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Study on Wireless Torque Measurement Using SAW Sensors

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1. Introduction

An acoustic wave is a vibration in an elastic medium that propagates in space and time, thus transferring the energy supplied by an excitation source along the medium in the form of oscillation or vibration. Acoustic wave propagation entails elastic deformation of the medium along the propagation axis or in other axes as well. In contrast to electromagnetic waves, acoustic waves do require a medium to propagate, and their propagation speeds depend on the mechanical properties of the wave-supporting material. Virtually any material is capable of supporting acoustic wave propagation, including silicon. Nevertheless, the piezoelectric properties of certain materials facilitate the wave propagation. Thus, for improving the electromechanical energy conversion, piezoelectric materials are usually chosen as the acoustic layer of many acoustic-wave resonators. Also known as sound speed, the acoustic-wave phase velocities are several times slower than those of the electromagnetic wave traveling in the same medium(Auld,B. A.,1990). There exist two types of acoustic waves, surface acoustic waves (SAW) and bulk acoustic waves (BAW). A surface acoustic wave is a type of mechanical wave motion which travels along the surface of a solid material. As shown in Fig. 1, the surface particles of an isotropic solid move in ellipses in planes normal to the surface and parallel to the direction of the wave propagation. The particle displacement is significant at a depth of about one wavelength. This motion decreases at the surface at thinner depths and increases at greater depths. As the size of the ellipses is smaller, its eccentricity changes for particles in the deeper material. Surface acoustic waves were discovered in 1885 by Lord Rayleigh (Rayleigh,1885); therefore, they are often named after him: Rayleigh waves. Rayleigh showed that SAWs could explain one component of the seismic signal due to an earthquake, a phenomenon not previously understood. The velocity of acoustic waves is typically 3000 m/s, which is much lower than the velocity of the electromagnetic waves.

On the other hand, bulk acoustic waves are longitudinal, shear-mode, or combination of both. Longitudinal waves travel through the medium parallel to the same axis of the oscillations or vibrations of the particles in the medium; that is, in the same or opposite direction as the motion of the wave as shown in Fig. 2. Longitudinal mode waves are confined in a resonant cavity, thus displaying a particular standing-wave pattern. All other

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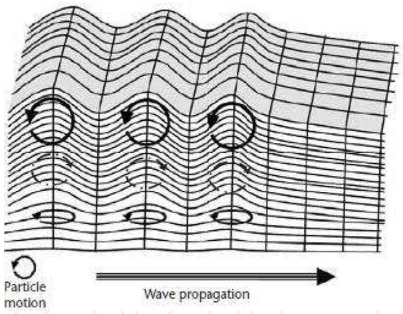


Fig. 1. Rayleigh wave propagation. (Auld ,1990).

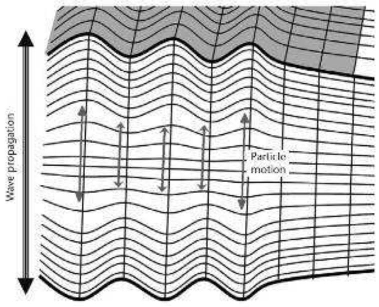


Fig. 2. The longitudinal-mode waves (Auld ,1990).

wavelengths experience destructive interference and are suppressed. While longitudinal modes have a pattern with their nodes located axially along the length of the cavity, transverse modes, with nodes located perpendicular to the axis of the cavity, may also exist. A transverse or shear-mode wave propagates and transfers its energy in the direction perpendicular to the oscillations occurring in the medium.

Although the existence of the Surface Acoustic Wave (SAW) was first discussed in 1885 by Lord Rayleigh, it did not receive engineering interest for a long time. The first SAW device was actually made in 1965 by White and Voltmer, who found out how to launch a SAW in a piezoelectric substrate by an electrical signal. White and Voltmer suggested that SAWs can be excited and detected efficiently by using an interdigital transducer (IDT) placed on a piezoelectric substrate(R.M. White and F.W. Voltmer,1965). Using IDT is a very convenient way on a piezoelectric substrate for excitation and detection of an acoustic wave, because very fine IDTs can be mass-produced by using photolithography, which has been well developed for semiconductor device fabrication, and proper design of the IDT enables the construction of transversal filters with outstanding performance. Starting around 1970, SAW devices were developed for band-pass filters, pulse compression radar and oscillators for TV sets and professional radio. Since 1980, the rise of mobile radio caused a dramatic increase in demand for filters, particularly for today’s cellular telephones.

All acoustic wave devices and sensors use a piezoelectric material, such as quartz crystal, to generate the acoustic wave. Piezoelectricity, which was discovered by Pierre and Jacque Curie in 1880, means “pressure electricity” due to the Greek word “piezo” for pressure. The Curie brothers were able to demonstrate the generation of electric charge in response to applied pressure or stress; this is so called the *direct piezoelectric effect*, as shown in Fig. 3. Piezoelectricity is received its name in 1881 from Wilhelm Hankel, and remained largely a curiosity until 1921, when Walter Cady discovered the quartz resonator for stabilizing

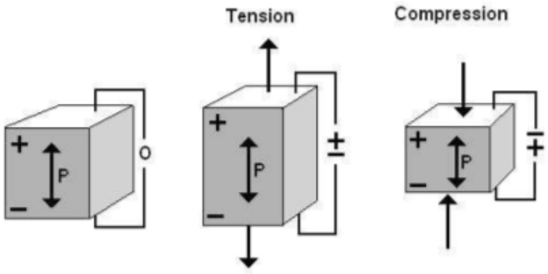


Fig. 3. The direct Piezoelectric Effect.

electronic oscillators. The piezoelectric effect has been understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry (Gautschi, G., 2002). For precision positioning purpose, the *converse piezo effect* is usually applied to produce precise displacements in response to the applied electric field, as shown in Fig. 4. The phenomenon is reciprocal, but not linear with hysteresis.

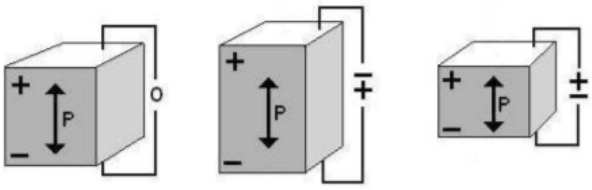


Fig. 4. The reverse Piezoelectric Effect.

Therefore, an oscillating electric field is used in piezoelectric acoustic wave sensors to create a mechanical wave, which propagates through the substrate and is then converted back to an electric field for measurement. Based on this principle, SAW devices have found diverse applications for measuring physical quantities such as temperature, pressure, torque, acceleration, tire-road friction, humidity, etc.. There are several methods to measure forces and torques. The force to be measured is often converted into a strain on a flexible element. The change of strain is subsequently measured by a sensor, for example, a piezoresistive, a capacitive or a resonant sensor. Unfortunately, the metallic resistance strain gauge is relatively insensitive such that the actual output voltage is usually only several mV of analog voltage before amplification and the gauges must not be significantly overstrained. The measurement range and overloading capabilities for strain gages are seriously restricted. In general, measurement instrumentation needs smaller sensing devices of lower power consumption and with large measurement range and overload capabilities. Digital microelectronics with greater compatibility is highly desirable. Noncontact and wireless operation is sometimes needed; in addition, batteryless devices are also necessary in some application cases.

SAW devices became important for sensor purposes in recent years. SAW sensors are applied as well as wired sensor elements in active circuits and as remote passive devices. The SAW sensors are passive elements, which do not need power supply, and can be accessed wirelessly, enabling remote monitoring in harsh environment. They can work in the frequency range of 10 MHz to several GHz. In addition, SAW sensors have the advantages such as compact structure, outstanding stability, high sensitivity, low cost, fast real time response, extremely small size (lightweight), and their fabrication is compatible with CMOS and micro-electro-mechanical (MEMS) integrated circuits technology. The SAW sensors are used for identification of moving object and parts (so called ID tags) and wireless measuring of temperature, pressure, stress, strain, torque, acceleration, tire-road friction, and humidity. The SAW sensors are well suited for measuring pressure in car and truck tires and tire-road friction monitoring. Their characteristics offer advantages over technologies such as capacitive and piezoresistive sensors, which require operating power and are not wireless. SAW has been used in electronics for many years, notably in quartz resonators which provide high Q-value as a result of the low acoustic losses. Exploiting the delay lines give a long delay in a small space with low acoustic velocities. SAW resonant sensors offer many benefits, such as improved sensitivity and accuracy, and reduced power consumption, among others. The resonance frequencies of the resonator-based sensors will be changed due to the action of the external excitation; therefore, we can use this characteristic of SAW device to detect the external force or torque via designing a interrogation (read-out) electronic circuit. Therefore, in this study we focus on designing an embedded system to measure the interrogation resonance frequency via a RF antenna set. In addition, this research‘s purpose is to establish a torque measurement based on a wireless SAW measurement system. Finally, we illustrate how to measure the torque wirelessly using the relation between the frequency shift and the torque, which is applied to a rotary rod.

