An Ion-Sense Engine Fine-Tuner

Lars Nielsen and Lars Eriksson

Environmental issues and lower fuel consumption require improved combustion engines. Several trends point toward use of feedback control directly from combustion, instead of using indirect measurements (as is mostly done today). One such trend is based on new sensors or improved interpretation of available sensor signals. An example is ionization current sensing, obtained by applying a sense voltage on the spark plug when it is not used for firing. The sensed current depends on the ions created, on their relative concentration and recombination, on pressure, and on temperature, to mention some of the more important factors. The signal is very rich in information but also complex to analyze.

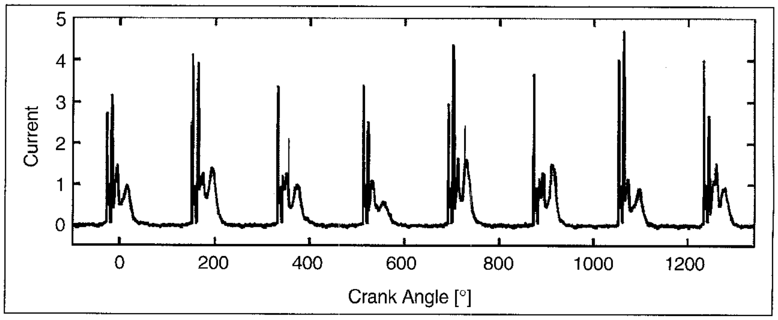


Fig. 1. A medical doctor can, from crude measurements such as EEG or EKG, draw many conclusions. Ionization currents, like the one in the figure, are in-cylinder engine measurements that are directly coupled to the combustion. Virtual engine-doctors and virtual engine fine-tuners are now being developed.

The main result of this article is a real-time closed loop demonstration of spark advance control by interpretation of ionization current signals. Such control is shown to be able to handle variations in air humidity, which is a major factor influencing burn rates, and consequently pressure build-up and useful work transferred via piston to drive shaft. This leads to a clear improvement in engine efficiency compared to traditional systems using only engine speed and load. The experiments are performed on a Saab 2.3 l, normally aspirated, production engine.

Inspired by the type of challenges and potential usefulness in interpretation of ionization current signals, the article begins with an outlook. Thereafter, the presentation focuses on closed loop ignition control by ionization current interpretation. Succeeding sections deal with the basics of ionization currents; spark advance control, especially principles relating pressure information to efficiency; the structure of the ion-sense spark advance controller; experimental demonstrations, and finally, some conclusions.

Outlook On Diagnosis and Feedback Control

The main message in this outlook section is: Research in modern engine control is challenging and fun! Engine development is not so mature that everything has already been tested. Instead, the availability of computing power has revolutionized the possibilities of sensor interpretation and combination. Another, perhaps more common, saying within the field is that engines are so difficult and complex that analysis of combustion quality, for example, is almost hopeless. Nevertheless, progress is being made leading to the ideas of virtual engine-doctors and virtual engine fine-tuners.

Virtual Engine-Doctors

Engines are difficult and complex, but before ruling out interpretation of complex signals one could consider the progress in human medicine. A medical doctor can draw conclusions from measurements such as EEG or EKG, that are indirect crude clues to what is going on inside the body. Engine measurements, for example ionization currents as in-cylinder engine measurements, are signals that are more directly coupled to the physics and chemistry of the process of interest, that is, the combustion (see Fig. 1). A virtual engine-doctor that detects and diagnoses serious malfunctions such as knock, which can harm the engine and misfire, which can harm the catalyst, is not a farfetched idea from that perspective. They also already exist. Ionization current interpretation can be used for both purposes. Knock is a pressure oscillation in the cylinder with a frequency determined by the geometry of the combustion chamber. The oscillation is present in the current measurement and can be extracted mainly by using a band pass filter in a well chosen time window of the current signal. When there is a misfire, then there are no resulting ions and hence no current which is easily detected. These systems are already used in production cars [1], [2]. Therefore, the basic hardware is already available and developing a virtual engine-doctor for combustion requires only additional signal interpretation in the electronic engine control unit (ECU), Fig. 2.

