HIGH-SPEED HIGH DYNAMIC RANGE RESONANT SAW TORQUE SENSOR FOR KINETIC ENERGY RECOVERY SYSTEM

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INTRODUCTION

Kinetic energy recovery system (KERS) also often called a “regenerative braking” has been known to the automotive world for more than half a century. In such a system, a braking torque created by normally driven wheels of a vehicle is allowed to back-drive an electric motor to charge a battery or to spin up a flywheel. Later, the kinetic energy of the vehicle stored in the battery or the flywheel is used to boost acceleration of the vehicle when needed. Nowadays, this technique has been introduced in parallel hybrid car systems where either an internal combustion engine or an electric motor or a combination of both provides motive power.

In 2009, FIA inspired optional addition of KERS to Formula 1 vehicles to promote the energy saving technology and increase the excitement of F1 by increasing overtaking opportunities. However, according to the FIA regulations, the maximum amount of the stored energy should not exceed 400 kJ per lap that would allow adding about 10% more power to the engine for almost 7s per lap. In order to be able to constantly monitor the amount of the additional power generated by KERS, FIA required a direct measurement of torque transmitted from/to the KERS electric motor mechanically coupled to the engine crankshaft. There were two candidates for the role of the non-contact and non-compliant KERS torque sensor: a magnetoelastic one and a SAW one. After careful consideration of all the requirements including the accuracy, the temperature range, mechanical tolerances, expected vibrations and available space, one team of the KERS designers opted for the torque sensor based on SAW resonators.

The use of SAW resonators in torque sensors has been discussed in a number of publications. The idea of non-contact torque measurement by SAW devices was first patented in [1]. Initially, two separate SAW devices and RF rotary couplers per sensor were used with an interrogator based either on two SAW oscillators [2] or two frequency tracking loops [3]. Later, an integrated sensing element with two SAW resonators on a single substrate having improved torque sensitivity was proposed and the CW frequency tracking interrogator was modified to be able to use a single RF rotary coupler [4]. The next step was to add one more sensing element containing two more resonators in order to cancel influence of bending on the torque sensor output [5]. The growing number of resonators in the sensor required changing the measurement method from CW frequency tracking to a pulsed interrogation in the time domain [5]. Addition of the third SAW resonator to one of the sensing elements for temperature compensation helped to improve considerably the accuracy of torque measurement [6]. The SAW torque sensors were developed for a number of applications, from those with relatively slow variation of torque like in the case of electrical power assisted steering [5] to highly dynamic ones like the engine output torque sensor [7].

However, the environment of the F1 vehicle is much harsher than the one that all the previously developed sensors faced. First, the speed of rotation in F1 engines goes up to 18000 rpm creating a significant centripetal force applied to the sensing element. Second, there are very intense engine vibrations with the expected magnitude up to 100g and unknown spectrum. Third, the operating temperature range starts at around 70°C and extends up to 160°C, far beyond the normal automotive limit of 125°C. Fourth, a very limited space does not allow installation of a traditional planar RF rotary coupler [8] connecting the sensor to the interrogation unit. The last point is that the instantaneous torque seen by the sensor can considerably exceed the specified average torque due to very strong torsional vibrations. All these factors have required considerable modifications of the sensor hardware and the interrogation algorithm. The aim of the paper is to describe these modifications.

The structure of the paper is as follows. Section I is devoted to the torque transducer design and its characteristics. Section II discusses the RF rotary coupler design, rotational errors and errors caused by mechanical tolerances. Modifications of the interrogation algorithm are described in Section III and the dynamic performance of the sensor is presented in Section IV followed by conclusions.