2. Wirelessly torque measurement

2.1 Literature reviews for wireless torque measurement

A **torque sensor** or **torquemeter** is a device for measuring and recording the torque on a rotating system, such as a bicycle crank, rotor, gearbox, crankshaft, transmission, or an engine. The torque measurement can be separated into two categories, which are static torque and dynamic torque measurements. For static torque measure, using strain gage applied to a shaft or axle as torque sensors or torque transducers is the most common way. Static torque measurement is relatively easy with respect to dynamic measurement, because the measured shaft or axle is static. However, dynamic torque is not easy to measure because the shaft is rotating. Therefore, for a dynamic torque measuring system, the torque effect is generally transferred into some electric- or magnetic-type signals transmitting via wireless technologies from the rotary shaft being measured to the static system. Dynamic torquemeters is usually used to measure the torque being transmitted between the two machines which are connected. There are several varieties of torquemeter couplings, which are used for continuous on-line torque monitoring. Torquemeter designs are faced with the task of detecting a physical change due to torsion in the coupling while the shaft is rotating. Therefore, the dynamic torque measurement is necessary to perform through non-contacting means and get the torque information to a stationary output device via wireless device. Over the years, many methods have been devised to measure the torsional effects exhibited by the coupling; from the past literatures or present commercial products, we can find the following types of non-contact torque measurement, which are strain gage type torquemeters using twist angle or phase shift (torsional deflection) measurement, magnetoelastic torque sensors, and SAW torque sensors. We will make a literature survey as the following.

2.1.1 Strain gage integrated with a wireless transfer system

In the 1930's, the first in-line torque transducer was used on the liner Queen Mary, where employed the phase displacement principle to measure torque. It needed a length of 4 meters to adequately measure the angle of twist with around ±5% accuracy because of crude electronics. The modern torquemeters use the twist between a pair of toothed flanges, which is used to generate sinusoidal signals in magnetic pickups in the form of internally toothed rings and circumferential coils, to measure phase displacement. Fig. 5 describes the modern torque transducer using the phase displacement principle. Then, the resultant phase change of the two signals is measured by digital electronics to compute the applied torque. Phase displacement transducers are best suited to high speed and high temperature applications and they can achieve the accuracies of ±0.1%.

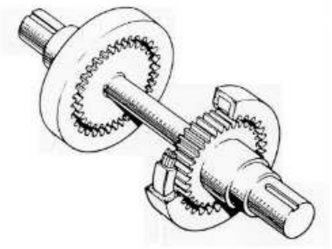


Fig. 5. The torquemeters using phase shift with 2 channels pick-up rings (Corcoran, joe and D'Ercole, Steve, 2000).

Different from the phase shift measurement, another way to measure torque uses the angle of twist resulting from the applied torque, which is measured using two angular position sensors and a differential transformer circuit. The measurement system consists of a differential transformer measuring system, two concentric cylinders fixed to a shaft either side of a torsion section and two concentric coils attached to the housing, as shown in Fig. 6. Both cylinders have circumferential slots, which rotate inside the coils. An alternating current flows through a primary coil and when the slots start to overlap due to shaft twist, a torque–proportional EMF is induced in a secondary coil. However, its performance is worse than the phase displacement transducer, but its cost is generally lower than the phase displacement transducer.

The strain gage is also called load cell, which is delivered by Load Delvin in 1856; the principle of the strain gage is using the relation between the resistance and the strain for metal materials. When the metal martial suffers pull or tension, its resistance will be increased due to the strain. Otherwise, the resistance decreases when the martial suffers pressure. According to the relation between the strain of the metal and the applid torque, the strain gages can be used to detect torque. However, the strain gage needs the electrical source to produce the variation of voltage for measurement so that the torque sensor using strain gage needs an external power supply. On one hand, a means to power the strain gauge bridge is necessary, as well as a means to receive the signal from the rotating shaft. On the other hand, the non-contact measurement is accomplished using slip rings, wireless telemetry, or rotary transformers. The first rotating strain gauge torque transducer employed a system of slip rings to make the electrical connections from the casing to the rotating shaft. For the slip ring torque transducers, there are two problems which should be noted. The first one is that the slip rings are carrying only millivolt signals from the strain

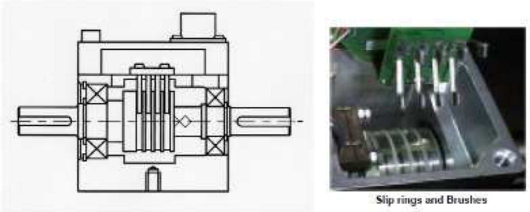


Fig. 6. The torquemeters using angle of twist resulting from the applied torque (David Schrand).

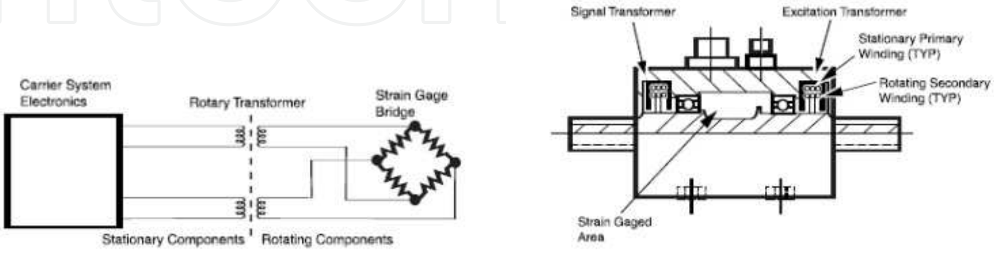


Fig. 7. The strain-gage type torquemeter with RTS (PCB load & torque).

gauges; therefore, the materials for both the slip rings and the brushes have to be carefully selected. The second is that slip ring torque transducers should be applied for slower speed and short-term test applications due to the lifetime of brushes. The rotary transformer system (RTS), which uses induction principles to transfer signal or power to the measurement system, became popular in the 1980's. RTS uses high-performance, high-temperature electronic components to be as a telemetry system but it only uses kHz carrier frequencies, not the MHz of radio systems. Several companies use the rotary transformer system with strain gauges, and with typical inaccuracies of ± 0.2%, and speeds up to 50,000rpm it can be a very cost-effective torque transducer.

For novel types of torque transducers, conditioning electronics and an A/D converter may be integrated into a microchip which is fixed to the rotating shaft; then, stator electronics read the digital signals and convert those signals to a high-level analog output signal. In this case, the wirelessly strain-gage type torque sensor, which needs a a bettery to support the power of the system, is not a passive device and it needs a wireless communication system to transfer the measurement data via RF. Wireless communication technologies are convent for remote control, such as ZigBee, Bluetooth or wirefire networks. ZigBee is a new communication technology in the wireless field and ZigBee comes from the bee which communicates with other bees about position of pollen via shape of dance. In the Fig.8 describes a measurement system using the strain gage integrated with Zigbee. The torque sensor integrated with ZigBee wireless communication sensor can detect the torque of shaft to prevent breaking due to the fact that the torque exceeds the material limit. The torque sensor systems with ZigBee involves of two parts, measuring unit (strain gages) and receiver unit (microprocessor). The measuring unit is used to measure torque from strain gages and transmit digital signal to receiver unit. Then, the MCU is used to perform A/D conversion and signal processing tasks. A simple MCU is enough perference for measuring task and transmit signals. After that the Zigbee chip transfers the digital signal into RF signal and transmits it to the receiver.

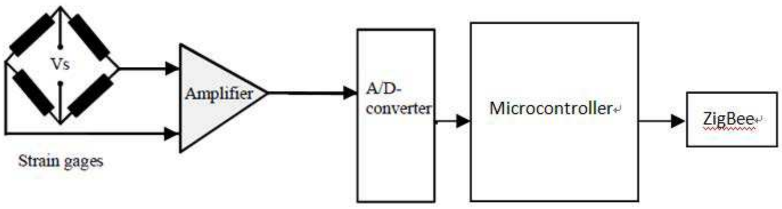


Fig. 8. The block diagram of ZigBee torque measuring system.

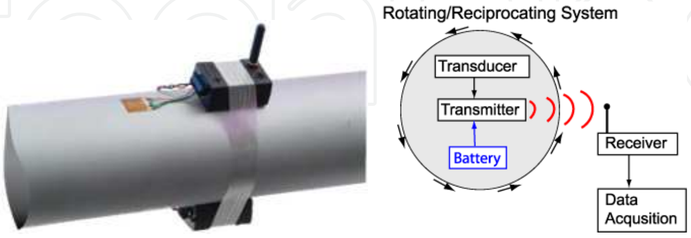


Fig. 9. The block diagram of wireless measuring unit (Binsfeld Engineering Inc.).

