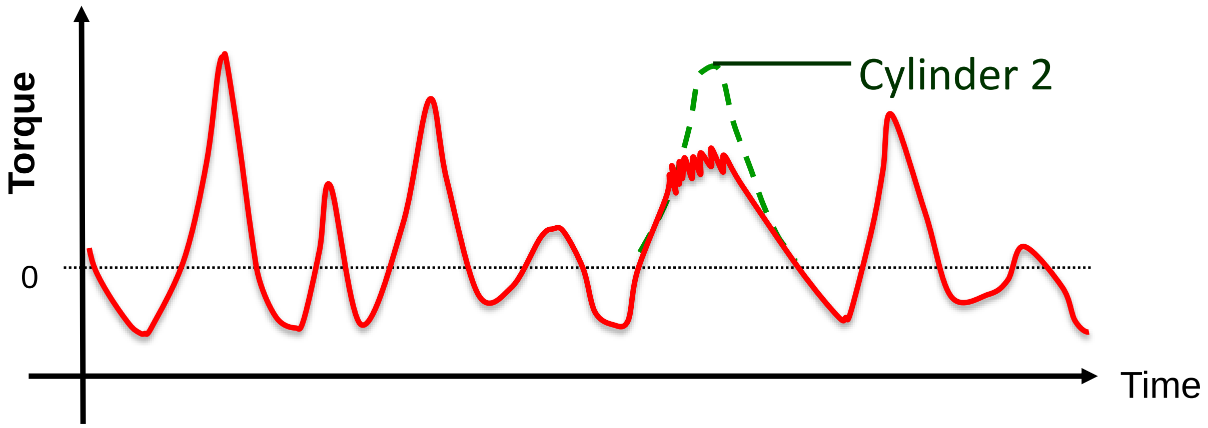
Impact on torque by normal combustion versus engine knock



TC – top centre – Dotted lines resulting torque pattern

Knock Detection

Torque peaks detected by a flexplate mounted torque sensor



- The torque sensor detects knock.
- Torque oscillations measured through a flexplate mounted torque sensor instead of a smooth torque peak.

Knocking typical up to 30 kHz oscillations

Knock Detection

Knock detection in real time provides opportunity for intervention

Once a flexplate torque sensor provides the information that engine knock is occurring in a cylinder it provides an opportunity to attenuate the in-cylinder knock by individually:

- Controlling the peak combustion chamber temperatures through compression ratio reduction
- Adjusting the rate of exhaust gas recirculation
- Calibrating in real-time the engine's ignition timing schedule
- Modifying the initial air intake temperature
- Retarding or advancing spark ignition

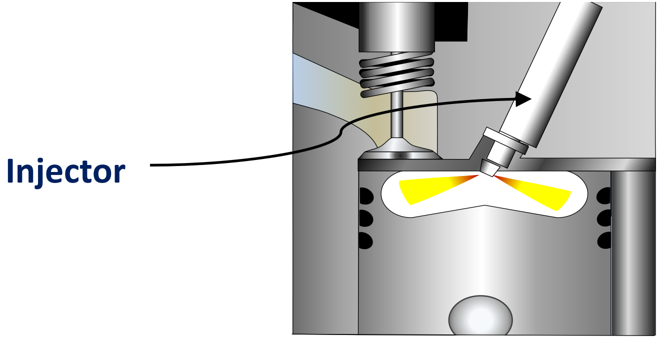
A reduction in engine knocking can optimize the combustion cycle and improve fuel economy by as much as 3-5%.

Source: GHG-TransPoRD, 7th Framework programme of the European Commission,DG, Research and Innovation, November 2014

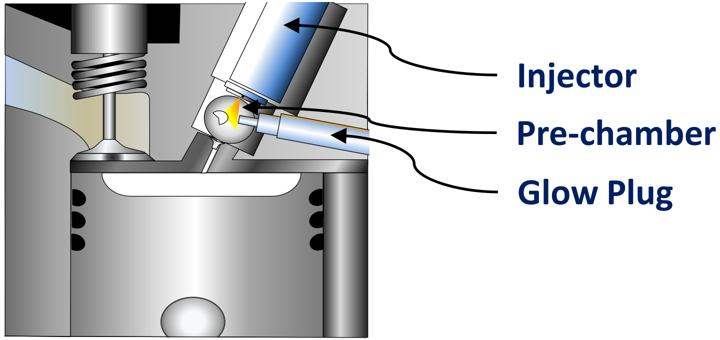
Direct Injection Gasoline

Injection sequence control in real time reduces CO^2

- Change from a single on/off pulse for a certain period of time and placed in one location, the MCU must handle a complex peak and hold waveform with methods for detecting valve motion. The process involves precise current measurements and significant high-speed switching to develop a current profile. And there may be more than one injection per cycle to control.



