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Wireless torque measurement system

Using a telemetry system, one can achieve, with an excellent quality / price ratio, a rotating contactless torque measurement instrument. Following lines introduce bases of such a reliable and accurate instrument. Following lines suppose some knowledge about usual torque measurement systems. Consequently it suppose an understanding of strain gages operations and of radio transmission. Upon request, some references concerning strain gages use as well as concerning industrial telemetry will be forwarded to the design engineer. Introduction Different type of sensors principles must be understood. If there are several means to translate mechanical energy into electrical equivalent signal, the most practical and the most accurate remain the one using strain gages. A lot of torque meters are based on strain gages. To build a rotating torque meter, it is possible to use different transmission means between stationary and rotating part. The accurate, efficient, reliable and smart solution is radio transmission and in between existing radio transmission technologies, the double frequency modulation is the best compromise.

Description

Strain gages, as a full bridge are implemented on a mechanical part that will, because implemented in a kinematics line, be subjected to the torque. This torque will induce deformations. Deformations will change strain gages resistance proportionally to the torque.

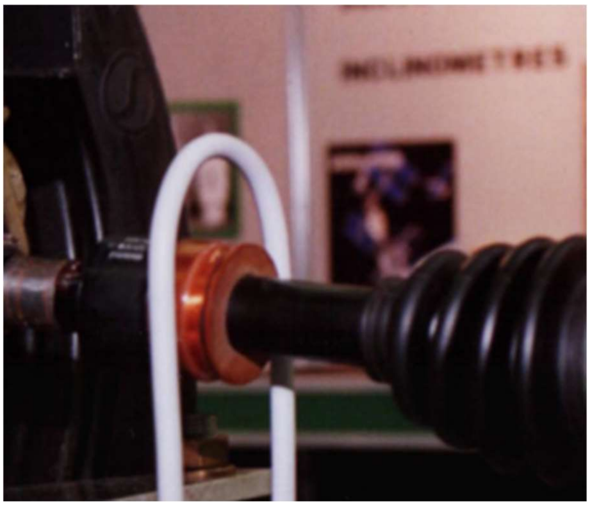
An electronic module including sub-modules as power supply, conditioner, formatting (voltage / frequency conversion) and transmitter will be installed aboard rotating part. The electronics supply a regulated voltage to strain gages bridge, receive the bridge output, amplify voltage measurement, converts it into frequency (sub-carrier) and output of the sub-carrier modulates the transmitter frequency.

Transmitter frequency or ‘ carrier ‘ will travel from a transmitting antenna to a receiving antenna. Then, the frequency is received, a stationary electronic look into it to search for the sub-carrier frequency (pass band filters) and this sub-carrier is converted into voltage corresponding to the measurement performed on rotating part.

Such a solution offers a contact free instrument eliminating frictions and consequently wear free. Without friction, measurements shows better accuracy.

The double frequency modulation radio link is insensitive to pollutions as dust, oil or water projections and is not bothered by electrical perturbations (if the choice of carrier frequency is appropriate). Another interesting point is the possibility to operate at high rotation speeds.

Main concerns for this kind of instrumentation are : 1/ determining if the shaft can be used to perform measurements; 2/ powering on board electronics.



First point will be the matter of a discussion later on, second point fit at this point of the discussion. In order to power properly rotating instrumentation, the strain gages bridge power supply must be considered. As in regular instrumentation a 10 Volt power supply is commonly used and as reduction of power consumption is very important, a good compromise value need to be chosen. Keeping in mind needed sensitivity and accuracy drives the engineer to select a voltage value in between 2 and 7 Volts. Because regulators in 5 Volts are efficient and rather low cost, the 5 V value took the advantage. From there, to power the telemetry, needing 3 to 4 Volts and strain gages bridge 5 Volts, the power supply average value can be approached. If 7 Volts would be sufficient, the existing batteries available come in standard (for one piece battery) in 3, 5 or 9 Volts. This is why 9 Volts is arbitrarily the technical value stated in specifications.

This value allows also the use of inductive power supply.

Calculations

The kinematics line has to be considered and, if possible an existing part of it will be used to sense the torque. Unfortunately, this may not be the best solution for accuracy and sensitivity. The other solution is to manufacture a specific mechanical part dedicated to the measurement. Selecting a shape is an expert job, to simplify, it will be considered in following part a shaft.

