Passive Wireless SAW Sensor Technology and Applications at Transense

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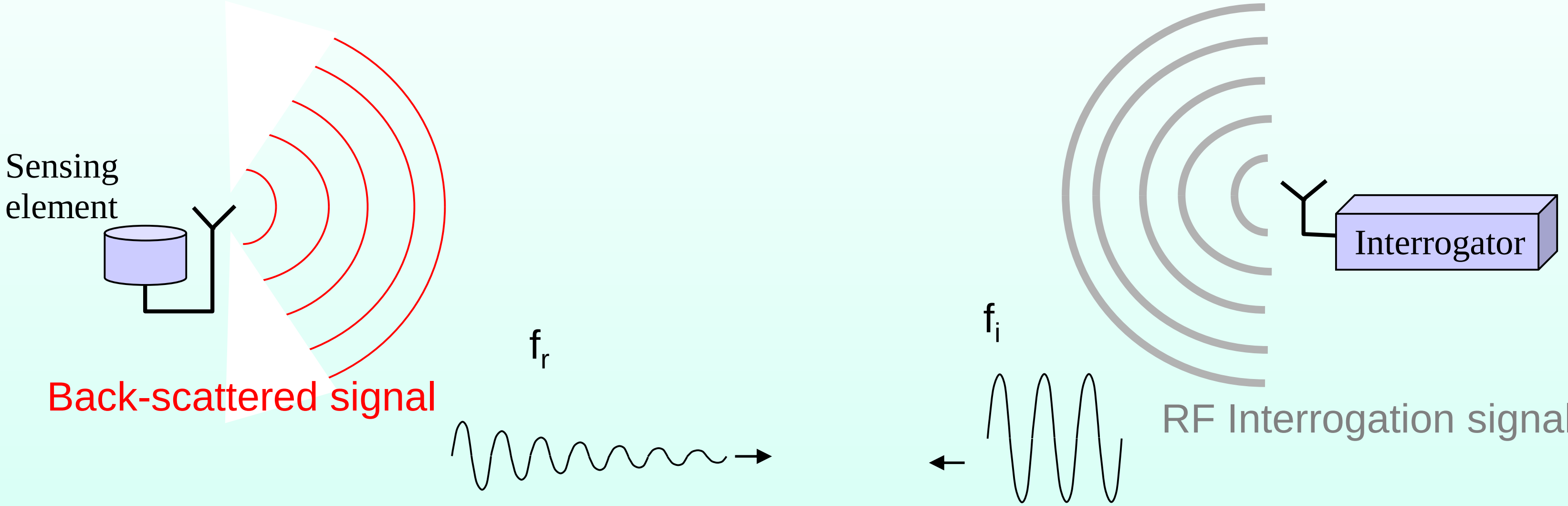
Outline

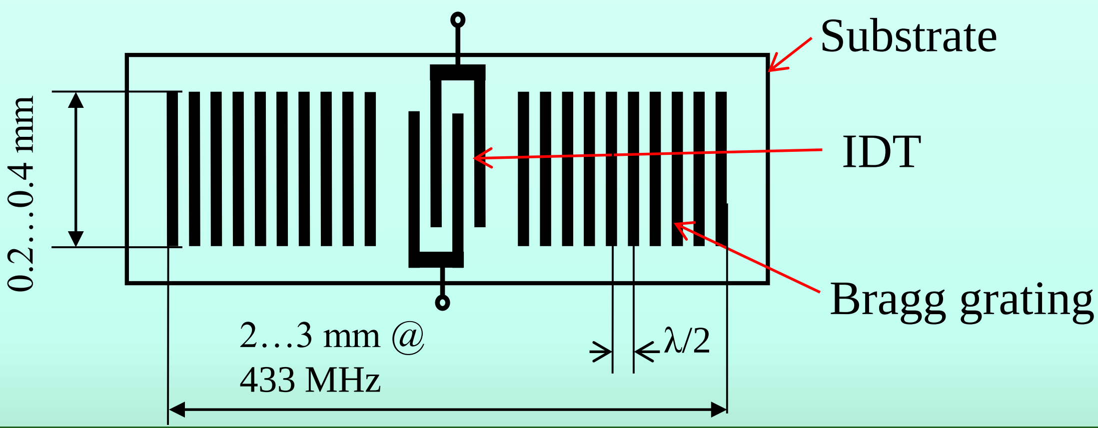
- Principle of operation of wireless resonant SAW sensors
    - Resonant SAW sensing elements
    - Wireless interrogation
- Torque sensing
    - Electrical power assisted steering sensors
    - Automotive and marine driveline torque sensors
    - Power generation and other Industrial applications
- Force and strain sensing
- Pressure and temperature sensing
- Temperature sensing
- Conclusions

Introduction

What is the passive wireless resonant SAW sensor?



SAW one-port resonator



- Operation in the UHF range

  $\lambda = 7.3\ \mu m$ @ 433 MHz

- Small dimensions, light weight and low cost
- High Q-factors Q = 10000-14000

Introduction

SAW resonator as a sensor

- Sufficiently high sensitivity of f_{res} to temperature T and strain s:

$$f_{res}(s, T) = f_{res}(T)[1 - S_s(T)\, s]$$

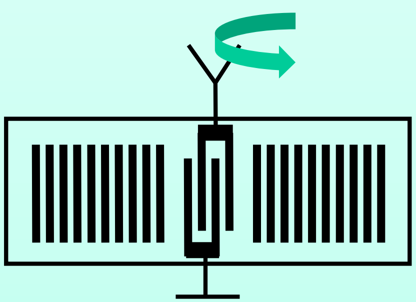
S_s = 1.25 ppm/µstrain for ST-X quartz (bending)
S_s = 3.7 ppm/ µstrain for Y+34° quartz (shear)
TCF = -50…30 ppm/°C for quartz

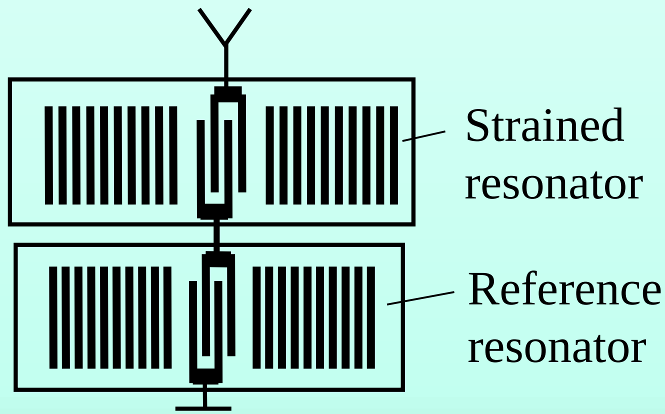
How to separate s from T?

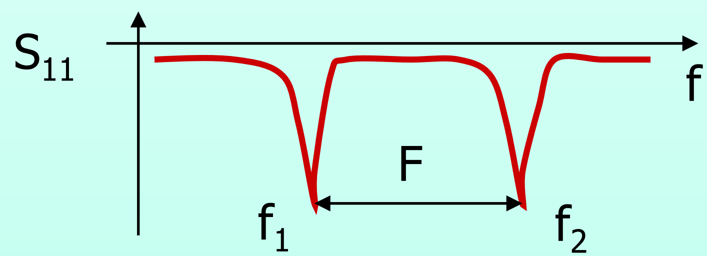
- Capability of working in a harsh environment

Quartz (T < 250°C), LGS (T > 250°C)

SAW resonator as a passive back-scatterer:







Difference frequency measurements:

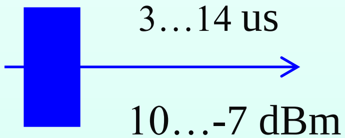
$$\Delta F = (f_2 - f_1)\, S_s s$$

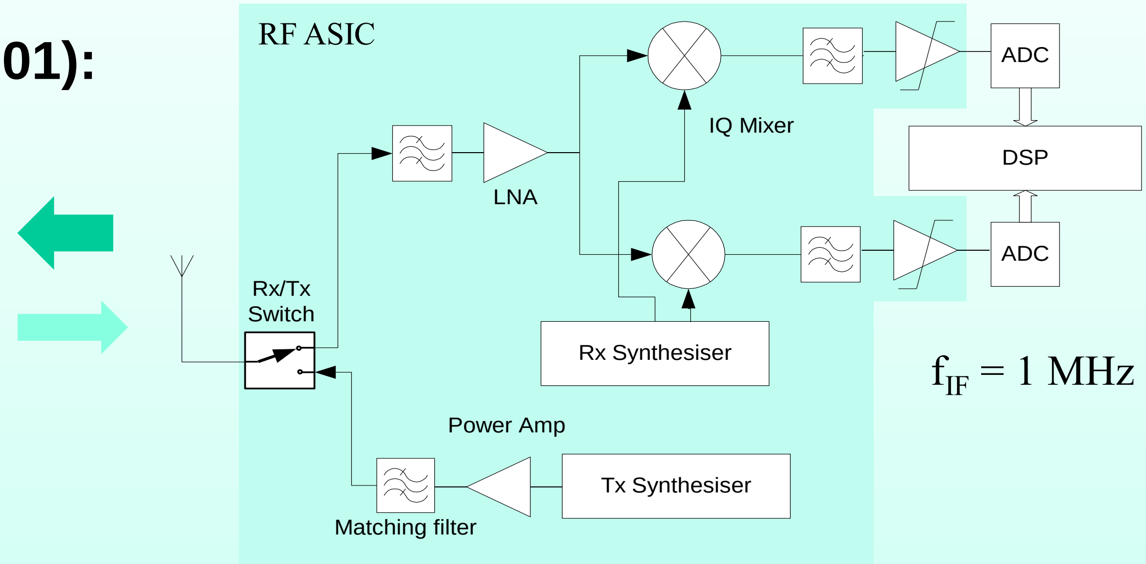
Introduction

Wireless measurement of f_{res}

Pulsed interrogator/reader (2001):

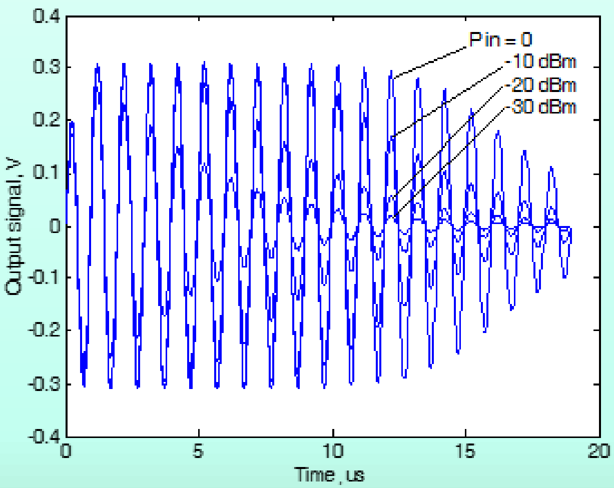
Interrogation pulse

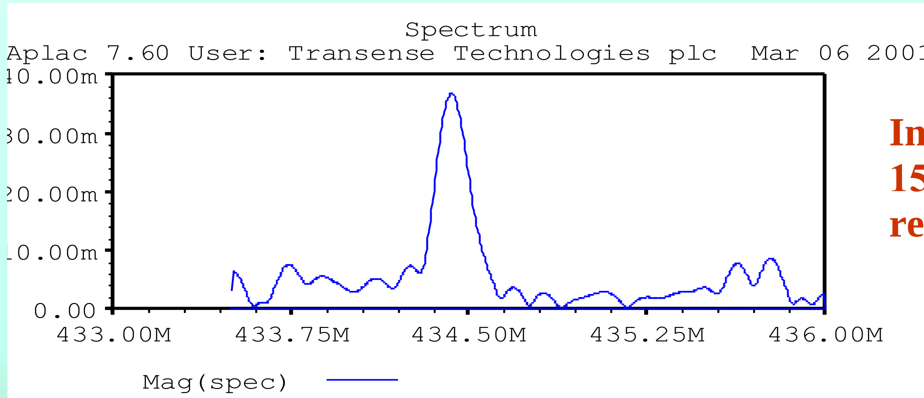




$f_{IF} = 1$ MHz

SAW response at the ADC input

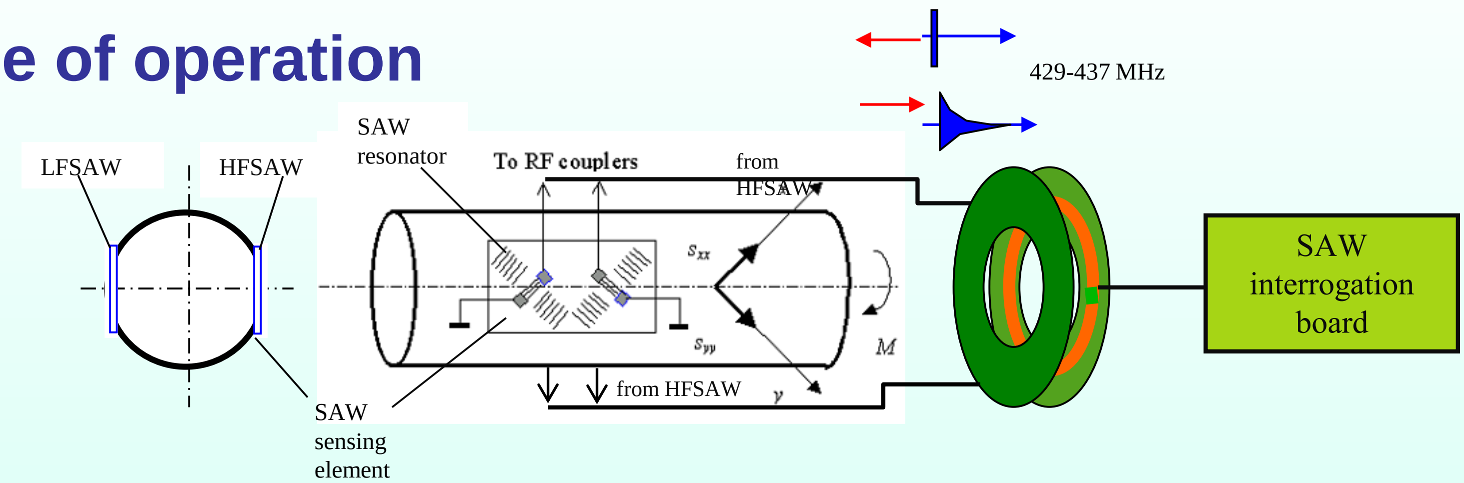




Interrogation time = 150…250 us per resonator

Torque Sensing

Principle of operation



SAW sensing elements

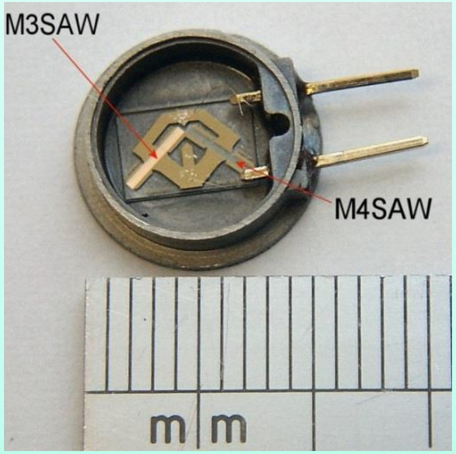
Low-frequency element (LFSAW)

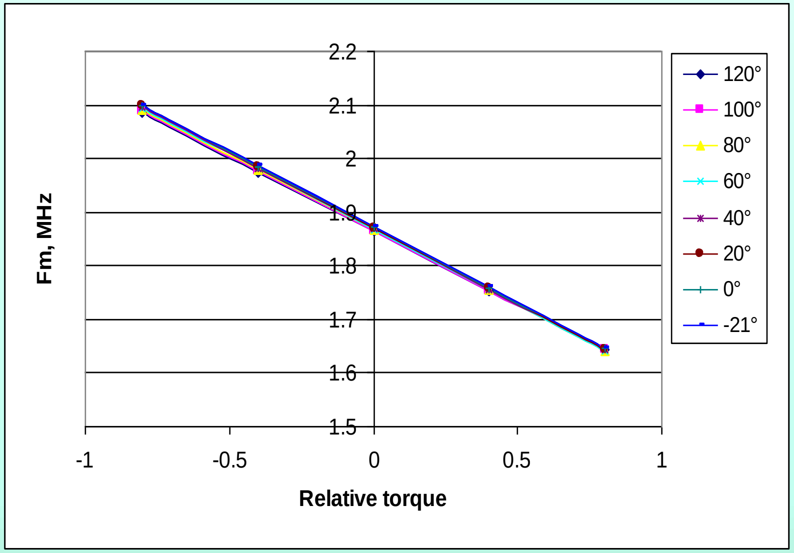
Y+34°-X±45° cut quartz,

metal package.

