SAW Resonant PWS for Automotive and Industrial Applications

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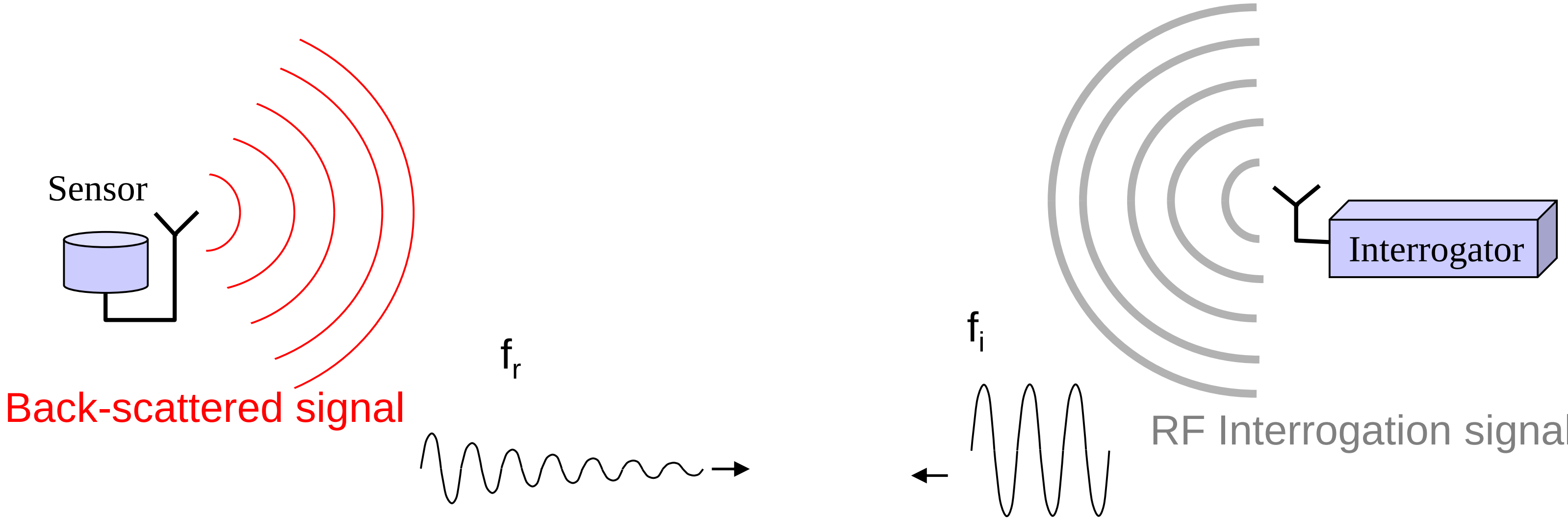
Agenda

- Introduction
- SAW sensing elements for temperature, pressure and torque
- Readers for wireless resonant SAW sensors
- Automotive applications:
    - Tyre pressure and temperature monitoring system (TPMS)
    - Torque measurement in EPAS and powertrain
- Industrial applications: Torque and temperature measurements in power generation and distribution industry
- Calibration issues
- Conclusions

Introduction

What is the passive wireless resonant SAW sensor?

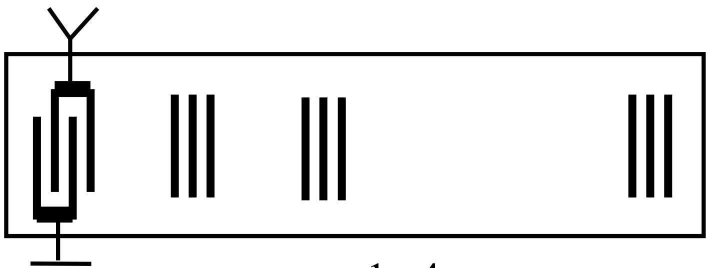


Advantages of SAW devices as passive wireless sensors:

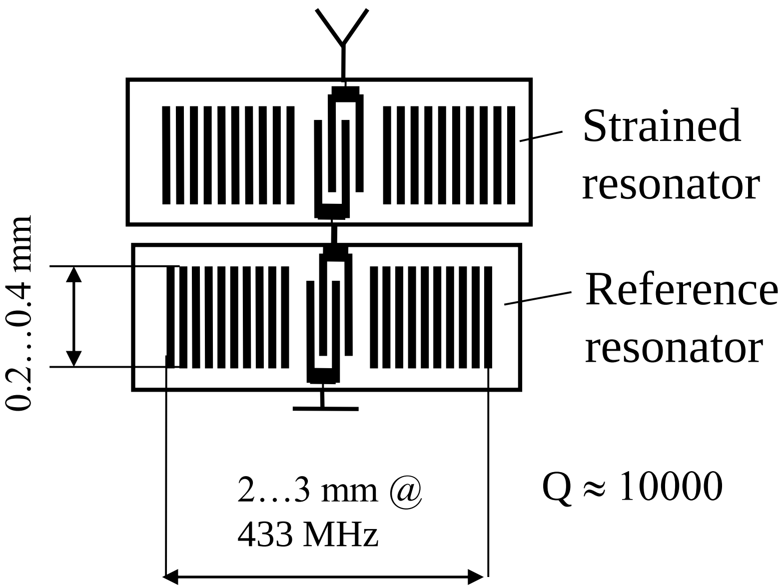
- Sufficiently high sensitivity to temperature and strain
- High Q-factors of resonators
- Operation in the UHF range
- Small dimensions, light weight and low cost of high-volume manufacturing
- Capability of working in a harsh environment

Introduction

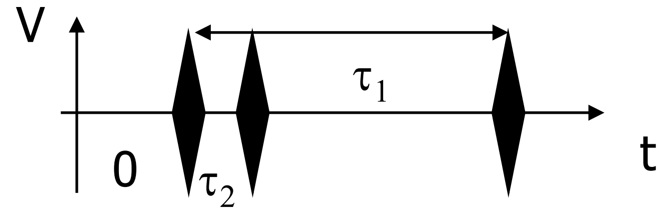
Two types of wireless SAW sensors:



$\tau_1 \approx 1...4\ \mu s$

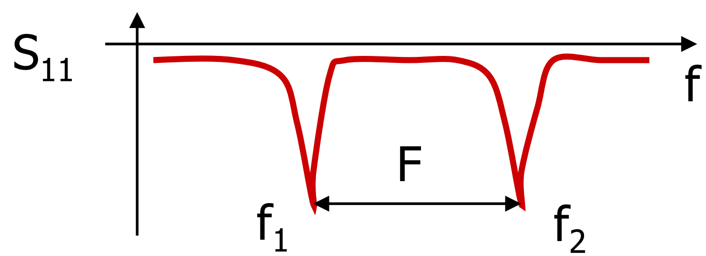


- **Reflective delay lines:**



Phase delay measurements: $\Delta\phi_1 = 2\pi f_0 \tau_1 S_s s$

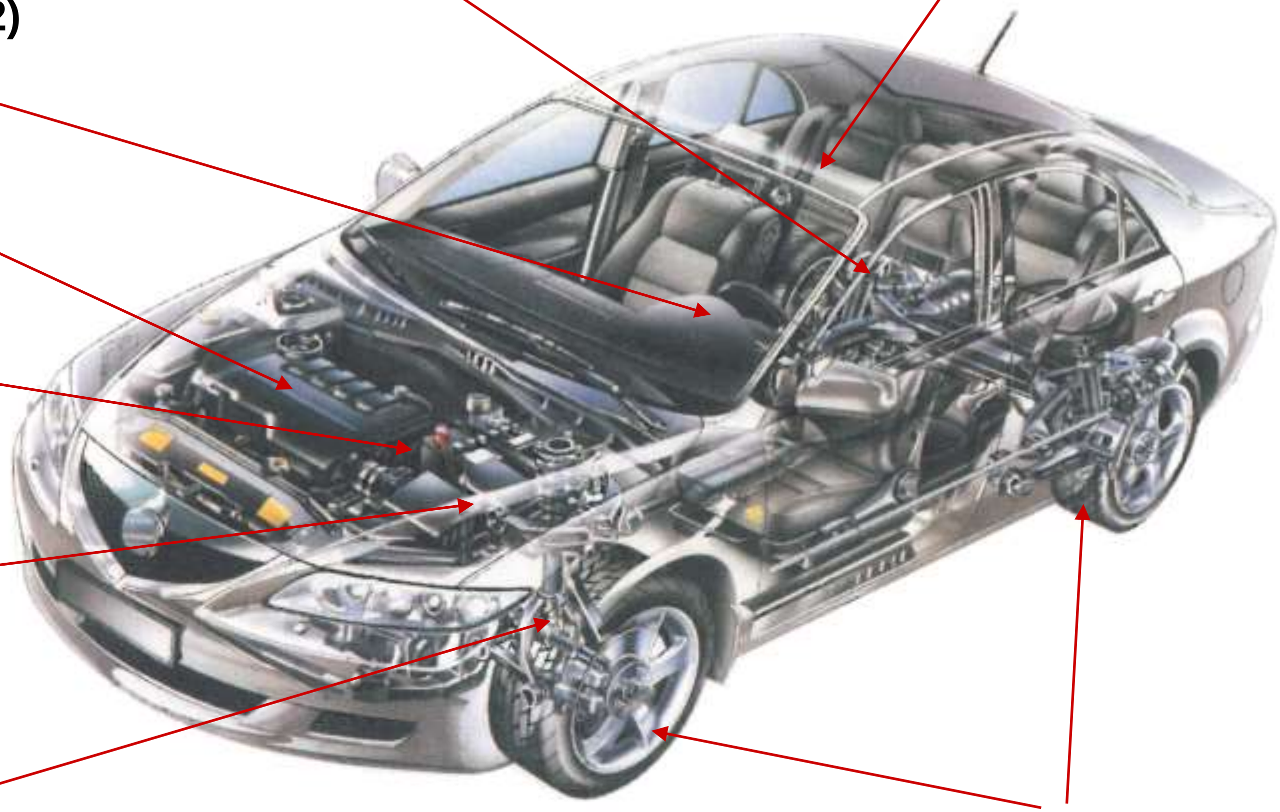
- **One-port resonators:**



Difference frequency measurements:

$$\Delta f_2 = -f_2 S_s s$$

SAW Sensors - Automotive Applications



4WD torque splitter sensor

Kinetic Energy Recovery System (KERS)

EPAS torque sensor (2)

Camshaft torque sensor

Crankshaft or flexplate torque sensor

Transmission output torque sensor

Drive shaft torque sensors (2 or 4)

TPMS sensors (4 or 5)

Over 8 SAW systems per vehicle

Vehicle equipped with 4 wheel drive, automatic transmission and EPAS

Challenges

- SAW sensing elements should be compact, suitable for high volume manufacturing and fully temperature compensated within –40° < T < +125°C.

- High repeatability & reproducibility and long-term stability is required – packaging is a very serious issue.

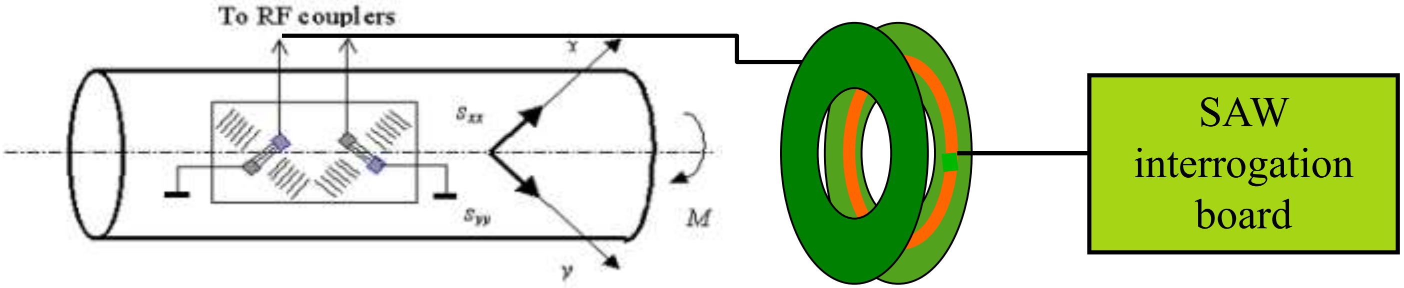
- SAW sensor interrogator (reader) should be accurate, fast and compact.