Conditioner input is V measurement (Vm), arbitrarily +/- 100 mV. Conditioner is providing 5 V regulated to the bridge V excitation (Ve). Maximum sensitivity for the sensor will therefore be +/- 20 mV/V. Then, calculation will be based on :

$Vm = Ve.k.\varepsilon$

where K is the strain gages coefficient and ε is the number of micro strength.

This number of micro strength correspond to the equation :

$\varepsilon = -\varepsilon = ML / \pi G R3$,

L being a length is not used as it is a section of the rotating shaft that is considered.

And G is = $E / 2 (1 + \mu)$. E is elasticity modulus and μ the Poisson Coefficient.

Then, pulling out R3 gives : $R3 = M/\varepsilon\pi G = [M/\varepsilon\pi].[2(1+\mu)/E]$ Square root gives shaft diameter.

In case of a tube, initial calculation will refer to the equation : $MR/\pi G (R4 -r4)$ Experts would use a limitation for Vm to half of the maximum value so they can save space for adjustments.

As stated earlier the active portion of the mechanical part is the section where strain gages are implemented. On a circular shaft, maximum deformations will occur following directions located at 45 angular degrees of the generating line. Two strain gages implemented at 45 degrees from each other and connected as half a bridge on a single generating line will give an idea of the torque.

To simplify and get read of homogeneity problems related to flexion moments, strain gages are implemented one near the other. Usually double fish bone strain gages are used and considering strength distribution uniformity problems, considering stability, sensitivity and accuracy, 4 of these double gages are used, placed at 45 angular degrees from each other on the shaft section and connected as a full bridge. In order to verify Vm, the relationship between sensitivity in mV/V and micro deformations in ΔR/R can be used. This will be written as

$Vm = 0,250 \Sigma \Delta R/R$ with ΔR1, ΔR2, ΔR3, ΔR4 as each strain gages resistor variation. $\Delta R/R = K.\varepsilon$.

This is purely theorical and practically one can be far from the calculation results even with a very good thermal compensation and all the care in implementation.

Mechanical facts

The accuracy is related to the mechanical part supporting strain gaging. Ideally, in catalogues, the accuracy is very good. It would be a mistake to believe the calibrated in lab conditions torque meters can reach accuracies of less than 0.1 % when used on a machine.

Mechanical part will already show differences before installation on a machine. Then, the kinematics line will induce some errors : misaligning, shear, traction, compression, and moreover if the mechanical part is inserted into the line with mounting means, the errors due to mounting devices. Flanges, teeth coupling, flexible couplings, knee joint couplings … all them will bring some kind of an error. The teeth coupling being one of the best solution.

Since telemetry allows to avoid frictions, the use of ball bearings is the wrong idea.

Accuracy concerns

Temperature effects is one of the factors causing errors. First of all, half bridges and bridges used will have an inherent compensation if the temperature surrounding the implementation is homogeneous. But operating conditions are not ideal and the choice of an auto compensation has to be done. Full scale temperature drift has also to be compensated. This is performed by using thermosensitive resistors in the bridge power supply line.

Electronics temperature drifts are well known and expressed in %/°C/full scale. When considering this type of errors, it has to be kept in mind the temperature of the rotating part and temperature of stationary part will not change in same proportions.

Temperature related errors are the most important but are not the only one. Linearity, aboard rotating part will be affected by the non-linearity of the mechanical part with strain gages bridge and non-linearity of the electronics where non linearity on stationary side will only be affected by the electronics errors.

Hysteresis is taken in account for the rotating part and mainly mechanical and strain gages side, electronics having very low hysteresis.

