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I.C.E. Net and Lost Power Estimation During Free Run-Up and Coast-Down

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Abstract. The measurement of torque–speed characteristic curve for an internal combustion engine (I.C.E.) gives fundamental information about its overall working conditions. In this work a very simple and effective method is presented and verified through tests on several spark I.C.E. It consists of a detection of spark pulses with a current clamp and of a data processing procedure that provides the torque–speed curve in real time. The main advantage of this method is that it provides an easy and economical way to check operating conditions of an engine without any particular setup. Results are presented for three engines for which manufacturer's data are available.

Sommario. La misura della curva caratteristica coppia–velocità di rotazione per un motore a combustione interna fornisce informazioni fondamentali sulle sue condizioni globali di funzionamento. In questo lavoro viene presentato un metodo semplice ed efficiente, che è stato verificato mediante tests effettuati su diversi motori ad accensione comandata. Esso consiste nella rilevazione della corrente di accensione delle candele con una pinza amperometrica ed in una procedura di elaborazione di tali segnali che fornisce la curva coppia-di rotazione in tempo reale. Il principale vantaggio di questo metodo è che esso costituisce un modo economico per controllare le condizioni operative di un motore senza alcuna preparazione preventiva. Vengono presentati i risultati relativi a tre motori per i quali sono disponibili i dati dichiarati dal costruttore.

Key words: Torque characteristics, Engine diagnostics, Data processing, Internal combustion engines, Automotive applications.

1. Introduction

The diagnostic of internal combustion engines (I.C.E.) requires the measurement of considerable information which defines engine operating conditions and are fundamental for engine setup and to validate dynamical engine models [1, 2].

Even if in recent times the attention is focused on emission control and hence on the detection of misfiring [3, 4], the most important characteristic of engine behaviour remains however the curve of net output torque M_n vs angular velocity n, but the test rigs for its determination, like brakes directly coupled to the crankshaft or roll benches used with the complete vehicle, are unfortunately very expensive. Moreover test conduction requires properly trained personnel and is not therefore applicable for periodic checks of the overall I.C.E. working conditions.

In this work a technique that allows the estimation of M_n–n curve through a simple measurement of the angular velocity during a free run-up and a free coast-down of the engine mounted on any vehicle is presented. The angular velocity can be determined by measuring spark pulses with a current clamp, and from the angular acceleration it is easy to obtain the output net torque.

Even if the principle is well known, its simple and reliable application required non-trivial data processing. Compared to other available procedures [5, 6], the developed system can be easily applied to factory testing at the end of the manufacturing process as well as in normal periodic checks in any car repair shop.

2. Measurement of Non-Stationary Torque During a Free Run-Up

The net power of an I.C.E. during a free run-up can be estimated by using the equation

$$J_R\dot{\omega} = M_m - M_r = M_n, \tag{1}$$

where ω is the angular velocity of the engine (the equivalent n [rpm] will be used from now on), J_R is the moment of inertia reduced to the engine crankshaft, and M_n is the net output torque given by the difference beetwen the motor torque M_m and the resistant torque M_r. The net torque is then dynamically balanced by inertia torque reduced to the engine crankshaft, and the net torque can be evaluated by measuring the angular acceleration during a free run-up. During the coast-down, obviously $M_m = 0$, and the deceleration of the engine is due to passive forces alone.

The reduced moment of inertia also depends on the motion of alternate masses (pistons, rods, gudgeon pins) and is not constant with the crankshaft angle, but it is composed of a constant part and of a periodic part. This seems to complicate the estimation of the net torque, but it will be shown later how Equation (1) can still be applied using the average moment of inertia J_{av}.

3. Estimation of the Engine Angular Acceleration

Even in the most favourable hypothesis of an I.C.E. available in a laboratory test setup, it is quite hard to directly measure the angular acceleration.

Only angular velocity can be directly measured by means of voltage (tacho) or pulse generators (optical encoders) applied to any rotating shaft linked in a kinematically rigid way to the crankshaft. From this measurement the angular acceleration can be estimated through an analog or digital differentiation by processing a signal whose amplitude or frequency is proportional to the angular velocity.