I. TORQUE TRANSDUCER DESIGN

The crankshaft of the engine was connected to the KERS electric motor by a short shaft that was an ideal part for installing the SAW sensing elements and thus turning it into a torque transducer. Bearing in mind very intense vibrations of the engine one could expect a strong variable bending force applied to the shaft. In order to minimize parasitic signals caused by bending, two SAW sensing elements had to be attached to the two opposite sides of the shaft. The first one, HFSAW [7], contained three SAW one-port resonators on Y+34° cut quartz connected in parallel. Two of them, with resonant frequencies $f_1 \approx 437$ MHz and $f_2 \approx 435$ MHz, were at ±45° to the X axis of the substrate and the shaft axis so that $F_{m1} = f_1 - f_2$ linearly depended on the applied torque M. The third resonator, with the frequency $f_3 \approx$ 433 MHz, was used for temperature compensation. Since it was positioned at a different angle to the X axis of the quartz substrate, $F_t = f_2 - f_3$ depended on temperature T differently compared to F_{m1} [6] allowing an independent measurement of T. The second sensing element, LFSAW [7], contained only two SAW resonators with frequencies $f_4 \approx$ 431 MHz and $f_5 \approx 429$ MHz positioned at ±45° to the shaft axis so that $F_{m2} = f_4 - f_5$ also linearly depended on M. Orientation of LFSAW relative to the HFSAW was such that $F_m = (F_{m1} + F_{m2})/2$ was sensitive to torque and insensitive to the bending force applied in the plane of the SAW devices (the influence of the bending force normal to the SAW devices was cancelled due to the differential character of the frequency measurement).

The SAW sensing elements were packaged in metal cans in all previously developed sensors [5, 7]. However, these packages could not be used for the KERS sensor because they would experience centripetal acceleration up to 4000g producing the force up to 36 N. It could easily detach the bonded packages from the shaft, especially when combined with violent vibrations. Besides, available space also made it difficult to use packaged sensing elements. As a result, it was decided to bond the 4x6 mm SAW die directly to the shaft surface that was specially processed to improve adhesion (see Fig. 1). Delamination of the SAW devices from the shaft was never observed even after very demanding "long run" tests on engine dynamometers generating more vibrations than real F1 vehicles. De-bonding of the gold wires was also never observed due to the fact that most of the bond wires' length was covered by an adhesive. The SAW devices were protected from the environment by a cylindrical sleeve pressed upon the thicker section of the shaft where they were installed. A specially designed seal provided sufficient hermeticity and the absence of a mechanical hysteresis. The assembled torque transducer based on the KERS shaft is shown in Fig. 2. The shaft diameter in its thicker part was selected to provide a 10-fold overload capability without causing a mechanical failure on one hand and, on the other hand, the resolution better than 0.2 Nm corresponding to 9 bits over the read range.

At the initial stage of the project, each transducer had to be individually calibrated over the specified torque read range ±50 Nm and the temperature range from 20°C to 160°C. Simultaneous calibration of three shafts was performed in the static rig shown in Fig. 3. Typical sensor characteristics are presented in Figs. 4 and 5. They were approximated by the mathematical model of the sensor described in [6]. The DSP in the interrogation unit calculated temperature T and torque M from the measured values of F_m and F_t by solving simultaneous equations of the model. Deviations of the calibration characteristics from the model at $70° < T < 130°$C did not usually exceed $\Delta F_t = \pm 2$ kHz for F_t and $\Delta F_m = \pm 1.7$ kHz for F_m. The error in F_m consisted of a non-linearity error (< ±0.7 kHz) and hysteresis caused by the bond. The latter increased with temperature so that ΔF_m reached ±4.5 kHz at T = 160°C.