$f_{M4} \approx$ 431 MHz,
$f_{M3} \approx$ 429 MHz,

$F_{m2} = f_{M4} - f_{M3} = S_2 s + F_{02}$





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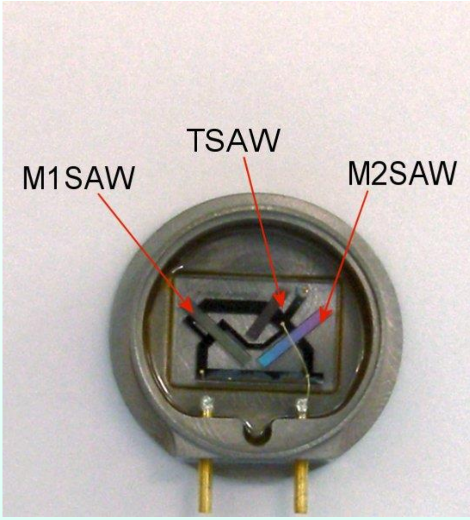
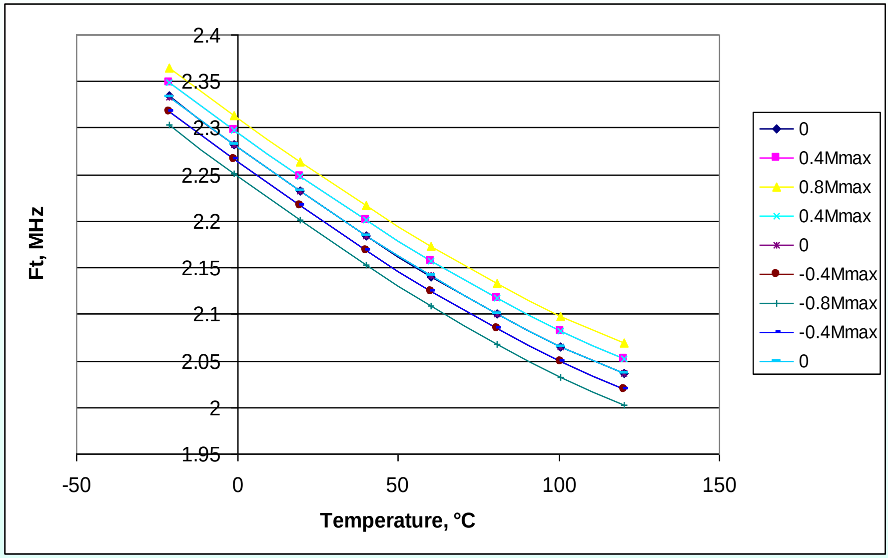
Torque Sensing

High-frequency element (HFSAW)

Simultaneous measurement of torque & temperature to achieve temperature compensation.

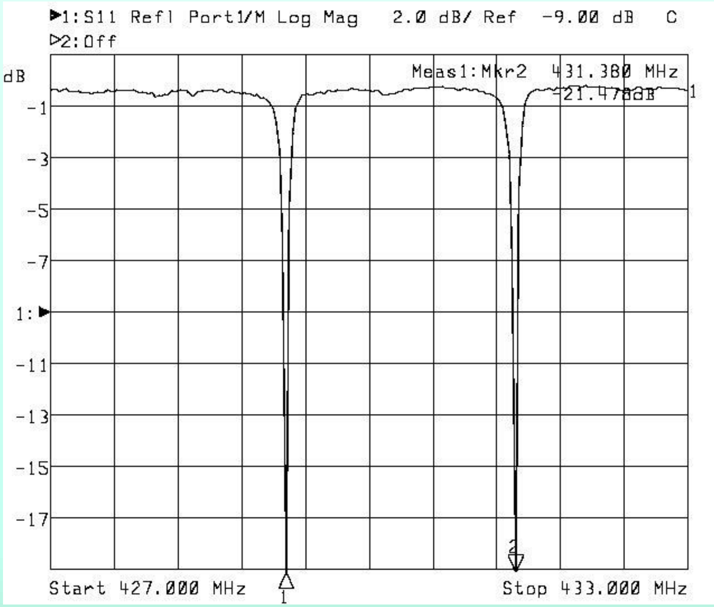


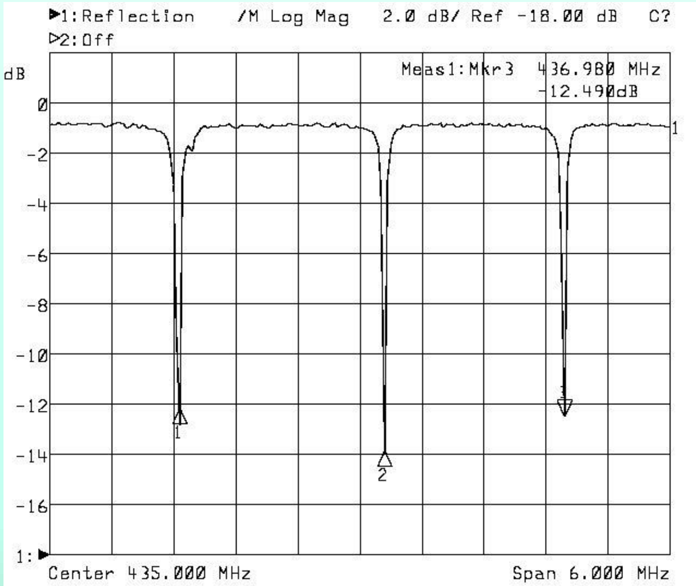


$f_T \approx 433$ MHz,
$f_{M2} \approx 435$ MHz,
$f_{M1} \approx 437$ MHz,

$F_{m1} = f_{M1} – f_{M2} = S_1 s + F_{01}$
$F_t = f_{M2} – f_T \approx -S_t T + F_{03}$

$M = [(F_{m1} + F_{m2})/2 – F_0]/S_M$





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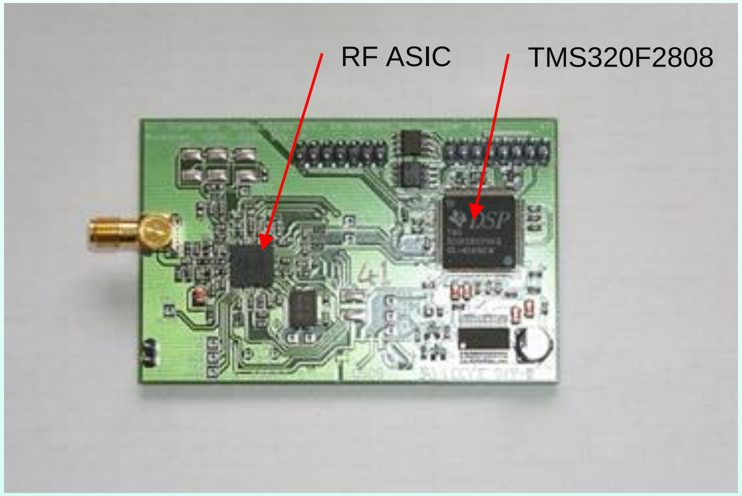
Torque Sensing