- Calibration procedure should be affordable

- **The system cost should be competitive!!!**

SAW Sensing Elements

Torque Sensor

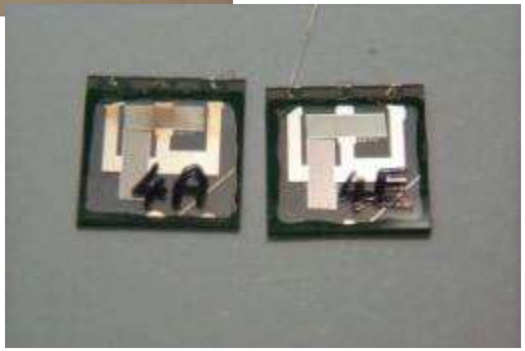


1. The first attempt (2000):

- ST-X cut quartz,
- Separate 200 MHz and 201 MHz dies,
- All-quartz package,
- The dies soldered to the shaft.

2. Single 200-201 MHz die (2002)

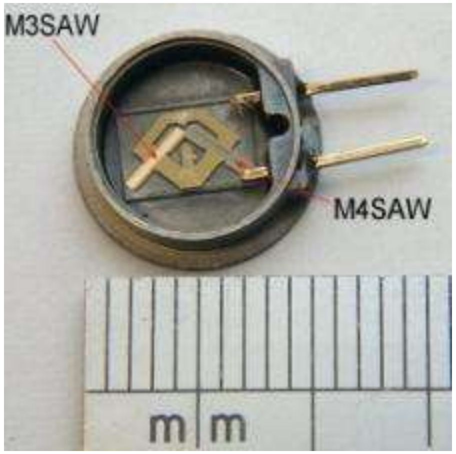
- Y+34°-X±45° cut quartz,
- Sensitivity to torque S_M is 3 times higher and variation of S_M with T is 8 times smaller.

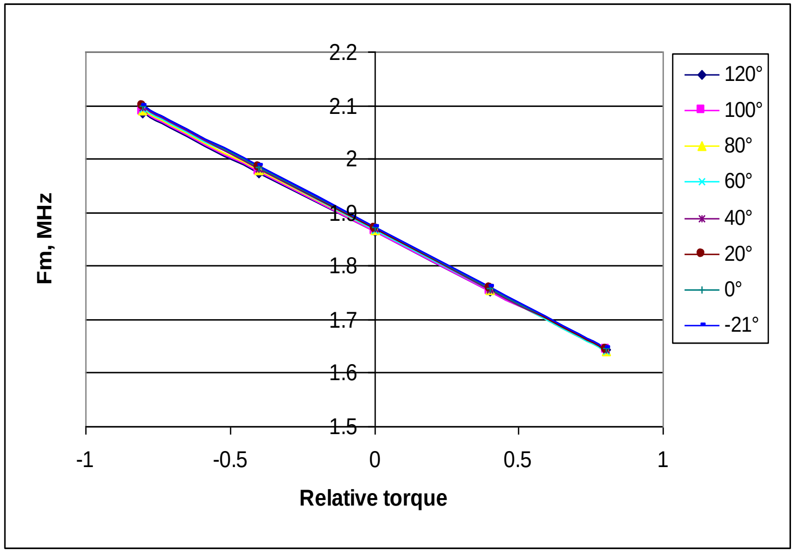


SAW Sensing Elements

3. Single 429-431 MHz die (2004)

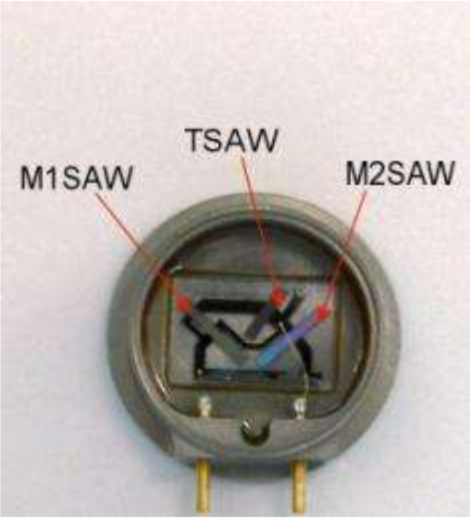
- Y+34°-X±45° cut quartz,
- Considerably smaller size,
- Metal package,
- Using a stiff high-temperature adhesive.

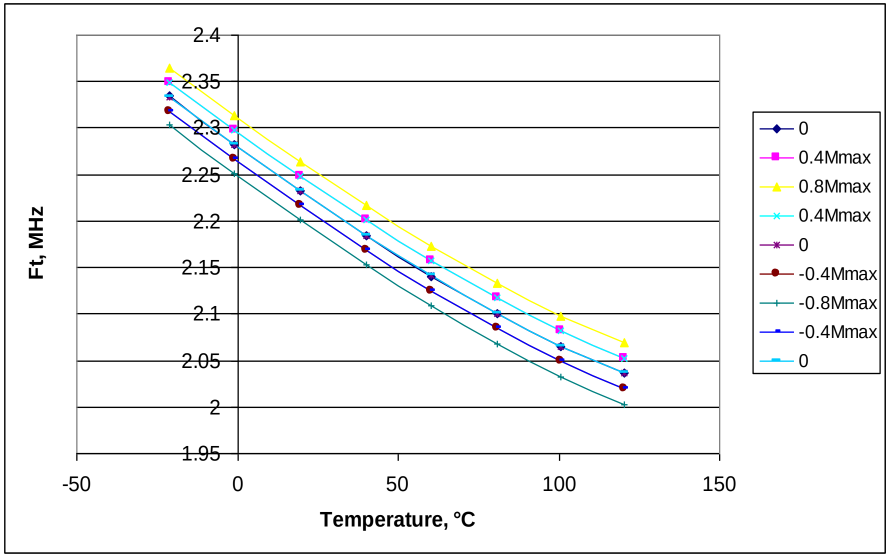




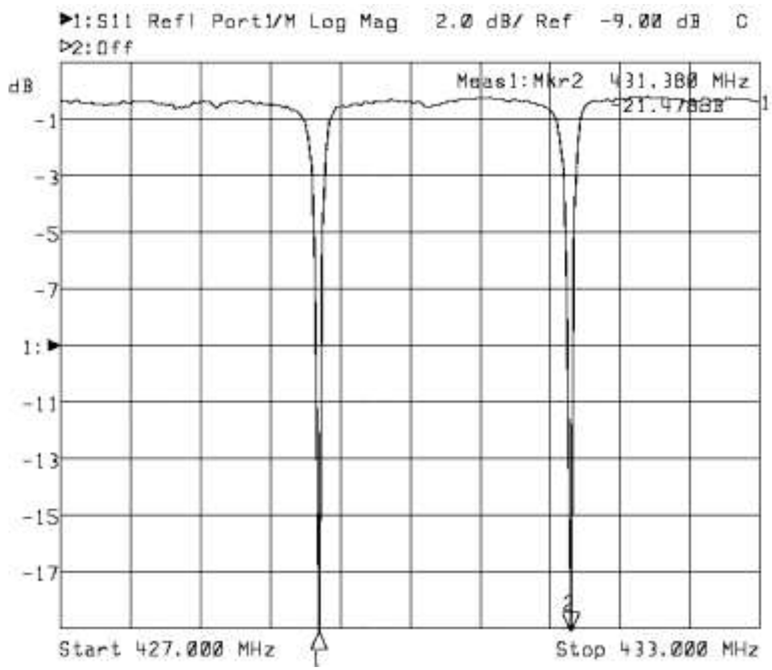
4. 433-437 MHz sensing element (2005)

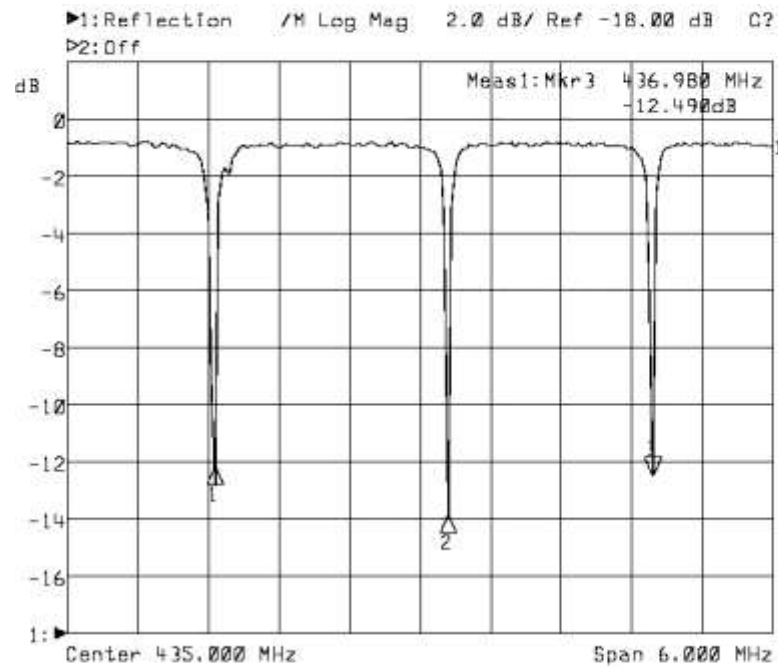
- Simultaneous measurement of torque & temperature to achieve temperature compensation.





Characteristics of the SAW Torque Sensing Elements





Unloaded $Q \approx 10000$

Five resonant frequencies need to be measured to to obtain a temperature compensated torque reading.

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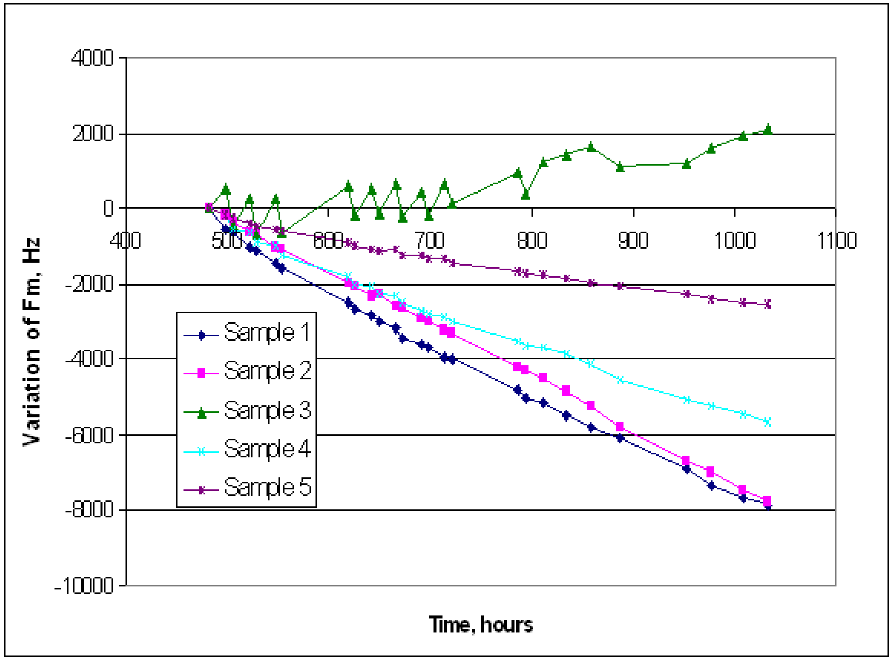
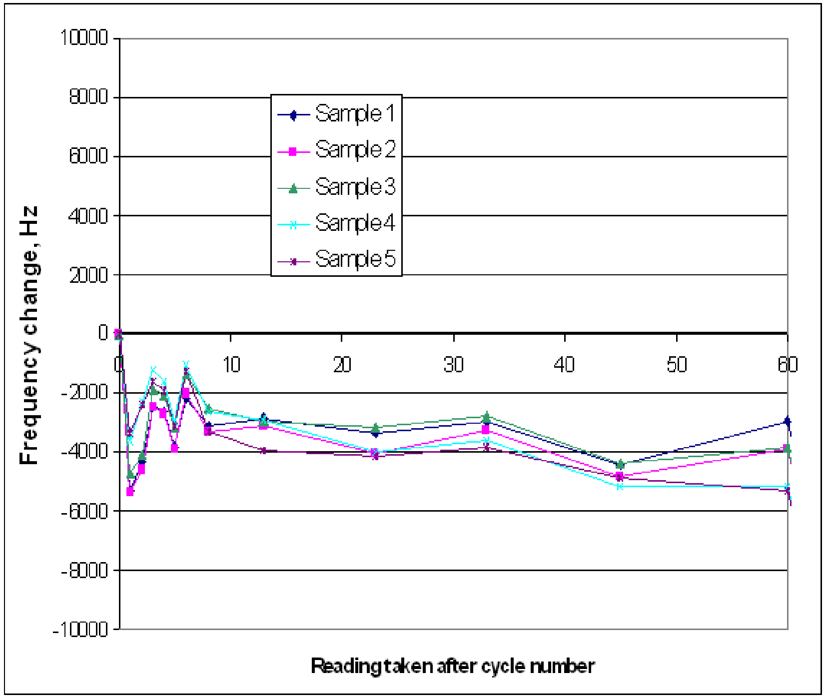
SAW Sensing Elements

