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Experimental verification of signal propagation in automotive ignition cables modelled with distributed parameter circuit

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Abstract: The paper analyses the possibilities of treating the ignition cable in the internal combustion engine as a distributed parameter system. It presents the experimental verification of computer simulations of signal propagation generated by ignition systems in the ignition cables, modelled by the distributed parameter system. The tests conducted to determine the wave parameters of ignition cables, as well as the results of numerical simulations and their experimental verifications, are presented. It is concluded that the modelling of the ignition cable by means of a long line gives positive results that can be used for the design of a spark plug with impedance equal to wave impedance of the ignition cable.

Key words: distributed parameter circuit, ignition cable, spark plug, ignition system, spark discharge

1. Introduction

The growing interest in ecology gradually makes diesel engines less popular in favour of petrol-powered spark ignition engines. The latest solutions have introduced hybrid cars that offer increased fuel savings. At first, hybrid vehicles have been something of an odd curiosity, a kind of treat for the drivers appreciating ecology but their popularity has been growing rapidly for some time now. The hybrid drive is a system composed of a petrol engine and electric motors, whose task is to support the combustion unit in the most difficult moments – when starting off and accelerating [9–14]. Two drives work in synergy, complement each other and provide better dynamics, greater savings and emit much less toxic compounds to the atmosphere.

The ignition system is an important element of the combustion engine as it considerably affects the natural environment. Its purpose is to provide an electrical spark igniting the fuel-air mixture in the cylinder at the right time and generating sufficient energy. The analysis of the engine operation and, in particular, its ignition system is necessary because it affects the combustion process in the engine and, consequently, the power, torque, fuel consumption and toxicity of the exhaust gas. The well-known models of the ignition system [3, 4, 6, 7] show the ignition cable as a distributed parameter model, that is, as the element with a determined value of resistance allowing the reduction of radio-electric interference.

A novelty in our study is an attempt to supplement the model of the ignition system with the ignition cable treated as a distributed element model (long line) including wave effects.

Systems with distributed constants are the systems where a continuous (non-point) distribution of capacitance, inductance or resistance becomes important (e.g. long cables or circuits with high frequency signals, where wavelengths λ become comparable to the size of electrical circuits). We often observe the effects of wave reflection at the ends of cables or multiple overlaps of reflected waves. It turns out that matching loads to the characteristic impedance of the cable is a significant problem. Since, at higher frequencies, the theory of circuits has a limited application, the theory of an electromagnetic field is used for the description. Such a situation takes place when signals of high frequencies or pulses with very steep slopes, that occur during the spark discharge in the ignition system, are transmitted.

The paper is organized as follows: the second part deals with experiments conducted with the use of a test stand equipped with a single-cylinder internal combustion engine, used to determine the waveform of the spark discharge. The results provided the basis for treating the ignition cable as a distributed parameter element. To confirm our assumptions the third part presents the results of tests and measurements conducted in order to identify wave parameters of typical ignition cables. The fourth part deals with numerical simulations determining the influence of the ignition cable on the waveform of the spark discharge voltage. The fifth part presents experimental verification of the results of computer simulations. The paper ends with a summary, conclusions and the proposed direction of further research.

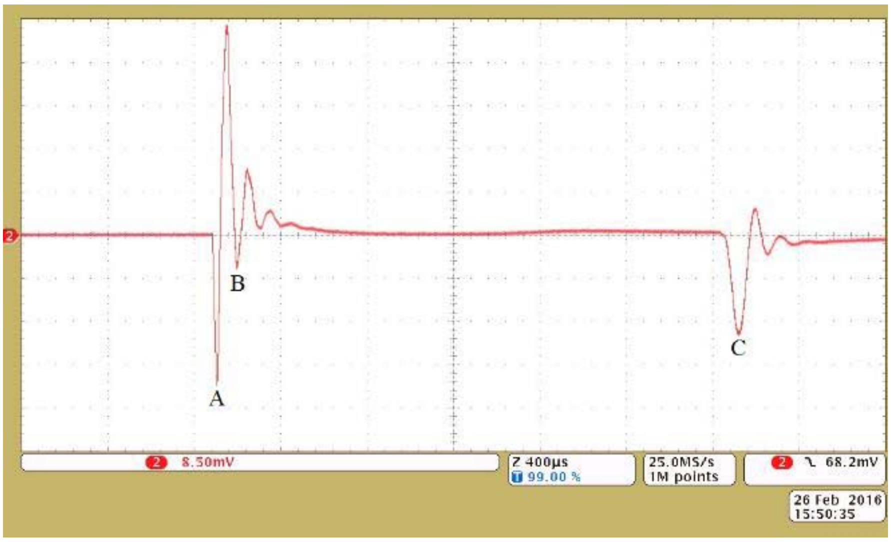
2. The experimental tests of spark discharge

The test stand presented in Fig. 1(a) was used in the experiments. It was equipped with a single-cylinder internal combustion engine cooperating with a typical ignition system. An “F” class conductor (according to ISO 3808-02), with a diameter of 7 mm, consisting of two insulating layers (silicone) separated by a fiberglass reinforcing material with a carbon-silicon core was used as an ignition cable.

