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The analysis of a combustion engine knock control system

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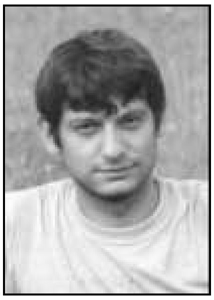

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Abstract

This paper deals with the phenomenon of undesirable detonation combustion in internal combustion engines. A control unit of the engine monitors the detonations using piezoelectric knock sensors. The detonations can be objectively measured by these sensors just outside a car. If the amplitude of the sensor output voltage is too small, it may happen that the knock combustion is not detected. The construction of a simple device for the detection of this disorder is presented and described in the paper.

Keywords: knock combustion; knock sensor; testing device.

Analiza sytemu kontroli spalania stukowego silników spalinowych

Streszczenie

Artykuł dotyczy zjawiska spalania stukowego w silnikach spalinowych. Opisano wspomniane zjawisko, przedstawiono prosty tester czujników spalania stukowego, jego model symulacyjny oraz opis matematyczny napięcia wyjściowego czujnika. Zjawisko spalania stukowego miejsce w sytuacji, gdy dochodzi do niewłaściwego, nierównomiernego i wybuchowego spalania paliwa w silniku tłokowym o zapłonie iskrowym. Zjawisko spalania stukowego jest bardzo niekorzystne, ponieważ powoduje znaczne obciążenie cieplne oraz mechaniczne elementów silnika. Aby zapobiegać temu zjawisku stosuje się odpowiednie paliwa o wysokiej liczbie oktanowej oraz układy sterowania pracą silnika redukujące możliwość spalania detonacyjnego. Ważnym elementem takiego układu jest piezoelektryczny czujnik spalania stukowego. Piezoelektryczne czujniki spalania stukowego są czujnikami generującymi napięcie na skutek uderzenia spowodowanego spalaniem stukowym. W trakcie spalania stukowego dochodzi do nagłego wzrostu ciśnienia na skutek pojawienia się fali dźwiękowej (rys. 1), co jest wykrywane przez czujnik. Czujniki spalania stukowego dostarczają informacji komputerom sterującym pracą układu zapłonowego. Układy te minimalizują spalanie stukowe poprzez sterowanie kątem zapłonu. Sterowanie to realizowane jest zwykle poprzez odpowiednie mapowanie tego kąta. Stosuje się procedury adaptacyjnego doboru kąta zapłonu, zgodnie z rys.3. Spalanie stukowe może być zredukowane poprzez właściwy dobór i przesunięcie kąta zapłonu. Przedstawiono konstrukcję prostego układu do testowania takich czujników, złożonego z rury i odpowiedniego ciężarka (kulki). Przebieg napięcia wyjściowego piezoelektrycznego czujnika spalania stukowego (rys. 8) może być przybliżony funkcja Bessela. Przedstawiono również symulację czujnika w pakiecie COMSOL rys. 9. Efekty symulacji przedstawiono na rys. 10.

Słowa kluczowe: spalanie stukowe, czujnik spalania stukowego; urządzenia testujące.

1. Introduction

A knock sensor allows the engine to run with the ignition timing as far advanced as possible. The computer will continue to advance the timing until the knock sensor detects pinging. At that point the computer retards the ignition timing just enough for stop the pinging.

The knock sensor responds to the spark knock caused by pre-detonation of the air/fuel mixture. As the flame front moves out from the spark plug ignition point, pressure waves in the chamber crash into the piston or cylinder walls resulting in a sound known as a knock or ping. This is caused by using a fuel with a low octane rating, overheating, or over advanced timing. Sometimes it can be caused by hot carbon deposits on the piston or cylinder head that raise compression. A knock sensor is comprised of piezoelectric materials; crystals that when impacted, generate a voltage (same idea as a BBQ ignitor). This voltage is monitored by the computer, and when an irregularity is detected, the computer corrects timing in VVT (variable valve timing) engines, or triggers a DTC Diagnostic Trouble Code) in older vehicles [1, 2, 3].

2. Engine knocking

Detonation can be prevented by any or all of the following techniques:

- the use of a fuel with high octane rating, which increases the combustion temperature of the fuel and reduces the proclivity to detonate;

- enriching the air-fuel ratio which alters the chemical reactions during combustion, reduces the combustion temperature and increases the margin above detonation;
- reducing peak cylinder pressure by decreasing the engine revolutions (e.g., shifting to a higher gear, there is also evidence that knock occurs more easily at high rpm (revolutions per minute) than low regardless of other factors);
- decreasing the manifold pressure by reducing the throttle opening, boost pressure or
- reducing the load on the engine.

