96A4011

I.C.E. NET AND LOST POWER MEASUREMENT DURING A FREE RUN-UP

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SYNOPSIS

The measurement of torque vs rpm characteristic curve for an internal combustion engine gives useful information about overall working conditions of the engine itself. In this paper a very simple and effective method to be applied to spark ICE is presented and verified through several tests on normal cars. It consists of a measure of spark pulses with a current clamp and of a following data processing procedure that gives the desired curve in real time. This method allows the easy and cheap verification of normally operating cars without any particular setup of the engine.

1 - INTRODUCTION

Devices for diagnostics of operating conditions of internal combustion engines (ICE) are always more diffused and allow to measure and estimate a lot of information useful for engine setup.

The most important characteristics remains however the torque vs rpm curve, but the test rigs for its determination, like brakes directly applied to a crankshaft end 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 ICE working conditions.

In this job a technique that allow the estimation of torque and power vs rpm curves through a simple measurement of the angular velocity during a free run-up of the engine mounted on any vehicle is presented.

The principle on which this work in based is well known, but for an application simple and reliable of it non trivial data processing have been required. The developed system can be easily applied to factory testing at the end of the manufacturing process as well as in normal periodic controls in any car repair shop.

2 - MEASUREMENT OF NON-STATIONARY TORQUE DURING FREE RUN-UP

The net power of an ICE during a free run-up can be estimated by using the equation

$$J_R\dot{\omega} = M_m - M_r = M_n \qquad (1)$$

where $\dot{\omega}$ is the angular acceleration of the engine, J_R is the mass moment of inertia of all rotating masses reduced to the crankshaft, and the difference beetwen the motor torque M_m and the resistant torque M_r gives the net output torque M_n. The net torque is then dinamically balanced by inertia torque reduced to the engine crankshaft, and the net torque and the power can be evaluated by measuring the angular acceleration during a free run-up.

Strictly speaking, the reduced mass moment of inertia depends also upon the motion of alternate masses (pistons, rods, gudgeon pins,...) and is not rigorously constant but it is composed by a constant part and by a periodic part. This seems to complicate the estimation of the net torque, but it will be clarified later how eq. (1) can still be applied using a constant average moment of inertia. The problem to be solved is then how to measure correctly the angular acceleration.

3 - ESTIMATION OF THE ANGULAR ACCELERATION

3.1 - Preliminary considerations about the nature of the signals

Even in the most favourable hypothesis of an ICE in a laboratory test setup, there is a strong difficulty to directly measure the angular acceleration.

The only possible direct measurement that can be made is that of the angular velocity by means of voltage (tacho generators) or pulse generators (optical encoders) applied to any rotating shaft rigidly coupled to the crankshaft. From this measurement the angular acceleration can be estimated through an analog or digital differentiation. This means that the angular acceleration must be evaluated anyway by the processing of a signal proportional to the angular velocity.

Fig. 1a shows the M-ω of an hypothetical engine that has a moment of inertia variable as shown in Fig. 1b. Using this characteristic curve, the ω-t curve during a free run-up has been obtained through a numerical simulation (Fig. 1c).

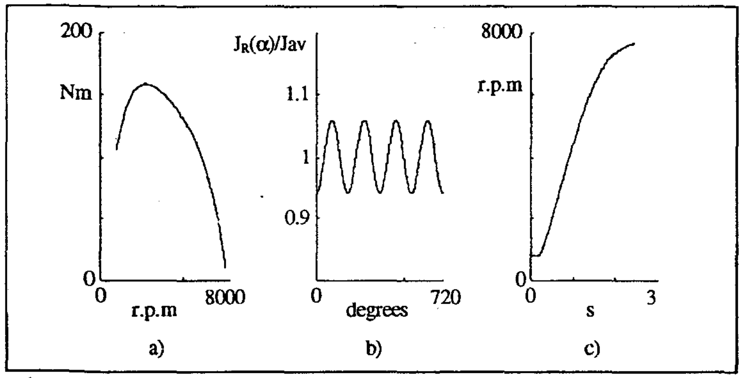

Fig. 1: a) Torque vs rpm characteristics of a fictitious ICE
b) Mass moment of inertia fluctuation (J_{av}=average moment of inertia)
c) Simulated free run-up

The angular velocity ω seems to grow up regularly, but if we try to numerically derive this curve to obtain the angular acceleration (to be multiplied by the moment of inertia to evaluate the net torque) we obtain the curve in Fig. 2a, and eliminating the time between fig. 1c and fig. 2a we obtain the characteristc curve M-rpm shown in fig. 2b.