Virtual Engine Fine-Tuners

The term virtual engine fine-tuner is inspired more by a skilled auto mechanic than a medical doctor. A human performing the task of tuning an engine, e.g. for best performance, would use several clues like test measurements and the sound of the engine, but also experience, e.g. about actual weather. The result

The authors are with Vehicular Systems, ISY, Linköping University, S-581 83 Linköping, Sweden. *The authors are indebted to Mecel AB and Saab Automobile AB for their invaluable support. The Swedish National Board for Industrial and Technical Development is also gratefully acknowledged for their financial support.*

 0272-1708/98/$10.00©1998IEEE

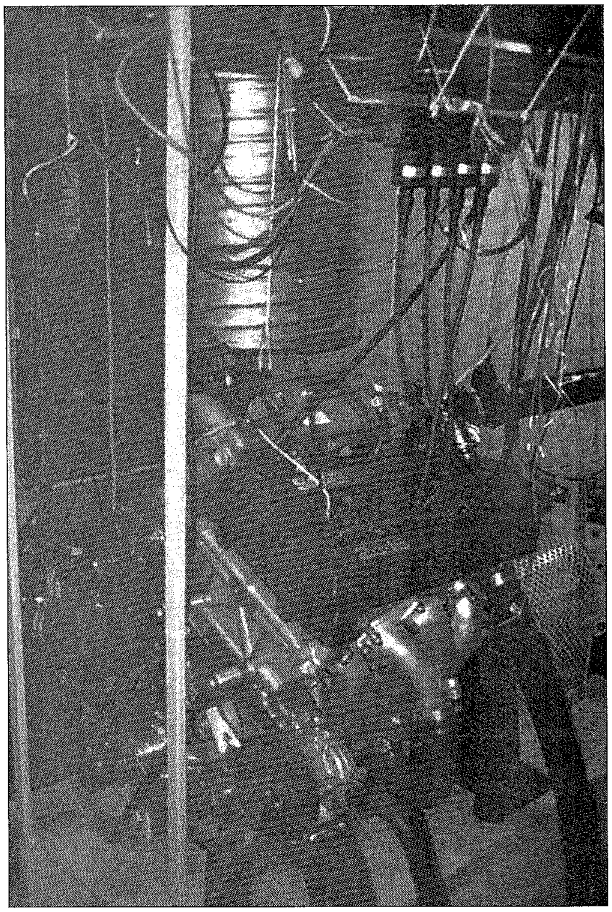


Fig. 2. The introduction of computerized engine controllers (here above the engine) has revolutionized the engine control era. Today they represent an impressive computing power and the development continues.

can typically be an increase of several percent in engine efficiency. One way to achieve engine tuning, shown previously, is to use feedback schemes that use a pressure sensor [3], [4], [5], but these systems have not yet been proven cost effective due to expensive pressure sensors.

With increasing computational power, it is now becoming possible to do engine tuning by feedback control from more advanced interpretation of signals to take care of circumstances previously not easily measureable. A multi-sensor idea is developed wherein a basic signal, such as engine speed or ionization current, is measured and several other sensor signals can be deduced from it (Fig. 3). Variations in engine speed, together with crank shaft models, can be used to conclude misfire by, for example, lacking torque pulse, or to estimate cylinder pressure from derived torque fluctuations [6], [7]. Using the spark plug as an integrated actuator and sensor leading to ionization current interpretation is the path taken here.

Thus the rest of the article is about one example of continuous engine tuning. Ionization current interpretation is used to derive in-cylinder pressure characteristics, and this information is used for feedback control to optimize engine efficiency, compensating for example for air humidity.

Ionization Current

In an ideal combustion reaction, hydrocarbon molecules react with oxygen and generate only carbon dioxide and water, e.g., isooctane gives

$$C_8H_{18} + \frac{25}{2}O_2 \rightarrow 8CO_2 + 9H_2O.$$

In combustion there are also other reactions present that include ions, which go through several steps before they are completed. Some examples are [8]

$$CH + O \rightarrow CHO^+ + e^-$$
$$CHO^+ + H_2O \rightarrow H_3O^+ + CO$$

$$CH + C_2H_2 \rightarrow C_{33}^+ + e^- .$$

These ions, and several others, are generated by the chemical reactions in the flame front. Additional ions are created when the temperature increases as the pressure rises.

