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TORQUE MEASUREMENTS AT THE ENGINE OUTPUT DURING SEA TESTS

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Abstract. *The paper presents the design and implementation of a torque measurement system based on slip-ring to assess the output torque of a marine engine. The measurements were to be done during sea tests in order to evaluate the actual operating condition of the power train. Different kind of propellers were used although the focus of the investigation were not directed to their hydrodynamics. The design of a halved slip-ring, to be mounted without the need of axis disassembling, is discussed and its dynamics is modeled in order to establish the contact conditions between brushes and signal tracks, and the resulting highest operating speed. Results from measurements are showed and the signal processing involved is also discussed.*

Keywords*: Torque measurement, Slip-Ring, Marine Engine*

1. INTRODUCTION

The increasing complexity of modern engines and their application leads to an increasing need for monitoring sensors and diagnosis systems in order to improve reliability (Collacott 1977). Combustion engines have become more and more automatized in the recent years, with the trend of the so called “electronic”-engine. Specially in the case of diesel marine engines the ability of getting on-line information about load, fuel consumption, engine speed, etc... helps not only lowering operational costs but also allows, to some extent, a predictive type of maintenance.

Nevertheless, even for new engine types, one may face situations where the mechanical power delivered by the engine must be measured and compared to its nominal specifications. If this is the case for a completed boat, there is only seldom the possibility of dismounting the power train without major, cost intensive, interventions on the hull or deck structure. For these situations the measurement of the mechanical power during sea tests may be the only alternative. This work discusses the design and implementation of the necessary equipment, in order to measure the mechanical power, through the measurement of the output torque, of a diesel maritime engine during a sea test. The results obtained are partially shown.

2. POWER AND TORQUE MEASUREMENT

The main objective of the work is the measurement of the output power of a diesel engine in different operating conditions, in maritime application. This kind of engine may also be used in trucks and in power plants where the same necessity may arise. In order to measure the mechanical power delivered by the engine its actual output torque is measured at the output axis and the obtained value is multiplied by the instantaneous speed, of course car must be taken with the presence of gear boxes and the related reduction ratios. Since the actual power is measured the overall efficiency of the power train, eventually with the gear boxes, must be considered when comparing the experimental values with the nominal ones.

Nowadays, with electronic engines the assessment of engine speed is quite easy, even for diesel ones. If it is fitted with individual fuel lines for each cylinder their pulsation, during the injection phase, can be used to generate a suitable signal, related to engine angular velocity. For engines with common rail technology the injection is controlled directly on the injection valves and no pulsation will be available. Nevertheless this kind of engine is already fitted with speed sensors which normally deliver a sequence of pulses per engine rotation.

To measure the output torque strain gages must be applied to a loaded portion of the output shaft, allowing its mechanical deformation to be assessed. On a shaft loaded in pure torque, the stress distribution on its surface indicates the use of 4 gages on a full bridge arrangement, each applied with sensitive direction at an angle of 45º with the shaft axis (Hoffmann 1989). A special strain gage rosette with two gages at 90º helps achieving good alignment, specially if they are to be applied to the shaft inside the machine room of a boat.. Figure 1 shows such a strain gage rosette applied to the output shaft of a diesel engine to be monitored.

Figure 1. Strain gage applied to output shaft

The main difficulty in torque measurement, besides the correct installation of the gages, lies on the fact that the signals rotate with the shaft, whereas the measurement equipment remains stationary. In order to get the signals out of the rotating shaft two common possibilities may be explored (Dally et alli 1993): telemetry and slip-rings. While telemetry appears as an interesting way, with signal conditioning, radio frequency emission and signal modulation circuitries embedded and mounted together on the rotating shaft and a reception and demodulating module stationary, its use may be difficulted by the available space and electro-magnetic interference.

The use of slip-rings, in turn, may suffer from the poor electrical contact between stationary brushes and contact lanes on the shaft. It also tends to be less costly than the telemetry solution. Since the steel shaft itself conducts electricity the lanes must be placed on a non-conductive sleeve.