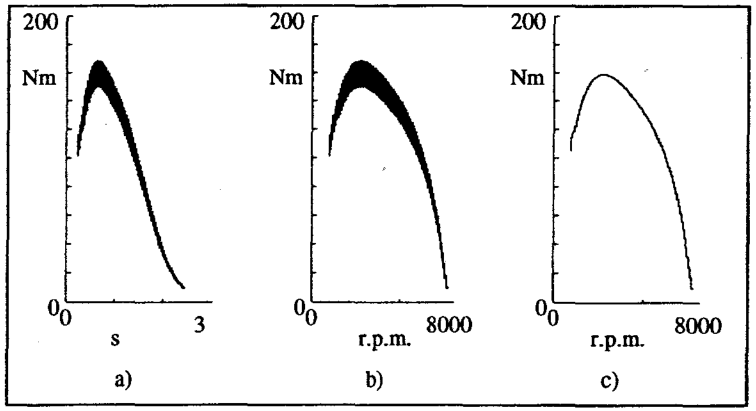

Fig. 2: a) Time derivate of fig. 1c) curve
b) Torque vs rpm curve from figs. 1c) and 2a)
c) As fig. 2b) low-pass filtered

It's clear how small oscillations depend upon the variability of J_R that produces a certain degree of irregularity in the engine rotation. These irregularities are strongly highlighted by numerical derivation process. A digital filtering of this signal is necessary to correctly estimate the angular acceleration without the oscillations due to the variation of J_R.

The angular velocity signal must then be filtered by a low-pass filter with a cut-off frequency sufficiently below the 2nd harmonic of the engine. In fact, the variable part of the mass moment of inertia of the engine varies with a fundamental frequency equal to the second rotation harmonic of the engine.

Fig. 2c has been obtained by low-pass filtering the signal shown in fig. 1c with a cut-off frequency of 8 Hz, and it perfectly matches the real characteristics M-ω of Fig. 1a. The chosen 8 Hz frequency corresponds to 1/4 of the 2nd harmonic of the engine rotating at 1000 rpm, that represents the minimum velocity for the engines that will be tested.

The angular acceleration must be anyway estimated through a derivation after a prefiltering of the angular velocity signal, and this is absolutely necessary to perform a correct estimation of the net torque even in the hypothesis of a perfect and noiseless measurement of angular velocity during a free run-up of the engine.

3.2 - Estimation of the angular acceleration from angular velocity signal

The possibility to measure ω through a tacho generator or an encoder has been mentioned before. Since the variation of the angular velocity is very fast, even the best tacho generator have an unsufficient dynamic behaviour to properly follow such variations, resulting in very high underestimations of the net torque. The best measuring system uses then a digital encoder that, thanks to the very good angular resolution and the absence of "inertia" in the electronic circuitry, allows the exact determination of the variation of ω.

In our case we decided not to use encoders, since the indirect measuring system that we wanted to develop must be of extremely simple use. The goal consists to apply it directly at the evaluation of th curve M-ω curve on any car, without applying any particular measuring device to the engine, and the necessity to mount an encoder on the crankshaft clearly constrasts with this philosophy.