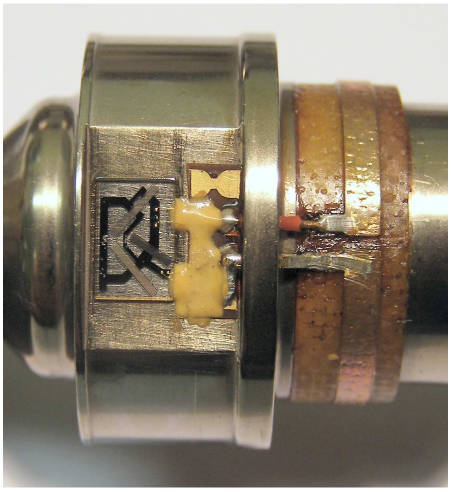


Fig. 1. The KERS shaft with the bonded HFSAW sensing element

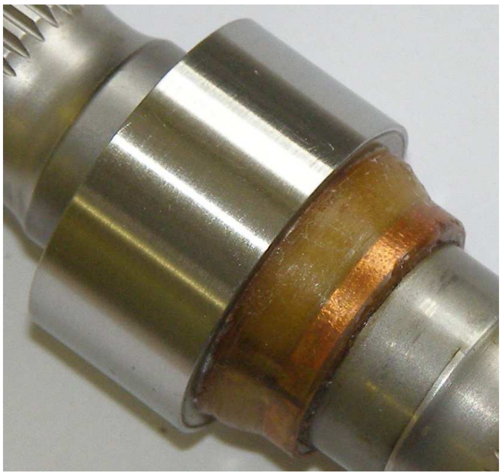


Fig. 2. Assembled torque transducer

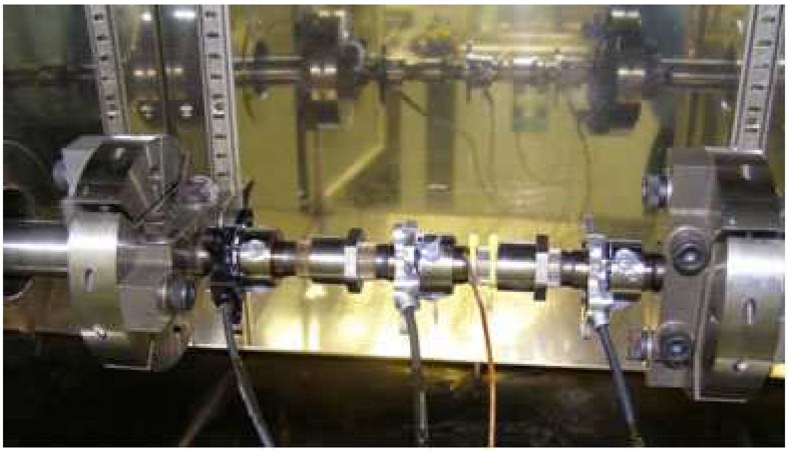


Fig. 3. A string of three sensors being calibrated within an environmental chamber over the full operational range of torque and temperature

Apart from the systematic errors mentioned above there were also random errors of the non-contact resonant frequency measurement. Typical standard deviations for F_m and F_t were σ_{Fm} = 300 Hz and σ_{Ft} = 420 Hz respectively if coherent accumulation of several SAW responses was not used in the interrogator. The total maximum error in torque can be estimated as

$$\Delta M = (3\sigma_{Fm} + \Delta F_m + \Delta F_0 + M\Delta S_m)/S_m \tag{1}$$

where ΔF_0 and ΔS_m are the errors in determining the torque characteristic offset $F_0 = F_m(0, T)$ and the torque sensitivity $S_m = \partial F_m/\partial M$ due to the error in the temperature measurement $\Delta T = (3\sigma_{Ft} + \Delta F_t)/(\partial F_t/\partial T)$. Theoretical variation of ΔM with temperature is shown in Fig. 6. At low temperatures T < 100°C, the errors were dominated by random noise in F_m and non-linearity of the torque characteristic. At higher temperatures, the error increased mainly due to the hysteresis of the torque characteristic and, to a certain extent, due to errors in the torque sensitivity estimation caused by the temperature measurement errors (the latter increased with temperature because S_m and $\partial F_t/\partial T$ dropped with temperature). Nevertheless, the global accuracy was still at the acceptable level of 1% FS even at the highest temperature.

II. RF ROTARY COUPLER DESIGN

Both HFSAW and LFSAW sensing elements needed to be connected to the interrogator through a non-contact RF rotary coupler that strongly influenced properties of the system. The shaft diameter and the available space were such that the coupler circumference could not be larger than approximately 0.14λ. It is noticeably smaller than the optimum