A challenging aspect of the slip-ring needed for the particular application is the fact that the shaft shall not be unmounted from the gearbox since it would cause misalignment which would need to be further verified and compensated in a laborous procedure. The installation of the gages in a midway position between the coupling with the gearbox and the mechanical sealing, as shown in Figure 1, demands the use of a partitioned sleeve to allow for the contact lanes to be placed around the mounted shaft.

2.1. Slip-Ring Design

The shaft length available between coupling and mechanical seal is of only 130mm. In order to allow the strain gages to be adequately applied the slip-ring assembly will have a partitioned hollow sleeve which will cover the gages on the shaft and will also serve as protection.

The electrical output signal from the full Wheatstone bridge formed by the strain gages is connected to the only two contact lanes on the sleeve. To save space the power supply of the bridge is accomplished by a 9V battery and a 5V regulator mounted on a circuit box, fixed on the sleeve. To improve signal to noise ratio the circuit also incorporates an instrument amplifier with adjustable gain. Two 9V batteries are used to build a symmetrical source for the amplifier. The three batteries mentioned, along with a fourth one for balancing purposes, are fixed on the circuit box.

The slip-ring assembly consists of:

- ✔ 2 Partitioned sleeves (nylon)
- ✔ 2 Contact lanes (copper)
- ✔ 1 Circuitry and power supply box (aluminum)
- ✔ 6 Brushes (carbon)
- ✔ 3 Holders (steel and wood)
- ✔ 1 Fixation plate (steel)

The whole assembly is sketched on Figure 2. Figure 3 schematically shows a cross section which reveals the hollow space underneath the sleeve, covering the strain gages.

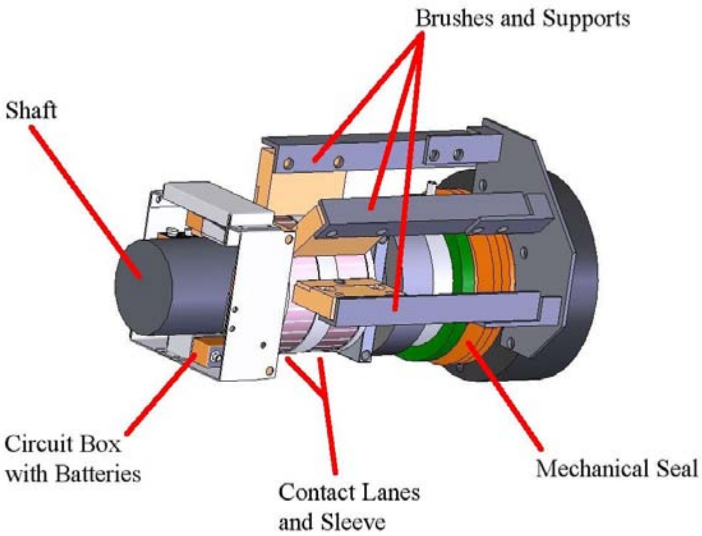

Figure 2. Complete design of the Slip-Ring

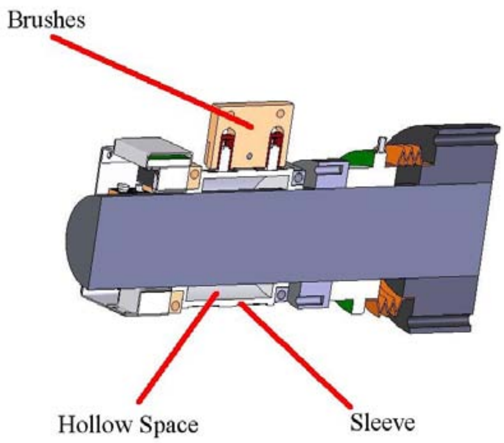

Figure 3. Cross section scheme of the Slip-Ring

2.2. Mechanical Characteristics

One of the main problems of the design is the use of the partitioned sleeve, due to mounting reasons. The two half sleeves are pressed against the shaft and fixed in place by two clamps. On the other hand each of the contact lanes are cut from a thin copper plate and wrapped around the sleeves, tensioned. The lanes have their extremities fixed on one single half sleeve by screws, thus guaranteeing that there is only one discontinuity along the perimeter of the sleeve.