Long-term Stability of Torque Sensors



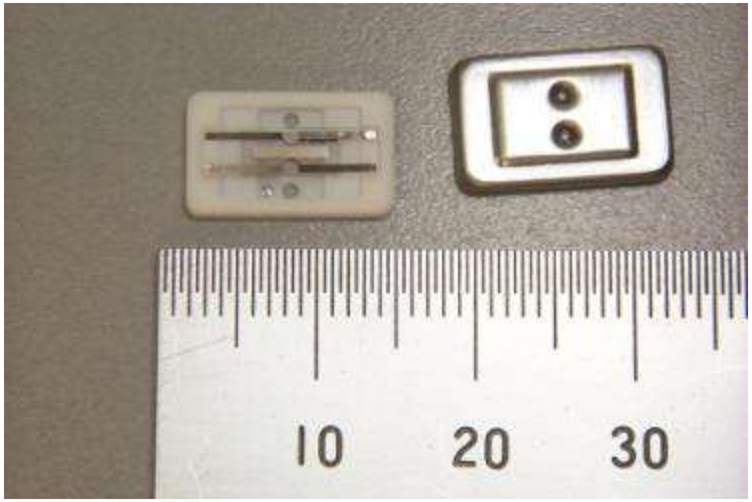
Accelerated ageing test shows that the error can be up to 3% FS after ≈350000 km

Thermal cycling from –40°C to +125°C:



SAW Sensing Elements

Pressure & Temperature Sensor

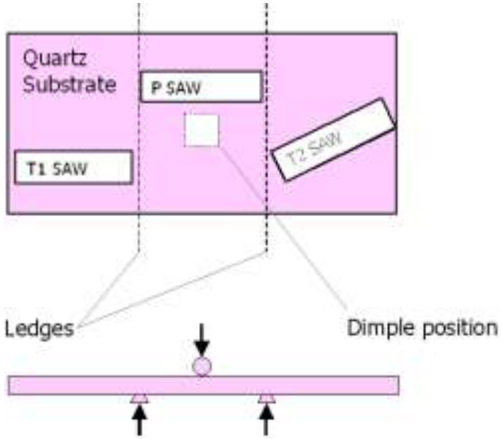


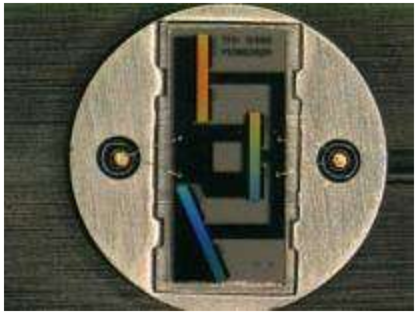
1. The first attempt (2001):

- No micromachined diaphragms,
- Double-sided SAW device on ST-X cut quartz with 434.06 and 434.49 MHz resonators for P measurement
- Separate die with 433.34 MHz resonator for T measurement.

2. TPMS button (2002):

- All-metal package,
- Single SAW die on ST-X cut quartz with three resonators at 434.04, 433.88 and 433.45 MHz,
- Mechanical preloading during packaging.





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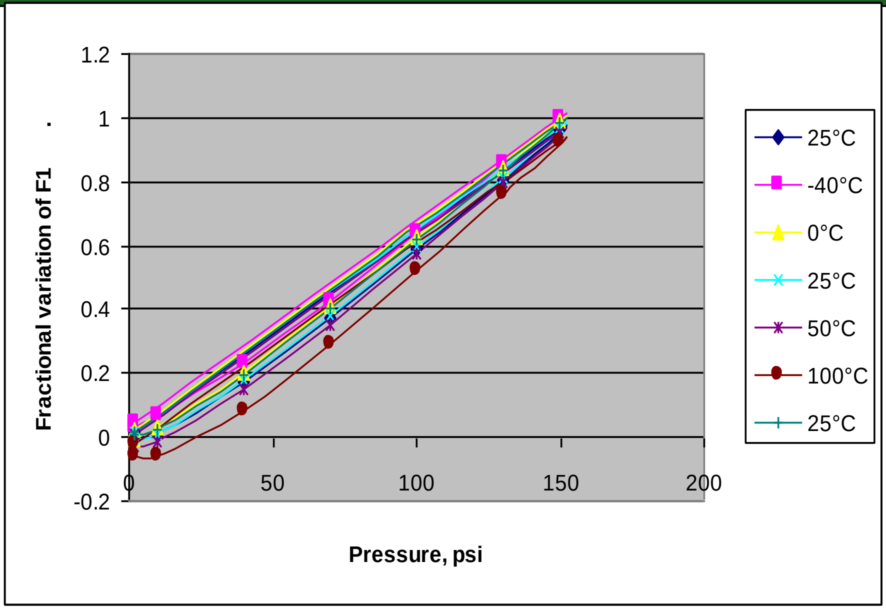
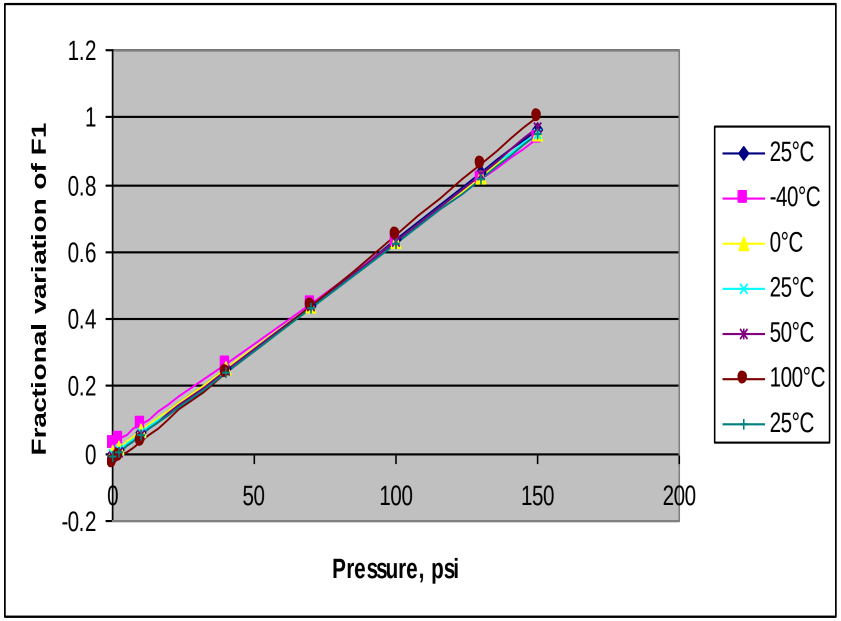
SAW Sensing Elements

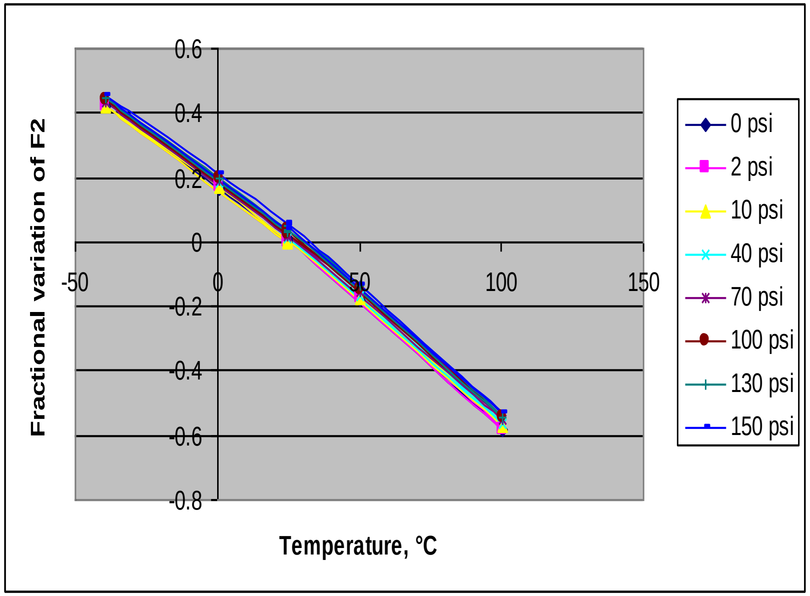
Calibration characteristics of the TPMS sensor

Before optimization of the package materials



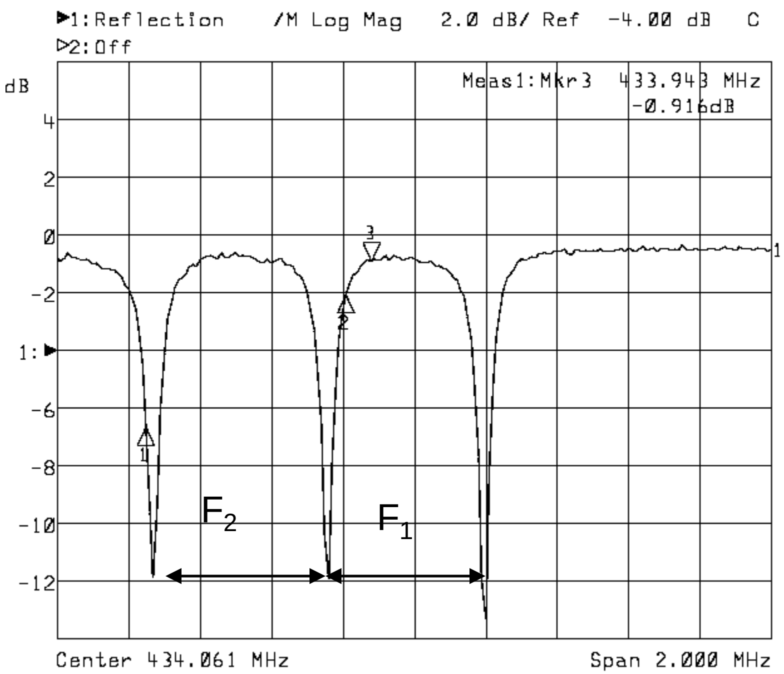
After optimization of the package materials