At detonation combustion occurs to rapid changes in pressure (Fig. 1). These fast pressure changes, are generated by sound waves, which are in modern automobiles captured by the knock sensor [4].

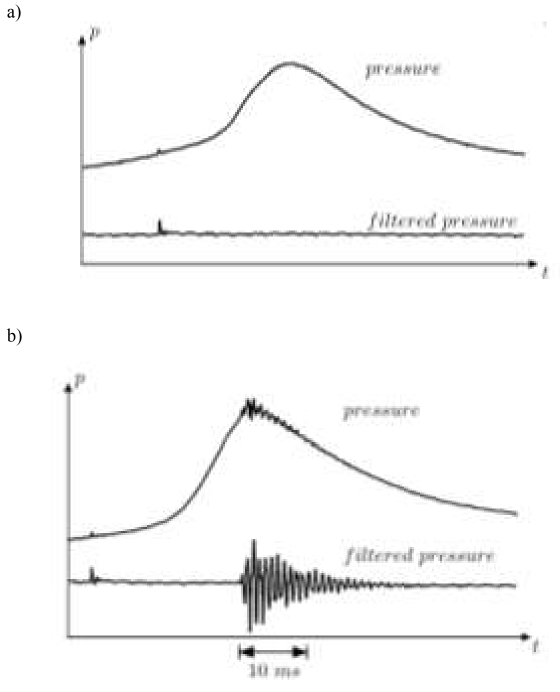

Fig. 1. Bandpass output signal: a) non-knocking combustion, b) knocking combustion [1]
Rys. 1. Pasmowoprzepustowy sygnał wyjściowy czujnika spalania stukowego: a) w spalaniu bezstukowym, b) w spalaniu stukowym 1]

3. Adaptive knock control

At dynamic engine transients, mismatches of the ignition angle occur resulting in increased knock occurrence rates. The response time of knock control can be reduced by a feed-forward control angle $\alpha_l(n)$ stored in an adaptive ignition angle map. Contrary to lambda control, a successful global error model has not yet been found. The values of the ignition angle map must therefore be adapted in every individual engine operating point for all cylinders.

The ignition angle at one cylinder is the sum:

$$\alpha_e(n)=\alpha_i(n)+\alpha_k(n)+\alpha_l(n), \tag{1}$$

where α_e is the effective ignition angle, α_i is the open loop ignition angle from fixed map, α_k is the knock control ignition angle, and α_l is the learned ignition angle from adaptive map.

The average knock control ignition angle $\overline{\alpha}_k(n)$ is the basis to teach the adaptive ignition angle map $\alpha_l(n)$ into the direction of retarding. A fixed advance angle α_a is superimposed to the teaching process providing a forgetting function of the thought angles. The learned ignition angle is

$$\alpha_l(n)=(1-k_l)\alpha_l(n-1)+k_l\left(\overline{\alpha}_k(n-1)+\alpha_a(n-1)\right). \tag{2}$$

The factor k_l determines how fast the learning process is [5]. The illustration of knock control with feed-forward adaptive ignition angle map is shown in Fig. 2.

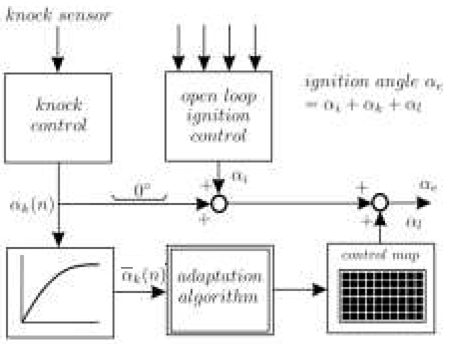

Fig. 2. Knock control with feed-forward adaptive ignition angle map [5]
Rys. 2. Sterowanie spalaniem stukowym z adaptacyjną mapą kąta wyprzedzenia zapłonu [5]

The usual actuation is to retardation of the ignition angle, shifting the energy conversion process backwards and thus reducing peak pressures and temperatures. Alternatively, may be reduced the boost pressure of a turbocharger. The knock control ignition angle is calculated at discrete combustion cycles n as

$$\alpha_k(n)=\alpha_k(n-1)+\Delta\alpha_k-\beta\cdot\Delta E_y(n) \tag{3}$$

where $\Delta\alpha_k$ is a permanent ignition angle advance, and $\beta\Delta E_y(n)$ the ignition angle retard at knocking. A typical control cycle is shown in Fig. 3. The knock control ignition angle $\alpha_k(n)$ is added to the ignition angle obtained from the ignition map.