Figure 1 shows the M_n–n curve of an hypothetical engine that has a variable moment of inertia. From this curve, the n–t curve during a free run-up has been obtained through a numerical simulation. The engine rotational speed n seems to increase regularly, but a time derivative of this curve to obtain the angular acceleration leads to results shown in Figure 2 (left); eliminating the time, the characteristic M_n–n curve shown in Figure 2 (center) is obtained. Small torque fluctuations clearly depend on the variability of J_R that produces an irregularity in the engine rotational speed that is heavily highlighted by the numerical derivation process. A digital filtering [7] of this signal is then necessary to correctly estimate the angular acceleration without the oscillations due to the variations of J_R.

The angular velocity signal has been filtered with a low-pass filter with a cut-off frequency sufficiently below the 2nd harmonic of the engine, i.e. the fundamental frequency of the variable part of the moment of inertia of the engine. Figure 2 (right) has been obtained by low-pass filtering the signal shown in Figure 2 (center) with a cut-off frequency of 8 Hz, and it perfectly matches the real M_n–n curve of Figure 1 (left). The chosen cut-off frequency corresponds to 1/4 of the 2nd harmonic of the engine rotating at 1000 rpm, that represents the minimum velocity for the tested engines.

The angular acceleration will be estimated through a derivation of the filtered angular velocity signal; filtering must be performed anyway even in the ideal condition of perfect and noiseless measurement of angular velocity.

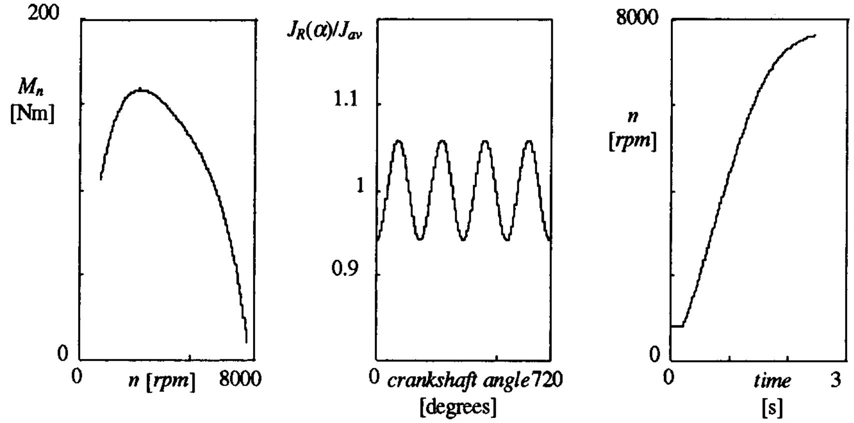

Figure 1. M_n–n curve for a fictitious I.C.E. (left), mass moment of inertia fluctuation (J_{av} =average moment of inertia) (center), simulated free run-up n–*time* curve (right).

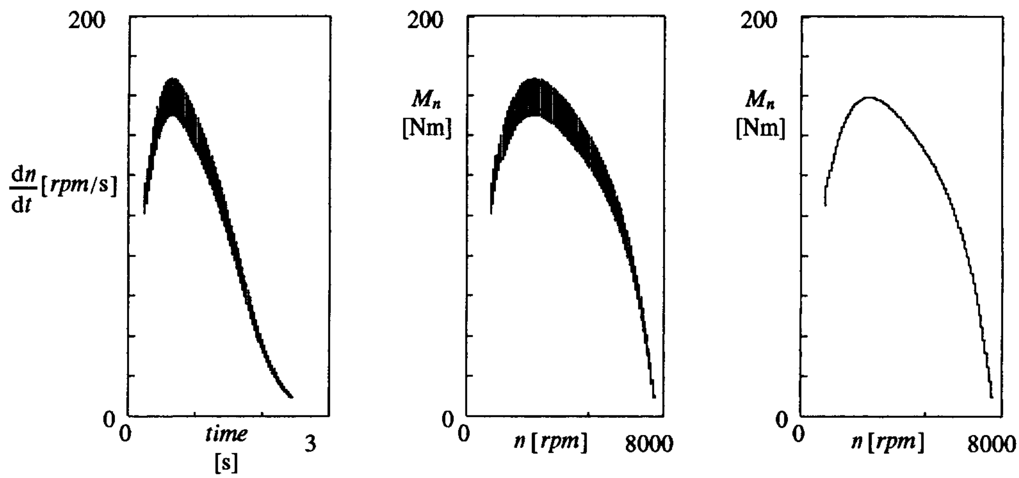

Figure 2. Time derivative of n–*time* curve of Figure 1 (right), M_n–n estimated curve (center), low-pass filtered M_n–n curve (right).