This discontinuity causes the electrical contact to a single brush to eventually break and, therefore, losing the transmitted signal. In order to deal with this problem each lane is in contact with three brushes, in different angular positions, assuring that at least one of them will remain in contact while the other one will go through the discontinuity in the lane. The total of 6 brushes are pressed against the lanes through mechanical springs in linear guides.

Another important parameter is the eccentricity and deviation from a perfect circular path along each lane. Since the shaft will be rotating at different angular velocities these form errors will dynamically excite the brushes and contribute to the failure of the signal transmition. Although the errors, mainly due to eccentricity, may vary from mounting to mounting, it is worth knowing the profile of the contact lanes and the geometry of the discontinuity, for they will be necessary inputs for a dynamical model of the system.

The slip-ring without brushes is mounted on a test rig in a balancing machine and the lane profiles deviation are measured with the help of laser displacement sensors, as shown in Figure 4.

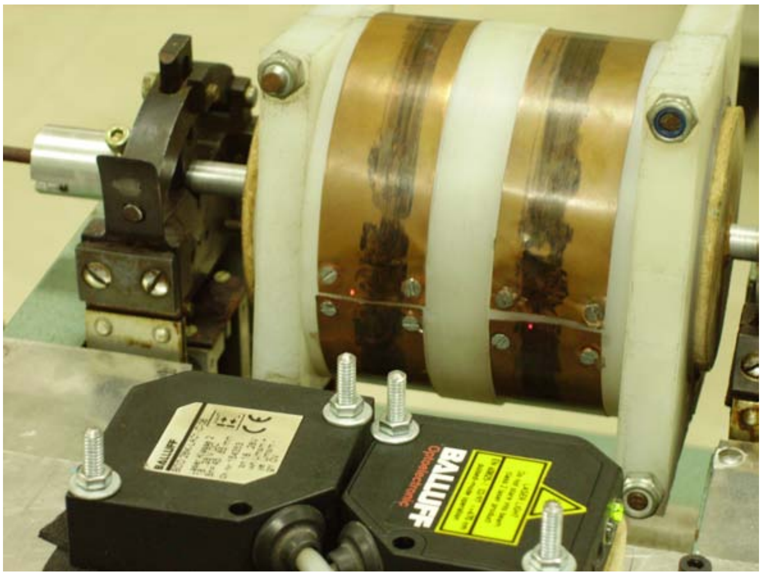

Figure 4. Measurement of lane profiles

The laser beams are easily seen on the picture, together with the fixing clamps and the discontinuities on both contact lanes. The assembly is set into rotation at, approximately, 1630 rpm and the signals of the laser sensors and a reference pulse are recorded to obtain the desired lane profiles. The discontinuities, however, due to their size and change on the reflective characteristics, cannot be adequately measured with this method. Figure 5 shows the deviations of both lanes from the ideal circle as measured in about twelve complete revolutions. The angles are measured regarding the reference 0º angle from the balancing machine.