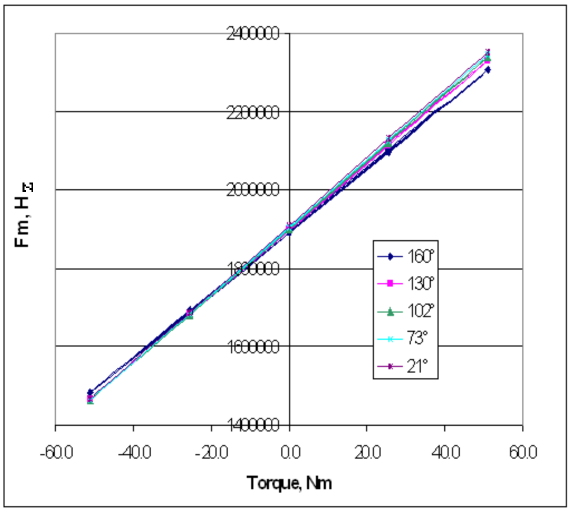


Fig. 4. Variation of F_m with torque at different temperatures

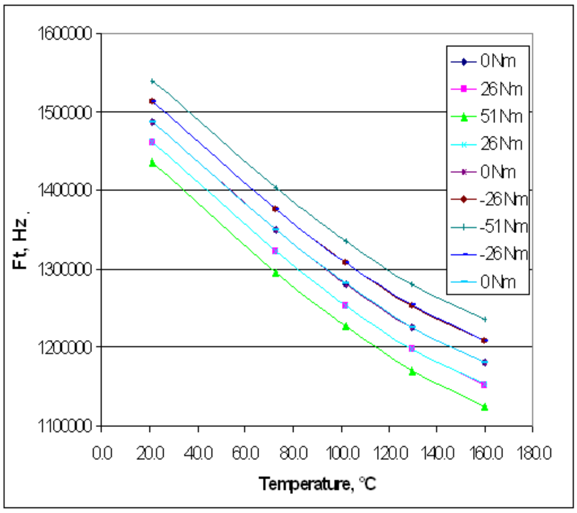


Fig. 5. Variation of F_t with temperature at different torque values

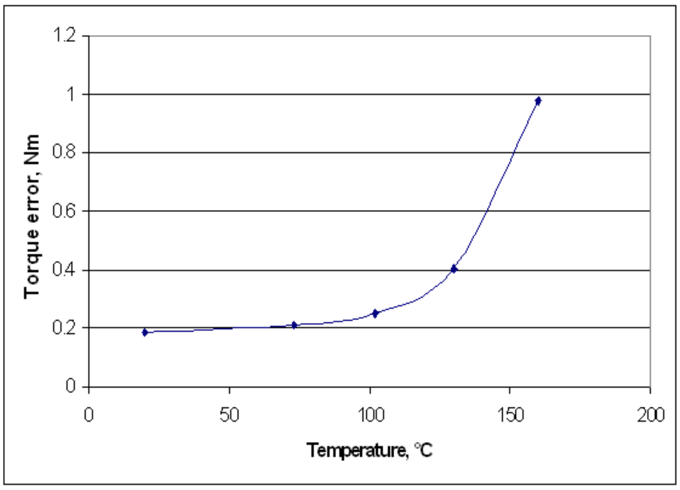


Fig. 6. Global maximum torque measurement error at M = 35 Nm

length of a coupler based on coupled microstrip lines. Moreover, only one half of the circumference could be allocated for each sensing element that could make the coupler efficiency even worse. Finally, the requirement of the high rotational speed also dictated the use of a cylindrical coaxial design rather than a planar design [4, 8] that was easier to reinforce with a glass fibre wrapped around the rotor. The rotor couple can be seen in Fig. 1 and the reinforced one can be seen in Fig. 2.

Electrical connection of the sensing elements and the interrogator to the coupler is illustrated in Fig. 7 (ground planes of the 50 Ω microstrips are not shown). Simulations of the coupler showed that the insertion loss was $|S_{41}| \approx 11$ dB for the nominal 1mm rotor-stator gap and it varied with the rotation angle only by 2.2 dB. Angular variation of the output impedance was also minimal: $\Delta X_{44} \approx \Delta R_{44} < 1\ \Omega$. Based on this data one could expect a small variation (less than 0.8 kHz) of the measured resonant frequency with the rotation angle. In reality, the angular variation of the measured torque turned out to be less than ±0.04 Nm (see Fig. 8) which corresponded to the F_m variation below ±350 Hz. It was well below the sensor resolution.

A relatively high insertion loss of the coupler followed from its small size has not seriously affected the amount of random errors in the measured frequency. Due to a high sensitivity of the receiver of the pulsed interrogator, they were still determined by the phase noise of the local oscillator rather than the Rx additive noise. In the absence of coherent accumulation of the SAW response the standard deviation of the measured frequency was 200-300 Hz and it could be reduced down to 100-150 Hz by means of coherent accumulation of five SAW responses.