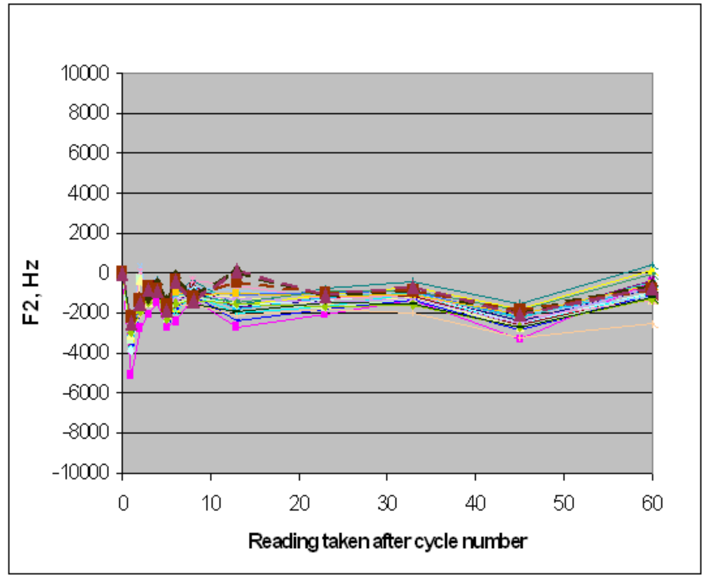


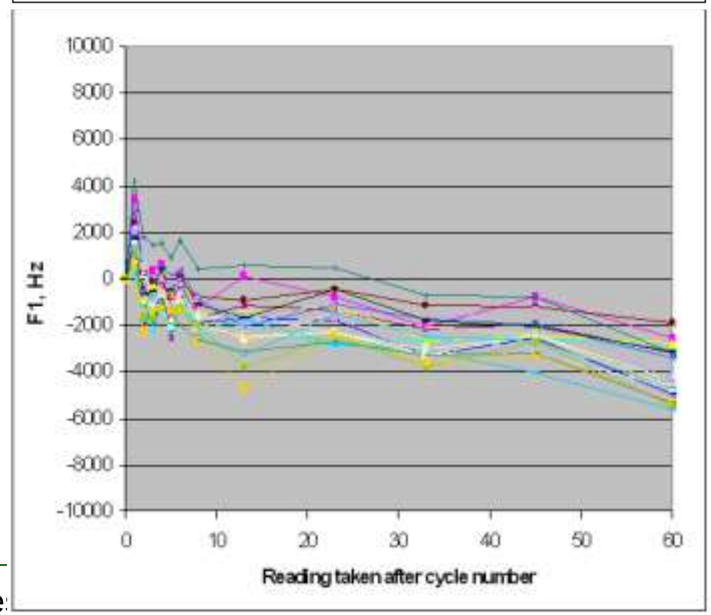
SAW Sensing Elements

Frequency response of the TPMS sensor



Long-term Stability of the TPMS Sensors





Max error of 1.8 psi for the 10 bar sensor

Reader for resonant SAW sensors

Two different classes of sensors:

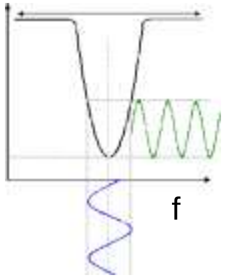
• Short range interrogation (Torque sensor – close coupling, fast interrogation, strong input signals, small Rx dynamic range, no problems with Rx/Tx isolation)

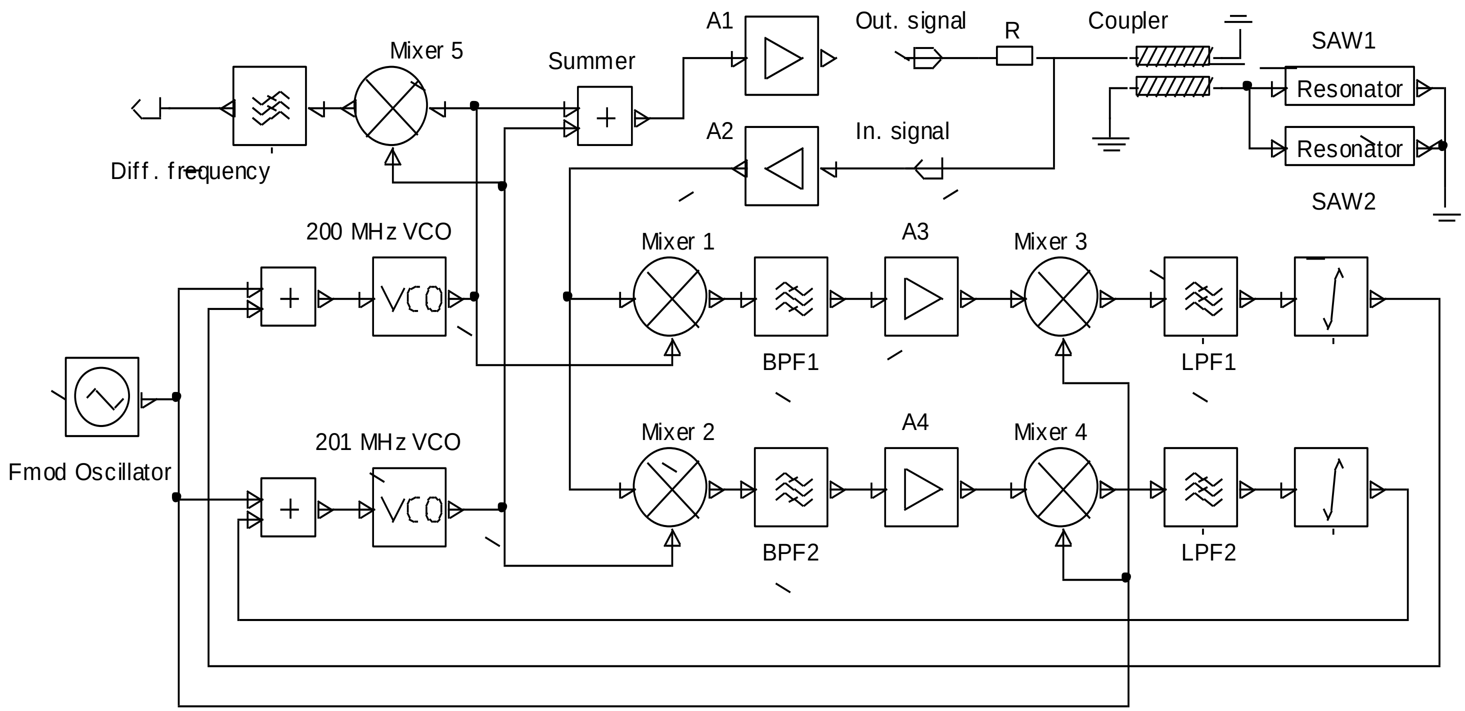
• "Long" range interrogation (TPMS sensor – antenna coupling, slow interrogation, large Rx dynamic range > 60 dB, Rx/Tx isolation > 100 dB)

Short range reader

1995-2002:

Two frequency tracking loops using FMCW signals





Reader for resonant SAW sensors

FMCW frequency tracking interrogator for EPAS (2001)

$\Delta F \approx \pm 50$ Hz

@ 200 MHz

$\tau = 0.6$ ms.

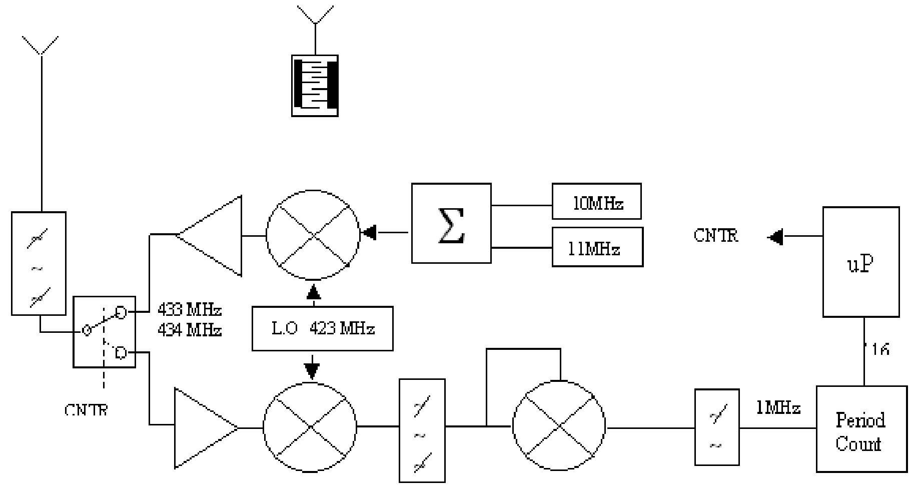
Prototype EPAS shaft (2002)

Reader for resonant SAW sensors

“Long” range reader

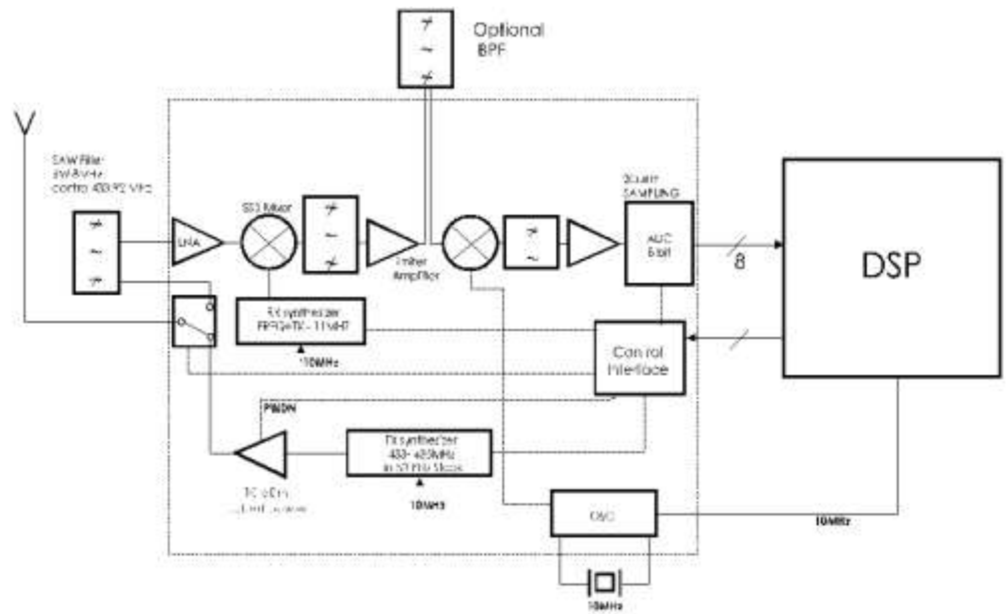
1. The first attempt (2000):

- Simultaneous pulsed excitation of two 200 MHz SAW resonators,
- Measurement of the frequency difference by means of zero counting,
- Frequency errors $\approx$10 kHz.



2. Pulsed interrogator (2001):

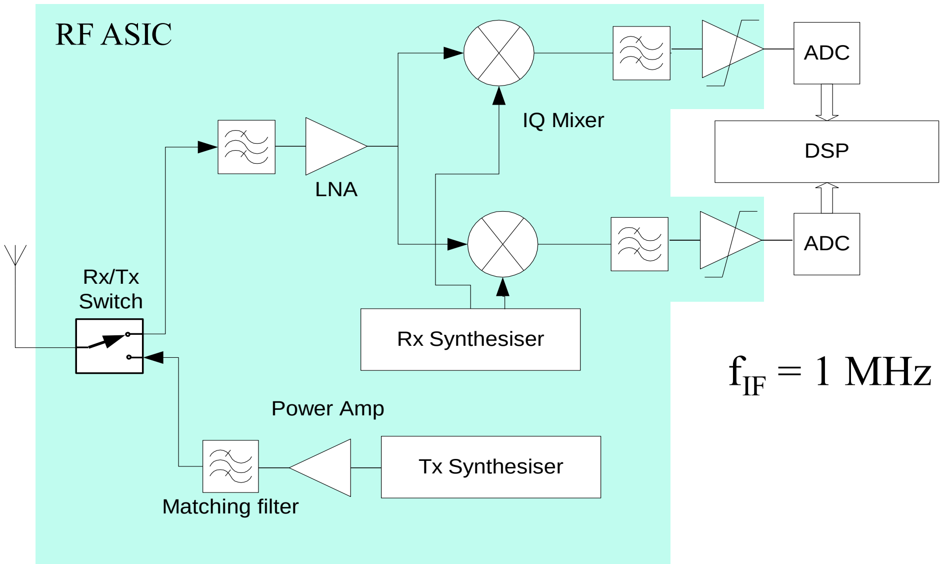
- Sequential pulsed excitation of resonators,
- Based on two off-the-shelf 433 MHz transceivers,
- Coherent accumulation of several SAW responses,
- Spectral analysis of the SAW responses in the DSP and parabolic interpolation between spectral lines,
- Frequency errors <1 kHz.