Readers for non-contact torque/force sensors

2005



2016

"Standard" reader

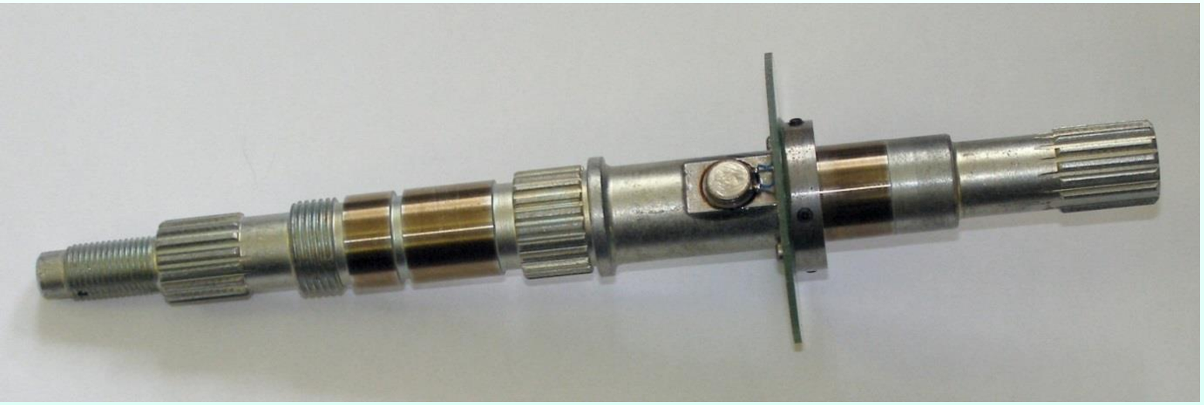
Main parameters:

Output power:	0.5…10 mW,
Frequency range:	425…442 MHz
Rx sensitivity:	-88 dBm @ SNR = 17 dB, BW = 4 MHz
Rx/Tx isolation:	>100 dB,
Random errors:	$\sigma_F \approx$ 60…300 Hz,
Systematic errors:	ΔF < 1 kHz,
Measurement time:	150 us (short range, no coherent accumulation)
	250 us (accumulation of 5 responses).

Interrogates sequentially up to 5 resonators.

Torque Sensing

Non-compliant EPAS torque sensors



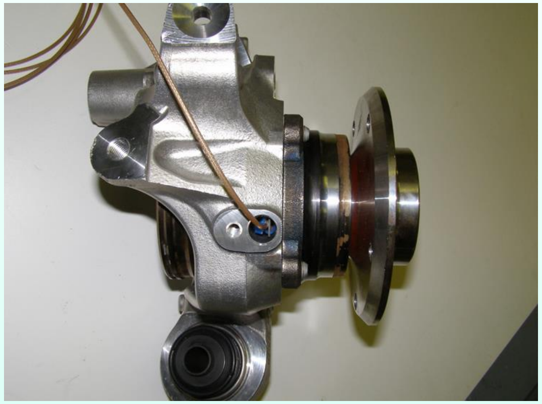
Torque sensitivity: 14 kHz/Nm
Temperature sensitivity: 3 kHz/°C

EPAS sensor specification:

Torque measurement range:	$\pm M_{max} = \pm 10 \ldots \pm 40$ Nm
Torque resolution (3σ)	$< 0.003 M_{max}$
Overload capability (die-shaft bond):	$> \pm 10 M_{max}$
Torque measurement combined error:	$< \pm 0.01 M_{max}$
Hysteresis	$< 0.002 M_{max}$
Torque reading update rate:	2 kHz
Temperature range:	-40°C…+125°C
Temperature error:	<2°C

Torque Sensing

Automotive powertrain torque sensors

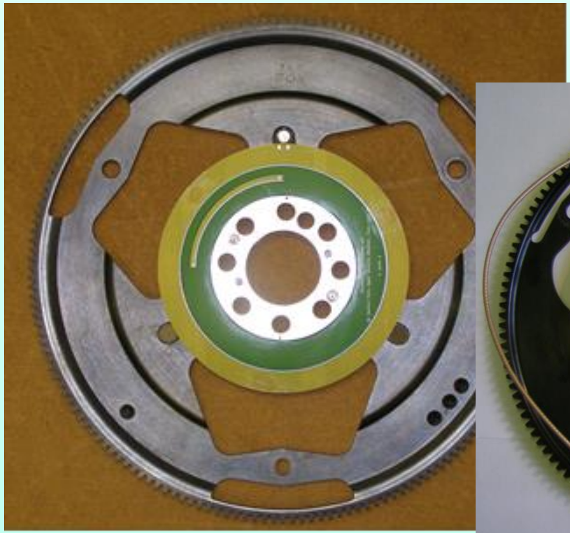


Driveshaft torque sensor:

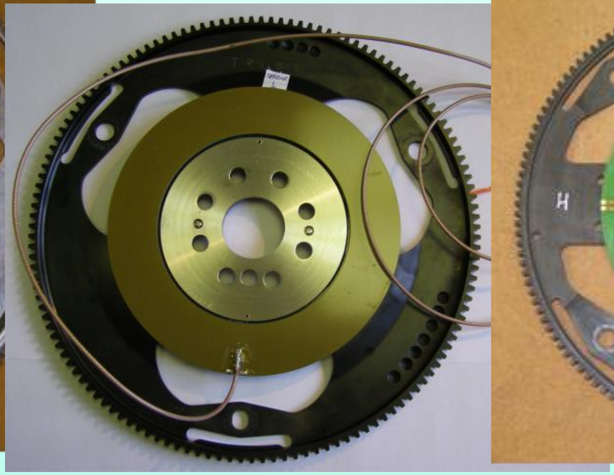
M_{max} = 3000 Nm,
T_{max} = 150°C,
Error < 21 Nm,
Update rate = 2 kHz.

F1 KERS torque sensor:

M_{max} = 100 Nm,
T_{max} = 160°C,
Error < 1.3 Nm,
Update rate = 3.3 kHz,
Ω_{max} = 18000 rpm.



V8



L4

V6

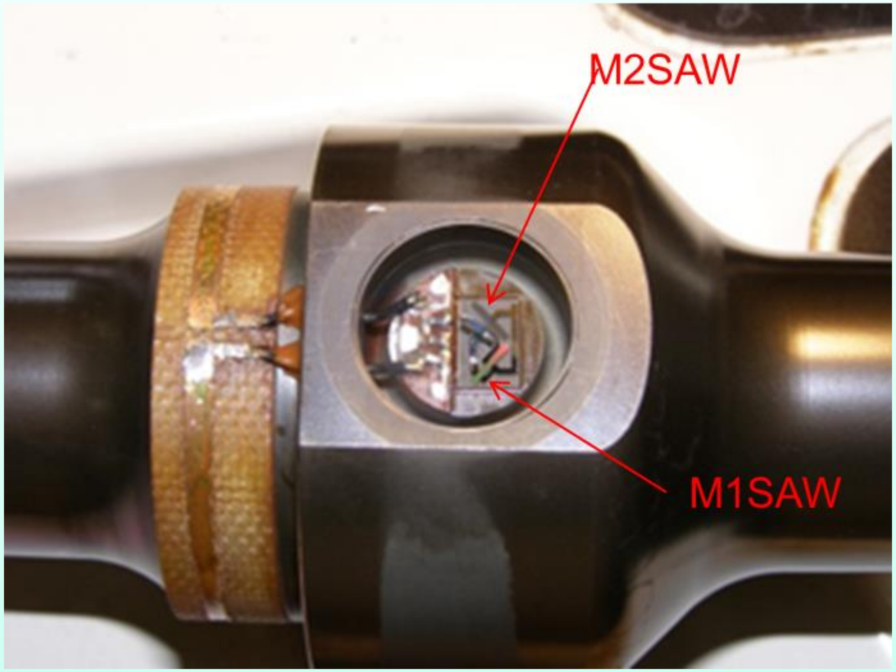
Flexplate torque sensors:

M_{max} = 400…600 Nm,
T_{max} = 125°C,
Error < 4…8 Nm,
Update rate = 3.3…6.7 kHz.