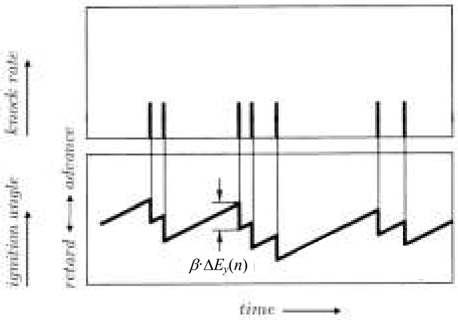

Fig. 3. Control of knock occurrence rate by ignition angle shifting [5]
Rys. 3. Sterowanie częstością występowania spalania stukowego przez przesunięcie kąta zapłonu [5]

4. Knock sensor output signal

Sound waves generated by detonation during the combustion have a frequency of between 6 to 20 kHz. Their frequency can be approximated by:

$$f_{mn}=c_0\sqrt{v/273\mathrm{K}}\cdot\beta_{mn}/d\,, \tag{4}$$

where c_0 is the sound propagation velocity at 273 K, v is the temperature within the combustion chamber, d is the cylinder diameter, β_{mn} is the Bessel function (e.g. β_{10} = 0,5861, β_{20} = 0,9722, β_{30}=1,2197).

From the parameters $c_0 = 330$ m/s, $\nu = 2500$ K, $d = 0.089$ m we can calculate the knock resonance frequencies $f_{10} = 6{,}6$ kHz, $f_{20} = 10{,}9$ kHz, $f_{30} = 13{,}7$ kHz.

Bessel functions are defined as the solutions $y(x)$ of the Bessel's differential equation:

$$x^2 \frac{d^2 y}{dx^2} + x\frac{dy}{dx} + \left(x^2 - a^2\right)y = 0\,. \tag{5}$$

It is possible to define these functions by its Taylor series expansion around $x = 0$:

$$J_\alpha(x) = \sum_{m=0}^{\infty} \frac{(-1)^m}{m!\,\Gamma(m+\alpha+1)}\left(\frac{x}{2}\right)^{2m+\alpha}. \tag{6}$$

where Γ is the gamma function, a shifted generalization of the factorial function to non-integer values.

The Bessel function of the first kind is an entire function if α is an integer (Fig. 4). The graphs of Bessel functions look roughly like oscillating sine or cosine functions that are decreasing proportionally to $1/\sqrt{x}$ (see also their asymptotic forms below), although their roots are not generally periodic, except asymptotically for large x. The Taylor series indicates that $-J_1(x)$ is the derivative of $J_0(x)$, much like $-\sin(x)$ is the derivative of $\cos(x)$; more generally, the derivative of $J_n(x)$ can be expressed in terms of $J_{n\pm1}(x)$ by the identities below [7].

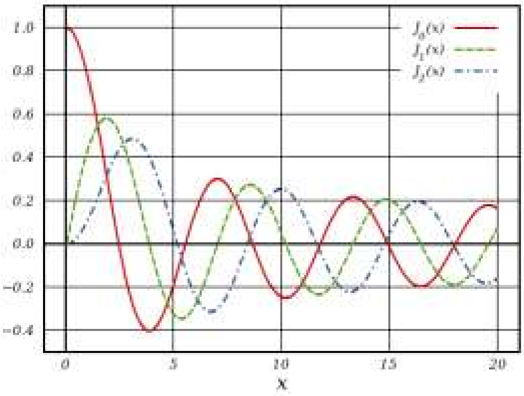

Fig. 4. Bessel function of the first kind, $J_\alpha(x)$, [6]
Rys. 4. Przebieg funkcji Bessela pierwszego rodzaju, $J_\alpha(x)$, [6]

A simple but effective test of the knock sensor is shown in Fig. 5. The sensor is attached to a cylindrical metal body. The plastic tube is adjusted so as to allow for the impact of the metal balls with different heights h.

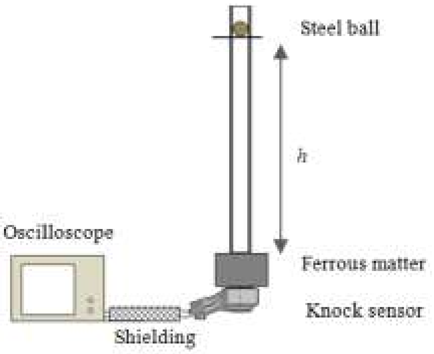

Fig. 5. Testing device
Rys. 5. Urządzenie testowe

The spheres impact on a metallic material with a height of 1.8 cm and a diameter of 3.4 cm generates sound waves. These waves are captured using a knock sensor. The output voltage signal, which is shown in Fig. 6, corresponds to the Bessel function.