The possibility to measure n with a tacho generator or an encoder has been mentioned before but, as the n variation is very fast, tacho generators do not follow such variations with sufficient precision resulting in a high underestimation of the net torque, while digital encoders, thanks to their very good angular resolution and the absence of "inertia" in the electronic circuitry, allows a correct measurement of the engine rotational speed but their use contrasts with the extreme simplicity desired for the indirect torque estimation measuring system. As the estimation of M_n–n curve is required without applying any particular measuring device to the engine, the use of an encoder on the crankshaft or on the flywheel clearly was not considered.

The simplest method to measure the angular velocity of a spark I.C.E. in a non-intrusive manner is the use of a transducer capable either to detect ignition system pulses directly on the low voltage part of the circuit (or with a current clamp on high voltage spark cables) or to use specifically designed output pins available at the regulator/rectifier unit. These pulses must be converted to a signal proportional to the angular velocity of the engine by a frequency-voltage conversion.

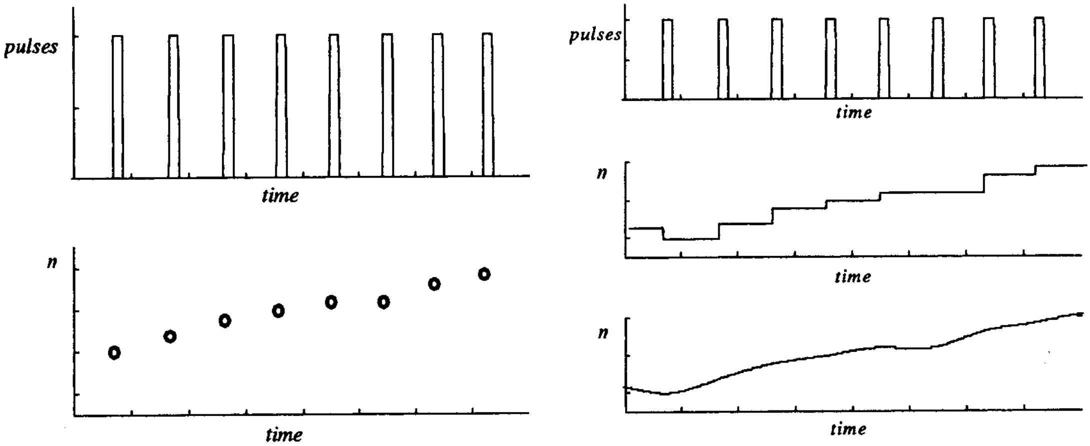

Figure 3. Estimation of *n–time* curve from ignition system pulses (left). Real time pulse to n conversion (right): pulse train (top), Sample & Hold processed (mid), Sample & Hold processed with low-pass filtering (bottom)

Spark pulses happen with a frequency that ranges from 1 pulses/2 revs. (one cylinder engine) to 2 pulses/1 rev. (four cylinder) for normal four-stroke engines. As the full throttle free run-up needs about 1 s to pass from 1500 to 6000 rpm, the time interval between two following pulses can range from 0.03 s (for a 1 cylinder engine) to 0.008 s (for a 4 cylinder engine), or, alternatively, $31 - 125$ pulses are detected during the whole run-up. From these pulses instantaneous angular velocity must be estimated and then derived with respect to the time to estimate the net torque M_{n}.

Common frequency-voltage conversion methods use a time window of length Δt inside of which pulses are counted. The number of counted pulses is clearly proportional to an average value of n. As the window must last enough to include a sufficient number of pulses to calculate the engine rotational speed, the estimation is wrong due to the very low frequency of ignition system pulses. In fact, for an engine that has N_{p} pulses for each turn of the crankshaft at a given rotational speed n, the number of counted pulses is

$$\text{counted pulses} = \mathrm{INT}(n\, N_{\mathrm{p}} \Delta t / 60). \tag{2}$$

If $\Delta t = 0.1\,\mathrm{s}$ and $n = 2000\,\mathrm{rpm}$ with $N_{\mathrm{p}} = 2\,\mathrm{pulses/rev}$, only six pulses are counted, while the non-truncated value is 6.67 pulses, resulting in an error of about 10%. Decreasing Δt reduces the number of counted pulses and the truncation error becomes greater; on the contrary it is impossible to increase Δt as the value of n estimated in the transient phase would be excessively averaged.