2.1.2 Magnetoelastic torque sensors

Besides of strain-gage type torquemeter, one way to achieve this non-contact measure uses the magnetic characteristics of the shaft with a series of permanent magnetic devices. The magnetic characteristics will vary according to the applied torque, and thus can be measured using magnetoelastic torque sensors, which are generally used for in-vehicle applications on racecars, automobiles, and aircraft. The United States Patent, the inventor Bunyer, Scott L(Bunyer, Scott L, 2007) in his patent " Magneto-Elastic Resonator Torque Sensor " , the torque sensor consists of a substrate and a magneto-elastic sensing component formed from or on the substrate. The magneto-elastic sensing component and the substrate together form a magneto-elastic torque sensor, which when subject to a stress associated with a torque, shifts a characteristic frequency thereof linearly in response to the torque, thereby inducing a pathway by which magneto-elastic energy is coupled to excite vibrations in a basal plane of the magneto-elastic sensor, thereby generating torque-based information based on resonator frequency thereof. Figs. 10-11 illustrate the torque sensing system using magneto-elastic resonator. A few years ago, a magneto-elastic device was developed in the USA, which uses a magneto-elastic sleeve fixed to a stainless steel shaft. This permanent magnet generates a magnetic field proportional to torque. The resultant magnetic field is less dense that the earth's field, hence internal shielding is needed for the hall-effect probes, which is fine for applications whose accuracy is not critical. The ABB Company proposed the magneto-elastic torque sensor, which is called Torductor®-S (ABB company, 2007). Since the sensor is part of the load-carrying shaft and Torductor®-S gives a true non-contact and rugged torque sensor without any moving parts. Therefore, the measured torque is the true transmitted torque, which enables Torductor®-S to combine high accuracy with high overload capacity and fast response at all times. A high output signal ensures integrity against electrical or magnetic interference from the surroundings. The magneto-strictive transducer, which is similar to the magneto-elastic torque sensor, is mechanically simpler than the magneto-elastic unit and relies on a pre-magnetized shaft proportionally changing its magnetic field when torque is applied. The magneto-strictive transducer is a low-cost transducer; however, zero drift with time and temperature and the effect of adjacent magnetic fields can be a problem for. These two devices can provide an accuracy of around ±1%.

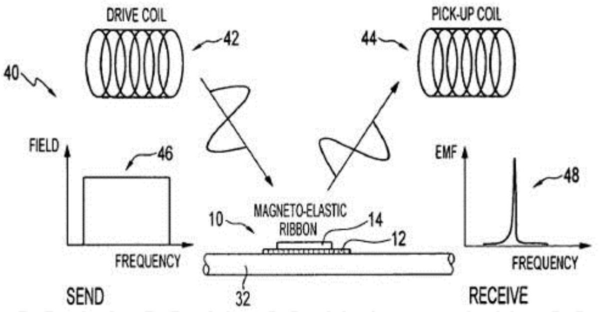


Fig. 10. The torque sensing system using magneto-elastic resonator (Bunyer, Scott L, 2007).

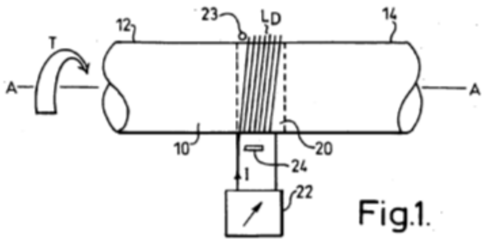


Fig. 11. The torque sensing system using magneto-elastic resonator (Bunyer, Scott L, 2007).

2.1.3 SAW torque sensors

Although the existence of the Surface Acoustic Wave (SAW) was first discussed in 1885 by Lord Rayleigh, it did not receive engineering interest for a long time. Until 1965, R.M. White suggested that SAWs can be excited and detected efficiently by using an interdigital transducer (IDT) placed on a piezoelectric substrate(R.M. White and F.W. Voltmer, 1965). This is because very fine IDTs can be mass-produced by using photolithography, which has been well developed for semiconductor device fabrication, and proper design of the IDT enables the construction of transversal filters with outstanding performance. Acoustic devices are robust in respect to temperature and mechanical stress discussed by Seifert et al. (F. Seifert, A. Pohl, R. Steindl, L. Reindl, M.J. Vellekoop, and B. Jakoby, 1999). They are reliable more than the lifetime of other electronic devices. Application of SAW devices to non-contact torque measurement was first suggested and patented in 1991 by A. Lonsdale and B. Lonsdale (A. Lonsdale, B. Lonsdale, 1991). Non-contact torque sensors based on SAW reflective delay lines were also introduced in (U. Wolft et al.; R. Grossmann et al. 1996). Since then some reasearchers fabricated and applied torque sensors based on SAW resonators to a number of industrial customers (A. Lonsdale, 2001; P. Merewood, 2000). In 2002, non-contact torque sensors based on SAW resonators application was proposed by Beckley et al. (J. Beckley, V. Kalinin, M .Lee, and K. Voliansky, 2002). Although the operation of both types of sensor was successfully demonstrated in the abovementioned publications, they did not cover such important aspects as limitations on the accuracy of the sensors resulting from their non-contact interrogation and the temperature stabilization of their sensitivity to torque. SAW resonators have been a commercial success on radio frequency applications, especially for filter and oscillator implementations. Their impact has made possible considerable reductions in size and power of the chipsets of mobile devices(Fujitsu Media Devices Ltd., 2006; Epcos AG, 2008). More modest and important applications of SAW resonators are the measurements in mass detector and pressure sensor devices with application in bio-particle detection(Martin, F., 2004; Talbi, A., 2006).

In recent years some instrument manufacturers of force and torque measurement devices have investigated instead of using resistance strain gauges. For example, one leading manufacturer of weighing machines now uses metallic and quartz resonant tuning fork technologies for industrial applications and the others have established some applications using surface acoustic wave (SAW) technology, optical technology, and magneto-elastic technology. Further commercial developments are taking place to enhance device manufacturability and improve device sensitivity and robustness in operation. Measurement on stiffer structures at much lower strain levels than before is possible now. Reviewing the world patents, we can find many torque measure patents using Piezo or SAW devices. In the United States Patent US 2003/0000309 A1, A. Lonsdale and B. Lonsdale claimed the patent of "Torque measurement", in which they proposed a method and apparatus for measuring the torque transmitted by a member comprises a SAW device secured to the member such that mechanical stress in the member due to torque transmitted thereby induces bending of the SAW device (A. Lonsdale and B. Lonsdale, 2003), as shown in Fig. 12. In another United States Patent, LEC, RYSZARD MARIAN, Magee et al. claimed the "Torque Measuring Piezoelectric Device and Method" using non-contact measurement of torque applied to a torque-bearing member such as a shaft. The method involves the use of a piezoelectric transducer mechanically coupled to the shaft for rotation therewith, and having electrical characteristics responsive to applied torque(Steven J. Magee, 2004). Electrical signal characteristics are changed by the torque-dependent transducer characteristics. In 2007, in another United States Patent, Steven J. Magee claimed that the sensor systems and methods are disclosed herein, including a sensor chip, upon which at least two surface acoustic wave (SAW) sensing elements are centrally located on a first side of the sensor chip. The SAW sensing elements occupy a common area on the first side of the sensor chip. An etched diaphragm is located centrally on the second side of the sensor chip opposite the first side in association with the two SAW sensing elements in order to concentrate the mechanical strain of the sensor system or sensor device in the etched diagram, thereby providing high strength, high sensitivity and ease of manufacturing.

Low propagation velocity enabled the use of SAW devices for time delays and filtering in radar systems and television but their application burgeoned within the mobile phone market. Honeywell SAW sensors use small piezo-electric quartz die upon which two or three single-port resonators, with natural resonant frequencies around 434 MHz, are fabricated in aluminum using standard photo-lithographic techniques, as shown in Fig. 13. (Magee et al., Honeywell, 2007). A SAW resonator is excited by a short radio-frequency (RF) burst. The centrally placed interdigital transducer (IDT) converts the electrical input signal to a mechanical wave through the piezo-electric effect. The waves propagate from IDT to reflectors and back until a forced resonance exists as a standing wave. After the transmit signal is switched off, the resonator continues to oscillate but at a frequency modified by any applied mechanical and/or thermal strain. The decaying oscillation is converted back to an electrical signal via the piezo-electric effect and retransmitted to the SAW interrogation board where the frequencies are analyzed and converted to engineering parameters. A more recent development is the use of SAW devices attached to the shaft and remotely interrogated. The strain on these tiny devices as the shaft flexes can be read remotely and output without the need for attached electronics on the shaft. The probable first use in volume will be in the automotive field as, of May 2009, Schott announced it has a SAW sensor package viable for in vehicle uses.

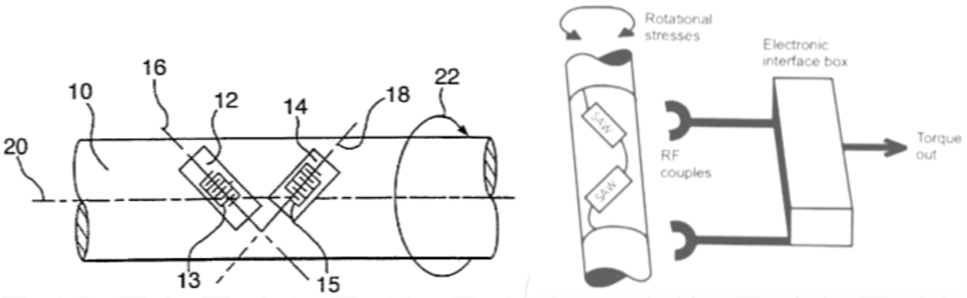


Fig. 12. The block diagram of a SAW torque sensor system. (A. Lonsdale and B. Lonsdale, 2003).

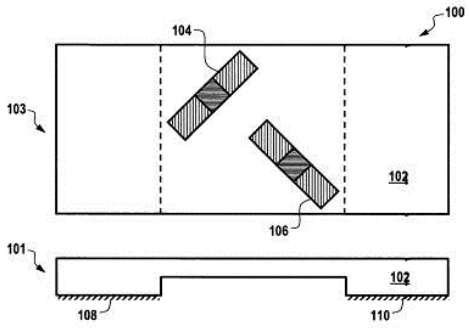


Fig. 13. The diagram of a SAW torque sensor system. (Magee et al., Honeywell, 2007).