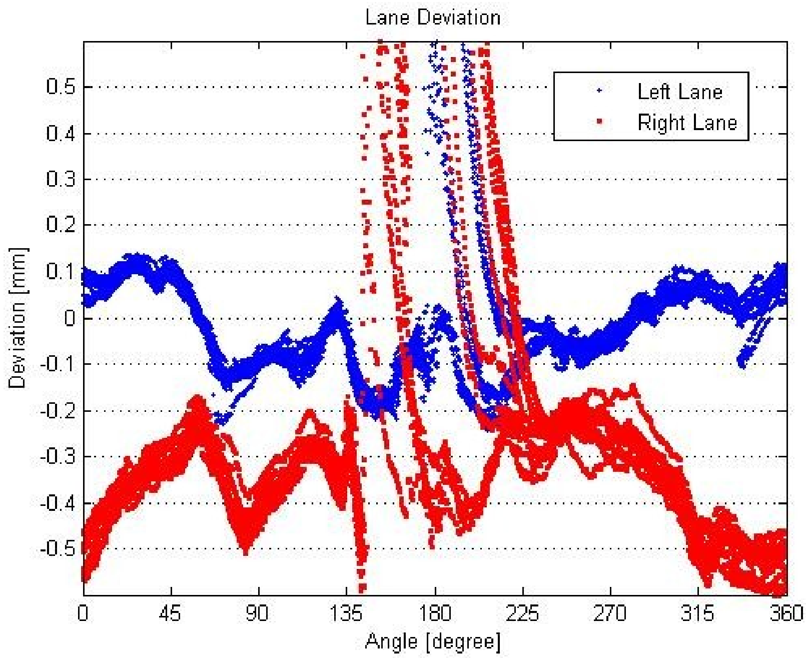

Figure 5. Lane deviations

It can be seen that the discontinuities, at approximately 170º for the left lane and 150º for the right one, disturb the values from the laser beams. The values outside the discontinuities agree quite well for each revolution of the ring. The deviations, not including the discontinuities, are bound to about -0.2mm to 0.15mm for the left lane and -0.6mm to -0.15mm for the right lane.

Measurements done with a gauge indicate that both discontinuities exhibits a depth of about 0.6mm. These values, together with the results from the laser sensors, are important inputs to evaluate, in a dynamical model, the contact of the brushes, and their capacity of signal transmission without failures.

3. SLIP-RING DYNAMIC MODEL

The dynamics of the brushes can be analyzed by a quite simple model with one degree of translational freedom for each brush. Considering the brush displacement as x, its mass m and the rigidity of the restoring spring as k, the differential equation governing the motion can be easily written as Equation (1)(Tenenbaum 2006):

$$m\ddot{x}+k(x-x_n)+f_{fc}=f_{exc} \tag{1}$$

where f_{fc} is the friction force between the brush and its guides and f_{exc} is the excitation force from the lane contact. The natural, unstretched length of the spring is x_n. The mass m and spring constant k were found experimentally. The mass being directly measured with a precision scale has a value of 0.00116kg but it may vary as the brushes are worn out. The spring constant was obtained by hanging different known masses through it and measuring the vibration frequencies. The mean of the calculated values establishes a constant k of 93,8 Nm.

The friction forces between brush and guides are more difficult to model. Nevertheless, they can be approximated by an overdamped viscous friction, since no vibration can be observed by displacing the brushes alone in their housings. The correct assumption for the spring preload due to x_n is also difficult to be precisely evaluated in an actual assembly, and will also show some variation during the brush wearing in service. Therefore this parameter will be only adjusted to reasonable values in the simulations.

The excitation force is modeled as a unilateral contact between the surface defined by the lane, with deviations and the discontinuity, and by the brush (Pogorelov 2005). It behaves actually as a very stiff non-linear spring acting only in one direction and respective friction force in the contact tangent plane.

The simplified system of one pair lane-brush is modeled in the software Universal Mechanism, suitable for the dynamical simulation of multi-body systems. The results obtained in terms of the brush displacement can be seen in Figure 6 for different angular velocities of the lane.