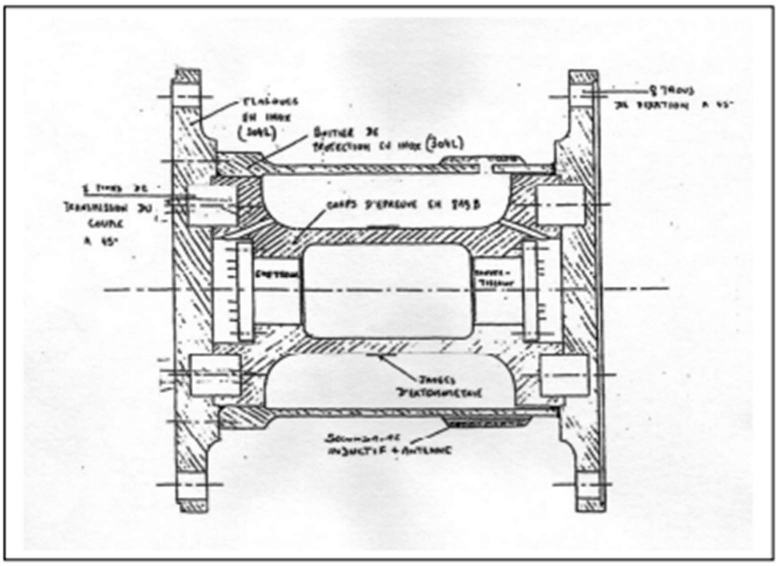
Other errors exists like zero error due to mechanical phenomenon, frictions, gaps and so on.

However, Regarding accuracy, it has to be considered, first of all the errors of the rotating part, then errors due to stationary part. To affect numbers on a specification for a torque meter, several solutions are offered, basically, Static error band = $\sqrt{Lin^2 + Hyst^2 + Repeat^2}$

Total error band = $\sqrt{\sum error^2}$, including temperature drifts with consideration to rotating and stationary part.. Then, the error at Full Scale Output is the difference in torque meter outputs at 100 % and 0 % of torque input at ambient temperature.

One can calculate the end point linearity as : Lin = (Max divergence @ ambient temperature/ Full scale output @ambient) . 100 in % FSO, Then, FSO @ ambient / 5 is Theorical Difference TD and TD/20 % point; TD/40 % point; 60; 80 and 100 gives theorical 20 % point as - actual 20 % / difference. - Repeat for 40, 60, 80 and 100 % (The largest difference / FSO @ambient) . 100 = End point linearity of FSO. Similar calculations can be achieved for hysteresis, repeatability, thermal zero shift and thermal sensitivity shift to end to the error calculation.

Again, what will come out from calculation is to be considered very carefully as from what will be determined in ideal conditions to what will happen on kinematics line the difference may be surprising.



The picture shows an instrumented shaft. Both flanges, left and right are attached to sensitive mechanical part by means of screwed cylinders, this ensure stiffness integrity of the proof body and full torque transmissions . Sensitive shaft has 4 fishbone strain gages assembled as a full Wheatstone bridge on its outside and electronic modules inside central holes. Strain gages bridge wiring is achieved through small holes In order to protect the full assembly a tube is slides over the central mechanical part and mechanically decoupled with elastic compound. Outside the protective tube a secondary coil has been prepared and connected to the central part of the sensor through small hole to AC/DC converter regulator. The active shaft has strain gages on the outside and telemetry modules inside. A tube is covering mechanical sensor. Expected accuracy of the mechanical torque sensing device will be in range of 0.1 % of full range.

Main lines have been described in the beginning of this discussion. Telemetry is a complete electronics including the conditioner. Conditioning strain gages will be achieve with, first of all a regulated power supply. The use of 5 V +/- 0,01 % is convenient as explained earlier. The strain gages bridge output should, if the bridge is properly balanced, a value that will be close to zero. Unfortunately, bridge balancing shows, sometime small errors and as the operation is not straight thru wires may just induce, when the signal is amplified, a saturation at receiver output.. It will then, be important to balance the bridge in order to display a true zero. As it is wireless operation, balancing the bridge can only be done by modifying its zero as resistive point of view. This is made by playing with resistors at differential amplifier input and measuring receiver output. Gain has also to be adjusted by adding a resistor onto the transmitter.

As the differential amplifier output will be entering an oscillator to create a sub carrier, the real zero will correspond to this sub carrier balanced value. Very often, the 100KHz +/- 20 % is chosen. Then zero will correspond to the 100 KHz, this frequency can be catch at receiver side. Full scale + value will therefore be 120 KHz and Full scale – value will be 80 KHz. Electronics are compensated for temperature drift.