A British company, Sensor Technology Ltd., has developed a Torqsense® digital RWT310/320 series transducers using surface acoustic wave (SAW) technology. Torqsense® is a registered trademark used for Electric or Electronic Transducers for providing electric or electronic sensors for sensing torque and owned by Lonsdale, Bryan, Lonsdale, Anthony. Based on a revolutionary new, patented, technology using SAW strain sensing elements, Torqsense® sensors offer a superior solution to non-contact rotary torque measurement in industrial applications. The SAW torque devices are strain sensitive elements with very high frequency modulating and it has the ability to convert an electrical signal into an acoustic signal with the same frequency. Because of a reduction in propagation velocity of about five orders of magnitude, the SAW device has a much smaller wavelength, which allows manipulation of an RF signal in a very small package. Therefore, we can consider a SAW device as a frequency dependent strain gauge, which can be used to measure the change in resonant frequency caused by the strain in the shaft. For dynamic torque measurement, the SAW device needs an RF couple to transmit the signal from the shaft to a fixed pick-up. It is a relatively low-cost device offering a ± 0.25% accuracy giving a total system accuracy of around ± 0.35% (patent Magee, 2007).

2.2 Types and applications of SAW devices

Wirelessly interrogated passive SAW sensors can employ one of the two basic types of SAW devices, one-port resonators(F. Jerems et al, 2001; A. Lonsdale, B. Lonsdale, 1991; A. Lonsdale, 2001; P. Merewood, 2000) and reflective delay lines (F. Schmidt, G. Scholl; A. Pohl, F. Seifert, 1997; U. Wolft et al.). Obviously, ordinary delay lines and two-port resonators can also be used as passive sensing elements, although they are less preferable because of the larger number of RF coupling devices are required (F. Schmidt, G. Scholl). If active components are allowed on the shaft then both the delay line and the resonator can be used in a feedback loop of a SAW oscillator, wirelessly coupled to an interrogation unit and wirelessly powered by an RF signal. This is an approach inherited from a traditional wired SAW sensor design.

2.2.1 Reflective delay lines of SAW devices

Most SAW passive sensors are designed using a reflective delay line. The surface acoustic wave in a reflective delay line propagates towards reflectors distributed in a characteristic barcode-like pattern and is partially reflected at each reflector. Fig. 14 shows the SAW delay line sensor and the principle of the sensor is drawn in Fig.15. Fig. 16 shows reflectors lined of same track and different tracks.

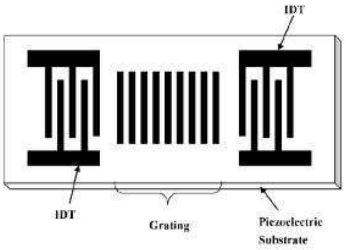


Fig. 14. The SAW delay line sensor.

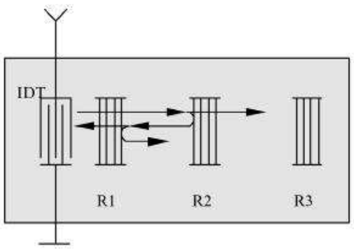


Fig. 15. The reflectors lined of same track (Weidong Cheng et al., 2001).

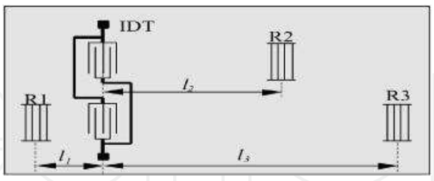


Fig. 16. The reflectors lined of different tracks(Weidong Cheng et al., 2001).

2.2.2 Resonators of SAW devices

SAW resonators exploit SAW propagation and electromechanical transduction to implement electronic circuits as filters, oscillators, and sensors. A SAW resonator is basically a resonant cavity in which a first transducer electrode converts the electric signal into a lateral mechanical wave. The resulting SAW propagates on the piezoelectric to reach the second electrode, where it is transduced back into the electrical domain. When arriving at the second electrode, and typically aided by one or more reflector electrodes, the acoustic wave bounces back in the direction of the first electrode, and the electromechanical conversion is repeated indefinitely, as depicted in Fig. 17. Thus, the acoustic wave is trapped in the cavity formed by the resonator electrodes.

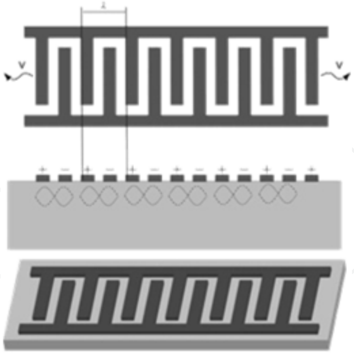


Fig. 17. The surface acoustic wave (SAW) resonator (Humberto Campanella, 2010).

The available photolithography resolution limits the dimensions of the IDTs and the piezoelectric layer determines the maximum operating frequency of the fundamental mode of the resonator. However, as well as other electromechanical resonators, SAW devices can be operated at over-tone modes to bypass near-to-fundamental bulk or other resonance modes. Typical frequencies for SAW-resonator-based applications are in the UHF band below 1 GHz, although high-performance commercial devices in the 1.5-GHz GPS and 1.9-GHz PCS bands are available so far(Epcos AG, 2002; TriQuint Semiconductor, 2009). The fundamental frequency of the SAW resonator mainly depends on the pitch of the IDTs, which is chosen to be equal to the SAW wavelength λ, and the sound speed of the piezoelectric layer v:

$$f_0 = \frac{v}{\lambda} \tag{1}$$

SAW resonators are found in two types of port configurations one-port and two-port resonators. One-port resonators are two-terminal devices, and they find application in oscillator circuits like VCOs or Colpitts oscillators. Two-port resonators behave more like narrow band-pass filters.

Fig. 18 shows a typical configuration One-port SAW resonators, The One-port SAW resonators have a single IDT generating and receiving the SAW, and two grating reflectors, which reflect the SAW and generate a standing wave between the two reflectors. The IDT and reflectors are fabricated on quartz crystal substrate or another piezoelectric material and patterned by photolithographic processes(Ken-Ya Hashimoto, 2000). As Fig. 19 shown, its equivalent circuit near resonance, where C_M and L_M are the dyamical capacitance and inductance, respectively, corresponding to the contributions of elasticity and inertia. On other hand, C_O is the static capacitance of the IDTs, and R_M is the motional resistance corresponding to the contribution of damping. On the other hand, two-port SAW resonators exhibit two IDTs, one of them generating the SAW, and the second one picking it. As with one-port devices, two grating reflectors aid the SAW to be reflected and confined between the IDTs. The generic connection is connected to the first and second IDTs as shown in Fig. 20 for two-port SAW resonator and Fig. 21 shows the resonator equivalent circuit.

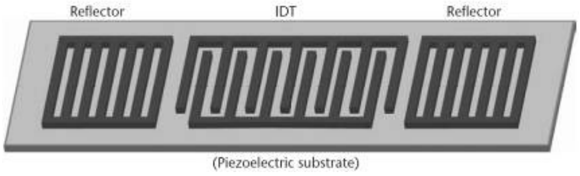


Fig. 18. The one-port SAW resonator (Humberto Campanella, 2010).

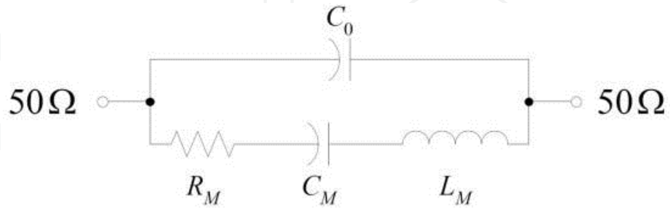


Fig. 19. The equivalent circuit for the one-port SAWR (Ken-Ya Hashimoto, 2000).

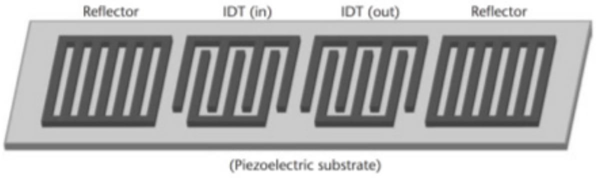


Fig. 20. The two-port SAW resonator (Humberto Campanella, 2010).

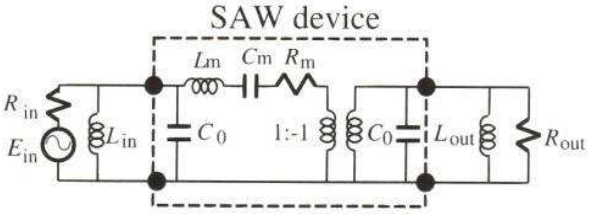


Fig. 21. The two-port SAW resonator equivalent circuit (Ken-Ya Hashimoto, 2000).

2.2.3 Characteristics of one-port SAW resonators

In this study, we using one-port SAW resonators device. Fig. 18 shows typical configuration one-port SAW resonators. Fig. 22 shows frequency response for resonator and in this study we just measure the resonance frequency ω_r or antiresonance frequency ω_a.

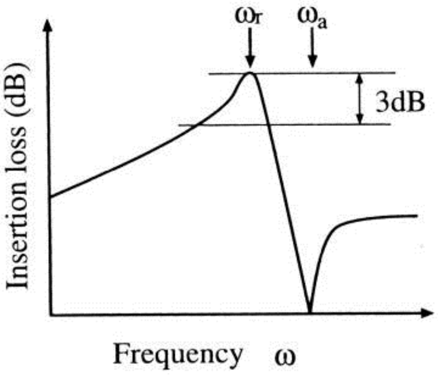


Fig. 22. The frequency response for a resonator (Ken-Ya Hashimoto, 2000).