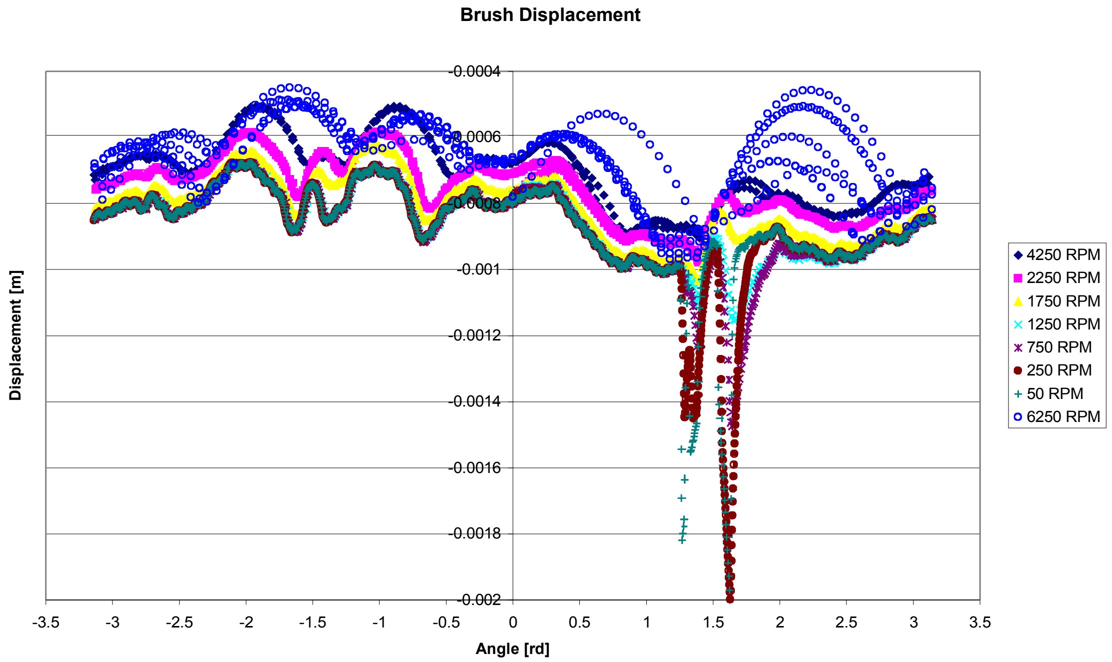

Figure 6. Simulated lane displacements for different speeds

For small angular velocities the brush follows adequately the lane profile as can be seen. For speeds above about 1700 RPM deviations from the profile can be recognized, deviations that are quite rough at 4250 RPM and above. With the simplified model, the measured lane profiles and the simulation it is possible to determine the working conditions of the slip-ring and eventually signal transmission problems.

4. APPLICATION

The slip-ring assembly designed and described earlier was used to measure the output power of a diesel marine engine during sea tests at Guanabara bay in Rio de Janeiro. The tests were conducted with two different propeller types in order to verify their adequacy and the engine performance. Figure 7 shows the the slip-ring assembly in place. The strain gage circuitry completed at the shaft is hidden by the sleeve and cannot be seen.

Figure 7. Slip-Ring assembly in engine output shaft

The torque was measured from the output of the strain gages end multiplied, after unit conversion, by the engine speed obtained from the electronic engine control. The signals were digitally recorded with a four channel ORCHESTRA system from 01dB Metravib, and analyzed with the corresponding software and spreadsheets.

During the measurements the instrument amplifier failed due to electrical reasons and the unamplified bridge voltage output was fed directly to the contact lanes. The obtained, low voltage, signals from the Wheatstone bridge were thus heavily contaminated with noise. Nevertheless, the spectral analysis showed major noise components in frequencies above 60Hz. Since the main interest was the overall performance and output torque of the engine in a very low frequency range, it is possible to filter out the noise done with a low-pass filter with cut-off set at 15 Hz. Figure 8 shows the original, noise corrupted signal, and its filtered version along with its the RMS values. It is worth mentioning that the signal had an voltage amplitude of about 5mV and was correctly transmitted through the slip-ring.

Different operating conditions were chosen for the sea test, at defined engine speeds, and the transient behavior between these velocity levels were also recorded. The measured output torque and output power can be seen in figures 9 and 10 respectively. The vertical axis of both graphics are normalized for contract reasons.