Direct Injection

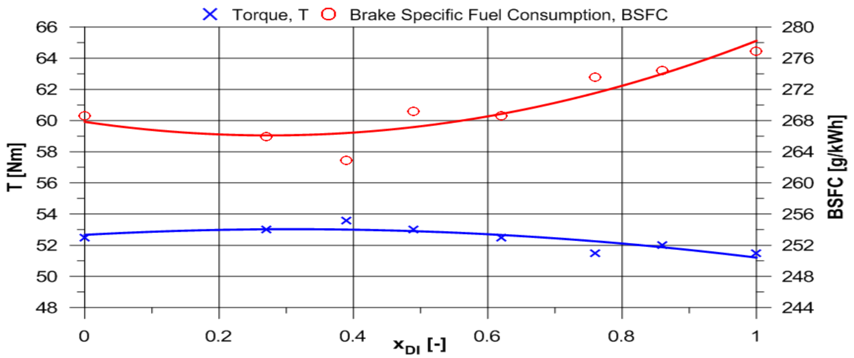


Indirect Injection

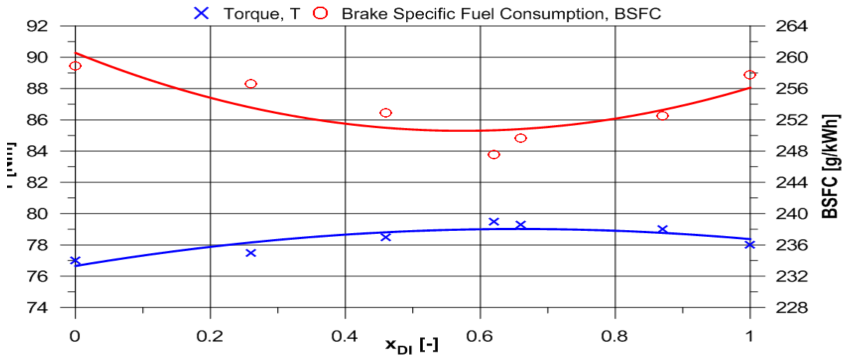
Replacing port with direct injection can result in a 10-15% improvement in fuel economy and horsepower and as much as a 25% reduction in hydrocarbon emissions.

Direct Injection Gasoline

Torque curve versus fuel consumption



Indirect Injection



Direct Injection

- Brake specific fuel consumption (BSFC) is a measure of the fuel efficiency of an engine.
- The torque sensor can correlate fuel injection to match peak engine demand.

At an engine rotational speed of 2000 RPM.

Engine Misfire

Engine Misfire

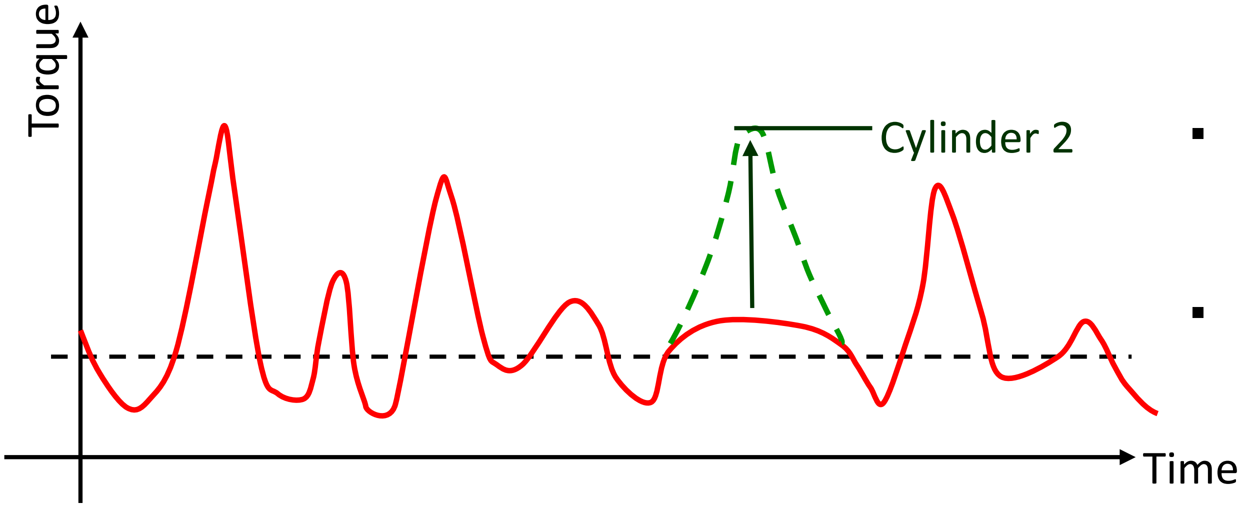
An engine misfire occurs when one or more of the engine cylinders inside fails to fire correctly due to an interruption of the air-to-fuel ratio inside the combustion chamber or missing ignition. As engine components wear, engine misfires intensify. A lean misfire occurs as a result of an imbalanced air or fuel ratio. Engine misfires can also be mechanical and occur as a result of worn piston rings, defective fuel injectors, leaking head gaskets, broken rocker arms and worn valves and cylinder walls.

- Misfires cause unburnt fuel to enter the exhaust pipe producing high levels of HC emissions.
- Unburnt fuel can enter the catalytic convertor, burn, and cause heat damage to the catalyst .
- Existing methods of misfire detection (crankshaft speed vs cylinder firings) are insufficiently accurate or (in-cylinder pressure sensing) too expensive.
- Most OBD II misfire detection methods do not detect in real time (OBD II uses a “block learn” strategy to track misfires) or indicate why a specific cylinder is misfiring.