The aim of the experiment was to obtain the oscillograms of the voltage generated by the ignition system during the actual spark discharge. The measurement results are shown in Fig. 1(b).

It can be seen (Fig. 1(b)), that the oscillogram shows the waveform of a typical spark discharge as presented in many publications [1–7]. The time from the beginning of the discharge to point A is called the rise time of breakdown voltage. This is the voltage initiating the current flow between the spark plug electrodes (in the fuel-air mixture). The waveform rise time is about 1 μs, which corresponds to a frequency of 250 kHz. At the point B the electric arc ignites. The time interval

(a)



(b)

Fig. 1. (a) photo of the test stand; (b) oscillogram of the spark discharge voltage waveform

marked B–C is the duration of the spark. In this case it is about 1 µs. The duration of the spark depends on the value of spark energy. It is estimated that the energy of the spark in the cylinder where the compression takes place amounts to 70% of the energy generated by the coil, whereas in the cylinder where the piston is in the discharge stroke the discharge energy constitutes 30% of the total energy produced by the ignition coil [2].

The oscillogram shown in Fig. 1(b) provided the basis for the further analysis conducted for the discharge phase from the point 0 to A, that is the rise phase, and in more detail, the rise time of the pulse. This time (1 μs) proves to have a decisive influence on the possibility of treating the ignition system as an object cooperating with a distributed parameter system. As it is generally known, the postulate seems to be fully justified for very short rise times. Therefore, the next stage of our tests was conducted with the aim of determining the influence of the ignition cable on the form of the spark discharge voltage. The oscillogram of the output voltage waveforms of the ignition coil and the voltage at the end of the ignition cable that supplied the spark plug is shown in Fig. 2.

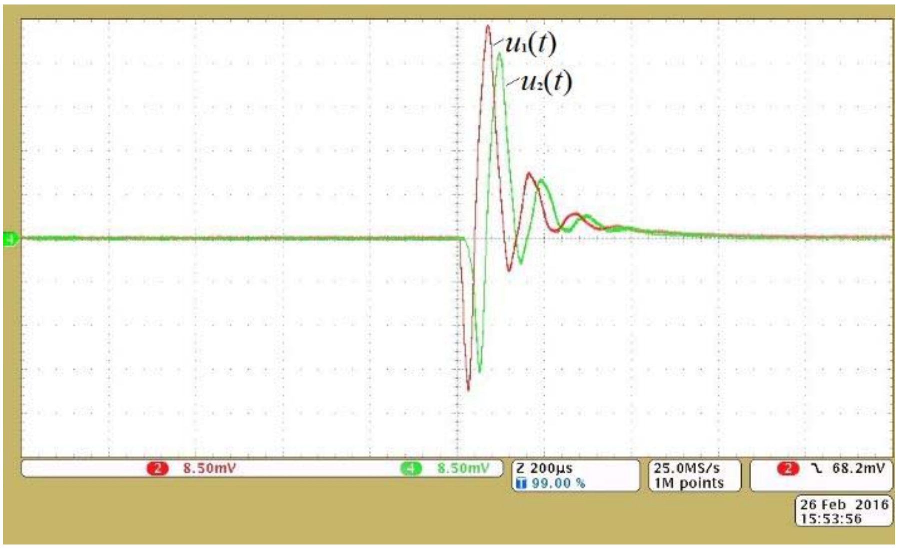


Fig. 2. The waveform of the secondary voltage of the ignition coil $u_1(t)$ and the voltage at the end of the ignition cable $u_2(t)$

The results of the measurements presented in Fig. 2 show that voltage waveforms $u_1(t)$ and $u_2(t)$ have different shapes. It is clearly visible that the $u_2(t)$ system response (output voltage at the end of ignition cable) is different from the response of the cable with modelled concentrated resistance. Thus it can be seen that in the case of fast waveforms the effect of reactance elements R, L and C cannot be avoided. Hence, the ignition cable should be treated as a distributed parameter system.

3. Identification of ignition cables' wave parameters

As shown in the previous part, the increase of the voltage pulse generated by the ignition system and its shift in the phase on the spark plug allows us to treat the ignition cable as a distributed parameter element.

It turns out that matching loads to the characteristic impedance of the cable is a significant problem.

The cable can be treated [5–8] as a long line if the signals in the line satisfy condition (1). Taking into account only the growing slope of the pulse and the condition $d \ll \frac{k}{4}$, we can write the following relationship:

$$l \geq \frac{\lambda}{4} = \frac{v}{4 \cdot f}, \tag{1}$$

where λ is the wave length, f is the frequency, v is the speed of the electromagnetic wave in a long line, d is the distance between cables.