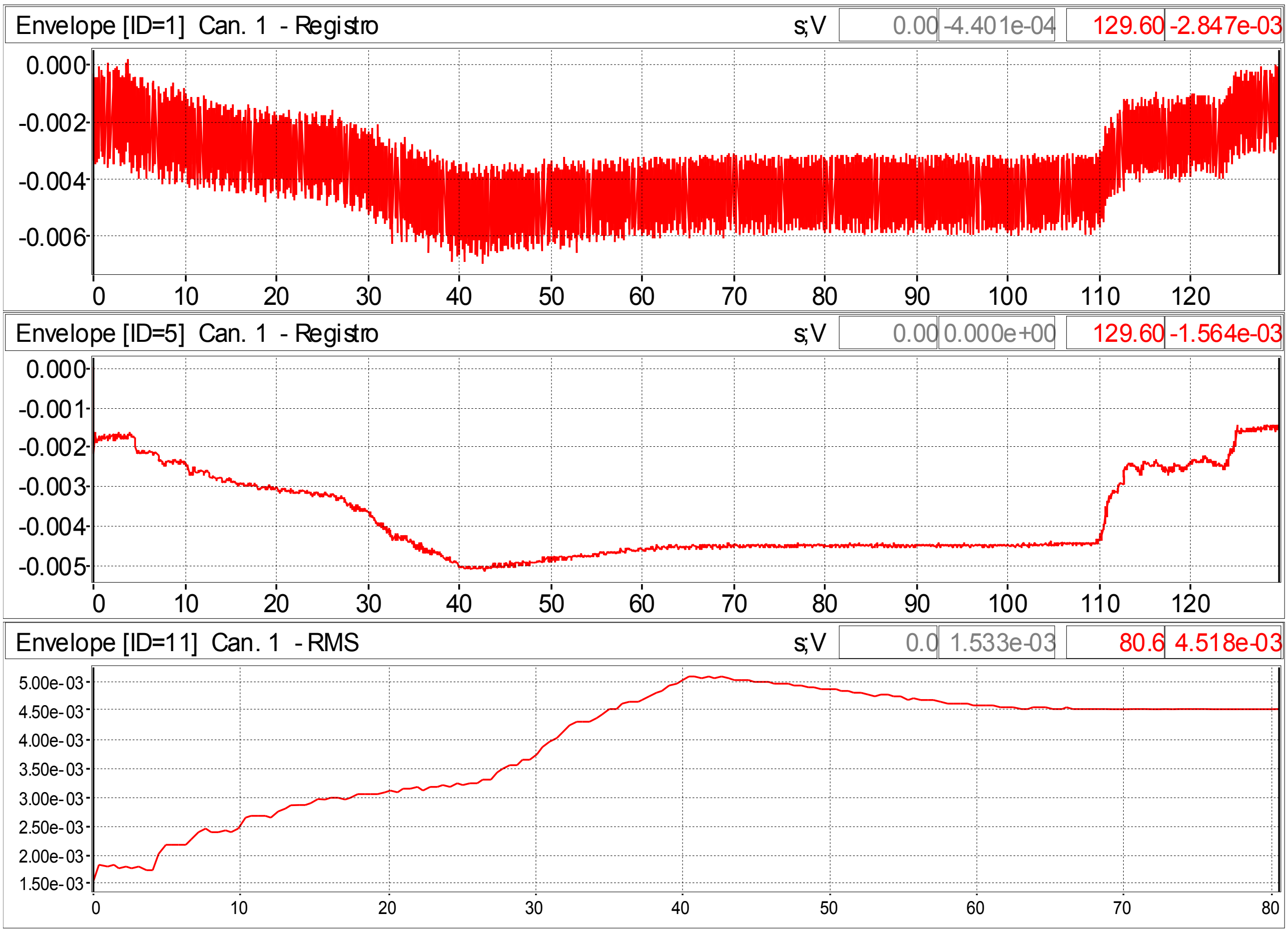

Figure 8. Actual torque measurements
Original signal [V], low-pass filtered version of the signal [V], signal mean (RMS) [V]

The example measurement shown in figure 8 is related to a wide-open-throttle acceleration, while the results from figures 9 and 10 were obtained from the run through different engine speed levels (1000, 1500, 1800, 2100 and 2500 RPM respectively), and the transients between them. Due to the gear box at engine output the actual velocity of the output shaft, where the slip-ring is mounted, is 1.92 times smaller than the engine speed. The slip-ring can thus operate well in these conditions, specially with three redundant brushes in order to guarantee electrical contact to the lanes.