From the equivalent circuit of one-port SAW device in Fig. 19, we have

$$\omega_r = \frac{1}{\sqrt{L_M C_M}}, \tag{2a}$$

$$\omega_a = \frac{1}{\sqrt{\frac{L_M C_M C_O}{C_M + C_O}}}, \tag{2b}$$

where C_M and L_M are the dyamical capacitance and inductance, respectivly. On the other hand, C_O is the static capacitance of the IDTs, and R_M is the motional resistance corresponding to the contribution of damping. Fig. 23 shows typical electrical resonance characteristics of one-port SAW resonator. As shown in Fig. 22, the conductance G takes a maximum at the frequency above the resonance frequency ω_r; in addition, there exists the anti-resonance frequency ω_a where the resistance G^{-1} takes a maximum.

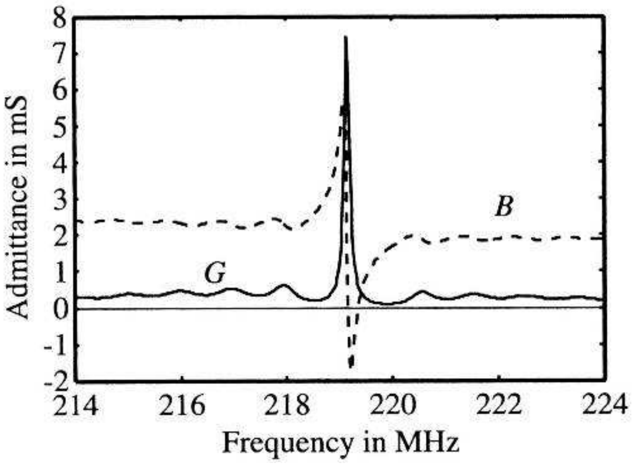


Fig. 23. The electrical resonance characteristics of one-port SAW resonator (Ken-Ya Hashimoto, 2000).

As mentioned in Ref. (Ken-Ya Hashimoto, 2000), C_M and L_M can be obtained from the measured C_O, ω_r and ω_a. R_M can be determined by G^{-1} at $\omega = \omega_r$. The capacitance ratio γ is frequently used as a measure of the resonator performance, and is for:

$$\gamma = \frac{C_O}{C_M} = \frac{1}{(\omega_a / \omega_r)^2 - 1}, \tag{3}$$

which corresponds to the inverse of the effective electromechanical coupling factor. The quality factor Q at the resonance frequency is called the resonance quality factor, which is denoted by Q_r. This is also an important measure, which is shown by:

$$Q_r = \frac{\omega_r L_M}{R_M} = \frac{1}{\omega_r C_M R_M}, \tag{4}$$

Both resonance frequency ω_r and antiresonance frequency ω_a will be shift by temperature change and effect of applied stress. Effect of temperature can have a considerable affect on propagation velocity for surface acoustic wave device, since many of the material constants involved are themselves temperature dependent. The temperature dependence of surface wave attenuation for quartz in particular has been studied over various temperature and frequency range(M. R. Daniel and J. De Klerk, 1970). Different piezoelectric materials, propagation directions, and cuts all show different temperature dependencies over different range. It is thus possible to engineer that a SAW device has specific temperature characteristics, which has led to the development of several SAW based temperature sensors(D. Hauden et al., 1981; J. Neumeister et al., 1990; M. Viens and J. D. N. Cheeke, 1990). In effect of applied stress also contributes to acoustic wave attenuation and velocity change, and has been studied extensively by Slobodnik(A. J. Slobodnik, 1972). In this study, the attenuation is due to the generation of surface acoustic waves in the gas in contact with the SAW device. In other words, the shear vertical component of the wave causes periodic compression and rarefaction of the gas, resulting in a coupling of acoustic energy from the SAW device into the air.

2.2.4 Applications of torque sensors based on SAW resonators

Although the existence of the Surface Acoustic Wave (SAW) based on torque measurement was first discussed in 1996 by A.Lonsdale (A. Lonsdale et al.). Torque (radial strain) transducers are one of the more common devices used by development engineers. Knowledge of torque and rotational speed can be used to indicate power, from which the efficiency of gearboxes, transmissions, electrical machines and many other systems can readily be assessed. To apply the SAW element principle, two devices are used in a half bridge, analogous to the classic resistive strain gauging configuration; one positioned so as to be sensitive to the principal compressive strain and the other positioned to observe the principal tensile strain. In the absence of bending moments and axial forces, the principal stress planes lie perpendicular to one another at 45° to the plane about which the tensional moment is applied. This is illustrated in Fig. 24.

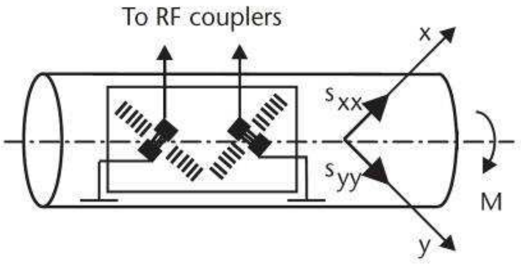


Fig. 24. Torque sensing element based on SAW resonators(Stephen Beedy et al., 2004).

In this SAW sensors applied rely on the fact that the torque M applied to the shaft creates two principal components of strain, $S_{XX} = -S_{YY} = S$. As a result, one of the SAW devices is under tension and the other one is under compression, causing the opposite change of resonant frequency in the devices. The resonators have the same or better performance for the same size of substrate and are less demanding in terms of the receiver bandwidth and sensitivity. Resonator Q factors are about 10,000. The torque sensor interrogation system can employ continuous frequency tracking of reflected frequencies from the two SAW resonators.

This applied can achieve temperature compensation and eliminate sensitivity to shaft bending. From the technique described it is apparent that the output signal will be in the frequency domain as shown in Fig. 25.

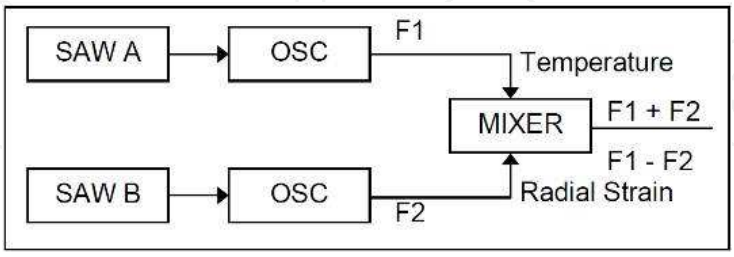


Fig. 25. The schematic of frequency domain for SAW signals(A. Lonsdale, 1993).

3. Wirelessly measurement architecture based on SAW device

An acoustic wave is a disturbance in an elastic medium that propagates in space and time, thus transferring the energy supplied by an excitation source along the medium in the form of oscillation or vibration. There exist two types of acoustic waves: surface acoustic waves (SAW) and bulk acoustic waves (BAW). In this study, two one-port SAWRs (manufactured by *f*-tech Corporation) with the resonant frequency of 433.42 MHz and 433.92 MHz are used to be torque sensing devices for this study. The specifications for the SAWR (433.92 MHz) are descibled in Table 1. Fig. 26 shows the wafer of the SAW resonators using in the experiments and Figs. 27 and 28 show the die size of the SAWR and its microimage.

Fig. 26. The Wafer of f-tech SAWRs (433.92MHz).

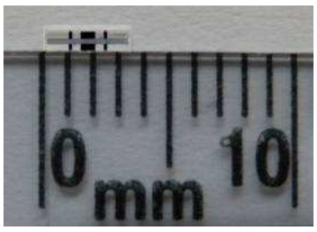


Fig. 27. The photo of the SAWR's die size.

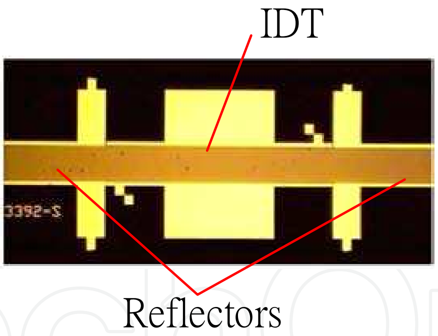


Fig. 28. The microimage of the SAWR's die.

Item	Unit	Min.	Typ.	Max.
Center Frequency, f_r	MHz	433.845	433.92	433.995
Insertion Loss, IL	dB	-	1.5	2.0
Unloaded quality factor, Q_U		-	12000	-
Loaded quality factor, Q_L		-	1880	-
RF Equivalent RLC Model				
Motional Resistance, R_M	Ω	-	18.5	-
Motional Capacitance, C_M	fF	-	1.653	-
Motional Inductance, L_M	μH	-	81.35	-
Shunt Static Capacitance, C_0	pF	-	2.4	-
Turnover Temperature, T_0	°C	-	30	-
Frequency Temperature Coefficient, FTC	ppm/k^2	-	0.032	-

Table 1. 433.92 MHz SAWR specifications (www.f-tech.com.tw).