When an engine misfires it produces a higher level of HC emissions

Misfire Detection

Torque peaks detected by a flexplate mounted torque sensor

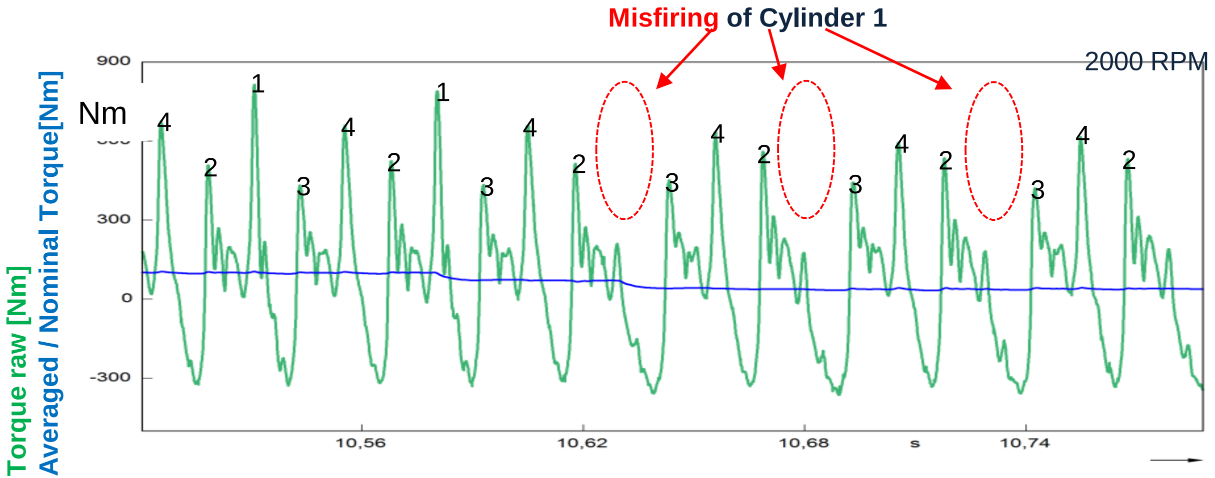


- **The green dotted line indicates a misfire event in torque pulse of the signal.**
- **Measurement is possible over the full RPM as a result of the available signal bandwidth**

A torque sensor fitted to the flexplate will identify in real time which cylinder is misfiring and provide an accurate value for the misfire to assist in diagnosis and intervention.

Misfiring Data

Torque peaks detected by a flexplate mounted torque sensor

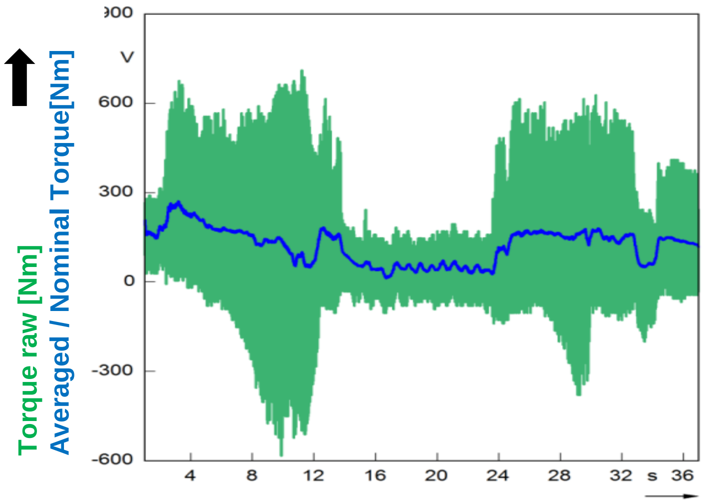


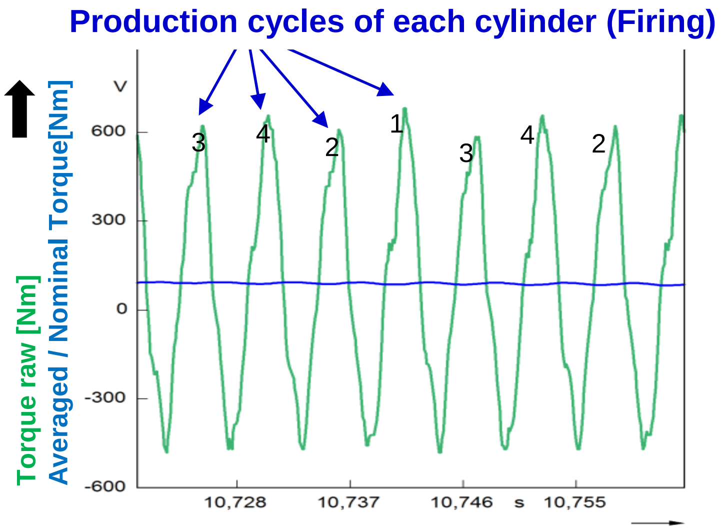
The graph shows the effect of misfiring in the measurement signal.

