
Development of a Magnetoelastic Torque Sensor for Formula 1 and CHAMP Car Racing Applications

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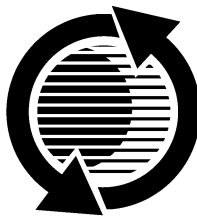
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ABSTRACT

The benefits of a magnetoelastic torque sensing system and its application on Formula 1 and CHAMP Car racing driveshafts are identified. In particular, the use of circumferential remanent magnetic bands on the shaft itself has enabled a design that satisfies the application's demanding packaging requirements. The criteria used to determine the suitability of a given shaft material for optimal magnetoelastic characteristics and concurrent mechanical strength are illustrated. Shaft material and geometry are shown to have significant effects on sensor performance. Design considerations for the magnetic field sensor layout and signal conditioning circuit are also presented. The racing driveshaft application is shown to add particular challenges in terms of temperature, packaging, and kinematic tracking. Magnetization and calibration processes associated with field operation of the sensor are discussed. Selected results from extensive track testing with Stewart-Ford in Formula 1 and Visteon-Patrick Racing in CART are presented and analyzed. Successful development and implementation of the racing torque sensor as a basis for extension to mass production automotive applications is suggested.

INTRODUCTION

Measurement of torque is useful in a diverse range of industrial fields, for it is one of the two fundamental physical quantities (the other being speed) needed to analyze rotating drive mechanisms. Specifically, the torque being transmitted by a race car's driveshaft (also often referred to as half-shaft) can provide a wealth of information about the performance of the powertrain and chassis. Other locations of the measurement could also be potentially valuable in quantifying and analyzing transmission efficiencies.

Visteon Racing first implemented the non-contact drive-shaft Torque Sensor System to support the Stewart-Ford Formula 1 racing program[1]. Following an extensive survey of all existing torque sensing technologies including those used for non-automotive applications, the categories of technologies viable for open-wheel racing were reduced to two: telemetric strain gauge technology and magnetoelastic polarized band technology. It was felt that developing a telemetric strain gauge sensor would be superfluous given that various competitors had already reached a fairly advanced stage of development for such a system. It was also felt that at the most fundamental level, a torque sensing system requiring neither components attached to nor functional contact with the shaft would be far more desirable, not only for racing applications but eventually for production car applications as well[2]. From this basic premise, the development team worked to apply magnetoelastic polarized band sensor technology[3],[4] to the Stewart Grand Prix drive-shaft.

Magnetoelasticity is the term used to describe the interactions found in many materials between magnetic system quantities (e.g., field, magnetization) and elastic system quantities (e.g., stress, strain). MDI* torque sensor technology operates on a specific manifestation of magnetoelasticity termed the Inverse Wiedemann Effect [5]. By this effect, a magnetic field can be caused to arise in the space around a torsionally stressed member. In the chosen design, circularly polarized bands of magnetoelastically active shaft material create a magnetic field that, in polarity and intensity, is a near perfect linear analog of the torque transmitted. The transducer uses no excitation power and requires only a magnetic field sensor array in addition to the shaft to construct a complete device (see Figure 1).

* MDI refers to Magna-elastic Devices, Inc., Carthage, IL, USA

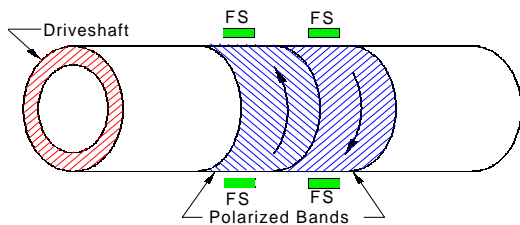


Figure 1. Schematic representation of the driveshaft torque sensor system. Note the air gap between the field sensors (FS) and the shaft.