It was also important to minimize variation of the measured frequency with the relative position of the stator and the rotor couples in order to ease the requirements on mechanical tolerances. The cylindrical design turned out to be quite insensitive to the axial displacement of the stator relative to the rotor by up to 1 mm – variation of F_m did not exceed 200 Hz if the radial displacement was below 0.1 mm. Variation of F_t was larger, up to 2.6 kHz, probably due to the fact

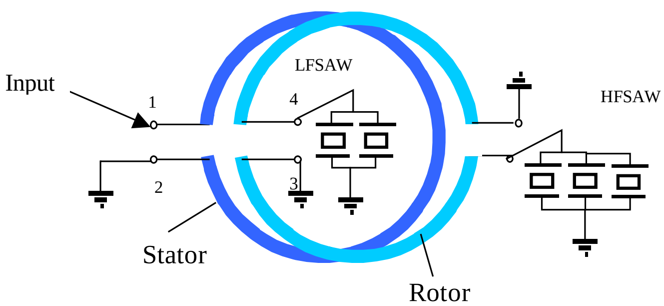


Fig. 7. Electrical connection of the sensing elements to the coupler

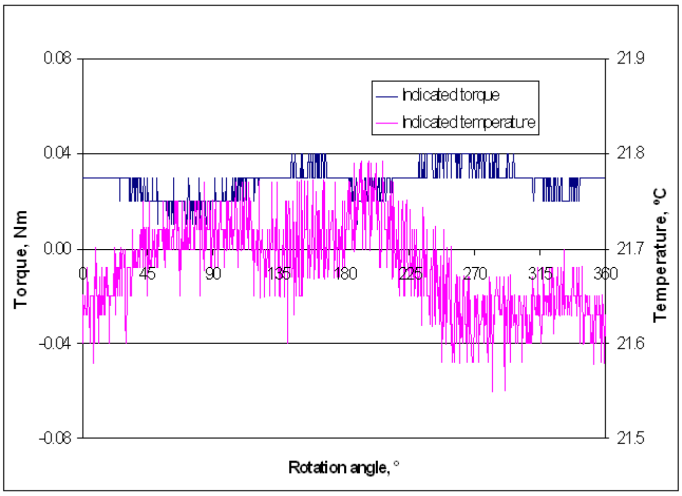


Fig. 8. Angular variation of the measured torque and temperature (40 readings are averaged)

that the temperature sensitive resonator had the design different from the other four resonators. It is however less critical because of a smaller influence of the temperature errors on the torque measurement errors.

III. INTERROGATION ALGORITHM

Non-contact measurement of the SAW resonant frequencies was performed by the interrogator containing a pulsed RF transmitter and a double superheterodine receiver described in [5, 7]. Similar to the interrogator presented in [9] it measured the frequency of each resonator, one after another, by analysing the spectrum of the natural oscillations excited in it by short RF pulses. The main difference was in the ability of the interrogator to accumulate coherently several SAW responses for reducing the influence of noise. Besides, it was based on the transceiver in the form of an RF ASIC that allowed a considerable reduction of its size.

As soon as the unit was switched on, it performed a search of all five resonators by sweeping all possible interrogation frequencies covering the entire range from 428 to 438 MHz with the aim to find the best ones, f_{i1}, f_{i2}, f_{i3}, f_{i4}, f_{i5}, that were as close to the resonant frequencies as possible. After that, by using the selected interrogation frequencies, an accurate measurement of the resonant frequencies was performed. The cyclic sequence of interrogation of the five SAW resonators was as follows: $f_1 - f_4 - f_2 - f_5 - f_1 - f_4 - f_2 - f_5$ …– $f_1 - f_4 - f_2 - f_3 - f_5 -$ …, as shown in Fig. 8e in [7]. The frequency f_3 needed for temperature measurement was interrogated only once every $N = 500$ cycles since the variation of T is much slower than the variation of M.

After the k-th cycle of interrogation of the torque measuring resonators and K-th cycle of temperature measurement, the new interrogation frequencies were selected to be closest to the previously measured resonant frequencies:

$$f_{i1,2,4,5}\,(k+1) \approx f_{1,2,4,5}\,(k), \quad f_{i3}\,(K+1) \approx [\, f_3\,(K) + f_3\,(K-1)]/2. \tag{2}$$

This way a continuous tracking of the instantaneous resonant frequencies was implemented similar to the tracking used in the flexplate torque sensor [7]. Accumulation of five SAW responses gave the resolution for F_m around $3\sigma_{Fm} \approx 450$ Hz and hence, the dynamic range of 65.6 dB (for the specified measurement range of ±50 Nm). It took 250 µs to measure one frequency and 500 µs and 0.5 s to updated the torque and the temperature values respectively. The assumption was that the variation of the resonant frequency f_r during 1 ms satisfied the tracking condition

$$\Delta f = f_r(k+1) - f_r(k) < (B - \Delta f_i)/2 \tag{3}$$

where $\Delta f_i = 55.6$ kHz was the distance between the neighbouring interrogation frequencies, $B = \min(B_{DFT}, B_{exc})$, $B_{DFT} =$ 700 kHz was the range of Fourier transform and $B_{exc} = 880$ kHz was the bandwidth within which the SAW resonator was efficiently excited by the RF pulse, i.e. the peak of its energy spectrum exceeded a certain threshold providing the required value of σ_{Fm}. However, it was impossible to guarantee validity of (3) in the absence of information on dynamic behaviour of f_r.