Torque Sensing

SAW shear strain sensor directly bonded to the shaft

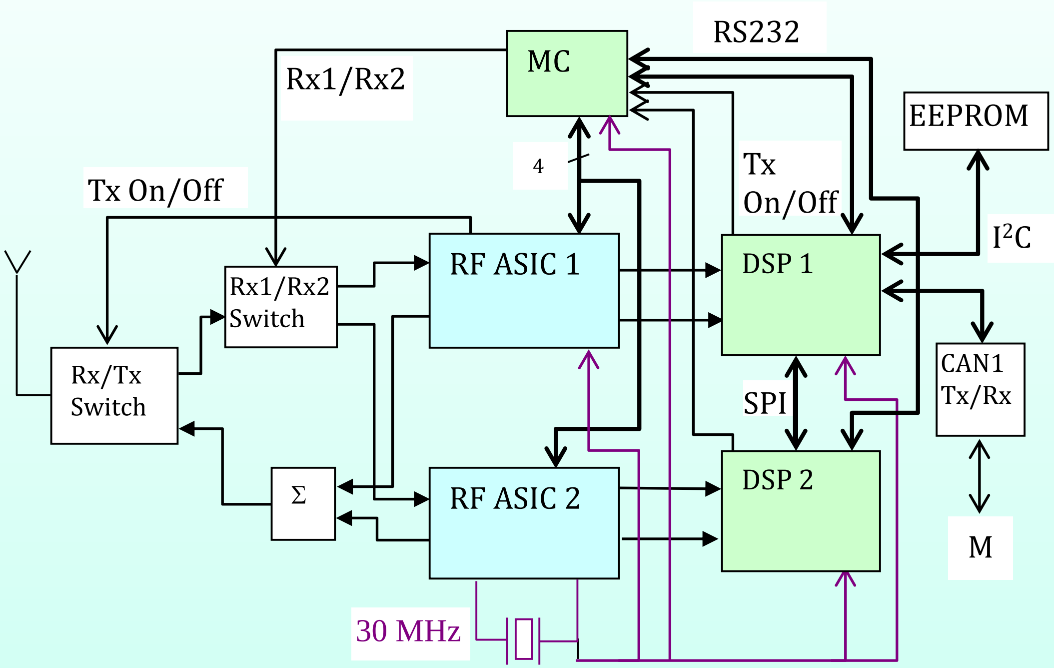
Torque sensor for the input gearbox shaft

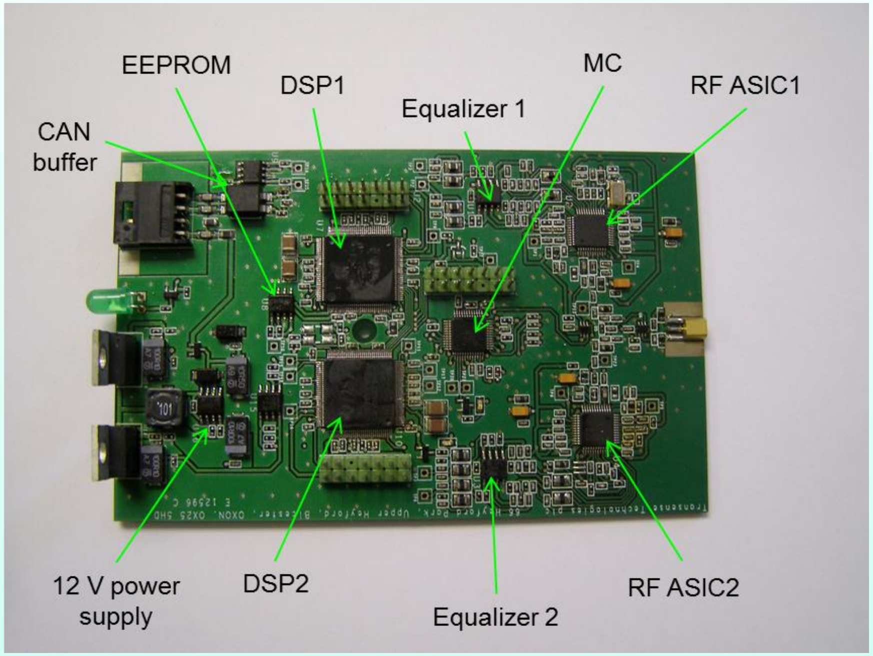


M_{max} = 1000 Nm,
T_{max} = 150°C,
Error < 6 Nm,
Update rate = 3.3 kHz,
Ω_{max} = 12000 rpm.

Torque Sensing

High-speed reader for powertrain sensors





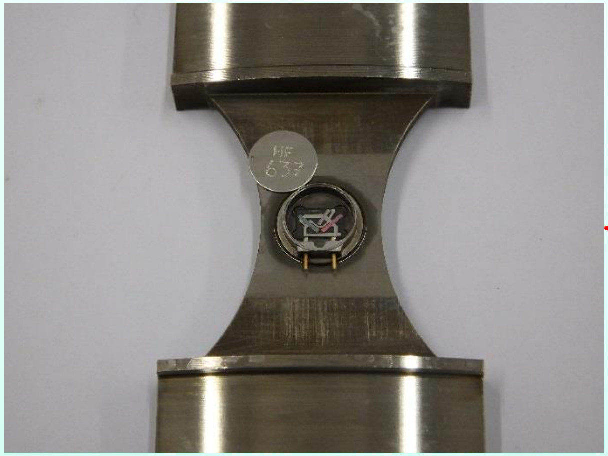
Can interrogate two SAW resonators simultaneously (no coherent accumulation).

Torque/strain/force update rate: 16.13 kHz

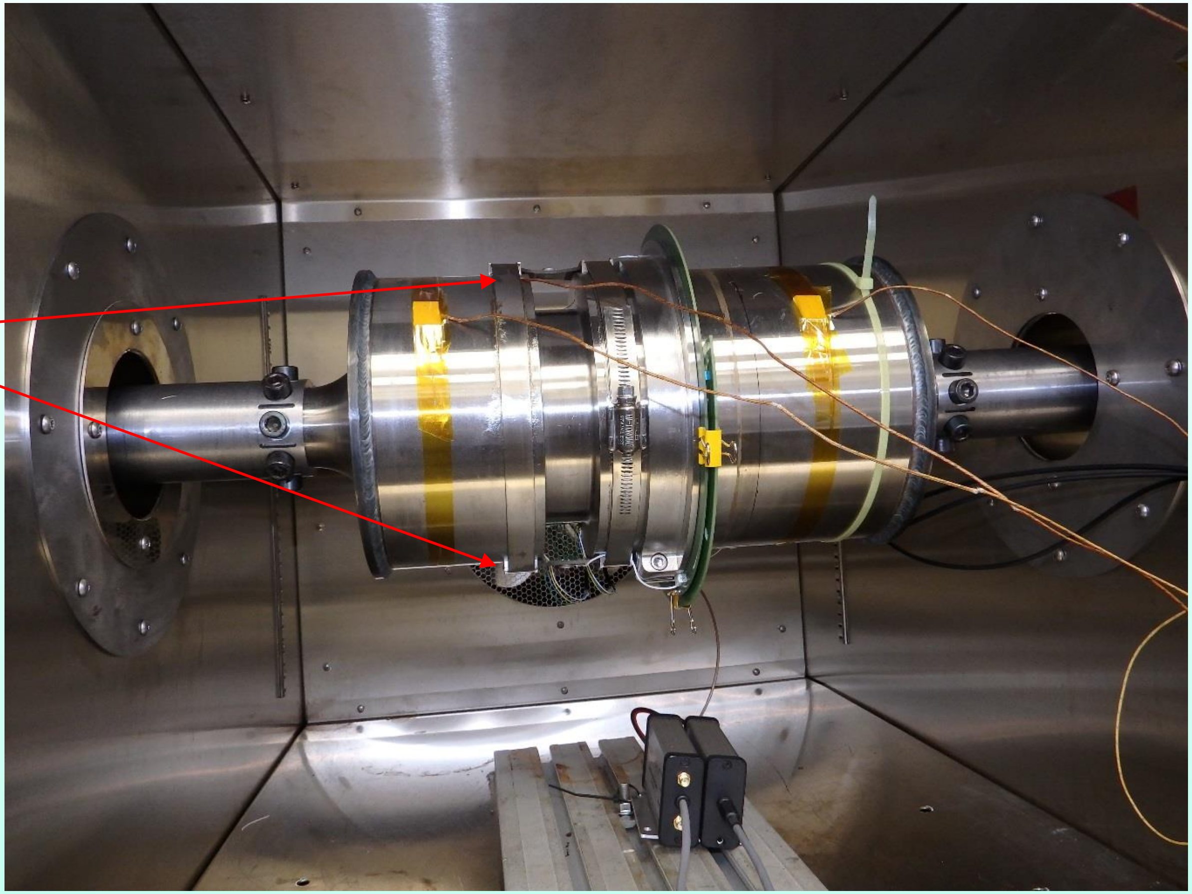
Max interrogation power: P_{int} = 10 dBm,
Interrogation frequency range: 420-440 MHz,
σ_{Fm} = 326 Hz (<0.15%FS)