Since at higher frequencies the theory of circuits is of limited use, it is reasonable to assume that for the short rise-time (approx. 1 μs) of voltage pulses generated by the ignition system (which in the frequency domain corresponds to 250 kHz) the ignition cable can be treated as a long line.

Numerical simulations included determining the influence of the ignition cable on the waveform of the spark discharge voltage represented by the following relation:

$$U_2 = U_1 \left(\cosh \gamma l - \frac{Z_C}{Z_0} \sinh \gamma l \right). \tag{2}$$

The wave parameters in (2) were determined from the following equations:

$$Z_C = \sqrt{Z_0 Z_Z}, \qquad \tanh \gamma l = \sqrt{\frac{Z_Z}{Z_0}}, \tag{3}$$

where U_1 is the voltage at the input of the ignition system, U_2 is the voltage at the output of the ignition system, Z_0 is the input impedance of a long line in an idle state, Z_Z is the input impedance of a long line in a short-circuit condition, Z_C is the wave impedance of a long line, γ is the propagation constant of a long line, l is the the length of a line.

In order to confirm our assumption, the tests of the selected types of ignition cables were carried out. Three types of ignition cables meeting the requirements of the ISO 3808-02 standard were used.

A series of measurements wear made on a test stand, modelling the actual arrangement of ignition cables. The ignition cables were marked as 1, 2, 3, where:

- 1 is a class “F” cable of 7 mm in diameter, made of two insulation layers (silicone) separated by a fiber-reinforced nylon material. The reactance wire-wound core is made of twisted resistance wire.
- 2 is a class “D” cable of 7 mm in diameter, made of one insulating layer (EPDM blend) with a carbon-acrylic core.
- 3 is a class “E” cable of 7 mm in diameter, made of two insulating layers (silicone) separated by a fiber-reinforced nylon material with a conductive carbon-Kevlar core.

As it is known, the identification of long wave parameters can be made by measuring the input impedance of the line in the idle state and in the condition of short circuit [4, 5]. The averaged results of the measurements obtained by means of a programmable LRC bridge at a frequency of $f = 250$ kHz are shown in Table 1.

Table 1. Measurement results of ignition cable impedance

Cable number	**Impedance at idle state**	**Impedance in short-circuit condition**
	[kΩ/m]	[kΩ/m]
1	2.200 – j13.040	6.079 – j0.0089
2	3.880 – j11.864	9.186 – j0.3614
3	3.800 – j12.872	8.570 – j0.3229

4. Numerical experiments

Assuming that the voltage at the $u_1(t)$ input of the line is sinusoidal and considering the wave parameters (of the tested ignition wires) calculated from the measurement data presented in Table 1 we obtained the corresponding voltage waveforms at the end of the line [8–10].

The waveforms are presented in Fig. 3.

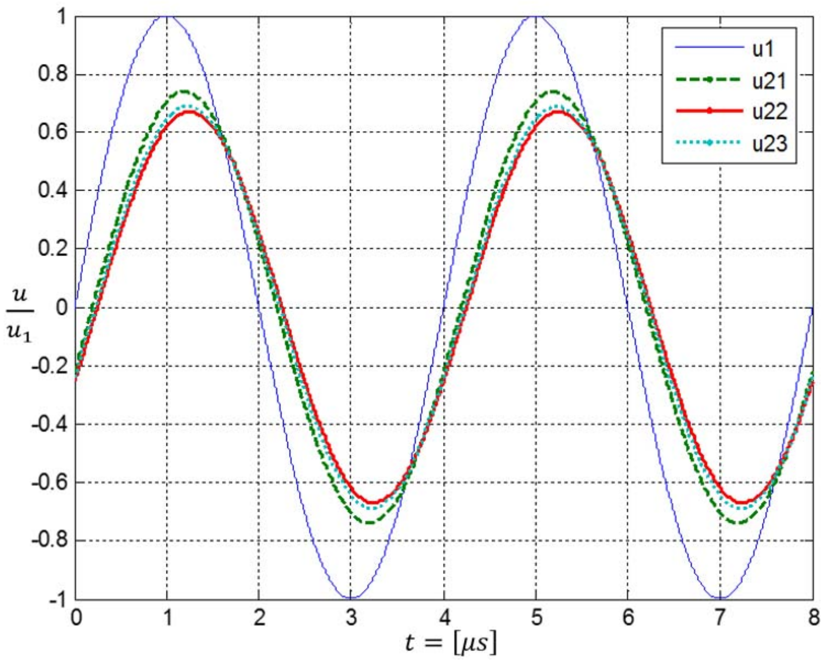


Fig. 3. Voltage at the end of the line for sinusoidal voltage at the input of the line

On the basis of the simulation results it can be concluded that the approximation of the ignition cable by means of a long line gives positive results. The time shift of $u_2(t)$ voltage and the change of its amplitude are observed, as in the case of the waveforms shown in Fig. 2.