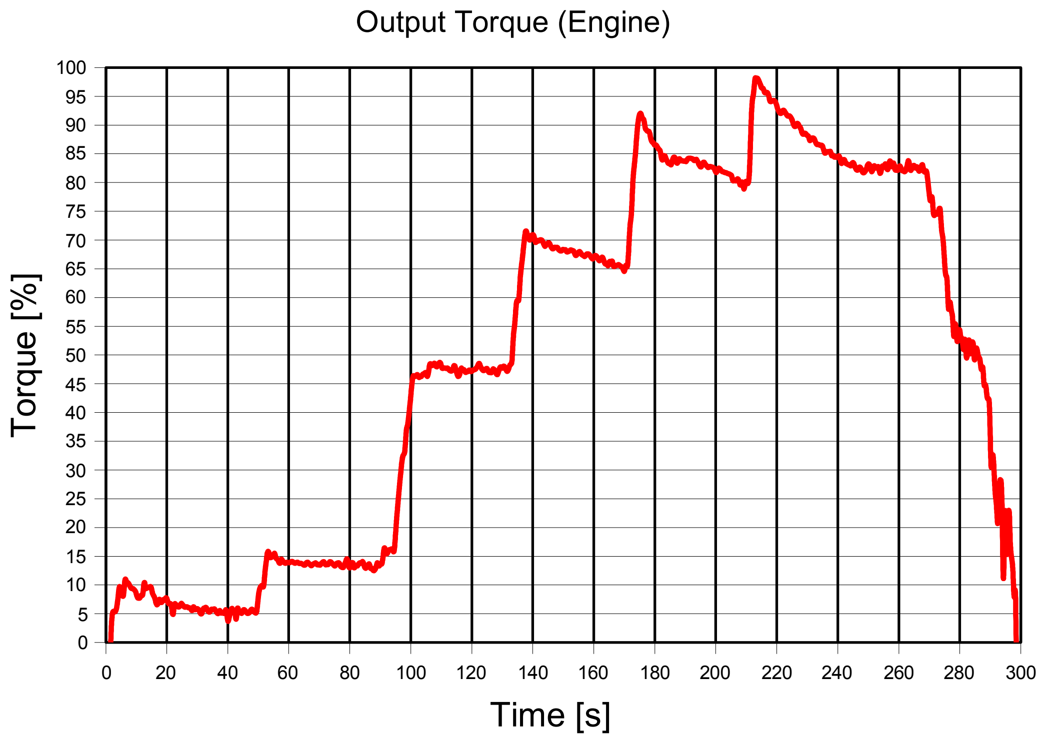

Figure 9. Measured output torque (normalized)