- **As long as cylinder 1 is working properly there is a clear peak visible. After shutting down this cylinder the corresponding peak is disappearing.**
- **With the help of this signal resolution misfiring can be detected immediately after the first incidence. Current detection time required of the ECU is between 1 and 2 seconds.**

Engine Control

Torque peaks detected by a flexplate mounted torque sensor

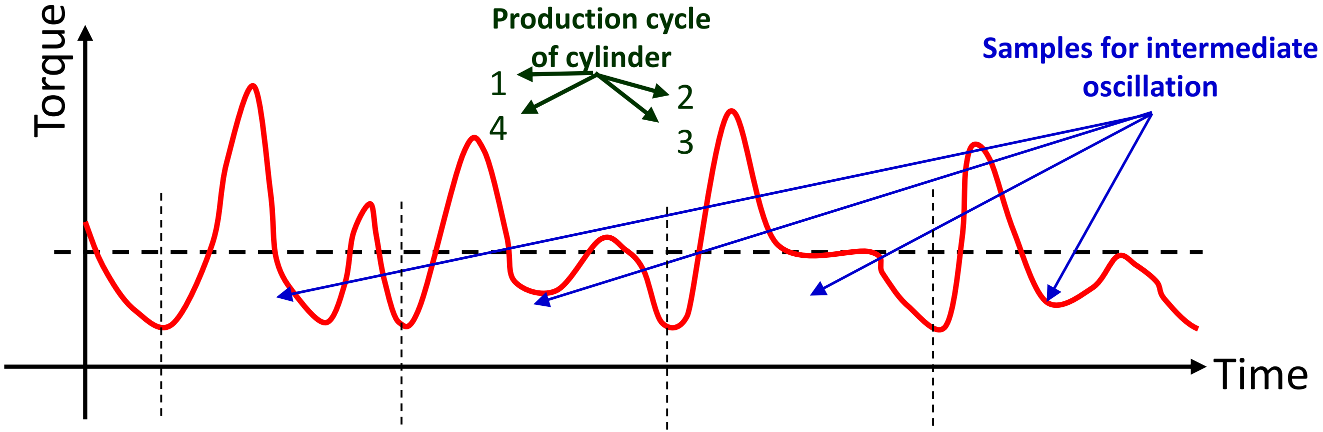




- The raw signal supplies a lot of detail information; for example the production cycle characteristic of the cylinders.
- The right graph is an enlargement of the graph on the left where the firing of each cylinder is clearly visible.

Engine Control

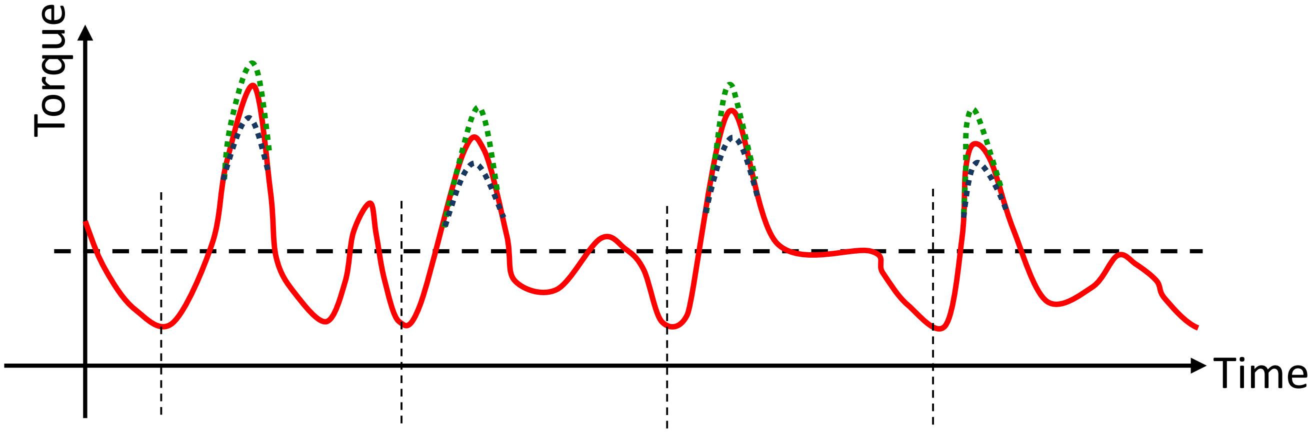
Torque sensing through the flexplate provides real-time feedback



- Full signal bandwidth for high dynamic changes
- Individual cylinder analysis possible
- Closed loop combustion control
- Compensate for tolerances, engine to engine variation, cylinder balancing, fuel and air composition variability, etc.

Fuel Quality

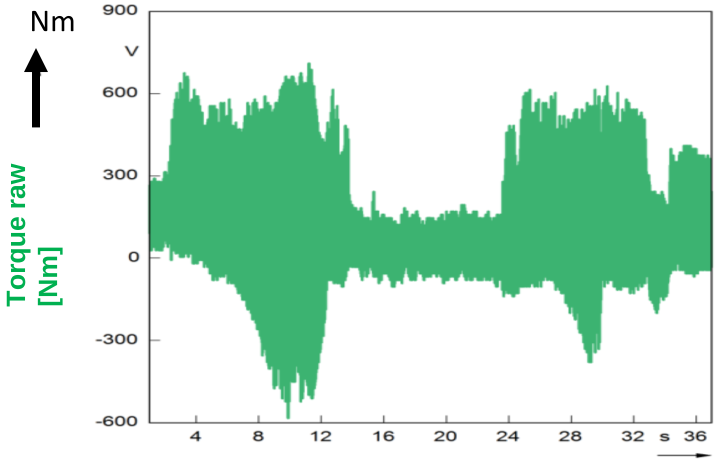
Torque sensing through the flexplate provides real-time feedback