The sub carrier frequency is modulating the carrier frequency. This vehicle is chosen in range 150 to 300 MHz. These high values prevent against saturated frequency bands but are low enough not to be directional. It is obvious the carrier frequency is not the one dedicated to measurement and therefore perturbations are not affecting measurement itself. What is requested is no perturbation comes to damage the sub carrier frequency.

The transmitting antenna is, usually a ¼ th of the wave, so : $\lambda = V/ fz$ where, λ is the wave length, V is 300 MHz and fz the transmitter frequency. From wave length in meter divided by 4, it is possible to find antenna length. But, there again, calculation and reality are two things. If with a transmitting frequency of 300 MHz, the wave is one meter, ¼ wave will become 25 cm and this may not be a practical value for mechanical installation on a shaft. There, the experience will help in determining a length for a compromise in between practical value and calculated value. A 5 cm antenna may operate perfectly … For large diameter shafts, it is a little more complicated due to stationary waves. An antenna will, more or less be ¾ of the shaft, but if this value is over the wave length (1 meter for 300 MHz), then, problems could occur.

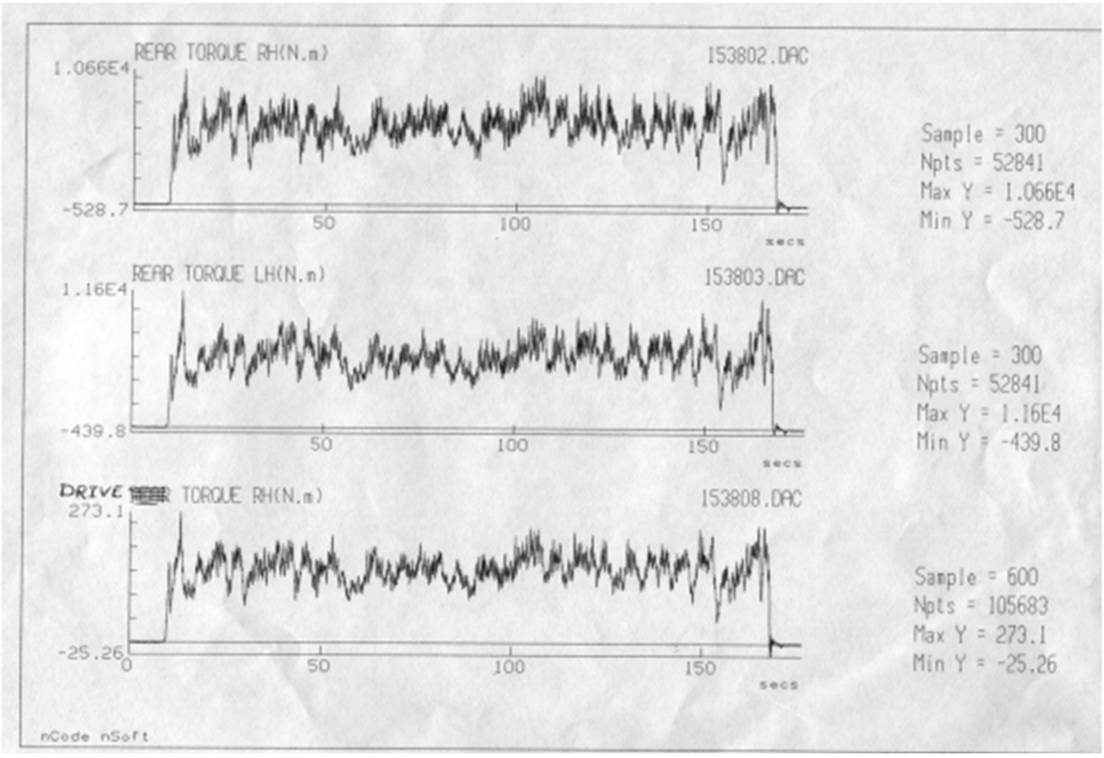
The same could happen with receiving antennas.

Receiver will pick up the carrying frequency, then discriminate sub-carriers to find the initial sub carriers requested. In the school case : 100 KHz +/- 20 %. The pass band filter will provide continuously the frequency that will be transformed in a voltage equivalent to the measurement.