The usual frequency-voltage conversion based on pulse counting is then not applicable and a different method has been developed based on the direct evaluation of the time interval between two consecutive pulses, that clearly is inversely proportional to actual angular velocity (Figure 3, left). Estimated angular velocity from variable time intervals has acceptable errors when interpolating the obtained points with a polynomial. It is clear, however, that such conversion must be performed in a post-processing phase of the signal previously acquired and converted in a digital form.

To on-line estimate the angular velocity through a continuous conversion of pulses (and also of its derivative) and then the M_{n}–n curve, an algorithm has been developed that is applicable

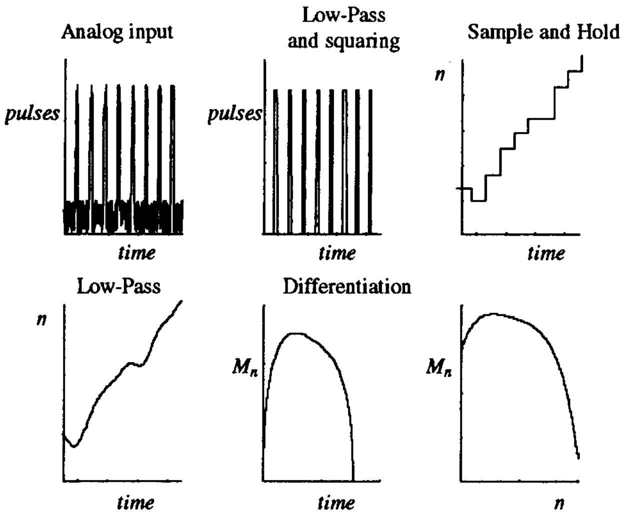

Figure 4. Signal processing steps to obtain M_n–n curve.

to hardware devices for signal conditioning of acquired pulses or to real-time processing with a programmable DSP.

To limit problems inherent in the digital form of acquired data, it is necessary to introduce a Sample & Hold circuit between two consecutive angular velocity estimation points and then to smooth the step curve with a low-pass filter whose effect is similar to a regression applied to the points of Figure 3 (left). The process is shown in Figure 3 (right); the algorithm, analogically or digitally implemented, results in a simple real-time system that gives, with a further analog or digital derivation step, the desired M_n–n curve.

4. Test Conduction

The proposed measuring system has been developed and tested by using a National Instruments® DSP board for PC programmed with the signal procedure sketched in Figure 4.

Analog pulse signal, always very noisy, is digitized, filtered to reduce the magnitude of disturbances, squared through threshold ideal pulses 0–1 comparators; the estimation of the distance between consecutive pulses, whose reciprocal is proportional to n, is made and held until the next estimation. A digital low-pass filtering and the derivation with a further low-pass filter give the M_n–n curve with the possibility of directly visualizing the n–*time* and M_n–*time* and to save these results on a file to obtain the M_n–n curve by eliminating the time between them.

The system has been numerically tested with a simulated train of noisy pulses for the fictitious engine shown in Figures 1 and 2. Results of the simulation (Figure 5) highlight the very good agreement obtained with Figure 1 (left).

5. Experimental Results

Several spark I.C.E. have been tested by measuring pulse signals from the ignition system and by processing pulse trains to verify the validity, the simplicity and the applicability of the developed method.

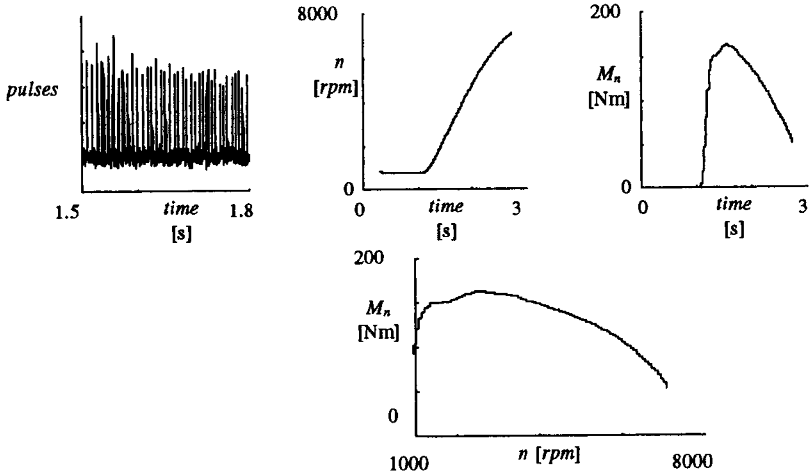

Figure 5. Estimation of M_n–n curve for the fictitious engine with simulated pulses and added noise.