Overcoming the specific challenges of the racing driveshaft application has resulted in implementation of a "smart" driveshaft, which functions both as a load-carrying mechanical member and as a *naturally wireless* torque transducer. This integrated approach to torque measurement has yielded a novel and robust solution to the design problem at hand. Its ability to perform in the tasking racing environment (very high temperature, vibration, and stress levels) also suggests a technology with significant future promise for mainstream automotive applications.

THE NEED FOR A RACING TORQUE SENSOR

OVERVIEW – Before delving into the details of torque sensor design and development, it would be beneficial to understand the specific uses of such a device in the racing arena. As mentioned earlier, driveshaft torque measurement is a fundamental parameter in evaluating and improving the performance of a racing vehicle. Such information is typically very difficult to measure on the track, and heavy reliance is made on laboratory dynamometer data and lap simulation models. These approaches rarely yield fully representative results, however, because it is difficult to simulate true racecar behavior. Modeling the complex interactions among engine, gearbox, final drive, and aerodynamics can be prohibitively time-consuming and costly. Thus from powertrain to chassis to aerodynamic analysis, the torque actually transmitted to the driving wheels constitutes an invaluable performance metric. Specifically, three major uses for a driveshaft torque signal can be identified:

1. Actual horsepower measurement and in-vehicle dynamometry
2. Tuning and/or real-time control of the differential
3. Aerodynamic drag estimation and correlation with wind-tunnel data

In-Vehicle Dynamometry – Due to powerplant-vehicle interactions, there is generally a significant difference between the installed power and uninstalled power delivered by a race car's engine. Analogous effects are known to appear on other vehicles, e.g., gas turbine engines on aircraft [6]. Such discrepancies reflect the many dynamic effects associated with the vehicle being

in motion, effects which are oftentimes lost in the laboratory measurements. This lack of track-related information makes it difficult to evaluate the effectiveness of engine modifications or mapping changes in the electronic controls. In addition despite tight tolerances and the many steps that are taken to ensure good repeatability in engine manufacturing and assembly, it is a well known fact that there may be variations in engine power from one particular unit to another that for the purposes of racing could be significant.

By measuring net torque delivered at the wheels (through the driveshaft) in real time, and combining this measurement with simultaneous speed measurement which has been standard on racecars for many years, it is possible to measure true power. Such measurements provide a valuable tool in the comparison of new revisions of engine mechanical hardware, electronic mapping, or a combination thereof. In addition, they help to determine what specific conditions on the track create discrepancies between predicted engine behavior and actual performance. Modifications and development of engine calibration can now be based on installed engine performance measured with this in-vehicle dynamometer rather than a less tightly correlated laboratory dynamometer. The chance to have throttle-torque-speed maps that are obtained from real track data allows the race engineer to more effectively tune the engine for improved driveability.

Tuning and Control of the Differential – Although undoubtedly useful, the evaluation of engine performance via driveshaft torque sensors is still somewhat indirect due to the fact that the measurement is made further downstream in the powertrain. With respect to the differential, however, driveshaft torque measurement provides very direct benefits. Monitoring the torque delivered at each rear wheel reveals precious information about the response of the drivetrain to a variety of cornering conditions. Once this information has been analyzed, data-driven modifications to the differential's setup can be made. In the CHAMP Car series, for example, in which oval tracks are very common, the level of stagger can be ascertained and tuned to the specific track. In Formula One racing, torque feedback can be taken a step further, by being used in real-time. An embedded controller utilizes the torque signals as inputs to enhance the differential's control strategy as the vehicle enters and exits corners.

Aerodynamic Drag Estimation – Typically, a racing chassis manufacturer will invest hundreds if not thousands of hours in wind-tunnel testing in an effort to quantify and optimize aerodynamic performance. Wind-tunnel measurements are often used to create three-dimensional maps of aerodynamic downforce as a function of front and rear ride height, or aerodynamic drag as a function of front and rear ride height. To complement and substantiate these maps, track tests such as coast-down tests and wide-open-throttle tests are often carried out. These

tests provide some track-based indication of vehicle performance at steady-state conditions. The main limitation inherent in these types of tests, however, is the fact that during real race conditions the vehicle is very rarely in a steady state. As a result, coast-down tests and wide-open-throttle tests are only marginally effective in revealing aerodynamic drag and downforce as a function of acceleration or deceleration. Use of driveshaft torque allows a more granular assessment in that knowledge at all times of driving torque at the rear wheels can help account for any discrepancy between expected and achieved acceleration as being attributable to aerodynamic drag.