Torque sensor for marine applications

Plate transducer

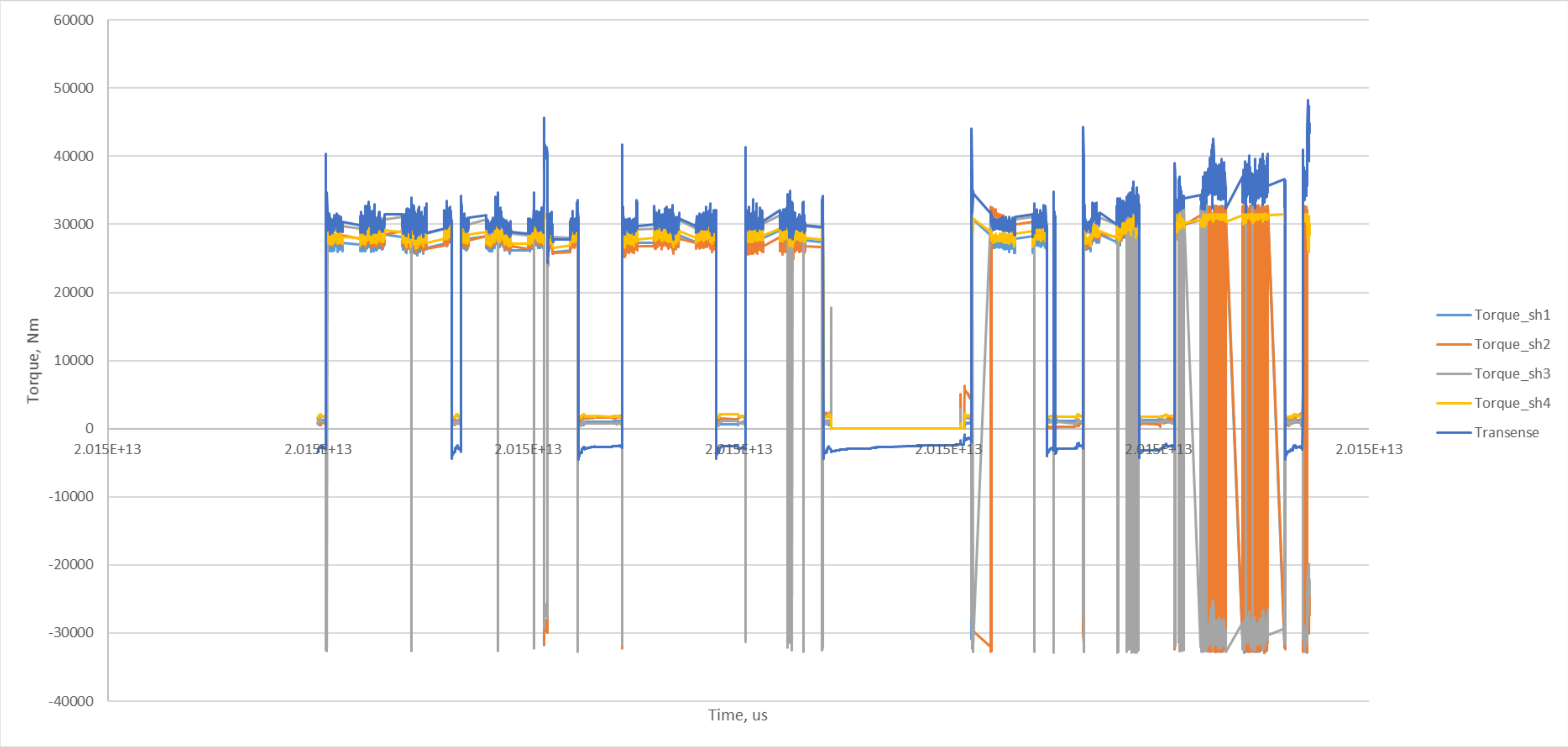


Calibration of plate transducers is performed on the test shaft of the same diameter as the marine shaft

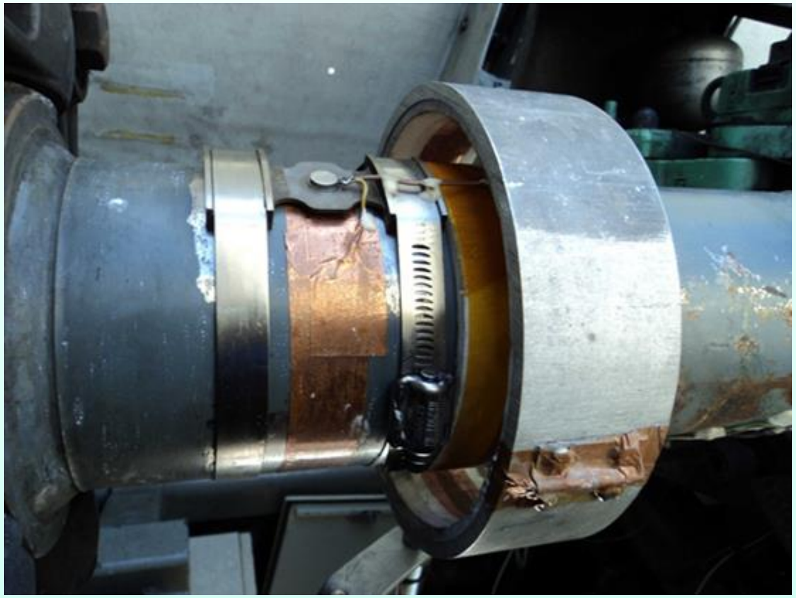


Shaft diameter:	180 mm,
Max torque:	M_{max} = 56 kNm,
Error after calibration:	$0.013M_{max}$.

Torque Sensing



Torque sensor for wind turbines (condition monitoring)



Shaft diameter:	120 mm,
Max torque:	M_{max} = 5 kNm,
Error after calibration:	0.007M_{max}.

Torque Sensing for Industrial Applications

Torque sensor for a tap changer in high power transformers

Shaft diameter:	60 mm,
Max torque:	M_{max} = 500 Nm,
Temperature:	-40° C…+140° C
Error after calibration:	0.015M_{max}.

Torque Sensing for industrial Applications

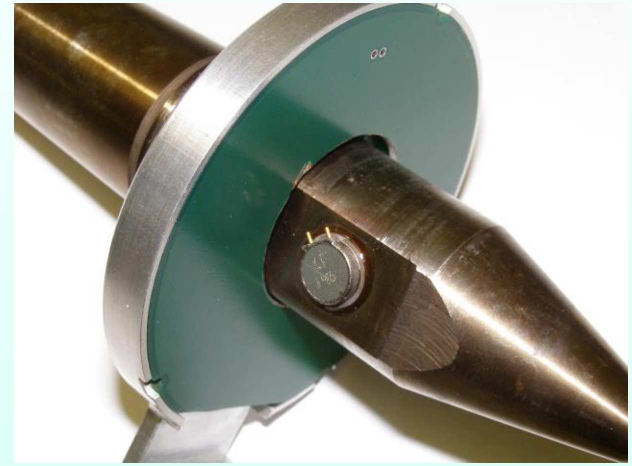
Torque sensing in industrial gearboxes (condition monitoring)

- More than 20 non-contact (near-field) RF couplers were developed for 40-340 mm high-speed shafts of gearboxes.
- Methods and software for simplified calibration of the gearbox shafts were developed.