5. Verification of test results

The results of the computer simulations shown in Fig. 3 were verified by the measurement system. The experimental tests consisted in recording the voltage $u_2(t)$ at the end of the line for three different ignition cables supplied by a sinusoidal input voltage. The test stand equipped with a sinusoidal voltage generator, digital oscilloscope, ignition cables tested and the load modelling the spark plug with the impedance $R_{ob} = 1$ MΩ is shown in the Fig. 4.

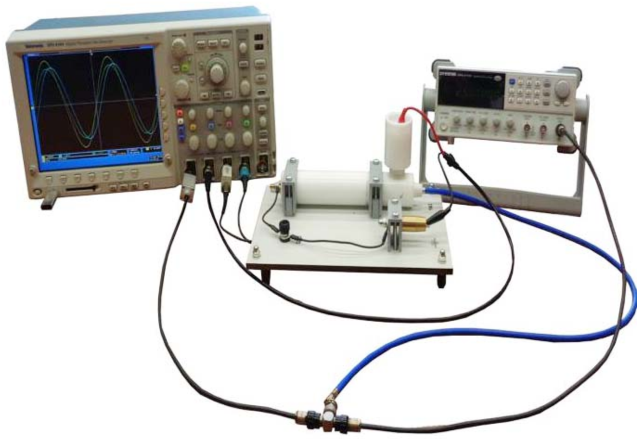


Fig. 4. Test stand

By supplying the sinusoidal voltage $u_2(t)$ to the input of the line and using the ignition cables whose characteristics and measurement data are shown in Table 1, the corresponding voltage waveforms at the end of the line were recorded. The waveforms are shown in Fig. 5.

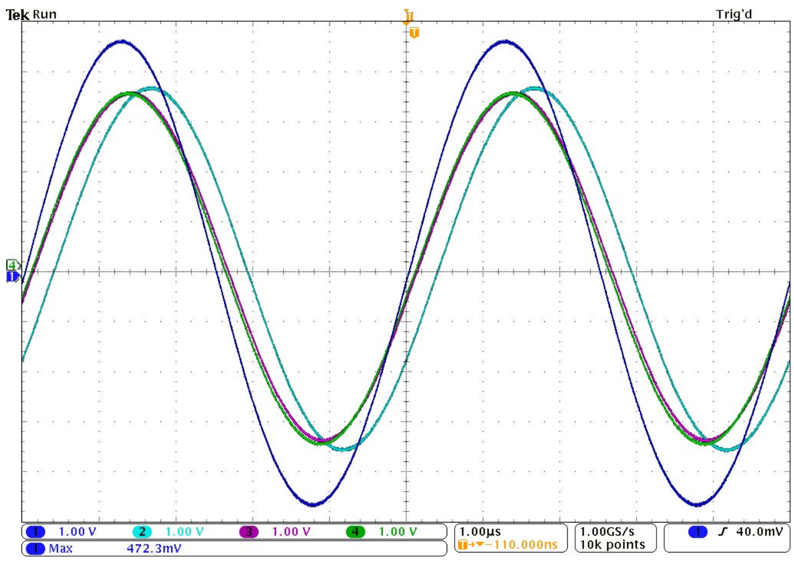


Fig. 5. Oscillograms of voltage waveforms at the ends of ignition cables supplied by sinusoidal voltage

As can be seen the voltage $u_2(t)$ obtained in the experiments was shifted in phase with respect to $u_1(t)$ and decreased its amplitude – as in the numerical simulations (Fig. 3).

6. Conclusions

On the basis of experimental results, it can be concluded that modelling of the ignition cable by means of a long line gives positive results. The time shift of $u_2(t)$ voltage and the change of its amplitude are observed, (as in the numerical calculations shown in Fig. 1(b)). The differences that can be seen by comparing the waveforms shown in Fig. 1(b) and Fig. 2 result from different wave impedances of the ignition cables used in the experiment.

In the absence of wave matching, the effects of wave reflection at the ends of cables or multiple overlaps of reflected waves are commonly observed.

Hence, matching electrical loads to the characteristic impedance of cables constitutes a significant problem. The results obtained give the basis for the considerations related to the design of the spark plug. In the optimal solution, the impedance of the spark plug should be equal to the wave impedance of the ignition cable.

Further study will focus on numerical calculations of the input voltage in the shape of a damped sine wave (which more closely corresponds to the voltage obtained in the ignition systems) and the experiments for wave impedances modelling the spark plugs. Additionally, in order to obtain a mathematical description (model) of the spark discharge voltage on the spark plug, the authors intend to use a fractional calculus.

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