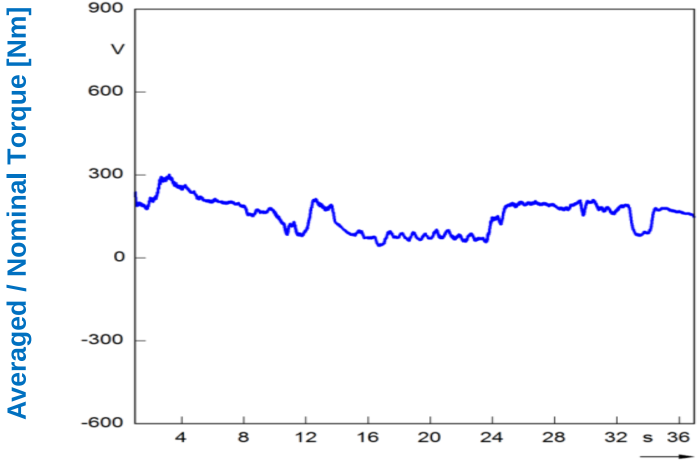


- **Green dotted line higher quality fuel**
- **Blue dotted line lower quality fuel**

Transmission Control

Flexplate torque sensing supports definition of the nominal torque

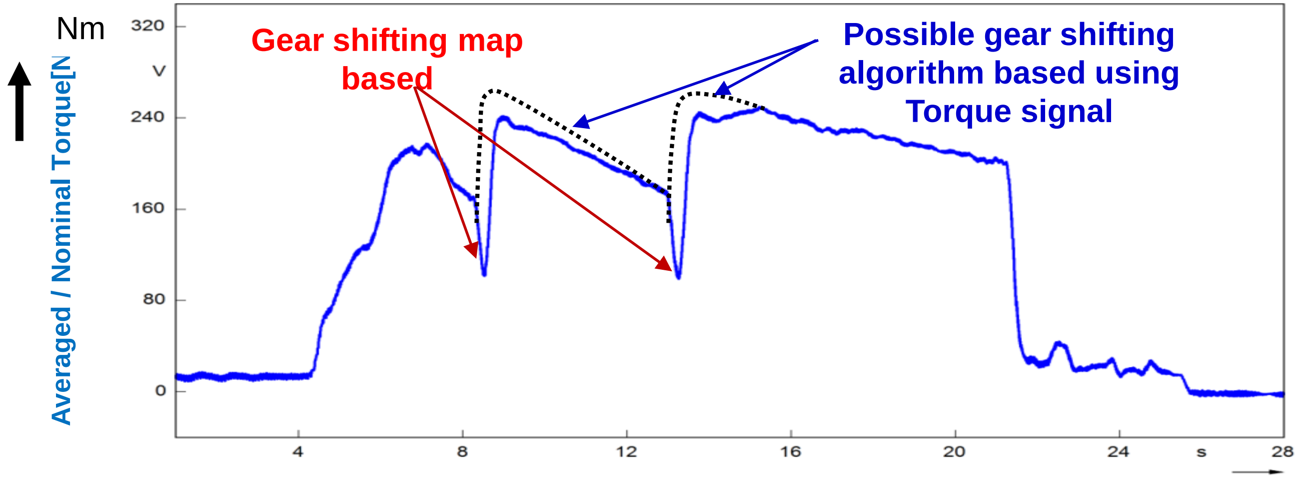




- **The magneto elastic measurement principle allows measurement of quick changing signals.**
- **Due to the measurement position close to the crank shaft the signal is widedly undamped.**
- **Averaging the raw signal leads to a smooth signal called nominal torque (blue) which is useful for gearbox control for example.**

Transmission Control

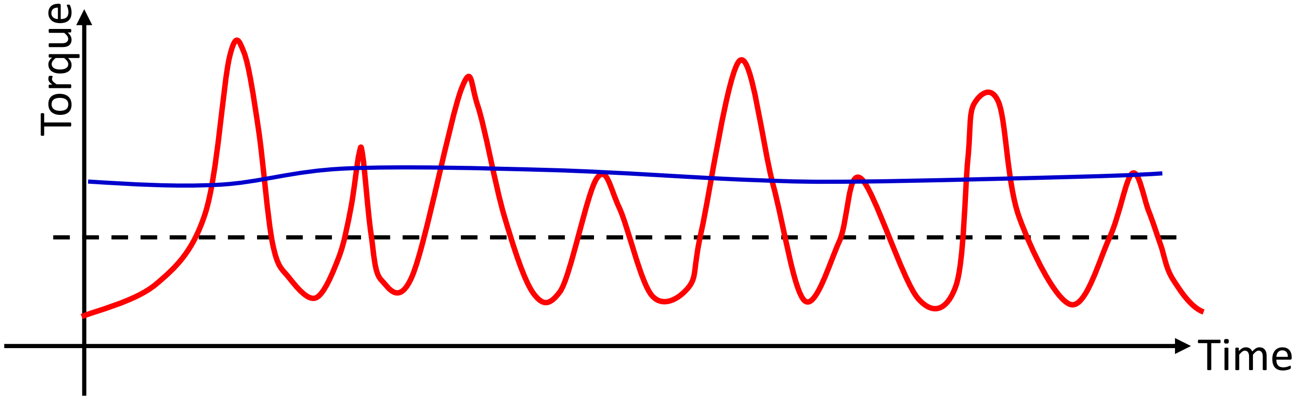
Engine demand as a function of the nominal torque



- The graph show a typical torque curve during acceleration with some gear shifting operations.
- Algorithms based on this signal can improve these shifting operations and continuously driving comfort.