The first experiments performed in realistic conditions on the engine dyno rig have shown that (3) was quite often not satisfied. A typical measurement result for the instantaneous resonant frequency f_5 sampled every 500 μs during the positive torque pulse at 11000 rpm is shown in Fig. 9a (green and blue traces represent measurement results shifted by 250 μs). Its expanded section is shown in Fig. 9b. One can see that there were a lot of sudden dropouts of the measured frequency happening in the areas where f_5 varied very rapidly with time. Sometimes the peak variation exceeded 550 kHz and the rate of change was up to 1 MHz/ms, most likely due to very intense torsional vibrations. This variation corresponded to the torque change by 130 Nm that well exceeded the specified measurement range of 50 Nm. Clearly, the dropouts could easily happen due to the next frequency reading being outside the SAW resonator excitation range and the range of the spectral analysis, especially bearing in mind that the previous interrogation frequency could be either at the bottom or at the top of the frequency pulse.

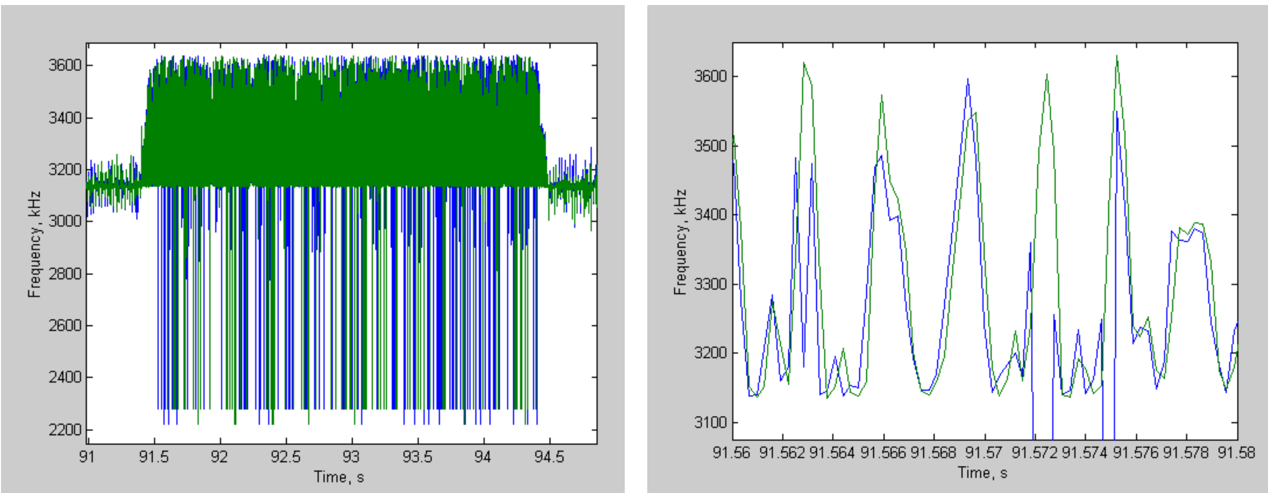
There could be another cause of the dropouts. The period of the frequency oscillations was comparable with the time needed for coherent accumulation of five SAW responses so the vibrations could easily destroy coherency. Simulations have shown that, depending on the phase angle of the torsional vibrations and its amplitude, they could reduce the peak energy spectrum of the accumulated SAW response to zero due to destructive interference. For this reason, it was decided not to use the coherent accumulation in the interrogator. This deteriorated the frequency resolution up to $3\sigma_{Fm} \approx$ 900 Hz but allowed better frequency tracking and reduced the frequency measurement time to 155 μs, the torque update period to 310 μs, the interrogation frequency update period to 620 μs and the temperature update period to 0.31 s.