Reader for resonant SAW sensors

3. Pulsed interrogator (2005):

- Based on the single RF ASIC chip,
- Improved frequency stability and reduced systematic errors due to IQ outputs
- Improved Tx/Rx isolation
- Shaped or rectangular interrogation pulse,
- Reduced dimensions and cost.



$f_{IF} = 1$ MHz

Main parameters of the interrogator:

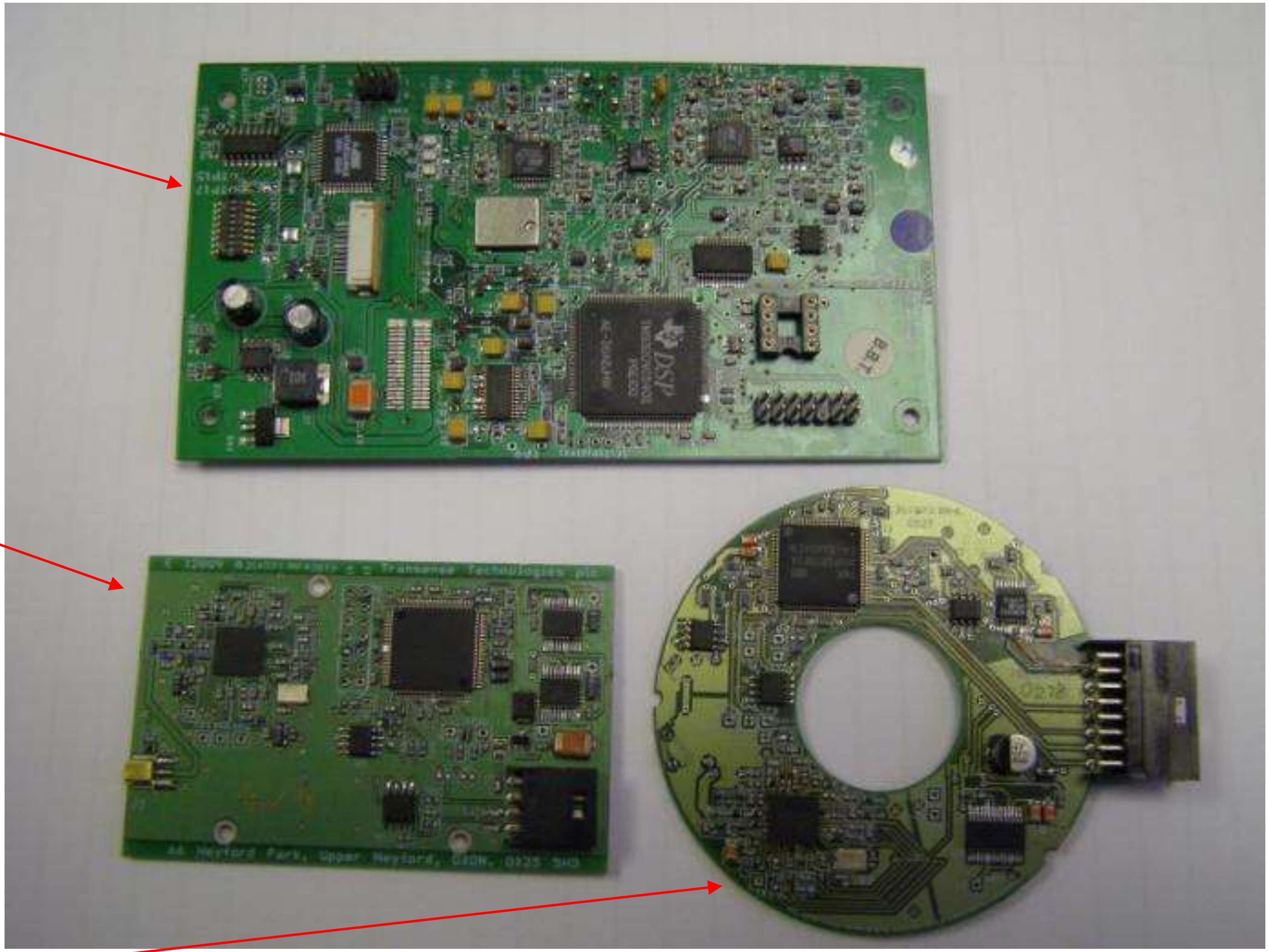
Output power:	0.5…10 mW,
Rx sensitivity:	-88 dBm @ SNR = 17 dB,
Rx/Tx isolation:	>100 dB,
Random errors:	$\sigma_F \approx$ 100…200 Hz,
Systematic errors:	$\Delta F < 1$ kHz,
Read range:	1…3 m,
Measurement time:	155 us (short range), 1 ms (long range)

Reader for resonant SAW sensors

Pulsed interrogator based on off-the-shelf components

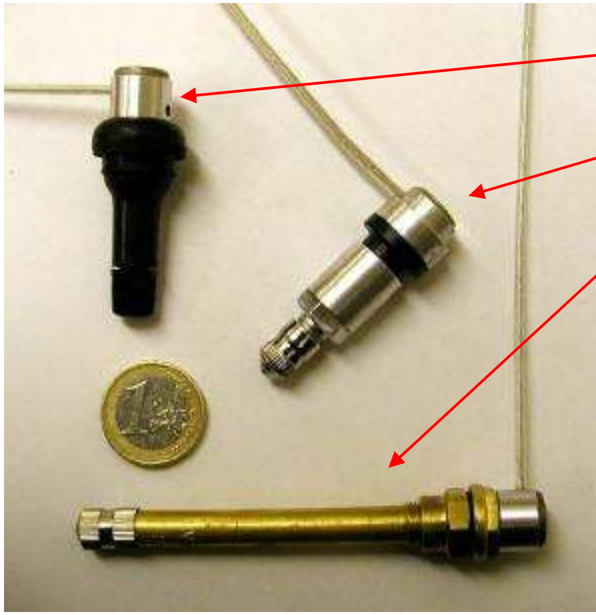
Pulsed interrogator based on RF ASIC

Pulsed interrogator for EPAS



Tyre Pressure and Temperature Monitoring System

1. TPMS for passenger cars



Snap-In rubber valve for cars

Screw-in metal valve for cars

Long reach truck valve

Interrogation electronics

Tyre Pressure and Temperature Monitoring System

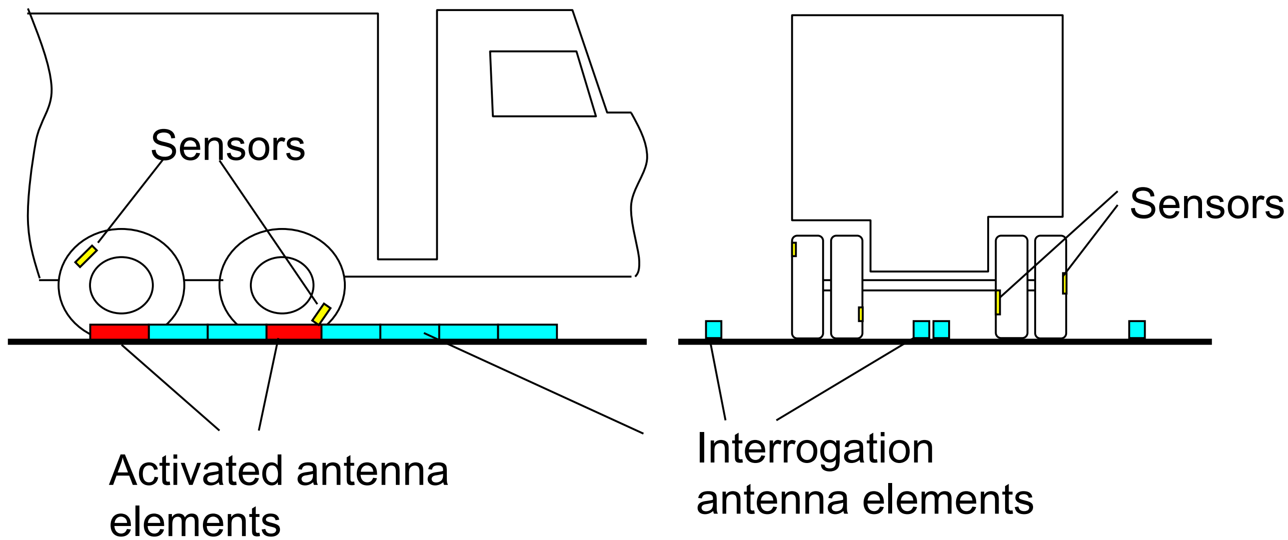
2. TPMS for tracks

Patch attached to a track tyre

TPMS Sensor Patch incorporates:

- SAW TPMS Sensor (Pressure & Temperature)
- RFID Tag containing TPM Sensor ID, calibration data. Additional data e.g. type of tyre, fitment mileage / date may be included.

Drive-by reader for 18-wheel truck



Tyre Pressure and Temperature Monitoring System

SAW TPMS Specification

Interrogation power:	0.5 mW,
Interrogation pulse length:	10…14 us,
Pressure resolution for 10 bar sensor:	0.35 psi,
Temperature resolution:	0.35°C,
Pressure accuracy for 10 bar sensor:	±1 psi,
Temperature error:	<2°C
Temperature range:	-40°C…+100°C
Read range:	1 m

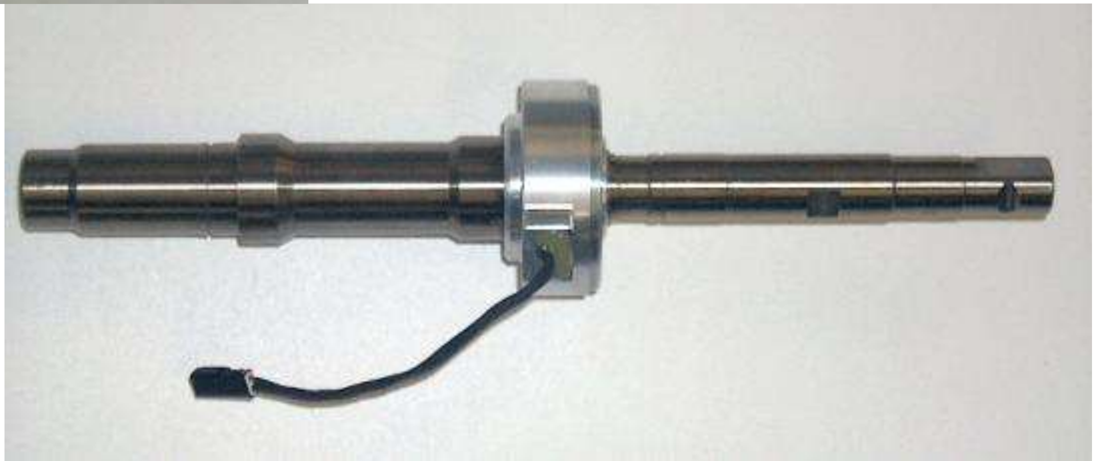
Stack TPMS

Stack TPMS – wireless, batteryless and compact. Completely re-defines tyre pressure and temperature monitoring in Motorsport: racing applications, cars, tracks & bikes. (www.stackinc.com)