MDI TECHNOLOGY APPLIED TO RACING

As mentioned earlier, few methods of measuring torque are generally well-suited to applications as environmentally challenging as automotive, not to mention motorsport. A rather extensive comparison of the various candidate technologies has been discussed in Garshelis et. al.[7] and Fleming[8] and therefore will not be repeated here. Suffice it to say that in the final analysis, there are certain specific attributes of magnetoelastic polarized band technology that strongly suggest its superiority for racing applications:

- Non-contact mode of measurement
- Torsional stiffness and consequent short axial extent
- Low cross-sensitivity to temperature
- Low mass and compact size

Despite these compelling advantages over other technologies, the magnetoelastic polarized band approach carries with it certain restrictions. The following considerations should be noted:

1. *Choice of shaft material.* Although there are a number of materials that can be made to function concurrently as shaft and transducer, the choice is limited. The material must at the very least be ferromagnetic and demonstrate favorable magneto-elastic properties. The magnetoelastic polarized band approach could not be used, for instance, with titanium or carbon-fiber composite shafts.
2. *Positional containment.* Angular articulation and axial plunge of the driveshaft with suspension travel result in motion of the very source of the torque-dependent magnetic field. To avoid variation of the detected field with position, it was found necessary to design a mechanism (discussed further in the section "Housing Assembly" below) that allows the magnetic field sensor array to track the trajectory of the driveshaft at all times.
3. *Magnetic environment.* The presence of ferromagnetic components, and the use of ferromagnetic tools, in proximity to the torque sensor, can be detrimental if not appropriately controlled. For instance, all transmission parts and tools must be regularly demagnetized prior to use on the vehicle.

TORQUE SENSOR SYSTEM ARCHITECTURE

INTRODUCTION – The driveshaft torque sensor system actually is comprised of two transducers, one magnetoelastic and the other electromagnetic. These sub-systems allow the measurement chain to traverse from applied torque, to torsional shear stress, to magnetic field, to a raw electrical voltage signal, to the final output which is a standard analog 0-5V. The links in the measurement chain, and the associated architecture, are shown in Figure 2 below.

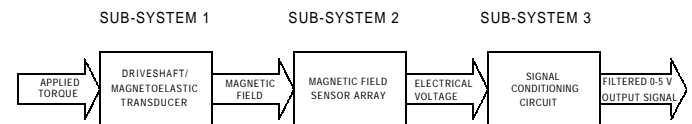


Figure 2. Torque Sensor System Signal Flow Diagram

MAGNETOELASTIC TRANSDUCER – Perhaps the most challenging aspect of the development of a race-worthy torque sensor lay in the detailed design of a suitable magnetoelastic transducer. The packaging benefits of an integrated solution were clear from the outset, but concurrently meeting mechanical and magnetoelastic requirements proved challenging. Mechanically, ultra-high strength (on the order of 2GPa tensile strength), toughness, and fatigue resistance were critical. The driveshaft is sized to have both minimum mass and adequate strength to transmit the required torque. As a matter of fact the driveshaft, while classified as a safety critical item, is often the single most highly stressed component of a racing transmission.

Beyond satisfying mechanical requirements, to perform adequately as a transducer, the shaft material needed to have sufficiently high magnetostriction and coercive force. Also, due to the high temperature of the application, low cross-sensitivity of the magnetoelastic transducer to temperature was essential. Hence at a minimum, the material's Curie temperature was required to be well above 150°C. A number of candidate ultra-high strength steels were evaluated, with varying degrees of success. Interestingly, certain alloying combinations originally selected to improve mechanical properties such as hardenability, are now believed to also contribute to the required magnetic properties.