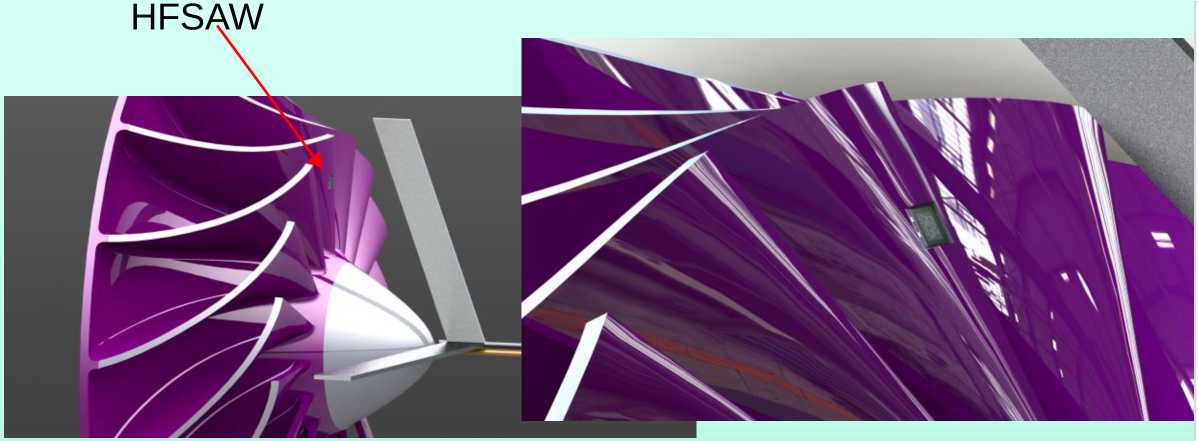
Force and Strain Sensing

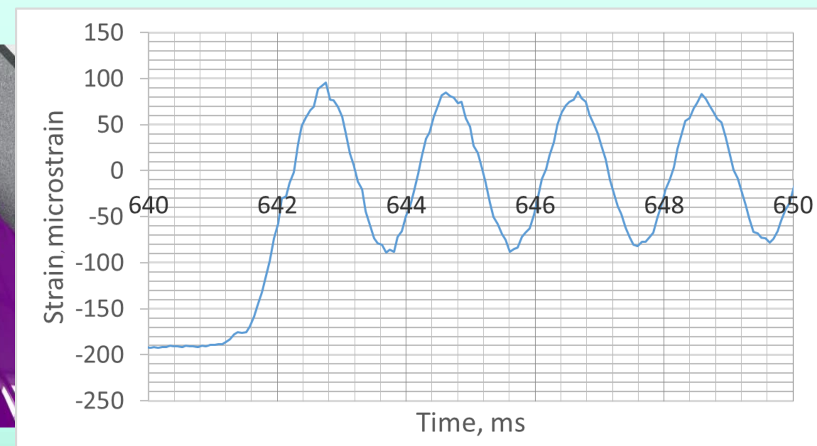
Axial force sensor for a lathe

Prototype lathe tailstock center instrumented with a SAW axial force sensor



Vibration sensor for gas compressor impeller blades

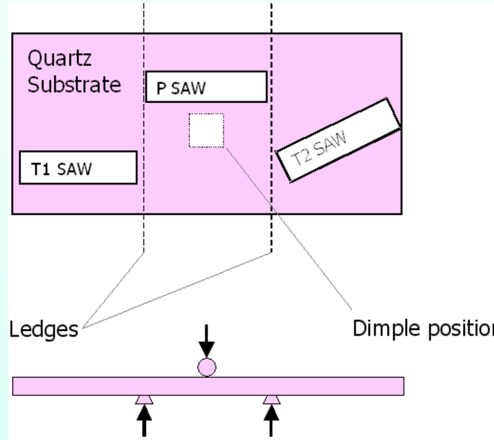


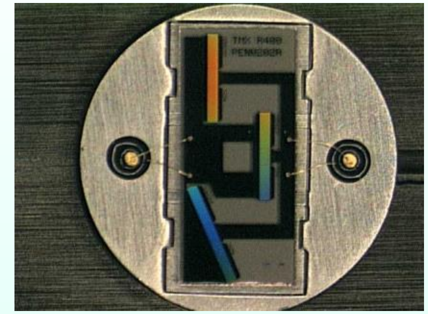


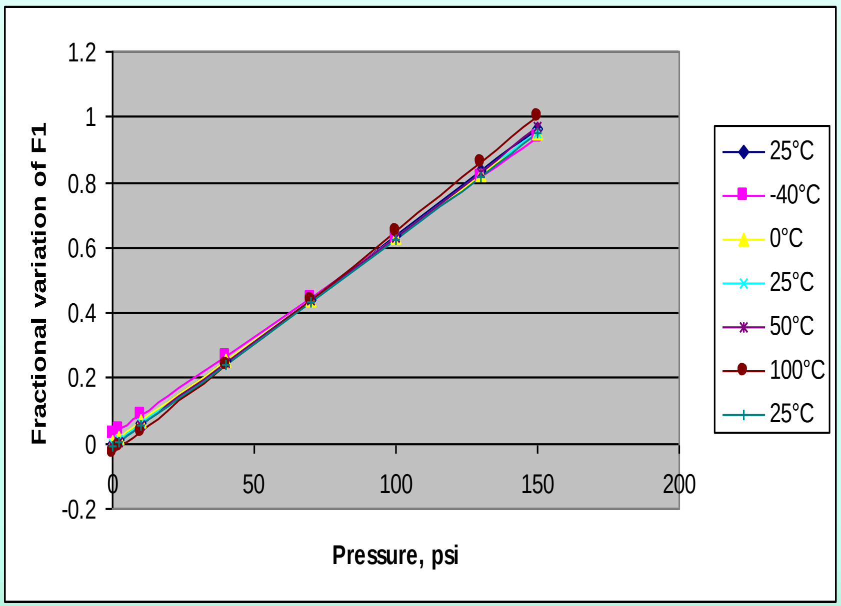
Pressure and Temperature Sensing

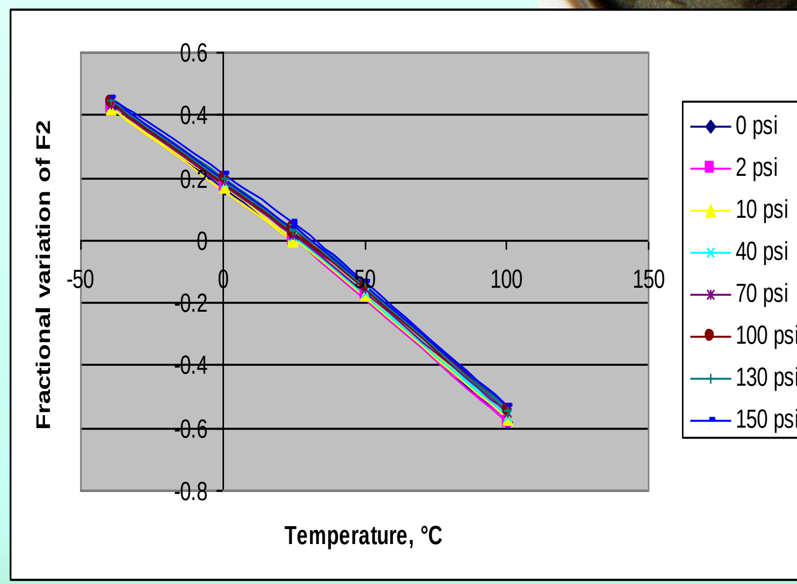
TPMS Sensor (2002)

- 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.