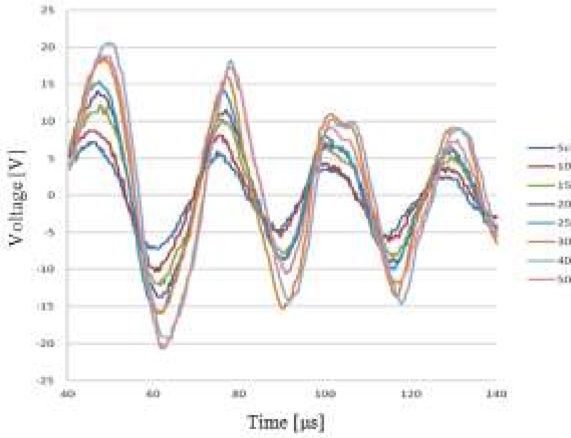

Fig. 6. Output voltage of the knock sensor
Rys. 6. Napięcie wyjściowe czujnika spalania stukowego

The sound reflection after the bullets' impact are shown in Fig. 7.

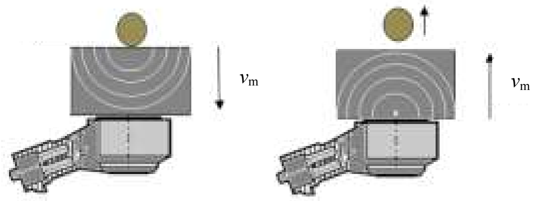

Fig. 7. Sound reflection after the ball's impact
Rys. 7. Odbicie dźwięku po uderzeniu kuli

The first two extremes of the measured signal provide us with the information on the state of the sensor.

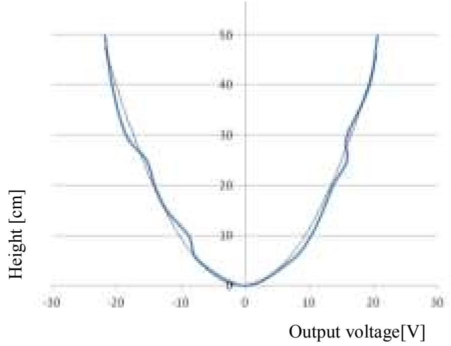

Fig. 8. Output voltage vs. the impact height
Rys. 8. Zależność napięcia wyjściowego od wysokości

The value of the generated voltage depends on the gravitational potential energy of the falling ball

$$E_p = m \cdot g \cdot h \tag{7}$$

where m is the mass of the ball (2050 mg), g is the acceleration due to gravity (9.81 m/s^2), h is the height of the ball above the surface (5 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 40 cm, 50 cm).

Calculation of the output voltage can be realized by means of the formula:

$$U = 20 \cdot \log\left(E_p + 1\right). \tag{8}$$

Restriction of reflection of the sound waves can be accomplished by changing the shape of a metallic material. An experiment was conducted where a steel ball was thrown directly at the sensor. In this impact we can already consider the Bessel function.

Fig. 9 shows the 3D model of a knock sensor and Fig. 10 shows a knock sensor simulation in the COMSOL [8] at pressure of 1N. In Fig. 10 we can see an electric potential of the sensor.

Fig. 9. 3D model of the knock sensor
Rys. 9. Model 3D czujnika spalania stukowego

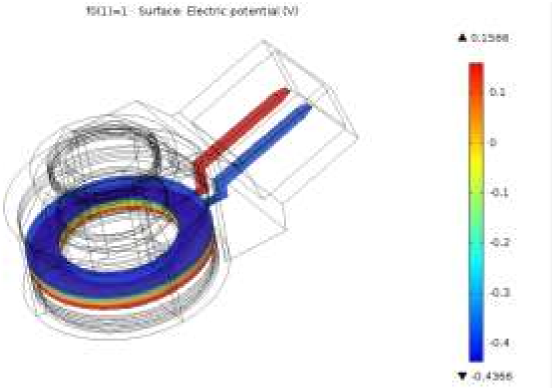

Fig. 10. Output potentials of the sensor for the 1N of force effecting on piezoelectric element
Rys. 10. Potencjały wyjściowe czujnika dla siły o wartości 1N działającej na element piezoelektryczny

5. Conclusion

A construction of the testing device for the knock sensor suitable for diagnostics of knock combustion in the internal combustion engines has been presented.

The output signal of the presented sensor has been described by Bessel functions. Using the first voltage extremes on the characteristics from Fig. 6 it is possible to create a reference for the evaluation of the polynomial residue. It should be taken into account that the velocity of sound in air is 330 m/s. This sound impinges on the walls of the combustion chamber and is detected by the sensor. The resonant frequency of the clicking of the motor is usually in the range from 5 kHz to 15 kHz. The sensor worked in the range to 37 kHz, which shall be taken into account on an own sensor resonance.

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