Another objective in the development of a suitable transducer was stability of the transfer function with repeated cycling at the high stress levels expected during race conditions. This consideration was necessary due to the fact that for any given material, the output is generally not a single-valued function of the applied torque but depends on the total history of stress variations[9]. Verifying the attainment of a stable response is best carried out empirically by checking for consistent results upon repeated cycling, as described in the section "Calibration/Break-In" below.

MAGNETIC FIELD SENSING ARRAY – At the present state of the art, there are three main types of vector magnetometers, i.e. devices which detect the magnitude of that component of the magnetic field which lies parallel to their sensitive axes. These are the saturable-core or “flux-gate” type, Hall-effect type, and magnetoresistive-type (MR) magnetometers.

Based on concerns about temperature cross-sensitivity of Hall effect and MR magnetometers, these classes of sensors were deemed inappropriate for the driveshaft torque sensor environment. The problem is that the offset and sensitivity changes over temperature of existing Hall and MR devices are of the same order of magnitude as the very fields of interest. Packaging considerations, i.e. proximity of exhaust gases and/or brake discs depending on the particular customer team, all but dictated the use of a field sensor with extremely low cross-sensitivity to temperature. For these reasons, Unitika MS930 saturable-core type torque sensor elements[10] were chosen. Each such element consists of a small diameter, solenoidal winding (coil) of high temperature insulated magnet wire, encircling a single strand of near zero magnetostriction amorphous metal fiber (core). In an effort to avoid potential problems from ambient magnetic field gradients and slight inhomogeneities in circular magnetization of the remanent bands, two diametrically opposed pairs of elements were used.

HOUSING ASSEMBLY – The magnetic field sensing array is contained in a Dupont Vespel® (polyimide) two-piece housing. In addition to the upper and lower Vespel housings, the overall assembly consists of: an aluminum protective cover; four Unitika elements mounted on two purpose-built printed circuit boards (PCB's); four titanium fasteners; “RTV” potting compound; and a racing-specification loom (see Figure 3). This two-piece housing, which is not intended to bear any significant loads, is designed to maintain the radial gap between the sense elements and the polarized magnetic bands on the drive-shaft. Vespel was selected for its dimensional and structural stability at high temperature, and its electrical insulating and self-lubricating properties. Several steps were taken to minimize housing-to-housing variability. These included the fabrication of PCB's designed for the ‘pick and placement’ of the field sensors; tightly controlled tolerances on the housing inner diameter; and machined pockets intended to minimize the variability of sensor location within the housing.

The aluminum cover serves several functions: it protects the wires and sensors from damage imparted by track debris, provides a strain relief facility for the wire, and holds the attachment points to which customer teams connect the unit to the racecar's chassis. It is important to note that only non-ferrous materials are used in the vicinity of the housing assembly. This assembly is mounted to the non-sprung end of the driveshaft to minimize relative axial motion between the shaft and the housing. A mech-

anism is needed to constrain the housing's axial and circumferential motion relative to the shaft, and to provide a means of attachment to the vehicle's chassis. The mechanism should not allow maximum axial ‘float’ to exceed 1mm throughout the suspension's travel from full jounce to full rebound. Many mechanism designs, from yoke assemblies to collar-tether devices, were attempted with varying degrees of success. To date, participating teams have been tasked with the design and fabrication of this device. Generally speaking, all other factors being held equal, designs which constrain the relative motion most effectively will yield the most accurate data.