Non-compliant EPAS Torque Sensors

EPAS torque sensor for OTR vehicle

EPAS torque sensor & interrogation board in one housing



EPAS torque sensor installed on a steering shaft with a pinion

EPAS Torque Sensors

Typical EPAS sensor specification:

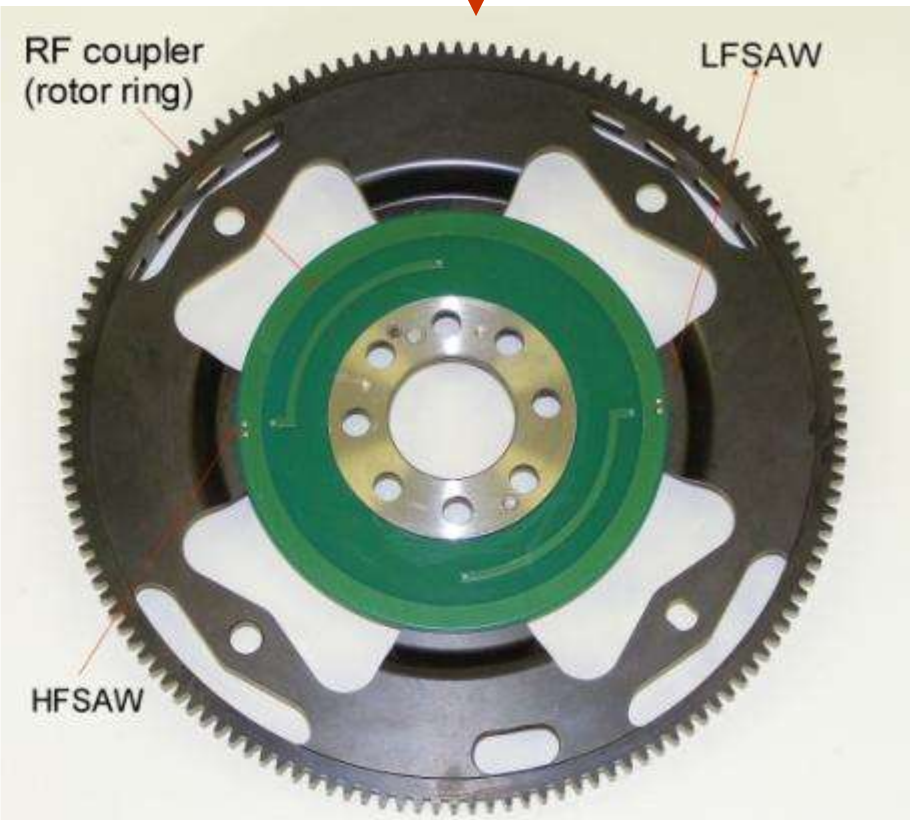
Torque measurement range:	$\pm$ 10 Nm
Torque resolution (3σ)	< 0.03 Nm
Overload capability (die-shaft bond):	> $\pm$ 250 Nm
Torque measurement combined error*:	< $\pm$ 0.2 Nm
Hysteresis	< 0.06 Nm
Torque reading update rate:	2…3 kHz
Temperature range:	-40°C…+125°C
Dynamic torque:	> 5 Nm/ms

* Includes non-linearity, repeatability, hysteresis, creep and temperature effects

Powertrain Torque Sensors

1. Fexplate torque transducer

Flexplate = steel disk with diameter from 24 to 36 cm and thickness from 2 to 4 mm connecting the crankshaft to the torque converter



Typical powertrain torque sensor specification:

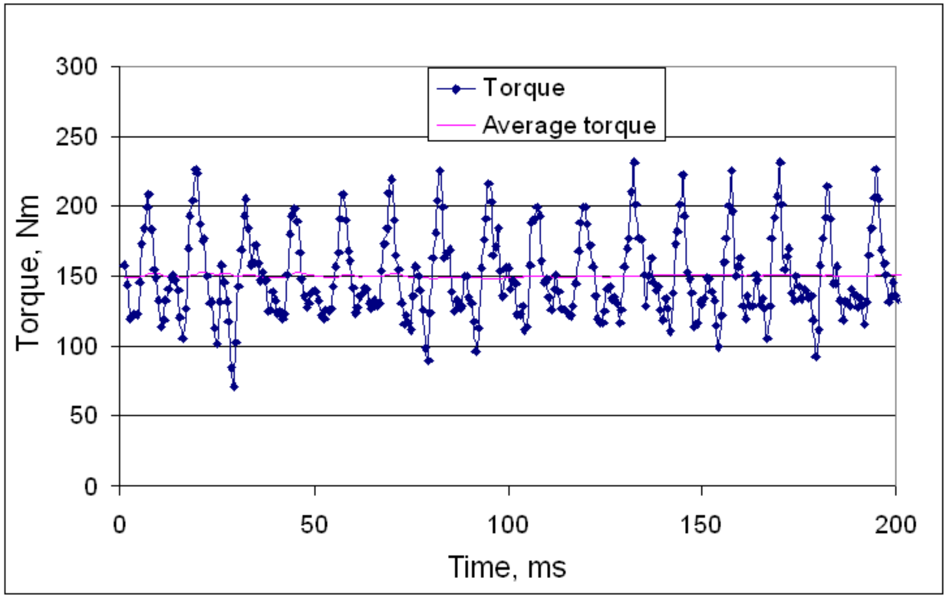
- Shaft/flexplate maximum torque: up to ±800 Nm
- Torque resolution: < 0.25% FS
- Torque measurement error: <1% FS
- Torque update rate (1 sensor): up to 6 kHz
- Temperature range: -40°C…+125°C

Powertrain Torque Sensors

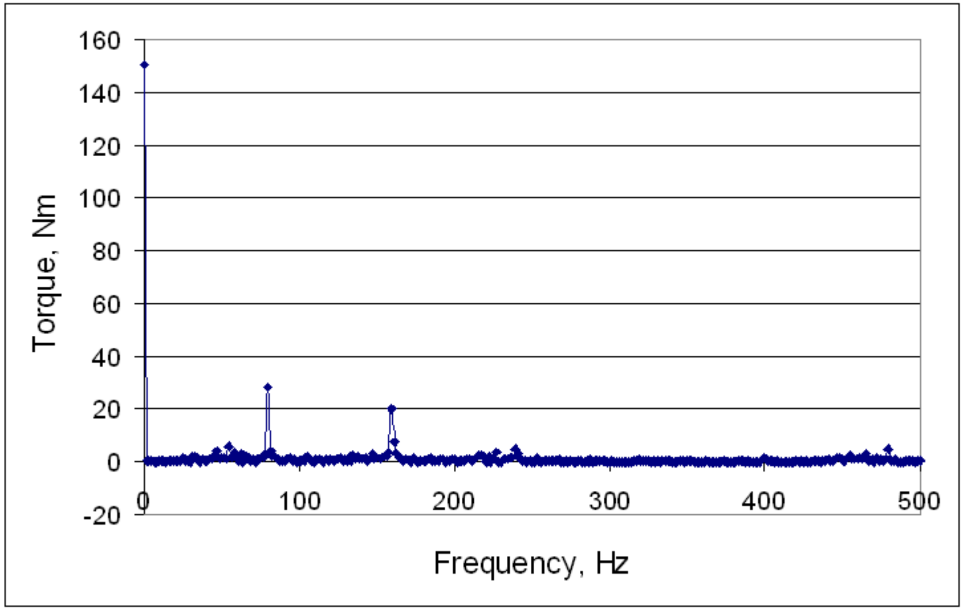
Dynamic performance of the flexplate with two sensing elements

Ω = 1600 rpm, M_{dyno} = 150 Nm, T_{engine} = 94°C, V6

Sensor readings:



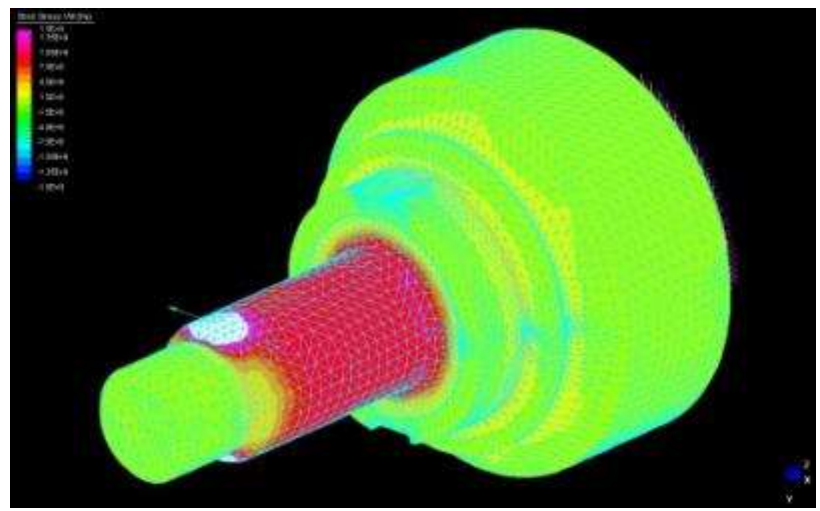
Torque spectrum:



Powertrain Torque Sensors

2. Driveshaft Torque Sensor

Torque range:	3000 Nm
Overtorque:	6000 Nm
Torque update rate:	2 kHz
Combined error:	< ± 8 Nm at M < ±200Nm
	for T< 116C,
	< ± 21 Nm at M < ±200Nm
	for T< 150C,



3. Torque sensor for F1 KERS (season 2009)

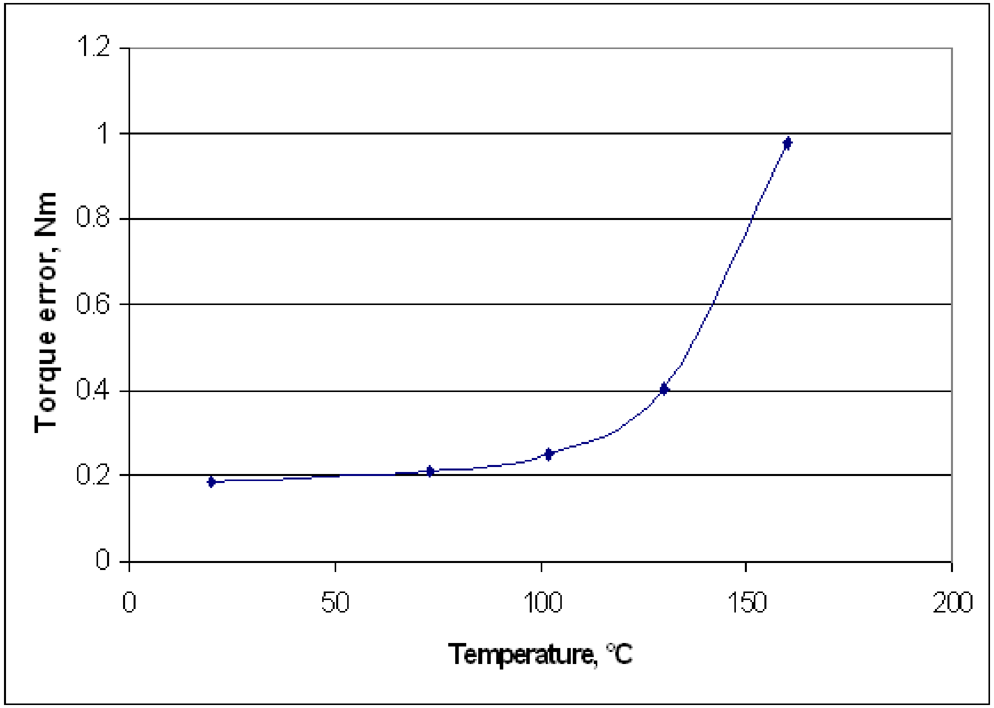
The KERS shaft with the bonded HFSAW sensing element