In this study, we used two one-port SAWRs to obtain the torque signal via measuring the frequency shift of SAWs, Δf , which is relate to the strain ε and the fundamental requency of the SAWR f_0. For each SAWR, the relation between the frequency shift and the strain can be described as follows.

$$f_0 = \frac{v_0}{4d}$$

where f_0 is the fundamental frequency of the SAWR, which mainly depends on the pitch of the IDT, d , and v_O is the speed of SAW.

Obtaining the variation of the fundamental frequency according the the variation of the speed and pitch for the SAW, we have:

$$f_0 + \Delta f = \frac{v_0 + \Delta v}{4(d + \Delta d)} = \frac{v_0 + \Delta v}{4d(1+\varepsilon)} \tag{5}$$

where ε is the strain. Neglect the variation of the SAW speed, becasue it is very small. Then, we have

$$f_0 + \Delta f \approx \frac{4df_0}{4d(1+\varepsilon)} = \frac{f_0}{1+\varepsilon} \tag{6}$$

Using Taylar expansion to consider the approximation, we can obtain the following.

$$\frac{1}{1+\varepsilon}=1-\varepsilon+\frac{1}{2}\varepsilon^{2}-\frac{1}{3!}\varepsilon^{3}+\ldots\cong 1-\varepsilon \tag{7}$$

then the frequency shift can be approximated as follows

$$\Delta f = f_0\cdot\left(\frac{1}{1+\varepsilon}-1\right)= f_0\,\frac{(1-\varepsilon-1)}{1+\varepsilon}\approx-\varepsilon f_0 \tag{8}$$

Therefore, we can obtain the relation between the frequency shift and the strain as follows

$$\Delta f = -\varepsilon\cdot f_0 \tag{9}$$

where Δf is the shift of the resonant frequency, ε is the strain and f_0 is the resonant frequency. In the implementation, two one-port SAW resonators oriented at $\pm 45^{o}$ to the shaft axis, which are shown in Fig. 29. Fig. 30 shows the locations of the two SAWR on the shaft; we also attach the strain gage with two directions of $\pm 45^{o}$ on the opposit side of the SAWR to obtain the actual strain as shown in Fig. 30. We use the network analyzer (Agilent E5071A) to measure the S11 value of this two SAWRs for obtaining the fundamental frequency of these two SAWRs as shown in Fig. 31. Then, we can find the relation between the frequency shift and the applied torque as shown in Fig. 32. Fig. 32 shows that the resonant frequency shifts for SAWR1 and SAWR2 on the location of $\pm 45^{o}$ will move in the opposite directions as soon as torque is applied to the shaft, because the stress‘s direction is inverse due to the applied torque as σ_x and σ_y described in Fig. 29. Therefore, we can obtain the value of torque measuring the difference between the two frequencies and this arrangement can compensate as mestioned in the past literature (A. Lonsdale, 1993). From the frequency shifts of the SAWR1 and SAWR2 measured in Fig. 32, we can obtain the actual strain which is computed according to Eq. (9).

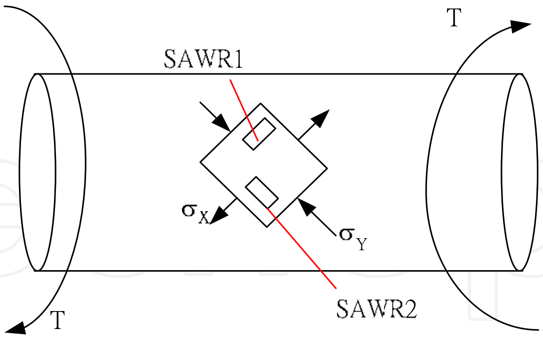


Fig. 29. The relation between the stress and the applied torque for the SAWRs.

Fig. 30. The setup of the SAWRs and the strain gage on the shaft.

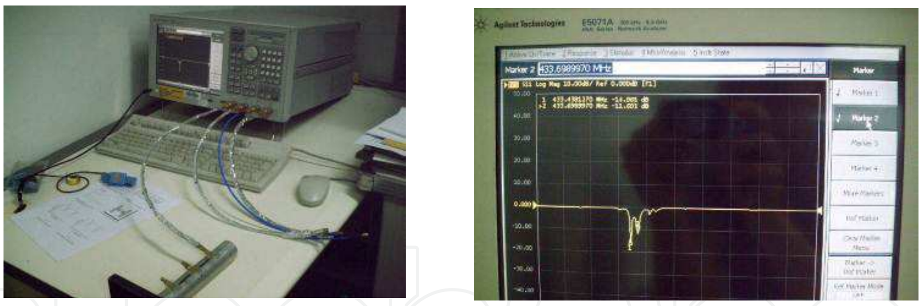


Fig. 31. Torque measurement using the network analyzer (Agilent E5071A).

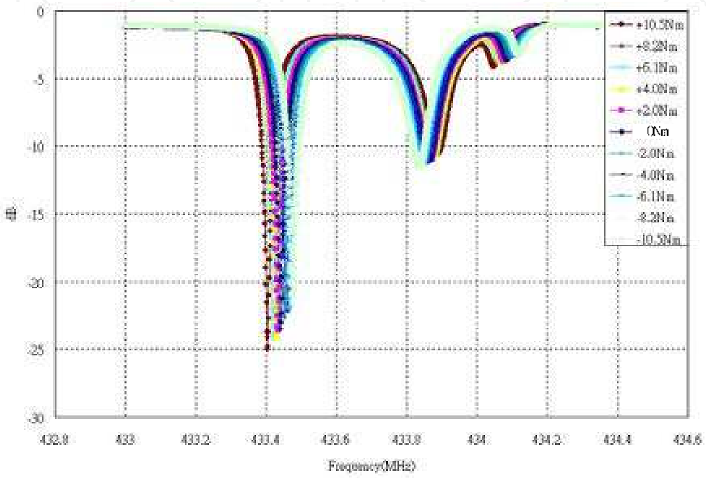


Fig. 32. The relation between the S11 value and the frequency of the two SAWRs.

Fig. 33 shows the relation between the applied torque and the strain, which is measured using the SAWRs. The theoretical torque can be computed as follows.

$$\tau_{\max} = \frac{Tc}{J} = \frac{T \times r}{\frac{\pi}{2}(r)^4}$$

$$\tau_{\max} = \frac{\sigma}{2} \tag{10}$$

$$\varepsilon = \frac{\sigma}{\mathrm{E}} = \frac{2\tau_{\max}}{\mathrm{E}}$$

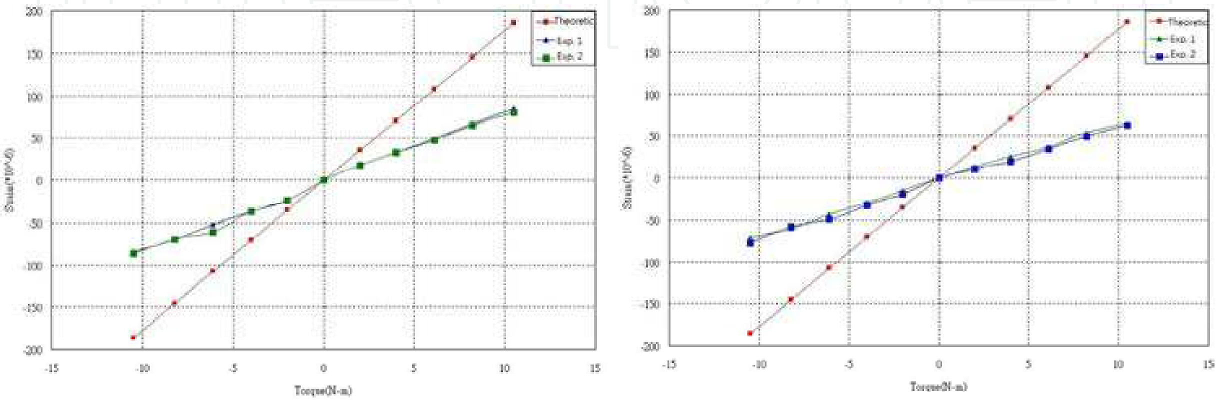


Fig. 33. The relation between the applied torque and the strain using two SAWRs.

where E is Young's modulus of the material, σ is the stress, ε is the strain, r is the radius of the torsion bar and T is the applied torque. Although the SAWRs response only 40% strain which is compared from the strain gage in Fig. 34, the relation between the torque and the strain is linear; therefore, we can measure the torque applied on the shaft according to the relation obtained in Fig. 34 for the SAWRs.

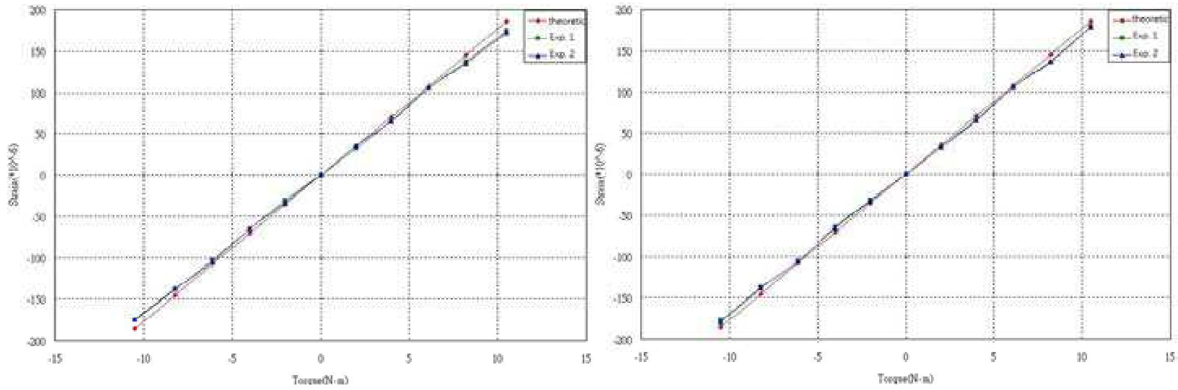


Fig. 34. The relation between the applied torque and the strain using the strain gage.