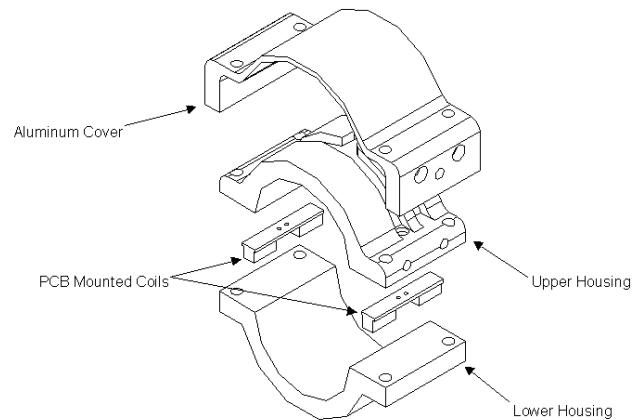


Figure 3. Exploded view of the magnetic field sensor array housing assembly

SIGNAL CONDITIONING CIRCUIT – As in many other applications which require accurate measurement of magnetic fields using saturable-core type magnetometers, a dedicated driver and signal conditioning circuit is needed. This circuit carries out certain functions specific to the sensing element being used, and other more generic functions downstream such as rectification, filtering, and amplification in order to provide a standard 0-5V linear analog output signal.

The driver circuit runs the saturable core in the sense element into and out of magnetic saturation by way of an alternating current of triangular waveform. Since the slope of the triangular driving current is constant, the resulting voltage waveform across the coil will be approximately a square wave. As the core is saturated by the field associated with the applied current, its inductance, and by extension its voltage, drops dramatically. Upon application of torque to the shaft, a torque-induced magnetic field will add to that applied by the excitation current. The net result, which lies at the heart of the operation of the circuit, is that the amplitudes of positive and negative currents needed to saturate the core will no longer be equal. The resulting asymmetry in the voltage waveform manifests itself as a second harmonic to the driving frequency. By measuring the phase and amplitude of this second-harmonic component, the amplitude and direction of the torque-induced magnetic field, and thus the torque, can be accurately determined.

SYSTEM PREPARATION & VALIDATION

MAGNETIZATION – Detailed magnetization procedures have been developed for each of the two types (CART/F1) of driveshafts. These procedures, which are quite standard [11], [12], consist of rotating the shaft in the presence of the fringing field from a narrow gap C-shaped electromagnet. They differ only slightly due to the unique geometry of each venue's driveshaft design. Driveshafts are magnetized initially upon receipt from the manufacturer and subsequently after each magnetic particle inspection type of non-destructive evaluation (NDE). The need for re-magnetization stems from the fact that the high currents associated with the NDE tend to compromise the integrity of the original remanent magnetization. Shafts which have been magnetized and are returned after NDE are first brought to a standard demagnetized state via specially fabricated solenoidal coils which can generate sizeable AC fields. Other steps taken to minimize variability include: 'boiler plate' procedure check lists for each shaft; tight dimensional and positioning controls on the magnetization fixture with digital readouts accurate to 0.001 mm; and the use of a laboratory grade programmable current supply for excitation of the magnetizing heads.

CALIBRATION/BREAK-IN – All newly magnetized or re-magnetized shafts are subjected to an appropriate break-in procedure prior to final calibration. This procedure consists of a series of loading cycles during which the magnetoelastic transducer's transfer function creeps toward its steady state value. The apparatus used to load the shaft consists of a rotary hydraulic actuator driving one end of the shaft with the other end held stationary. The applied torque, which is measured by an instrument-grade torque cell, is used as the reference standard for individual sensor calibration. Ultimately, it is the data from this final testing that provides the system transfer function (expressed in Nm versus Volts) which the team will use to acquire the desired torque measurement from their vehicle. To maximize the subsequent usefulness of the calibration data, customized data acquisition and manipulation software was written. The procedures simply calibrate sensor output voltages to input torque such that the results can be readily 'cut and pasted' from an electronic document to each team's on-board data acquisition system. Calibration procedures vary on a per venue per magnetization state (newly or remagnetized) basis. Generally, the calibration/break-in procedure is governed by the maximum positive and negative applied torque and the total number of cycles at these levels. Care must be given in the selection of the maximum positive and negative calibration torque levels. In fact, these limits were found to be specific to a given venue and track and often had to be obtained iteratively based on track data. If the peak applied torques are selected too low then the implemented system will have the potential to exhibit an unstable transfer function.