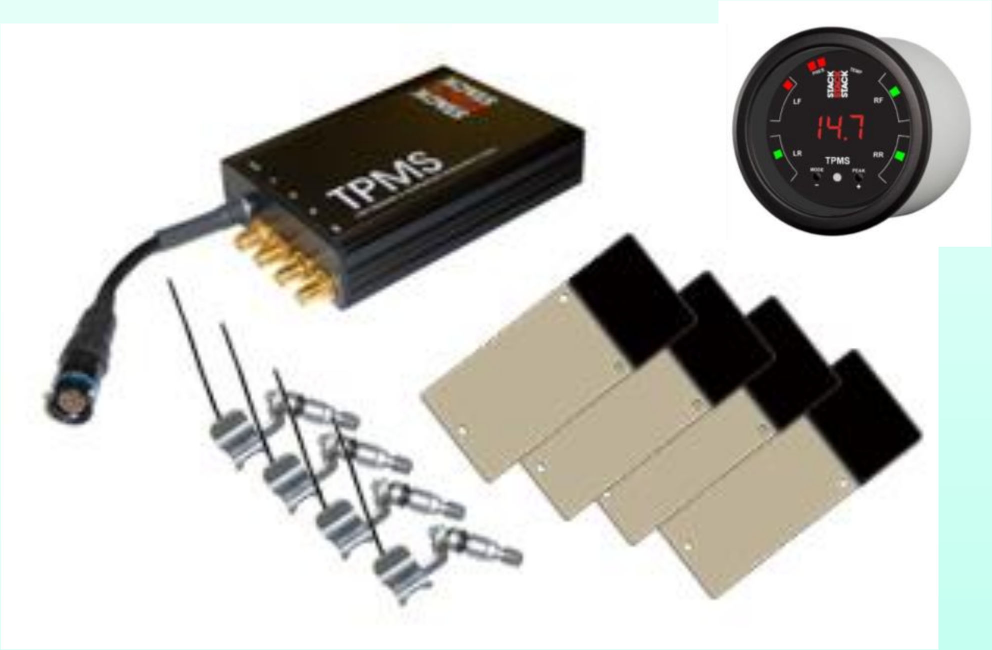




Pressure and Temperature Sensing

Stack TPMS

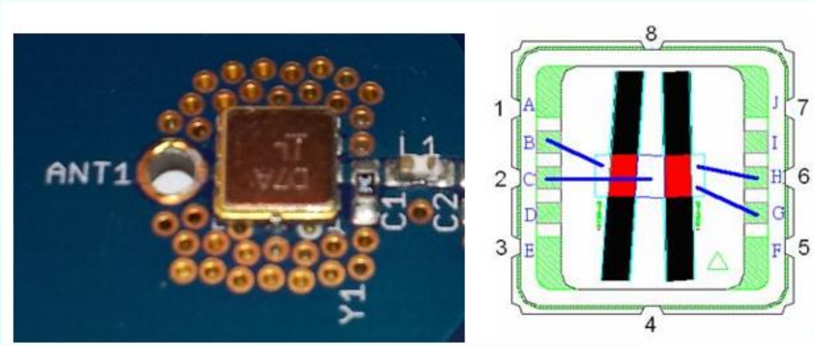
“Stack TPMS – wireless, batteryless and compact. Completely re-defines tyre pressure and temperature monitoring in Motorsport”. (www.stackltd.com)

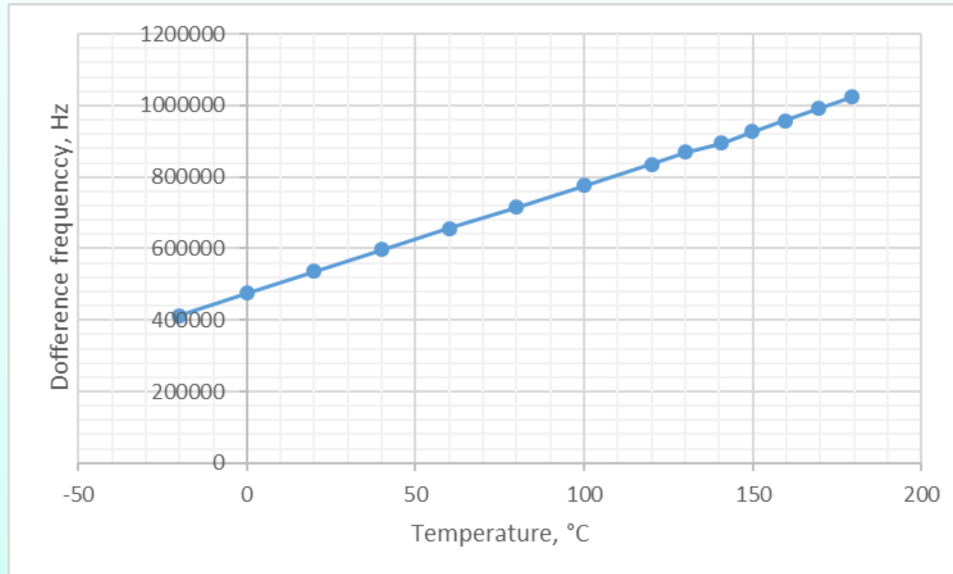


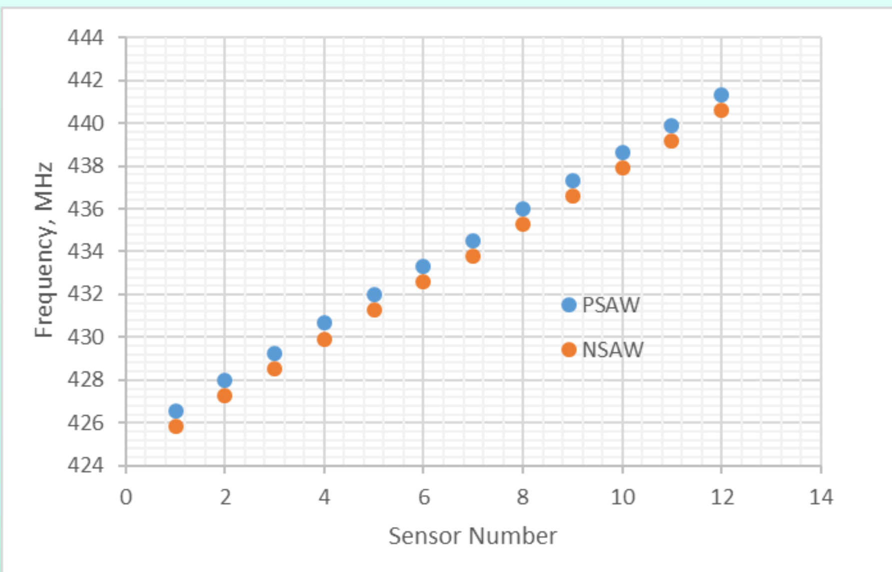
- Pressure range: 0-45 psi or 0-150 psi,
- Pressure resolution: 0.05,0.1 or 0.25 psi,
- Pressure accuracy: ±0.125, 0.25 or 0.5 psi,
- Temperature range: 20-100,125 or150°C,
- Temperature accuracy: ±1°C,
- Read range: 0.5-1 m.

Temperature Sensing

SAW temperature sensing element (2011)







12 sensors occupy the frequency range from 425 MHz to 442 MHz. One of them fits the European 433 MHz ISM band.

Temperature Sensing

Wireless SAW temperature sensing system

Specification:

- Interrogation power: -7…10 dBm,
- Interrogation range: up to 2 m (depends on antennas and environment),
- Interrogation time: 130 ms,
- Temperature range: -25…+125°C,
  -40…+180°C (for selected sensors),
- Temperature accuracy: ±3.5°C (two-point calibration)
  ±2°C (4-5-point calibration)
- Temperature resolution: <0.6°C

IntelliSAW system for switchgear monitoring

Conclusions

• Resonant wireless SAW sensing elements in various packages have been developed to measure torque & temperature, pressure & temperature and just temperature.

• Wireless readers have been developed for interrogation of SAW resonant sensors with the maximum update rate of 6.6 kHz (for one resonator) and 16.1 kHz (for two resonators).

• Non-contact resonant SAW sensing systems have been developed for measuring torque in EPAS, automotive and marine driveline, and some industrial condition monitoring systems.

• Wireless SAW pressure & temperature measurement system was developed for TPMS. It is being manufactured for motorsport market.

• Wireless passive SAW sensors are not a panacea but automotive, marine, aerospace, power generation and other industries are slowly adopting this technology for a number of suitable applications.

Thank You