Transmission Control

Emission and fuel consumption reduction through transmission control



- Reduced signal bandwidth for increased accuracy.
- Control of the clutch bite point.
- Control against bucking
- Real-time analysis instead of calculated torque

Represents two full rotations of the crankshaft

CO_2 Emissions and transmission

Emissions can be reduced through improved transmission control

- E-Clutch manual transmission coasting functions, previously only possible with automatic transmissions, can reduce fuel consumption by up to 10%
- Improves the accuracy and speed of dual clutch and CVT transmission selectivity
- Can provide diagnostic indications of early clutch wear
- Provides an option to reduce clutch mass by optimising clutch engagement
- Improves the match of engine load to gear ratio a benefit future WLTP testing
- Provides accurate and real-time feedback for next generation GPS based gear selection, predictive energy recovery and hybrid power delivery optimisation

CO_2 Emissions and transmission

Flexplate torque sensing can enable advanced transmission control

- CVT transmissions can provide a 2-10% reduction in in CO_2 output versus manual equivalents.
- DCT transmissions provide a 6% reduction in CO_2 output versus manual equivalents.
- Light weighting the clutch and transmission could produce 3- 9% CO_2 reduction.
- In-Gear efficiency improvements could reduce engine loading for CO_2 reductions of 1%-2%.
- For small cars piloted gearboxes (where gear changes and clutch control is handled electronically) CO_2 output reductions of 4-5% are possible.
- 6-speed manual/automatic gearboxes can contribute to 2.5-5% CO_2 reduction.

A flexplate torque sensor can assist in optimising clutch and transmission size, weight, and performance for potential CO2 savings of 19-22%.

It will require a fundamental change from conventional methods of engine and transmission torque measurement.

Source: GHG-TransPoRD, 7th Framework programme of the European Commission, DG, Research and Innovation, November 2014

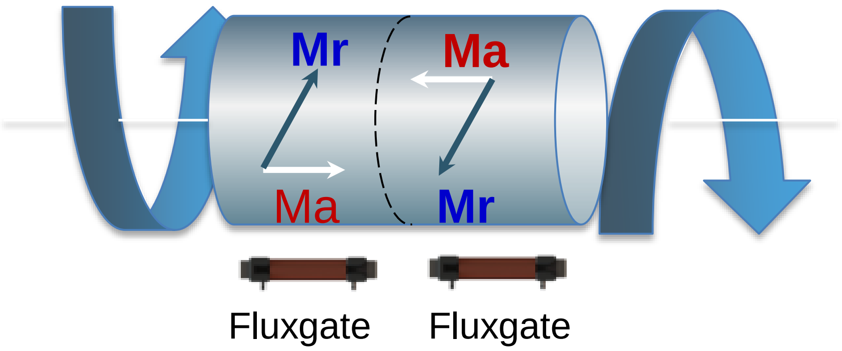
The Magnetoelastic Sensing Principle

Methode‘s Torque Sensor is based on the Magnetoelastic principles

Upon application of torque, the shaft is stressed.

As a result, the magnetization (Mr) is reoriented from its purely circular direction to a helical direction.

The torque thus develops a bulk axial magnetic moment and thereby gives rise to an external magnetic field in axial direction (Ma)



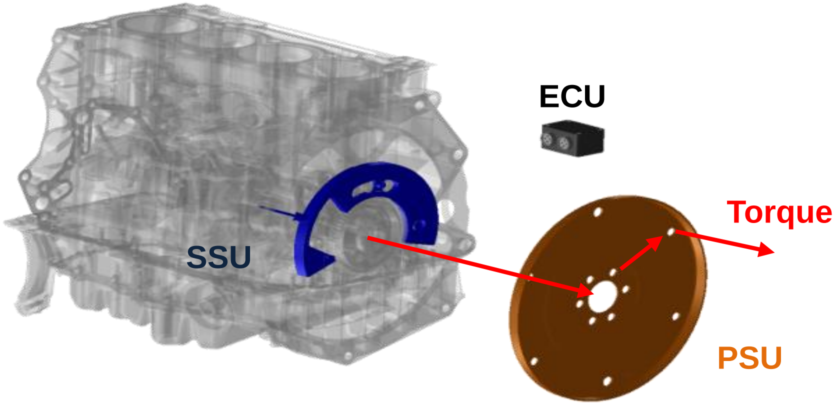
Methode Flexplate Torque Sensor

Methode Magnetoelastic Flexplate Torque Sensor consists of three components:

PSU - Primary Sensor Unit:
The by default exisiting flexplate which connects the engine and the converter.

SSU - Secondary Sensor Unit:
The fluxgates are combined in the secondary sensor unit. If torque is applied to the flexplate the changing in its specific magnetic encoding is catched up by the fluxgates. The electronic control unit can be integrated if temperature specification and available space are appropriate.

ECU - Electronic Control Unit:
The signal will be conditioned and transfered to a signal which is linear to the applied torque.