If they are set too high then the system may show excessive hysteretic behavior. The number of cycles must also be stipulated in order to ensure a stable transfer function. A sample final calibration obtained at the end of such a break-in process is shown below.

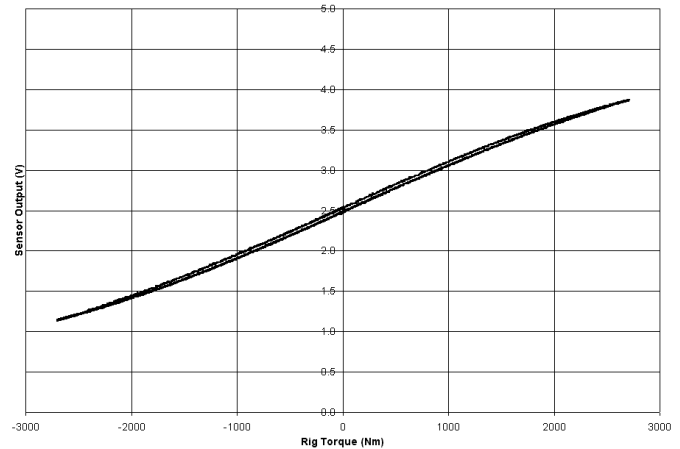


Figure 4. Sample Driveshaft Torque Sensor System calibration. Abscissa: Applied torque (Nm) Ordinate: torque sensor system output (V)

POST-TRACK CALIBRATION VERIFICATION – Occasionally and especially early in the development of the sensor it was necessary to re-calibrate each shaft after every test event. This proved particularly useful when trying to diagnose any apparent anomalies in sensor behavior. The re-calibration procedure is a very simple process whereby the shaft is subjected to one cycle of torque with an amplitude equal to the maximum positive/negative torque values as defined in the calibration/break-in procedure. A plot of sensor output voltage versus applied torque can then be compared to the pre-track calibration. This comparison can yield a wealth of information such as evidence of possible plastic yielding or fatigue damage. Such forms of irreversible metallurgical change are typically manifested by zero shifts or sensitivity changes. An ideal sensor will have the same transfer function pre and post track test and for that matter over its entire useful life.

CIRCUIT DIAGNOSTICS AND CHARACTERIZATION – Efforts to minimize circuit variability motivated the development of an infra-structure to characterize and compare every signal conditioning circuit to a designated reference ('golden') circuit. The system uses a programmable current wave form generator (amplifier) wired in series to adjacent solenoidal coils to simulate the magnetic field which emanates from a shaft under torque. This field is then detected by a reference ('golden') field sensor array which is connected to the signal conditioning circuit under test as though it were on a vehicle. The apparatus is also used to test the bandwidth of each circuit. Circuit bandwidth is defined as that frequency at which a 45° phase lag is seen in the sensor output signal with respect to the input current, or the output amplitude drops to

70.7% of the zero frequency amplitude. Knowing parameters such as the current amplitude and frequency sent to the coils and the number of wire turns allows the aforementioned signal conditioning circuit characterizations.

TRACK DATA DISCUSSION

Presented below is track data from one of many test sessions during which the torque sensors were utilized. The discussions associated with the track data will qualitatively focus on only the torque information and how it relates to vehicle conditions (it is recognized that other factors can and do have an influence). Because the data is proprietary to the participating teams, all scales have been removed from the graphs.