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

It's worth to say that spark pulses repeats with a frequency that goes from 1 pulses/2 revs. (one cylinder engine) to 2 pulses/1 rev. (four cylinder) for normal four-stroke engines. Considering that the transient free run-up phase lasts for about t_{acc}=1 s to pass from 1500 to 6000 rpm, it follows that the time interval between two following pulses can vary in the range 0.03÷0.008 s from a 1 cylinder to a 4 cylinder engine, or, alternatively, 31 to 125 pulses are detected during the whole run-up. From these pulses instantaneous angular velocity must be estimated and then derived w.r.t. the time to estimate the net torque.

Usual frequency-voltage conversion methods use a time window of length Δt inside of which pulses are counted. Counted pulses are clearly proportional to angular velocity ω. In our case, such a window should be extended enough to count a sufficient number of pulses to calculate the rpm, but the estimation is anyway excessively wrong due to the very low frequency of pulses given by engine ignition system. In fact, given the actual rpm of the engine and the number of pulses N_p for each turn of the crankshaft, the number of counted pulses is

$$\text{counted pulses} = \text{INT}\,(\text{rpm}\ N_p\ \Delta t / 60) \qquad (2)$$

If the time window is Δt=0.1 s long and the engine runs at rpm=2000 with N_p=2 pulses/rev, pulses counted are given by INT(2000*2*0.1/60)=6, while the exact value would be 6.67 pulses, resulting in an error of about 10%. Decreasing Δt reduces the number of counted pulses and the truncation error becomes greater, while it's impossible to increase Δt as the estimated rpm in the transient phase would be excessively averaged.

The usual frequency-voltage conversion based on pulse counting is then not applicable to our case and we developed a different method.

3.3 - Frequency-voltage conversion details

On the basis of the considerations detailed in the previous paragraph, the frequency-voltage conversion must be made by directly evaluating the time distance between two consecutive pulses, that clearly is inversely proportional to actual angular velocity, even if this time separation results quite low.

Estimation process is represented in Fig. 3, from which results that the angular velocity is estimated from variable time intervals, making acceptable errors when interpolating the obtained points with, for example, a spline curve. It's clear, however, that such conversion must be performed in a post-processing phase of the signal previously acquired and converted in a digital form.

We also tried to evaluate the angular velocity through a continuous conversion of pulses to have a real time estimation of the velocity and also of its derivative to immediately estimate the curve M-rpm.

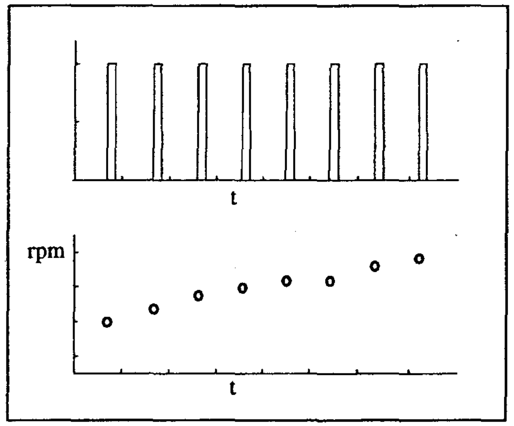

Fig. 3: Estimation of rpm from ignition system pulses

Such an evaluation must be realizable either by electronic devices for signal conditioning of acquired pulses or by real-time processing through a programmable DSP.

To tackle this problem, it is necessary to apply the principle described in Fig. 3 introducing a Sample&Hold circuit between two consecutive angular velocity estimation points and appropriately smoothing the step curve through a low-pass filtering that acts as a kind of linear regression applied to the discrete points of Fig. 3. The process is shown in Fig. 4. The algorithm can be performed analogically or digitally and results in a simple real-time system that gives, with a further analog or digital derivation step, the desired M-ω curve.