If the measurement of the resonant frequency in the torque sensor is performed by means of continuous tracking of S11 minimum at the input of the rotary coupler then a remarkably low standard deviation of the frequency measurement error of 0.3-0.4 ppm can be achieved at less than 1 ms update period. However the continuous tracking requires one automatic frequency control (AFC) loop per resonator. In this study, the RSSI value is used to obtain the resonant frequency of SAWR instead of measuring S11 minimum. Fig. 35 shows the fabricated torque sensor, which consists of the four microstrip lines and two SAWRs. The connection between the microstrip and the SAWR is established by the IC wire bonding machine. The parameters of the microstrip line are designed optimally by the software of Advanced Design System 2006A. Moreover, the wireless signals are transmitted by four coupling antennas, which are described in Fig. 36. The proposed wireless torque sensory system is described in Fig. 37.

Fig. 35. The rotational shaft equipped with two SAWRs.

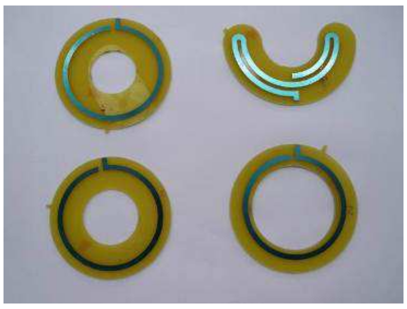


Fig. 36. The coupling antenna for the sensory system.

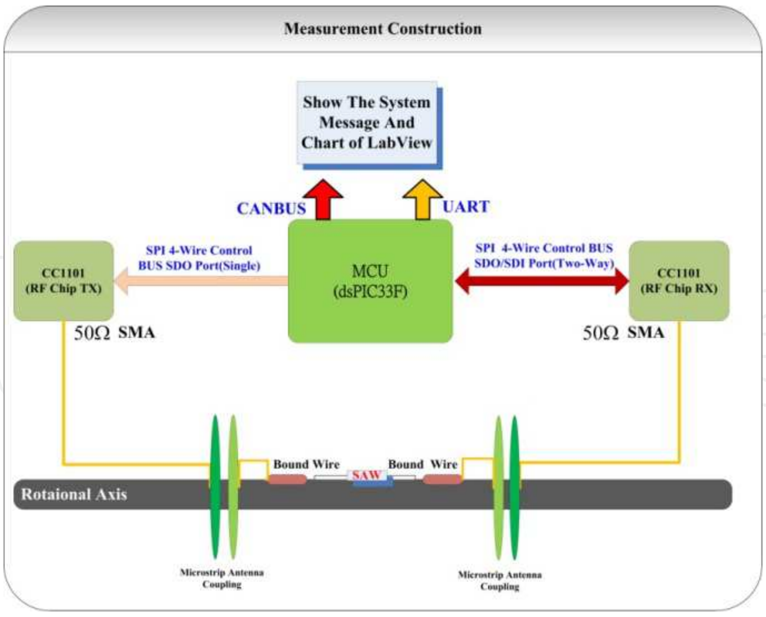


Fig. 37. The block diagram of the proposed wireless torque sensory method.

A wireless passive torque measurement system using SAW sensors is presented as shown in Fig. 38. To measure the torque via wireless sensing, a dsPIC architecture based on two SAW sensors via wireless RF signals is proposed in this paper. When the torque is applied to the shaft, the two SAWRs will change their resonant frequencies in opposite directions in the frequency domain. According to the past literature, measuring the difference between the two frequencies one can obtain the value of torque and achieve partial temperature compensation, which are performed by means of continuous tracking of minimumal S11 at the input of the rotary coupler. Different from the past method using the frequency with the minimal S11, this study tries to obtain the maximum of S21 to measure the value of torque via continuous tracking of output signal. An dSPIC33F microchip is used to control the RF chips (C1100) to achieve the transmitting and receiving task. The frequency with maximum received signal strength indication (RSSI), where the value of S21 is maximal, will be influenced by the applied torque. The measuring system mainly uses the RSSI signal with respect to the frequency to find the SAW center frequency value, and then the torque values can be obtain according to the frequency shifts. Therefore, the frequency, which has the maximal RSSI value, can be used to obtain the applied torque of the rotation shaft according to the frequency shift. In addition, to achieve the wireless transmission, two sets of coupling-type antenna are applied on the shaft. Finally, the torque signal is passed through CANBUS to integrate with the other vehicles electron systems. In this study, a wireless torque sensing system has been established to measure the torque of the rotaional shaft via the RF antenna.

To illustrate the process of the proposed wireless torque measuring system, a single electromagnetic RF interrogation system is studied to produce RF interrogation signals to the SAW device. According to the measurement of the frequency shift, the environmental influence can be measured by the specified relation via experimental results. A dsPIC33 chip is used to control the RF chip (C1100) to achieve the transmitting and receiving between 433.1MHz and 433.85 MHz, and the interval scanning frequency is 0.5 KHz. According to the response of the RSSI value with repect to the scanning frequency, the torque value can be obtained according the look-up table obtained by the experimental results in Fig. 34.

After all, the microcontroller (dsPIC33) itself is equipped with a controller area network (CAN) interface, which is responsible for the calculation of the sensor data and providing the communication with other electronic systems(dsPIC33FJ256GP710A user guid). According to above system, the CC1101 chip is a low- power consumption RF chip developed by Chipcon. The main operating frequency is designed at 315, 433, 868, and 915MHz. The receive chip of RF has an amplifier to enhance a signal, and then change the signal to IF (Intermediate Frequency). When the CC1101 plays an IF medium frequency receiver, the I/O signals are transferred to digital signals using A/D converter. On the other hand, the transmit chip of RF includes a LC VCO (LC Voltage-controlled oscillator) and a LO (Local Oscillator). Fig. 38 describes the block diagram of the proposed architecture using CC1100 and dsPIC to measure the frequency shift of the SAW devices. In the measurement system, the MCU's performance is the critical component, which dominates system bandwidth, sensitivity, and flexibility. Therefore, we choose the dsPIC33F to improve our measuring system. The dsPIC33F is a 16-bit DSC chip, which is developed by to integrate 16bits MCU and DSP with high speed computation. The dsPIC provides 84 commands, 16 registers and DMA as shown in Fig. 39. The wireless signals are transmitted by four coupling antennas, which are described in Fig. 37. Fig. 38 shows the flow chart of the proposed measurement system, which microchip controls two RF chips to perform transmission and receiving. Then, the signals are transmitted through the SAW via coupling antennas; at the same time, the dsPIC33 can obtain the RSSI with respect to frequency for SAW devices. According to the property of the SAW, the frequency intensity of RSSI is larger than others when the signal's frequency approaches the resonant frequency. After

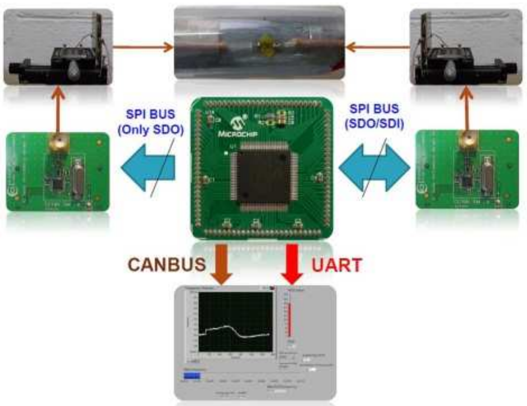


Fig. 38. The block diagram of the proposed measurement system.

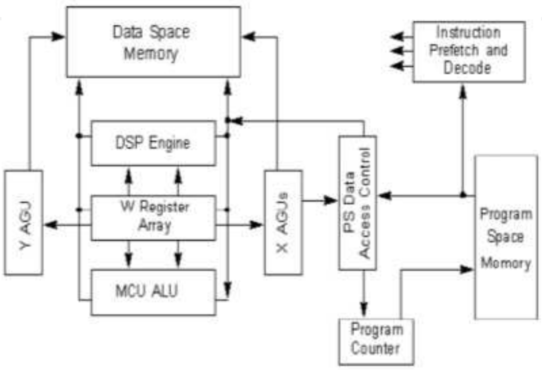


Fig. 39. The architecture of dsPIC33.

dsPIC33 receives the RSSI analysis for the signal in the scanning frequency domain, we can obtain a shift value of frequency with comparison from the initial resonant one for each signal. To control the RF transmit and receive modules of CC1100, the kernel of measurement system is programed in the microchip dsPIC33F which possesses UART and CANBUS transferring functions. The dsPIC33 controller is connected with CC1101 RF modules, which include transmitting and receiving task as shown in Fig. 38.