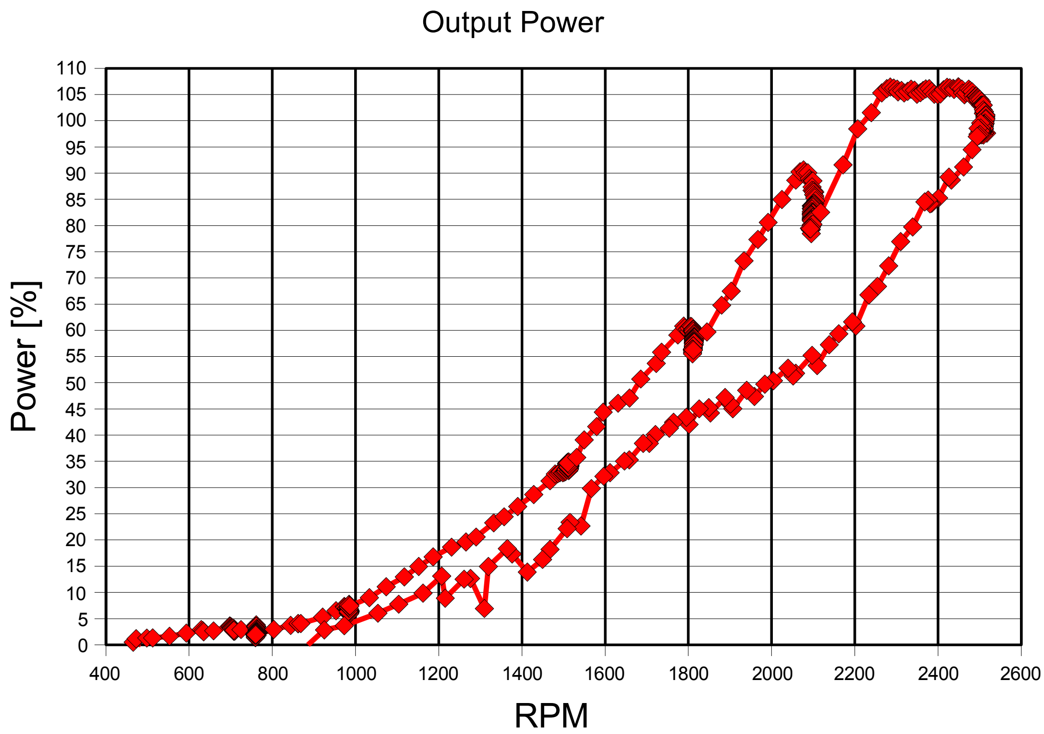

Figure 10. Measured output power (normalized)

It can be seen that, during the transient of speed changes, the output torque grows rapidly and decays as the speed is controlled to remain in specified levels. The output torque exhibits a similar behavior. The transient just before the full power condition shows a fast increase in output power, beyond the rated limit (100%), which is then controlled by the electronics to remain at 100% in full speed (2500 RPM).

5. CONCLUSIONS

The task of measuring the output power of an engine, through the measurement of the torque on a rotating shaft is a challenging one. Although telemetry might be the best choice in most situations for the signal transmission between shaft and the stationary equipment, some situations may require the use of slip-rings.

The use of slip-rings fro the signal transmition faces the problem of the electrical contact between brushes and lanes, specially due to the dynamical excitation of the brushes. The use of partitioned sleeves, allowing the mounting of the slip-ring in the middle of a shaft increases the form errors, therefore, increasing the complexity of the interaction with the brushes.

A slip-ring assembly, with partitioned sleeves and wrapped copper lanes, is designed tested and applied to measure the output power of a marine diesel engine. The successful design was able also to adequately transmit even the unamplified bridge signals from the strain gages. The torque signals were filtered and analyzed together with the engine speed in order to obtain the engine power.

The transient behavior of the engine, with its electronic control, can be seen in the results obtained. Due to the filtering of the signals effects from individual cylinders cannot be analyzed.

6. REFERENCES

Collacott, R.A., 1977, "Mechanical Fault Diagnosis", John Willey & Sons Inc., New York, USA, 584 p.

Dally, J.W., Rilley, W.F. and McConnell, K.G., 1993, "Instrumentation for Engineering Measurements", Carl Hanser Verlag, Munich, Germany, 677 p.

Hoffmann, K., 1989, "An Introduction to Measurements Using Strain Gages", Hottinger Baldwin Messtechnik GmbH, Darmstadt, Germany, 291 p.

Pogorelov, D., 2005, "Universal Mechanism 4.0 – User´s Manual", Bryansk State Technical University, Bryansk, Russia.

Tenenbaum, R, 2006, "Dinâmica Aplicada", 3a. Ed., Editora Manole, São Paulo, Brasil, 812 p.

7. RESPONSIBILITY NOTICE

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