GEARBOX TORQUE ANALYSIS – Gearshift events create “torsionals” as they are called in the art. These are torque oscillations and interactions created in the shafts (common throughout the entire drive-train) and in particular the driveshafts during an up or down shift. Figure 5 illustrates the existence of this phenomenon during a sequence of upshifts and downshifts. The torque drops associated with the shifts can be attributed to detailed shift events such as engine spark cuts, clutch disengagement, reaching a new gear ratio, and for a brief moment the fact that no dog rings are engaged. This leaves only the inertial torques necessary to accelerate or decelerate the rotating parts. As the vehicle traverses the straight-away note that the right and left wheel torques are balanced within reason (the straight may not be perfectly straight) until it approaches a turn. This would be expected unless the team were running stagger (different wheel diameters left vs. right, as is sometimes done in the CART series) with a locked differential, in which case a constant torque imbalance would be expected. As the vehicle enters the subsequent turn, a significant difference between the right and left wheel torque appears.

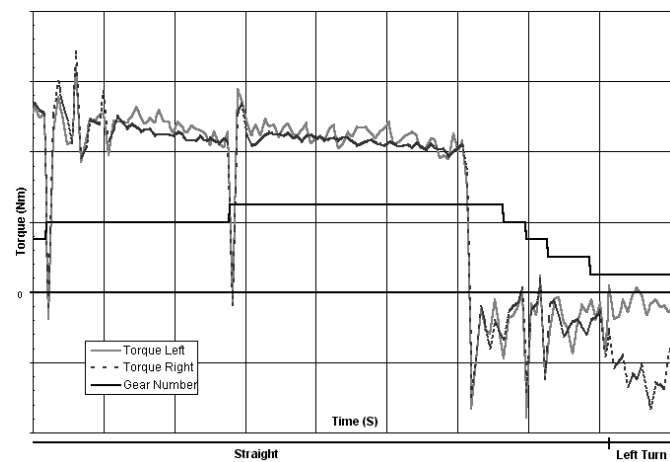


Figure 5. A plot of the left and right rear wheel torques during an upshift sequence on a straight-away followed by a rapid downshift sequence during corner entry.

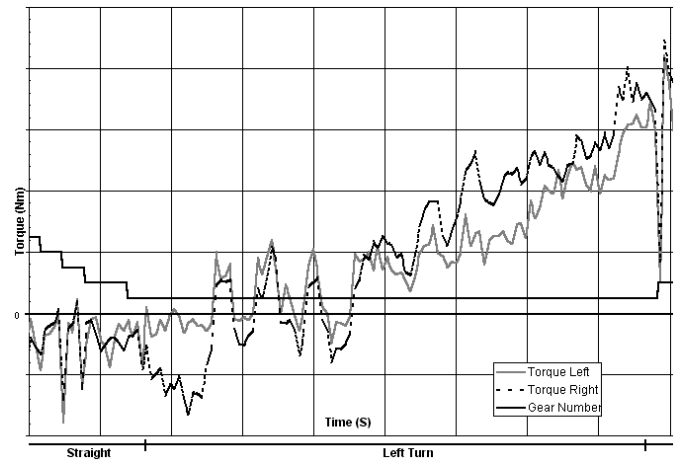


Figure 6. A plot of the left and right rear wheel torques during a downshift (deceleration) sequence on a straight-away followed by a left-hand turn sequence.

DIFFERENTIAL TORQUE ANALYSIS – Setup of the differential in the case of a mechanical Salisbury arrangement, or real-time control as with some F1 teams’ electro-hydraulic units, can have a significant impact in the ability of the vehicle to enter and exit turns most efficiently[13]. To date, it has not been uncommon for teams to rely almost solely on the feedback from the driver when fine tuning a vehicle’s setup for corners. Terms such as “over-steer” and “under-steer” are used by drivers to explain the handling of the car at the entry, apex, and exit of turns. Based on this information, parameters such as ramp angles (acceleration and deceleration), pre-load, and calibration maps can be adjusted to improve vehicle handling throughout the various segments of the turn.