It was also necessary to broaden the range of Fourier analysis up to B_{DFT} = 1.1 MHz by expanding sin/cos lookup tables in the DSP. The SAW excitation bandwidth was also broadened up to B_{exc} = 1.2 MHz by means of reducing the interrogation pulse width. Both measures helped satisfy the tracking condition (3). To further reduce chances of dropouts it was decided to switch from tracking of the instantaneous resonant frequencies to tracking of their average values so that

$$f_{i1,2,4,5}\,(k+1) \approx [31\, f_{i1,2,4,5}\,(k) + \; f_{1,2,4,5}\,(k)]/32, \tag{4}$$

$$f_{i3}\,(K+1) \approx [63\, f_{i3}\,(K) + \; f_3\,(K) + \Delta f_2\,]/64, \tag{5}$$

with the time constants of the digital low-pass filters around 20 ms and 20 s respectively. The correction factor Δf_2 was introduced to take into account variation of f_3 due to torque after the last measurement and was estimated on the basis of the measurements of f_2. Fig. 10 shows the measured frequency f_5 during the positive torque pulse after modifying the frequency tracking algorithm from (2) to (4) and (5) and implementing all other changes.



(a) (b)

Fig. 9. Variation of f_5 – 426 MHz during the positive torque pulse measured using tracking algorithm (2)

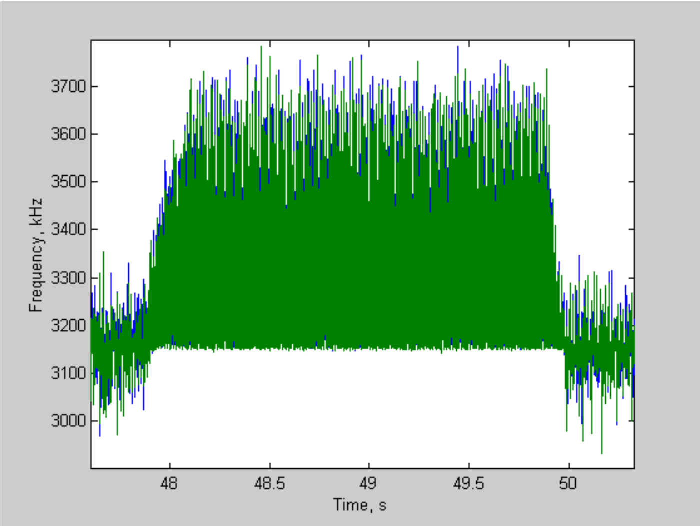


Fig. 10. Variation of f_5 – 426 MHz during the positive torque pulse measured using tracking algorithm (4)-(5)

One can see from Fig. 10 that the measurement had become much more stable in the dynamic mode after modification of the interrogation algorithm. The measured peak frequency variation reached 620 kHz corresponding to the positive torque variation of 140 Nm. Thus the sensor was capable of measuring variable torque changing by ±140 Nm without loosing tracking. The achieved static torque resolution was close to 0.1 Nm giving quite a high dynamic range of 69 dB.

IV. DYNAMIC PERFORMANCE OF THE SENSOR

Fig. 11 shows the results of testing of the torque sensor as part of the KERS on the engine dyno rig. Both positive and negative torque pulses were applied to the shaft while the speed of rotation varied from 9000 rpm to 18000 rpm. As one can see the measured torque, after low-pass filtering, closely followed the expected average torque without dropouts. The temperature varied slowly between 100° and 130°C and did not affect the accuracy of the torque measurement. This test proved that the temperature compensation of the sensor worked correctly in the dynamic regime.

Apart from a correct electrical performance of the sensor there was also a challenge of achieving sufficient mechanical robustness of the design. A lot of attention was paid to providing a good adhesion of the SAW substrates to the shaft,