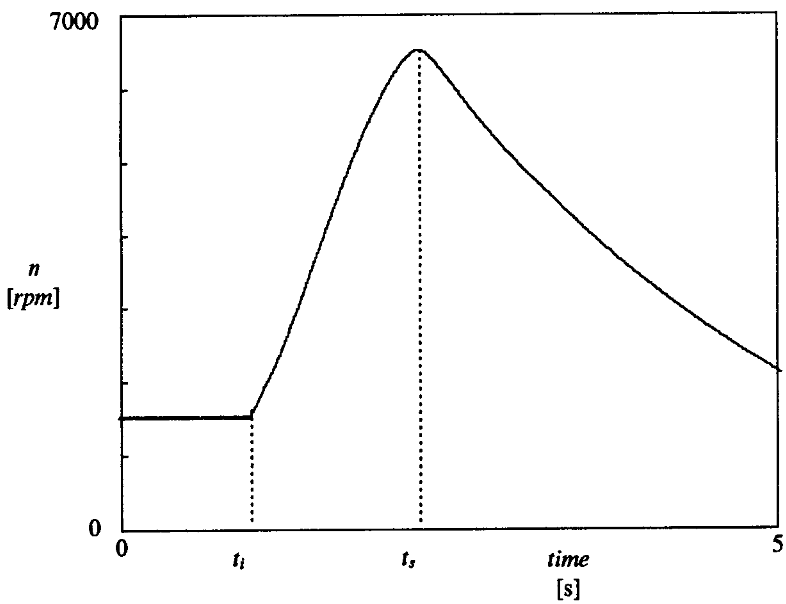

Figure 6. Experimental complete run-up and coast-down curve.

Figure 6 shows the *n–time* curve of a 4 cylinders, 750 cc carburetted engine. The part between t_i and t_s is the acceleration ramp properly said where the engine is fueled with full throttle. Beyond point t_s the engine, without fuel supply, slows down under the action of the resistant torque, and thus the method allows the determination of M_n between t_i and t_s and of M_r beyond t_s.

Figure 7 that the measured and manufacturer supplied *P–n* curves (i.e. engine power vs. rotational speed) for three engines match almost perfectly. In the same figure is also shown the curve of resistant power obtained from data acquired after t_s. Lost power depends both on mechanical losses and on pumping forces. These latter are in our case prevailing as the engine coast-down happens with closed throttle valve. The possibility to measure also the loss power

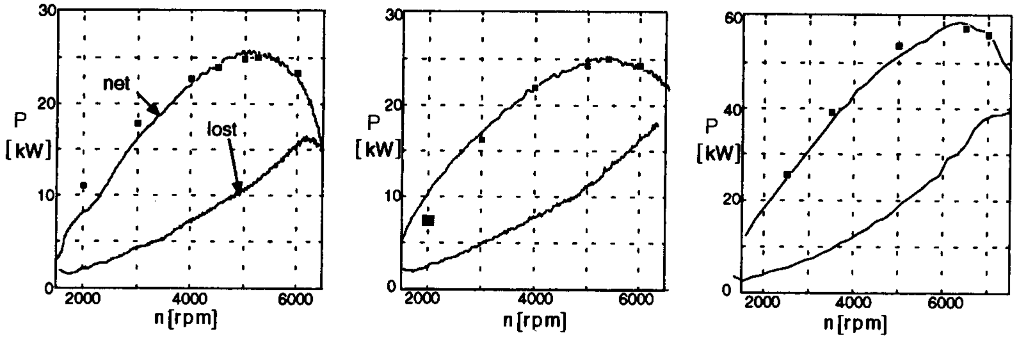

Figure 7. Net and lost estimated *P–n* curves (■ data supplied by manufacturer) for a 750 cc 4 cylinders carburetted engine (left), a 850 cc 4 cylinders carburetted engine (center) and a 1400 cc 4 cylinders electronic injection engine (right).

would suggest to perform the tests with throttle valve open during the run-up and the coast-down phases but stopping the fuel supply during the coast-down. It would be possible this way to estimate the real lost power with a good approximation.

6. Conclusions

In this work an efficient and economical procedure to estimate the net torque of an I.C.E. during a free run-up has been developed and validated. The possibility to measure lost power due to passive resistances during the coast-down phase has been proven. Experimental tests performed on several cars show a very good agreement with data supplied by the manufacturers.

Acknowledgements

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