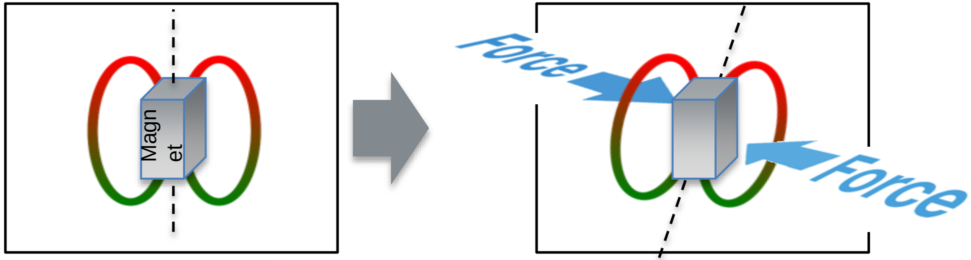


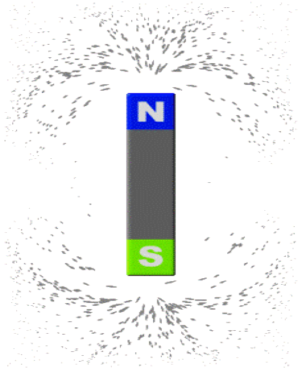
Physics of Magnetoelastic Sensors

Villari Effect

Inverse magnetostrictive change of magnetic properties (i.e. Magnetic susceptibility, permeability) of a material when subjected to a mechanical stress. This change is transformed into an electrical signal which goes through signal conditioning.

E. Villari (1836-1904)
Italian physicist



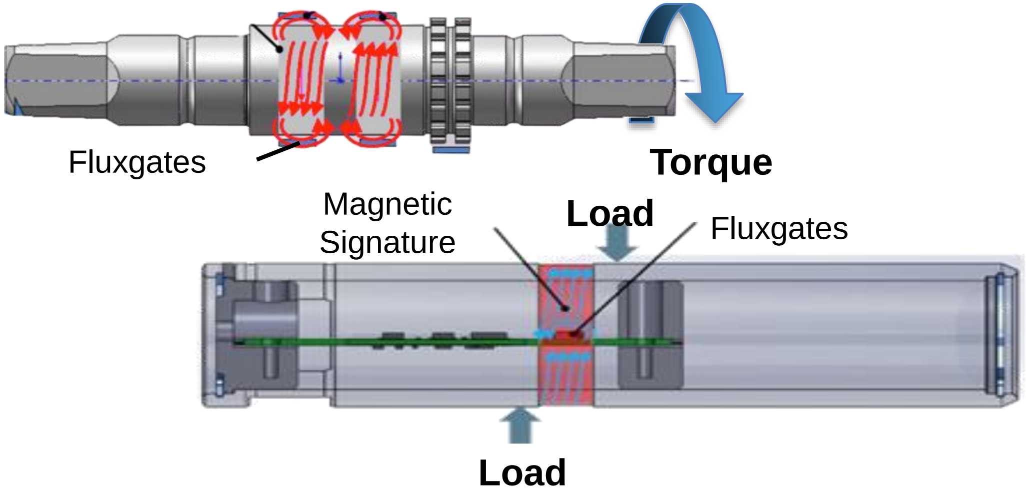


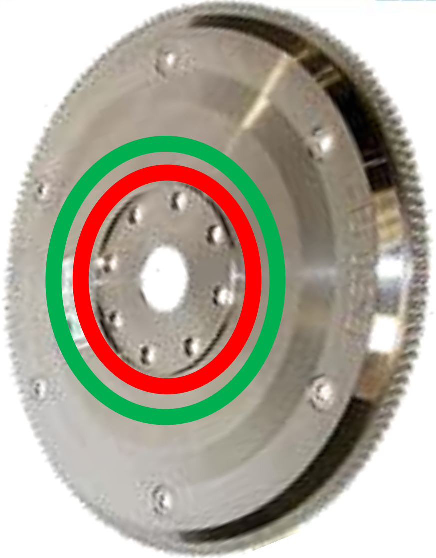
Magnetoelastic Sensor Technology

https://youtu.be/dOHDn4aMOIE

Torque and Force Sensing

Physics of Magnetoelastic Sensors

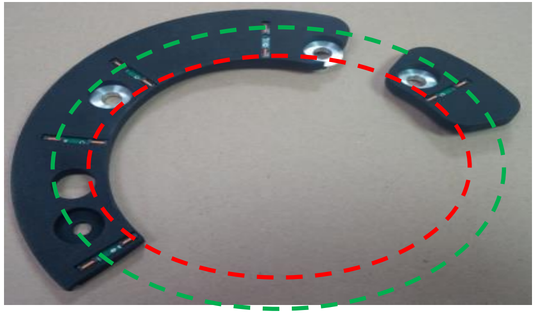




- Magnetic signature is applied to shaft by using the magnetic properties of the material
- Programming process results in establishing minimum two equal domains having oppositely directed circumferential magnetiziation
- Highly sensitive flux gates measure change in remanent magnetic fields induced by torque or force
- The coils are in bridge configuration and operated in "common-mode rejection"
- Signal output analogue or digital

Torque Sensor Installation

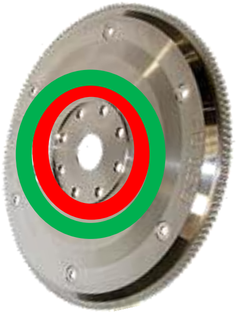
Flux gates are placed within the circumference of the flexplate



- **The sensor unit carries the fluxgates which measure the changing of the specific magnetic encoding of the flexplate. They are always positioned as pairs inline with a radial offset.**

- **The fluxgates will be sealed completely to protect them from the environment.**

- **The electronic control unit can be integrated if temperature specification and available space are appropriate.**