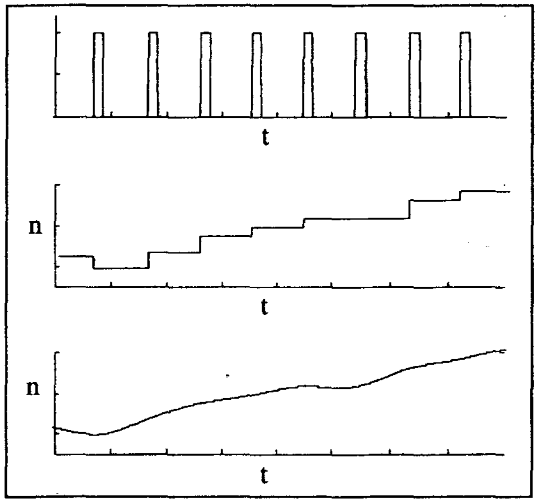

Fig. 4: Real time pulse to rpm conversion: pulse train (top), Sample&Hold processed (mid), Sample&Hold processed with low-pass filtering (bottom)

4 - TEST CONDUCTION

Measuring system has been developed and tested by using a National Instruments DSP board for PC in which the pulse signal is treated as described above and with other treatments shown in Fig. 5.

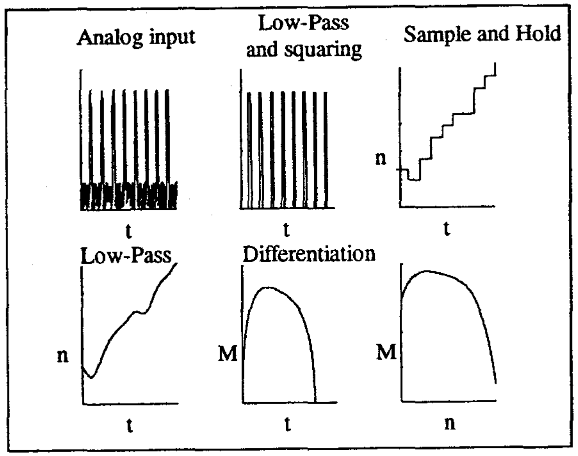

Fig. 5: Sketch of the complete signal processing steps to obtain M-rpm curve

Analog pulse signal, always very noisy, is digitized, filtered to reduce the magnitude of disturbances, squared through threshold comparators of ideal pulses 0-1, and then in a continuous manner is made the estimation of the distance between consecutive pulses whose reciprocal is maintained until the next estimation. A digital low-pass filtering and the derivation with a further low-pass filter gives the desired result with the possibility of directly visualize the ω-t and M-t and saving on a file these results to get later the M-rpm curve by eliminating the time between them.

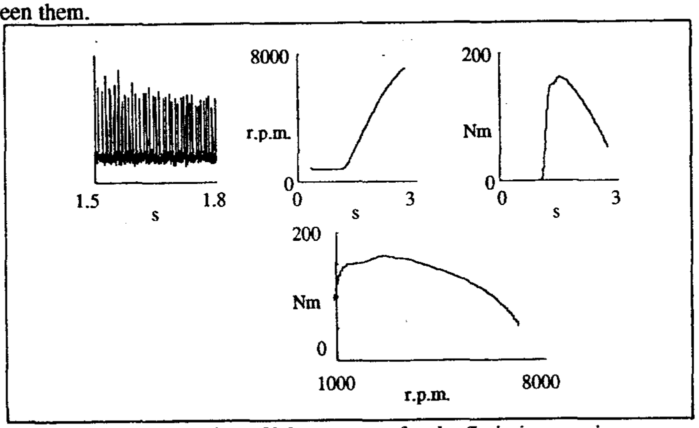

Fig. 6: Estimation of M-rpm curve for the fictiotious engine with simulated pulses and added noise

The system has been adjusted and tested through the construction of simulated noisy pulses related to shown in Figs. 1 and 2. Fig. 6 shows the results of the simulation and the comparison with Figs. 1c and 2c highlights the very good agreement obtained.

5 - EXPERIMENTAL RESULTS

With the proposed processing system some real engines have been tested, to effectively verify the validity, the simplicity and the applicability of the developed method.

Tests have been made directly on several cars, measuring pulse signals from ignition system.