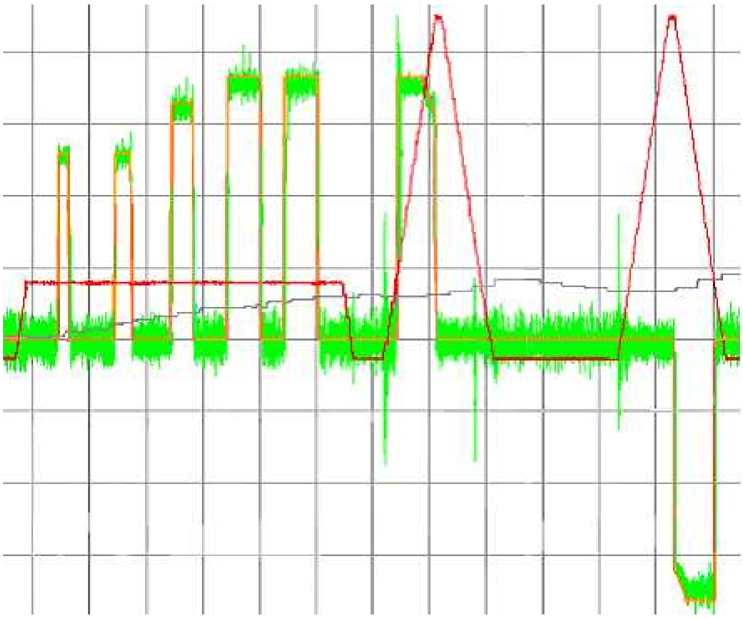


Fig. 11. Measured torque filtered by LPF (light green, 10 Nm/div), expected torque (orange), rpm value (red) and temperature (gray) against time (5 s/div)

mechanical strength of the RF coupler and a good bond between the rotor couple and the shaft, reliability of electrical contacts between the coupler and the SAW devices and a good balance of the assembled sensor. As a result, by the end of 2009 season the sensors supplied to one of the race teams worked successfully and enabled them to demonstrate the benefits of the KERS.

V. CONCLUSIONS

The torque sensor capable of working in the extreme environment of race cars has been developed for the F1 kinetic energy recovery system. The sensor was based on two SAW sensing elements containing five one-port resonators that were attached to the KERS shaft. The achieved dynamic range of the sensor was 69 dB, the update period was 310 μs and it could work at the rotational speed up to 18000 rpm and temperatures up to 160°C. The mechanical design of the sensor ensured its small size and provided sufficient mechanical robustness allowing to survive very intense vibrations. Despite its small diameter, the non-contact rotary RF coupler connecting the sensor to the interrogation unit ensured strong enough SAW response at its input, very small rotational errors and small sensitivity to the axial movement. A number of changes in the interrogation algorithm, in particular, in the frequency tracking procedure, significantly improved stability of the sensor performance in dynamic regime. At the end of the development stage, the sensor successfully worked on race cars.

REFERENCES

[1] A. Lonsdale, B. Lonsdale, “Method and apparatus for measuring strain”, Int. patent public. No. WO91/13832, 19 Sept. 1991, Int. Applic. No. PCT/GB91/00328, Int. filing date: 4 March 1991, Priority: 9004822.4, 3 March 1990, GB.

[2] R. Grossmann, J. Michel, T. Sachs, E. Schrufer, “Measurement of mechanical quantities using quartz sensors”, *Proc. Europ. Freq. and Time Forum,* pp. 376-381, 5-7 March, 1996.

[3] A. Lonsdale, “Dynamic rotary torque measurement using surface acoustic waves”, *Sensors,* vol. 18, pp. 51-55, 2001.

[4] J. Beckley, V. Kalinin, M. Lee, K. Voliansky, “Non-contact torque sensors based on SAW resonators”, *2002 IEEE International Frequency Control Symp.*, pp. 202-213, May 2002.

[5] V. Kalinin, G. Bown, J. Beckley and R. Lohr, “Pulsed interrogation of the SAW torque sensor for electrical power assisted steering”, *Proc. IEEE Int. Ultrason., Ferroelectrics, and Freq. Control Joint 50th Anniversary Conf.*, pp. 1577-1580, 2004.

[6] V. Kalinin, G. Bown, A. Leigh. “Contactless Torque and Temperature Sensor Based on SAW Resonators”. *2006 IEEE Ultrason. Symp*., pp. 1490-1493, 2006.

[7] V. Kalinin, R. Lohr, A. Leigh, G. Bown, “Application of passive SAW resonant sensors to contactless measurement of output engine torque in passenger cars”, *2007 IEEE International Frequency Control Symp.*, pp. 499-504, 2007.

[8] V. Kalinin, “RF Rotary Couplers for Contactless Torque Sensors Based on SAW Resonators”, *Proc. Europ. Freq. and Time Forum,* Toulouse, France, 22-25 April, 2008.

[9] M. Hamsch, R. Hoffmann, W. Buff, M. Binhack, S. Klett, “An interrogation unit for passive wireless SAW sensors based on Fourier transform”, *IEEE Trans. on Ultrason., Ferroelectrics and Freq. Control,* vol. 51, No. 11, pp. 1449-1455, 2004.