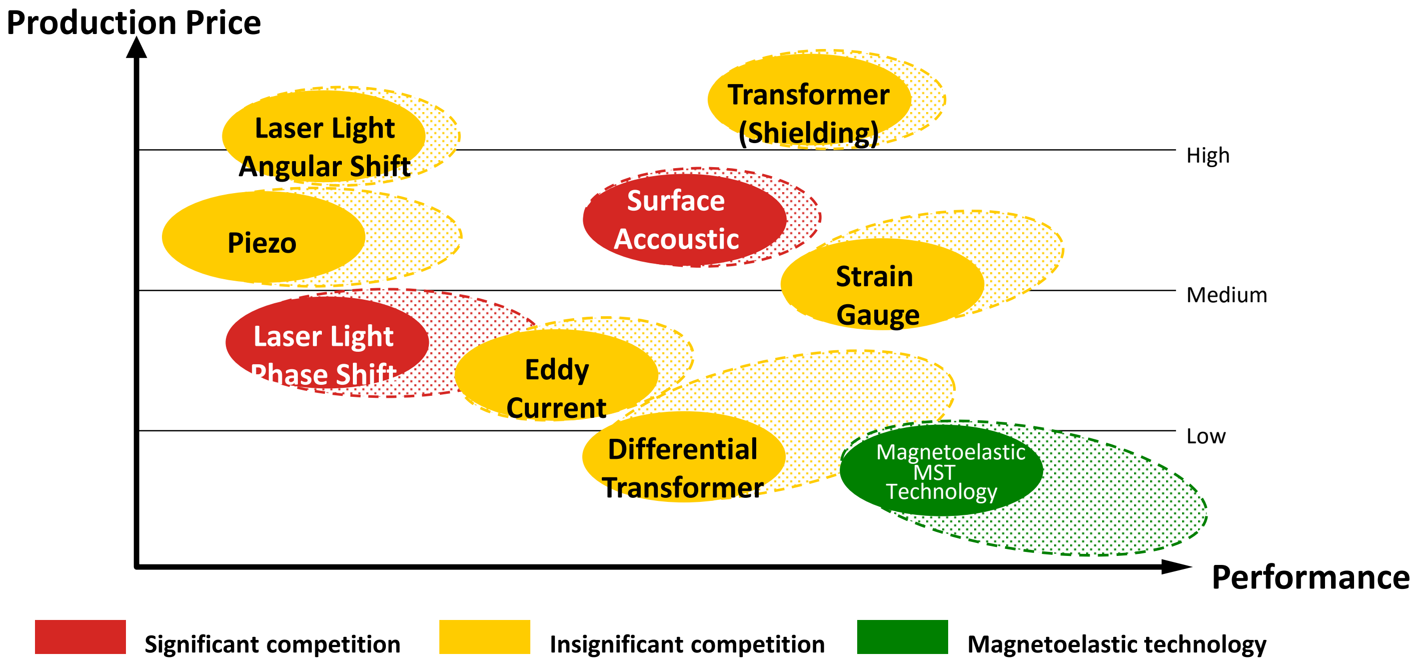


Torque Sensing Alternatives

Criteria	Accuracy (%)		Overall size	Non-linearity (%)	Reversal error (%)	Nominal tem-perature range ΔT (K)	Temperature influence (%)	Non-contact	Functional in harsh conditions
	<1 >1	0,1 0,1-0,5 >0,5	small medium large	0,1 0,1-0,5 >0,5	0,1 0,1-0,5 >0,5	>60 50-60 <50	0,1 0,1-0,3 >0,3		E.g. oil, water, dust, etc.
	green / red	green / yellow / red	green / yellow / red	green / yellow / red	green / yellow / red	green / yellow / red	green / yellow / red	green / yellow / red	green / yellow / red
Strain gage	green	green	green	green	green	yellow	green	red	yellow
Piezo	red	white	white	white	white	white	white	red	yellow
Surface accoustic wave	green	yellow	green	yellow	yellow	yellow	yellow	red	red
Laser light angular shift	red	white	white	white	white	white	white	yellow	red
Laser light phase shift	red	white	white	white	white	white	white	yellow	red
Differential transformer	green	yellow	red	yellow	yellow	green	yellow	green	yellow
Transformer (shielding)	green	green	yellow	green	green	yellow	green	white	yellow
Eddy current	green	red	red	red	red	yellow	white	yellow	yellow
Magnetoelastic Sensor from MST	green	yellow	green	green	yellow	green	green	green	green

Cost performance comparision

Comparison of production price and performance of competing technologies:



Magnetoelastic Summary

Robust

- Withstands harsh environmental conditions
- Operates in high temperature up to 210°C
- Submersible in caustic fluids

Durable

- Component Testing for 480,000 miles equivalent
- Key-Life Testing completed on production level

Easy Integration

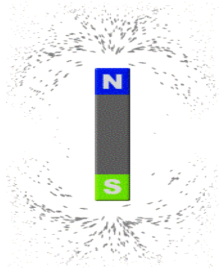
- Compact design
- Low space requirements
- Inside-shaft design-option

Reliable

- No accuracy loss during lifetime
- No wear over lifetime

Magneto-Elastic Sensors for sensing

- Torque
- Force
- Linear Position
- Angle
- Speed
- Direction



MAGNETOELASTIC SENSORS:
→ Non-Contact Sensing beyond the limits of conventional technologies

THANK YOU FOR YOUR ATTENTION