Figure 6 and Figure 7 show torque-vs.-time plots for a left-hand turn and right-hand turn sequence, respectively. From the torque data the entry, apex, and exit become apparent. Once again, the data shows an equal distribution of the torque between right and left until the vehicle enters a given corner. Upon entry, this torque distribution changes such that the more heavily loaded outside wheel (the wheel opposite the turn) transmits a higher (amplitude) torque. As the vehicle approaches the apex, in the case of a Salisbury type differential, the system now acts as an open differential and the wheels have very little coupling. The torques in this segment are relatively small and equal since the driver is transitioning from the brakes to the throttle. From the apex to corner exit, as the throttle is transitioned back to wide-open the differential couples the right and left driveshafts, once again creating an imbalance. Such torque imbalances create yaw moments that in turn can influence the impression drivers realize at different stages of a given corner. By monitoring, or even better, controlling these imbalances the performance of the differential can be optimized, thus improving overall vehicle dynamics.

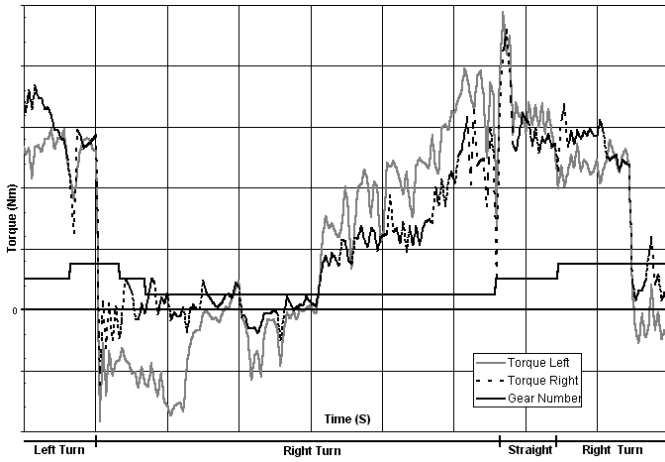


Figure 7. A plot of the left and right rear wheel torques during entry to and exit from a right-hand turn sequence.

ENGINE/AERO POWER ANALYSIS

Generating power curves from measured torque on the driveshafts is not difficult given the tangential speed of the associated wheel and the tire diameter. These are parameters typically available on most racing vehicles. Given the expression for power in Watts as:

$$P(W) = T(N \cdot m) \times \omega\left(\frac{\text{rad}}{\text{s}}\right) \quad (1)$$

An expression for the angular velocity (ω) can be found in terms of measured quantities by the following:

$$\omega\left(\frac{\text{rad}}{\text{s}}\right) = \frac{0.2778 \times V_t (\text{kph})}{R(\text{m})} \quad (2)$$

Where V_t is the tangential velocity in kilometers/hour of the associated wheel and R is the radius of the wheel in meters. Combining these equations yields the following expression for the power delivered to each wheel:

$$P(W) = 0.2778 \times \frac{T(N \cdot m) \times V_t (\text{kph})}{R(\text{m})} \quad (3)$$

A word of caution is necessary when using this equation to infer tractive power output: no effort was made to account for the dynamic behavior of the loaded tire radius R with wheel rpm and vehicle speed (aero loads). Furthermore, since the gearbox is a considerable source of inefficiency which is not reflected in this expression, the power calculated from (3) is somewhat removed from engine power output. Nonetheless, the use of the driveshaft torque measurement does allow the modeling and race engineers to better quantify powertrain losses and thus be left with only aerodynamic drag-related losses to infer. For example, a comparison of the amount of torque required to achieve a certain speed using different aerodynamic configurations on given portions of specific tracks can be made. Or, the impact of such real-life phe-

nomena as vehicle roll or response to a cross-wind on a given race car setup can be assessed.

CONCLUSION

Formula 1 and CHAMP car racing venues have provided an unusually exciting and challenging opportunity to develop innovative torque sensing technology. While there is still ample room for improvements, it has already demonstrated measurable benefits to various customer teams in the two major open-wheel series. More broadly, this application illustrates the benefits of interdisciplinary approaches to vehicle system design. Hopefully this paradigm shift, successfully implemented in these racing applications, will help accelerate torque sensor development in mainstream automotive applications such as electric power-assisted steering and torque-based powertrain control.

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