Fig. 7 shows the acceleration transient of a 4 cylinders, 750cc. carburettor engine. The part between t_i and t_s is the acceleration ramp properly said during which the engine gives net power. Beyond point t_s we have the deceleration transient during which the engine, without fuel supply, slows down under the resistent torque. This implies that, having also the deceleration curve, the method allows the determination of M_n between t_i and t_s and of M_r beyond t_s.

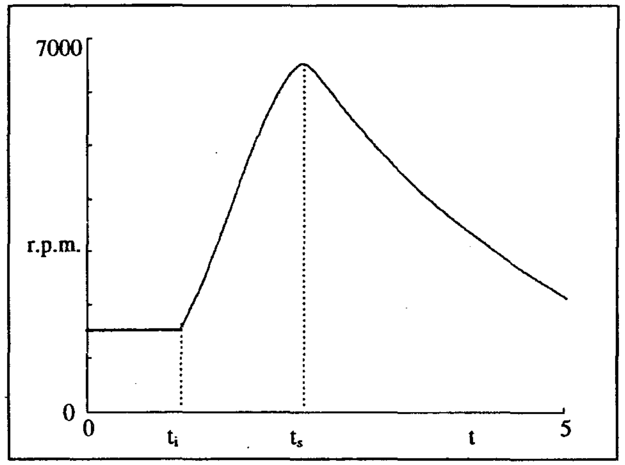

Fig. 7: Experimental complete run-up and run-down curve

Fig. 8a shows that the measured M-rpm curve and the one supplied by the manufacturer of the engine match almost perfectly. In the same figure is also shown the curve of resistent torque M_r obtained from data acquired after t_s.

Lost power depends both on mechanical losses and on pumping forces. These latter are in our case particularly high since the engine slow down happens with closed carburettor throttle butterfly valves, and become the main resistence applied to the engine. The possibility to measure also the loss power would suggest to perform the tests with butterfly valves open during the run-up and the run-down phases but stopping the fuel supply during the run-down. It would be possible this way to very simply estimate the real lost power with a good approximation.

In this job has not been possible, however, to use these optimal test conditions, but we think that obtained results prove anyway the capability to easily measure passive resistences.

Figs. 8b and 8c show other results obtained respectively for a car with 4 cylinders, 850cc. carburettor engine and for a car with 4 cylinders, 1400cc. injection engine.

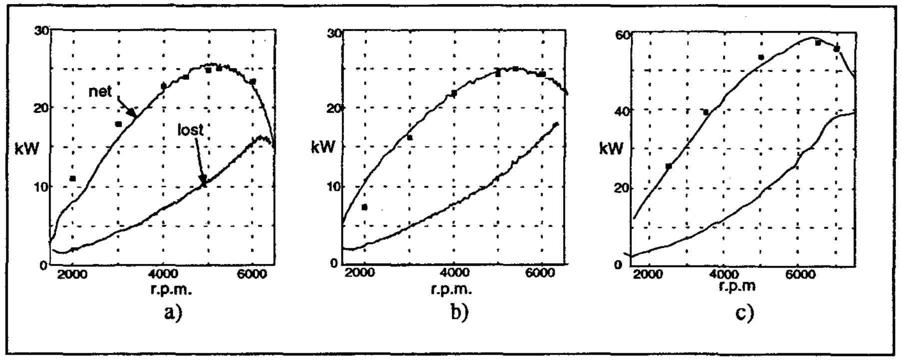

Fig. 8: Net and lost extimated power-rpm curves (■ manufacturer supplied)
a) 750 cc 4 cylinders carburettor engine
b) 850 cc 4 cylinders carburettor engine
c) 1400 cc 4 cylinders electronic injection engine

6 - CONCLUSIONS

This job has proven the possibility to measure the M-ω characteristics of an ICE during a free run-up with an extreme simplicity without the necessity of particular test devices but with only a simple measurement of the angular velocity ω of the engine.

At the same time the possibility of measure lost power due to passive resistences has been proven, and this greatly enhances the capabilities of the developed method.

Experimental tests performed directly on normal cars show an optimum agreement with torque vs rpm data supplied by the manufacturers.

Job partially funded with MURST and CNR contracts.

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