Assembled torque transducer

The shaft diameter was selected to provide 10-fold overload capability and torque resolution better than 0.2 Nm (9 bits over the read range of ±50 Nm)

Powertrain Torque Sensors

Accuracy of the torque sensor for F1 KERS



The max rotation speed: up to 18000 rpm

Max temperature: up to 170C

The global torque accuracy is better than 1% FS

Powertrain Torque Sensors

Dynamic performance of the F1 KERS torque sensor

(Telemetry data)

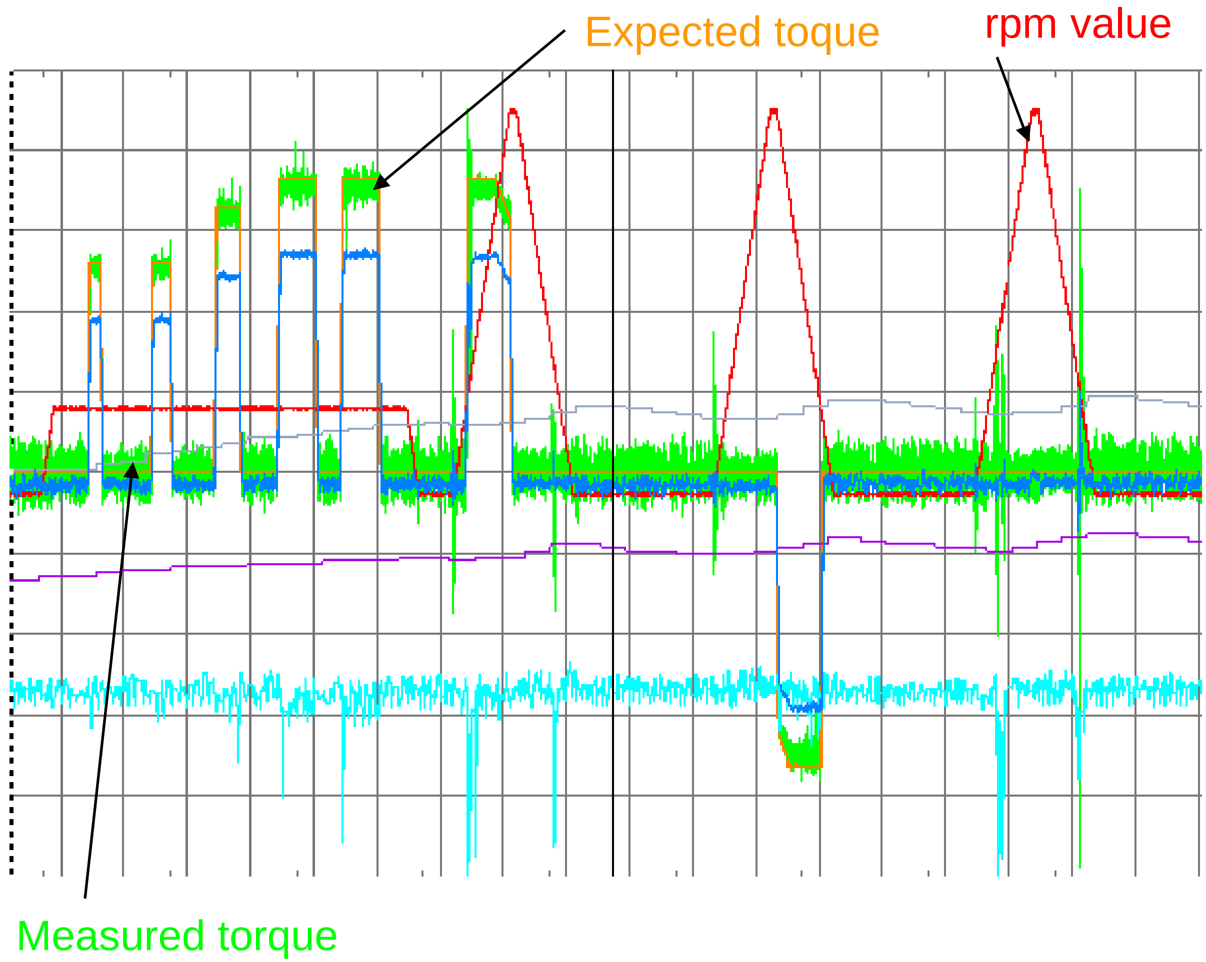
Engine dyno test:

9000…18000 rpm,

T = 100…130°C,

Torque M = 26, 33, 36.5 Nm

5 s/div



Torque Sensors for Industrial Applications

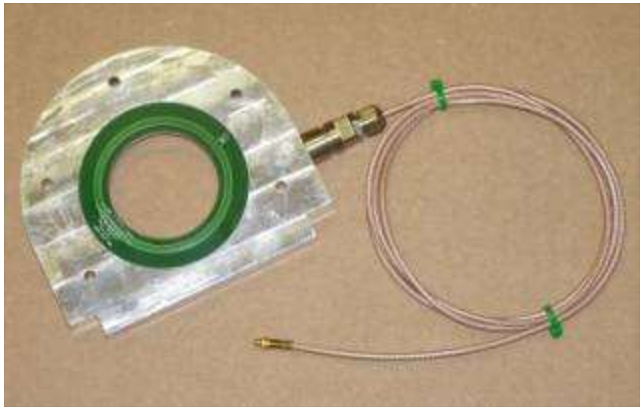
Torque sensor for on-load tap changers for high-power transformers

T = -40°C …140°C,

Torque M_{max} = 500 Nm

Resolution: 0.38 Nm

Temperature, °C	Non-linearity, Nm	Offset, Nm	Hysteresis, Nm	Max total error, Nm
-39.8	0.29	0.39	1.96	1.5
-0.8	0.34	0.21	1.88	1.3
31.7	0.35	-0.14	1.66	0.97
72	0.43	-0.29	0.68	1.5
101.8	0.42	-0.38	0.83	2.59
119.8	0.54	-0.28	2.55	4.25
138.87	0.63	-0.27	5.41	7.62



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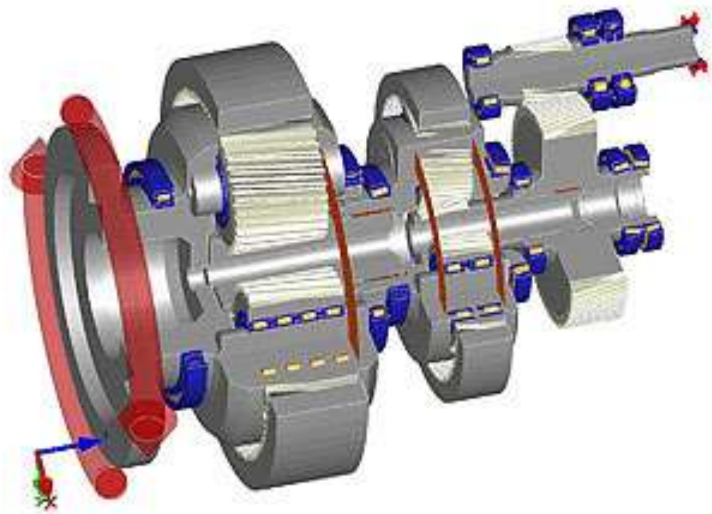
Torque sensor for output shafts of wind turbine gearboxes



Source: Romax/NKE

Example specification:

T = -20°C …80°C,

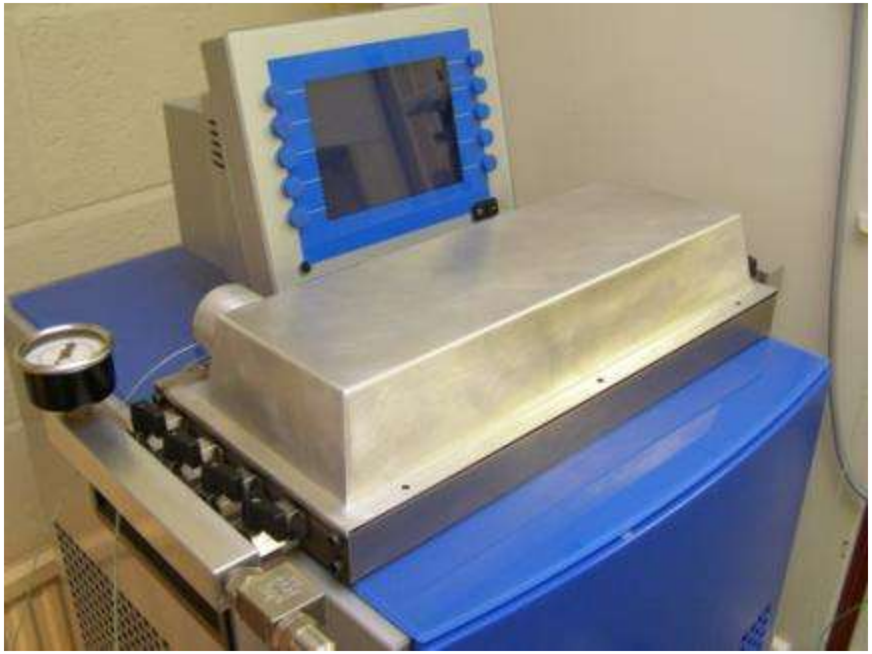
Torque M_{max} = 25 kNm

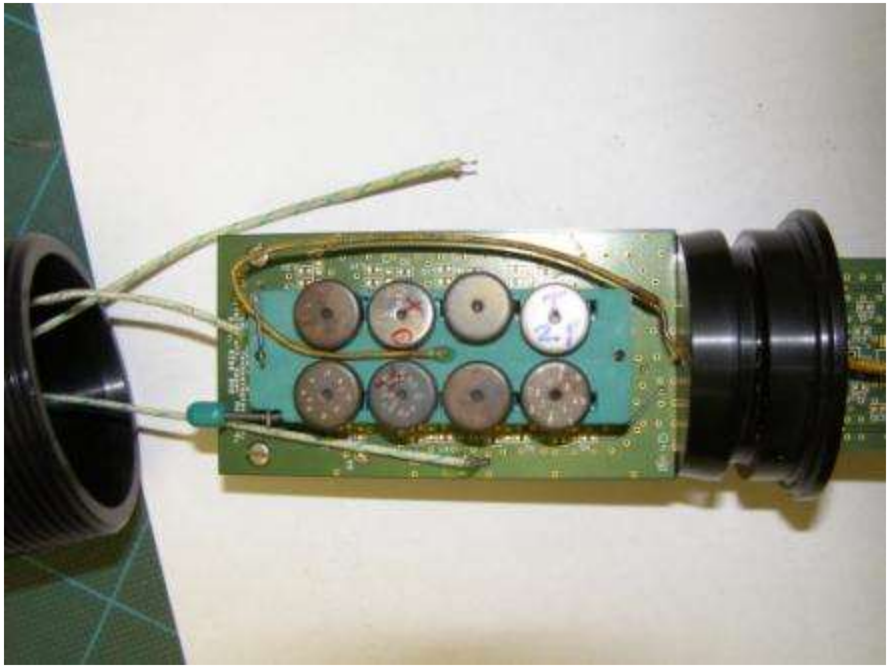
at 3000 rpm,

Shaft diameter = 20 cm.