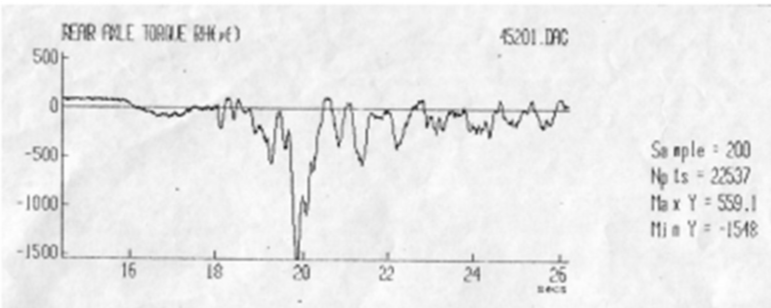
A bandwidth of DC to 10 KHz (- 3 dB) is easy reach. For a torque meter, this means, starting torque peaks can be measured. As well, through filters, continuous value can be observed and process.

Following motions plotted from a real world measurement show the torque applied to both rear wheels of a tractor in same time than the drive shaft torque.

This is done by using 3 telemetry systems operating simultaneously on different shafts and using different carrier frequencies. The 3 motions can be related. (Fig 3 : 3 torque measurements).



This is a commonly use solution for vehicle testing purposes and in order to determine the power on drive shaft, a speed measurement associated to torque will directly solve the problem.



Transient torque measurements are transmitted so one can see what is happening to the torque when the wheel shocks a rock or a side walk.

Some torque measurements are quite critical and redundancy has to be used. If the shaft is supporting two strain gages bridges, it is possible to use a two channels transmitter. In such a case, there will be two sub-carriers frequencies and, first one being 100 KHz +/- 20 %, second one will be 200 KHz +/- 20 %. Both will be mixed simultaneously to obtain a frequency multiplex. Frequency multiplex will then modulate the transmitter frequency. This is very convenient as there is no dephasing between both measurement and bandwidth remain available. Use of such a trick prevent losses of measurement if, for any reason, a strain gages bridge was damaged. It can be used also to measure two different full ranges. A small one will use the full scale accuracy up to the saturation and larger full range will take over offering on bottom side less accuracy but allowing measurements up to the maximum.

Obviously, frequency multiplex can make available more than two simultaneous measurement. 6 and 8 channels systems are available in order, for instance, to measure 6 components (3 forces and 3 moments as well, in case of 8 channels, as temperatures.

Power supplies

If battery power supply is convenient for punctual measurements limited in time, this is not applicable to all of the applications. Reason is temperature and acceleration restrictions due to these batteries. Temperature will reduce duration but Lithium batteries will operate up to 120 °C if needed. Combination of temperature and acceleration is not very good. For centrifugal accelerations, Lithium batteries will withstand, at least 3000 g's. Some Lithium batteries were shoot in mortars with accelerations up to more than 20 000 g's and both transmitters and batteries were reused several time on similar tests.

Since rotating machinery should, most of the time, operate during long period of time, anther solution has to be setted. Inductive power supply is a smart and effective solution. Basically, the inductive power supply is made, as a transformer, of a primary and a secondary coil. At the opposite of the transformer there is no metal in between both coils. Induced signal from primary onto secondary offers enough energy to the electronics. If temperature is not really a concern, as the secondary coil and primary are just windings of copper wires prepared on insulating support sandwiching Mumetal, if acceleration is not either a concern because of low mass of secondary coil, limitations are due to the distance between primary and secondary. Usual gap will remain below 10 mm max. Both coils need to be face to face. Bigger gaps can exist, if the power generator is supplying more energy, if the flux is oriented and so on.

The best solution in most of the cases is to rely on specialists experience and have them design, and sometime test, the inductive coupling.

Conclusions

To conclude on this subject, a good torque meter can be designed and manufactured, adapted to a dedicated application or with some possibilities to be use on several applications. A calibrated torque meter based on telemetry will push the limits in range up to several tons, the limits in centrifugal acceleration up to 100 000 g's, and will be maintenance free for years.

Such torque meters are implemented on vehicles : cars, trucks, trains, but also on test benches, production machinery as rolling mills and so on.

We have been been supplying torque instruments for more than 35 years.

References : • Telemetry and application (CETIM – Senlis France) • Telemetry Conference, Paris 2002 • Experimental analysis – Vishay Micromeasurement • Automotive telemetry – T.C.E. Laboratories • Telemetry standards (Range Commanders Council NM - USA)