The dsPIC33 MCU uses four lines of SPI to communicate with CC1101 module such as sweep scanning time. In addition, the RSSI value of CC1101 RF receiving module uses 8-bit digital signal to communicate with the dsPIC33, which controls two RF chips for transmitting and receiving via the SPI signals. For the RF chip which performs transmitting task, dsPIC33 is only set the frequency for transmitting in the register of CC1100. When the RF chip which performs receiving task, the dsPIC33 sets the frequency for receiving in the register of CC1100 and receives the RSSI value in DMA at the same time via SPI signals. Then, the RSSI value is transferred via UART to the host PC to describe the measurement results. The flow-chart of the above process is described in Fig. 40.

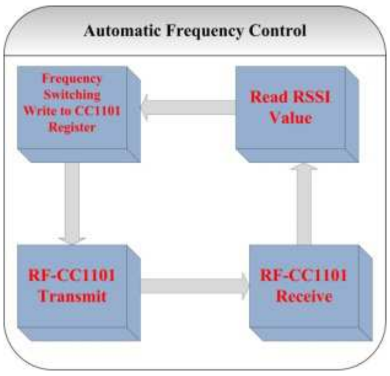


Fig. 40. The flow chart of the AFC Loop code in the dsPIC33F.

4. Experimental results and discussions

In this implementation, the SAW sensors with wireless RF coupling antennas as shown in Fig. 41, are attached on a shaft; the dsPIC33 microchip is used to achieve the transmitting

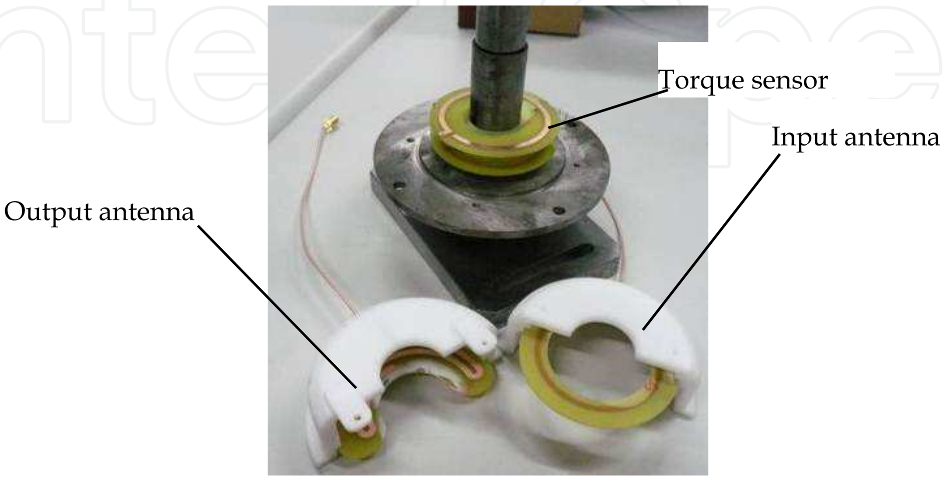


Fig. 41. The wireless torque sensory system.

and receiving RF signal tasks via the RF chips (CC1100). The program embedded in dsPIC33 microchip is coded using MPLAB software, which is the development environment based on C++ language. The microchip dsPIC33 is used to set the transmit frequency of C1100 from 433.1MHz to 435MHz and the interval between the scanning frequency is from 0.5 to 10 KHz for the specified bandwidth. On the receiver side of CC1100, the dsPIC33 makes the RF receiver chip's frequency to match the frequency of transmitting synchronously and then it read the DMA to obtain the intensity of the RSSI. Therefore, the frequency with the maximal RSSI value is obtained and transmitted to PC using CANBUS network. The flow chart of the above processes is described in Fig. 42. On the PC side, a Labview program is developed to display the frequency response as shown in Fig. 43. In this case, we have developed a simple virtual instrument whose purpose is similar to the network analyzer.

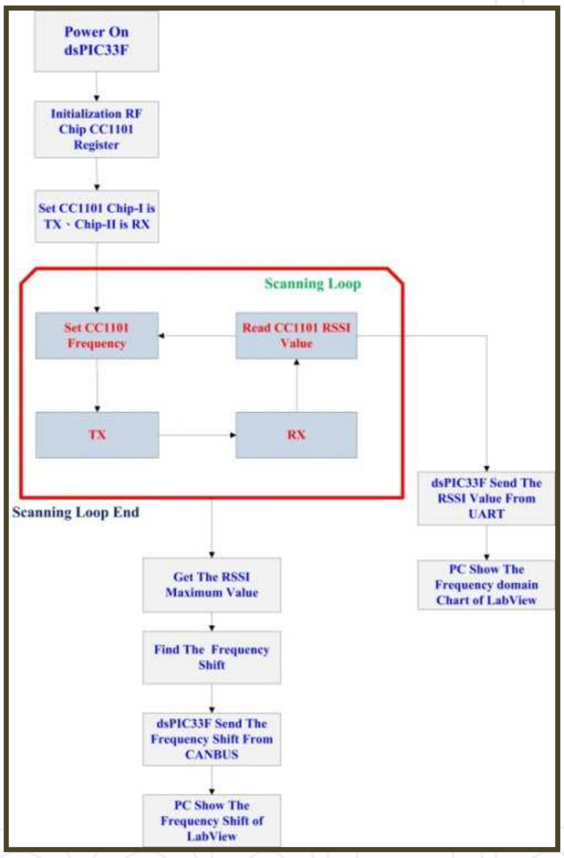
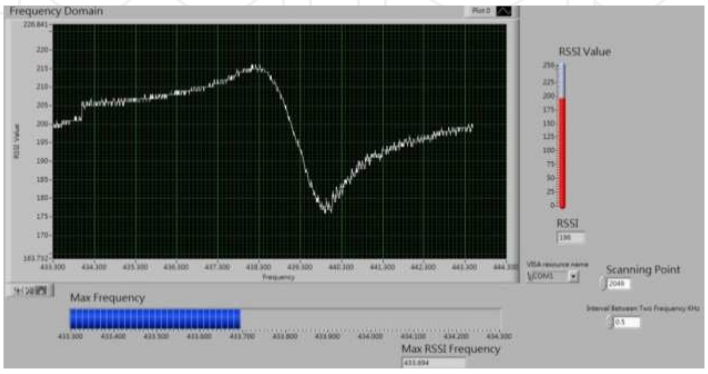


Fig. 42. The flow chart of the dSPIC 33F program.



VISA resource name COM1

Scanning Point 2048

Interval Between Two Frequency KHz 0.5

Max RSSI Frequency 433.694

Fig. 43. The RSSI response with respect to frequency in LabView interface.

Fig. 44 shows the relation between the torque and the frequency shift. We can establish a linear mapping relation between the torque and the frequency shift via using the experimental results in Fig. 44. Then, the torque can be obtained in real-time. For this wireless torque sensing system, the performance index for the sensory system is important for feasible applications. On one hand, we use dsPIC33F with a wide bandwidth to increase torsion sensor performance. On the other hand, different frequency scanning interval introduces the different measurement performance as shown in Fig. 45. The developed sensory system's bandwidth is described in Table 2. From the experimental results, we can summarize the following comments. (1) The smaller scanning interval will cause the lower system bandwidth, but the measurement system is more stable. (2) The less number of scanning points can improve the system performance with bad stability.

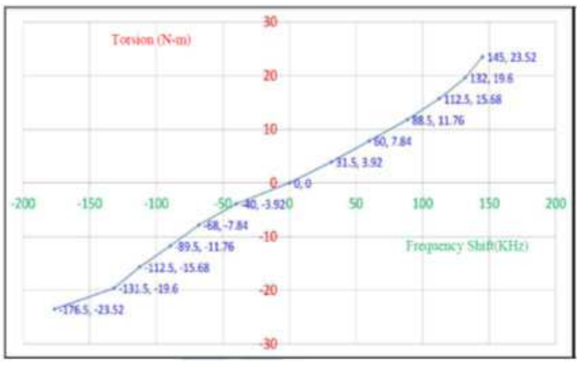


Fig. 44. The experimental results between the torque and frequency shift.

Fig. 45. Number of frequency scanning points v.s. the system bandwidth.

No. of scanning points	System bandwidth (Hz)	Scanning interval (KHz)	Perturbation (KHz)
2000	15	0.5	1
1000	38.43	1	2
500	64.11	2	4
200	191.35	5	10
100	383.1	10	20

Table 2. The bandwidth of the developed torque sensory system.

5. Conclusion

In this paper, we study SAW devices to establish a wireless torque measurement system, which uses the analysis of RSSI to obtain the frequency shift of SAW using embedded microchip dsPIC33F. From the experimental results, a prototype of virtual instrument based on microchip integrated with LabView is used to measure the frequency response of the SAW devices; that is, we developed a simple PC-based Spectrum Analyzer. The measurement through sweeping varies frequency to obtain intensity of RSSI signals can establish the relation between the torque and the frequency shift via the proposed measurement system using UART and CANBUS. The experimental results validated the proposed measurement system.

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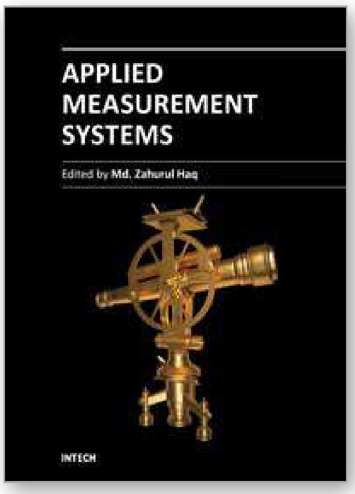

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