SAW Sensor Calibration

1. Calibration rig for TPMS sensors



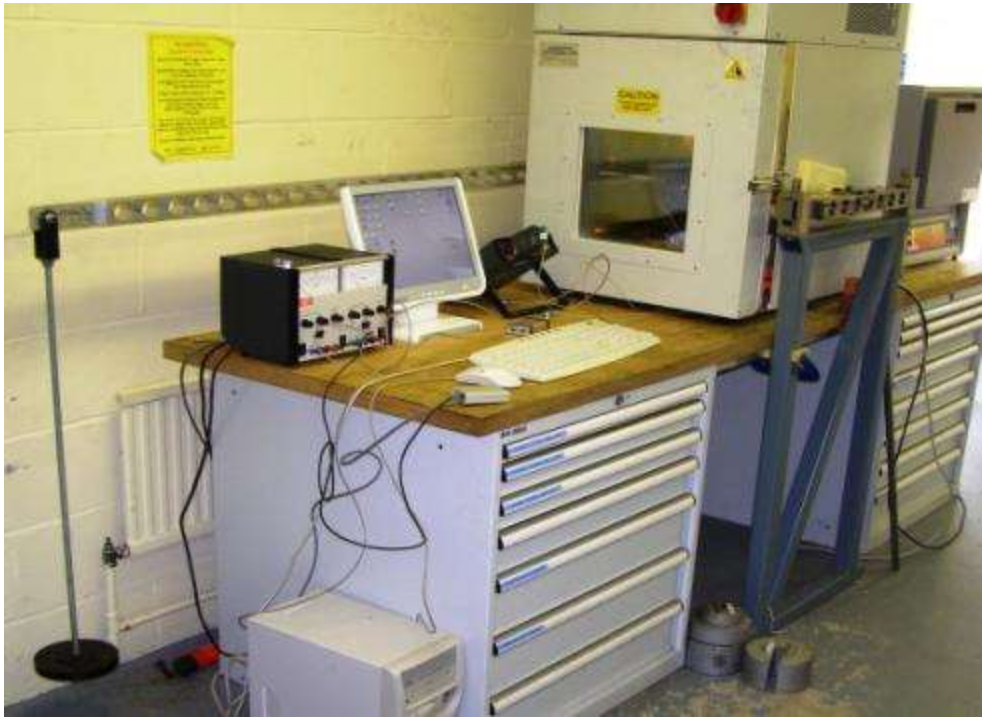


128 TPMS sensors can be calibrated in a fully automatic mode within one temperature cycle

SAW Sensor Calibration

2. Torque sensors

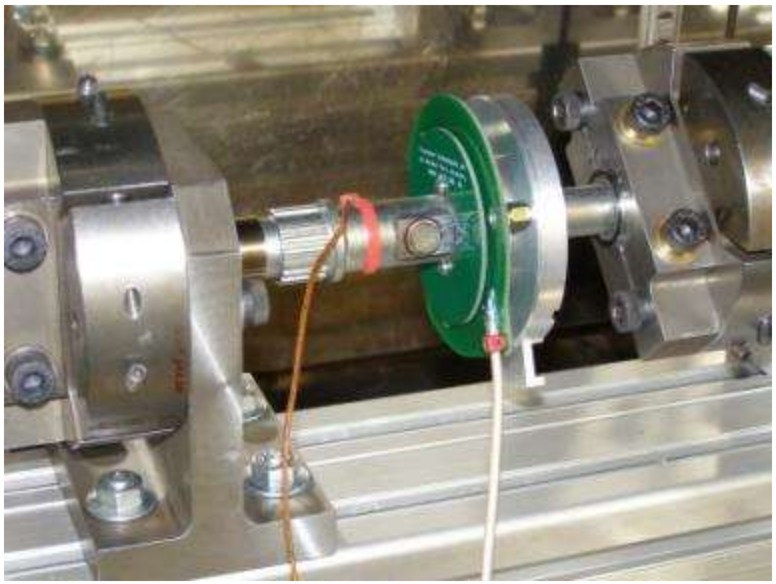
Flexplate torque sensor calibration rig:



Inside the oven:

Torque Sensor Calibration

EPAS torque sensor calibration rig:

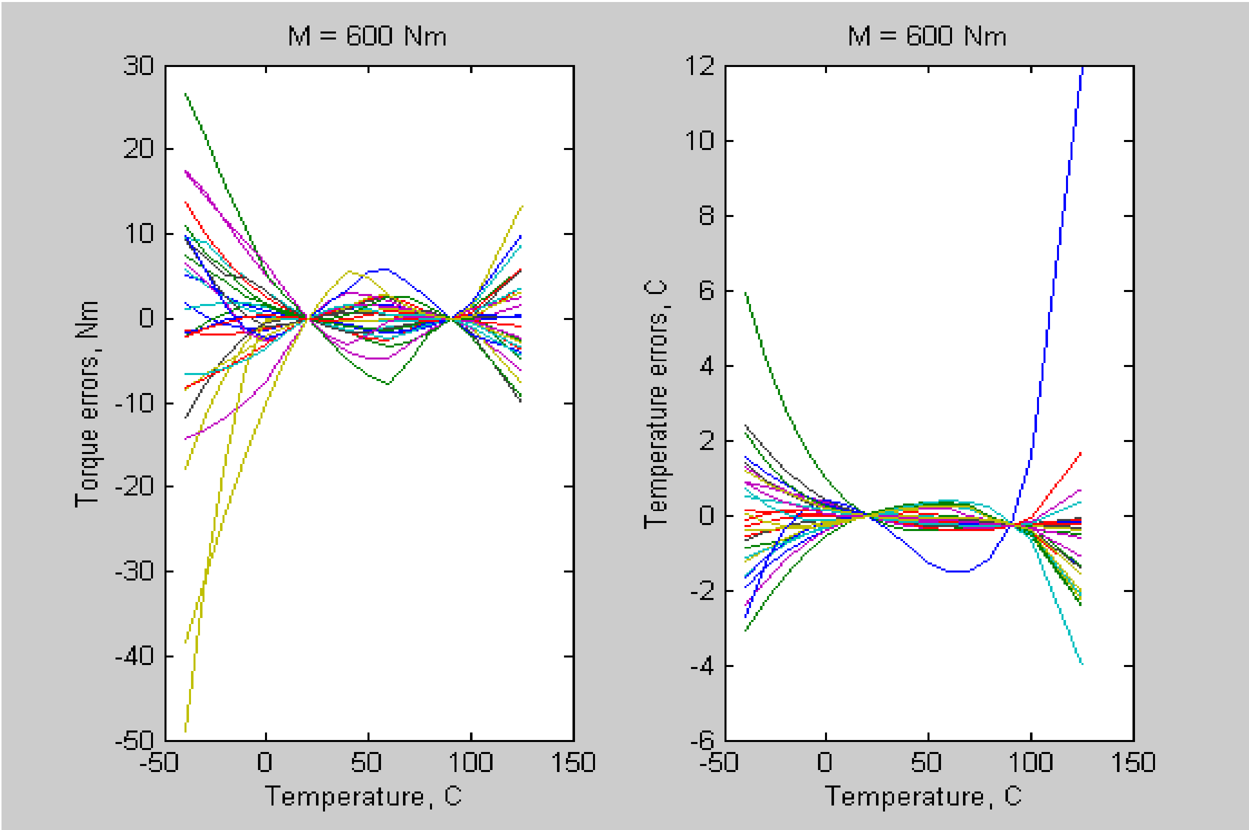


F1 KERS torque sensor calibration rig:

Torque Sensor Calibration

There are ways to reduce considerably complexity of individual calibration

1. Extra calibration errors are below 1% FS if individual calibration is performed only in two temperature points:



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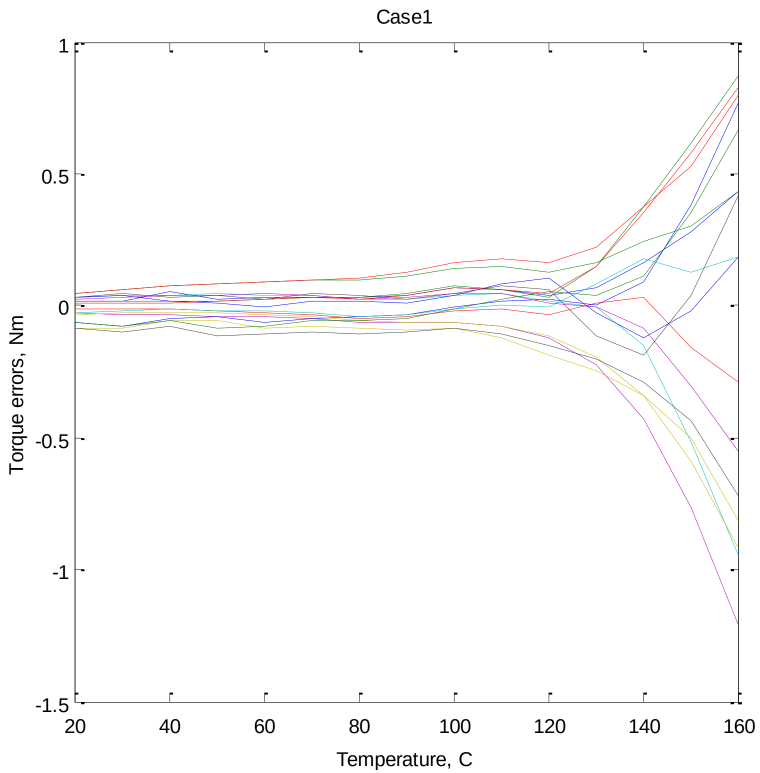
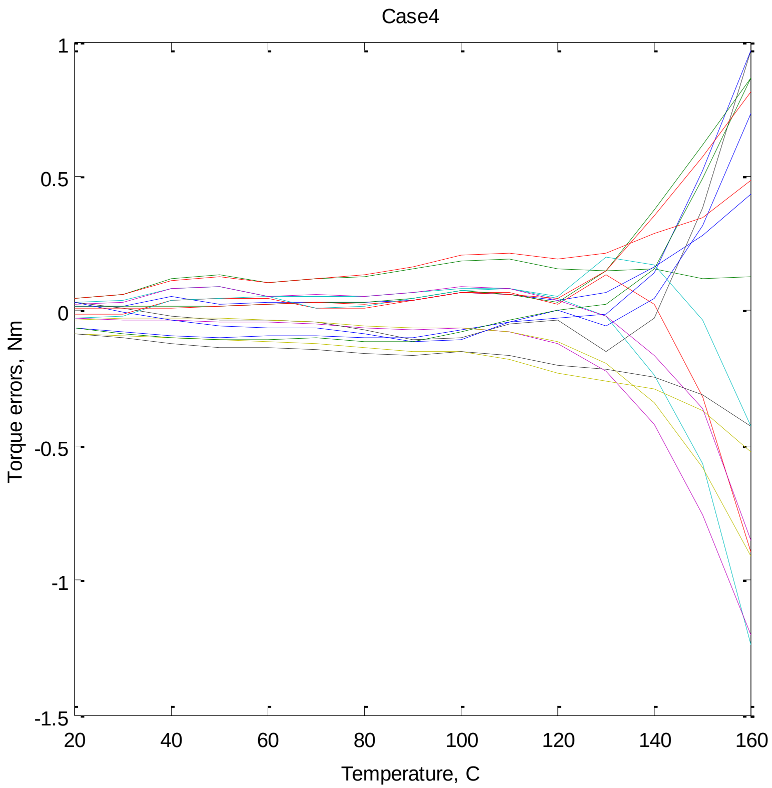
Torque Sensor Calibration

2. Total measurement errors are below 1% FS if individual calibration is performed only at room temperature and the offset is measured over the temperature range:

Full calibration of the KERS sensors:



Calibration with reduced complexity:



Conclusions

- Resonant wireless SAW sensors have been developed to measure temperature, pressure and torque in a number of applications.
- Some sensing systems have reached the stage of industrial manufacturing for niche automotive markets, e.g. motorsport.
- Mainstream applications (e.g. powertrain torque monitoring in passenger cars) are currently being developed.
- Some technical (mainly mechanical) and logistical issues still need to be resolved to accelerate adoption of SAW EPAS torque sensors by industry.
- Availability of cheap RFID readers will facilitate adoption of the resonant SAW TPMS sensors for passenger cars.
- The future is in development of faster interrogators and SAW sensing elements with ID function as well as improvement of packages for sensing elements.

Thank You