The processes creating the ionization current are complex and are also varying from engine cycle to engine cycle. Fig. 4 shows ten consecutive cycles of the cylinder pressure and the ionization current operating at constant speed and load. As can be seen, the cycle-by-cycle variations are significant. An important part of this article is to derive pressure characteristics from ionization current.

Detection

To detect the ions, a DC bias is applied to the spark plug, generating an electrical field. The electrical field makes the ions move and generates an ion current. A schematic illustration is shown in Fig. 5(a). The current is measured at the low-voltage side of the ignition coil, and does not require protection from the high-voltage pulses in the ignition, Fig. 5(b). Ionization current measurement systems are already in use in production engines for individual cylinder knock control, cam phase sensing, pre-ignition detection, and misfire/combustion quality/lean limit [1]. Also, work on detection of spark plug fouling by using the ionization current has been reported [9].

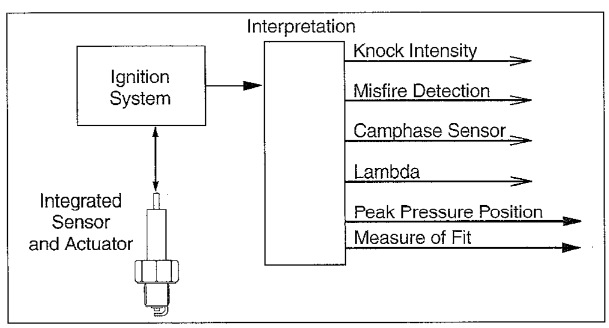


Fig. 3. The spark plug can, using signal interpretation, function as sensor for several parameters. Knock intensity and misfire are already implemented in production cars as a basis for virtual engine-doctors. Lambda sensing and peak pressure position estimation can be used in virtual engine fine-tuners. The peak pressure position (and a quality measure of it) is the information used in this paper.

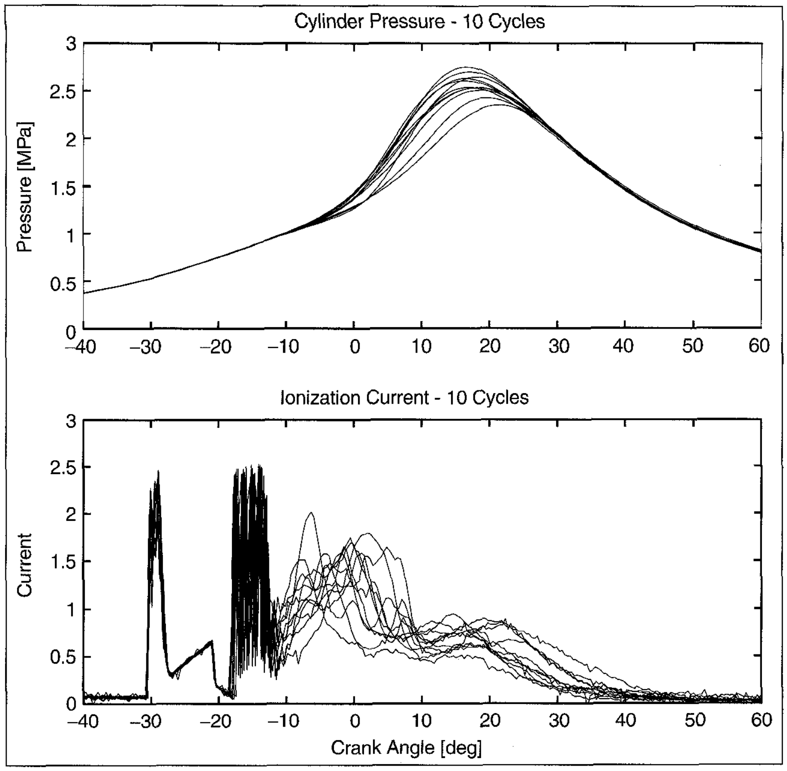


Fig. 4. Cycle to cycle variations are always present during combustion. The plots show ten consecutive cycles at stationary engine operation that clearly exhibit the cyclic variations.

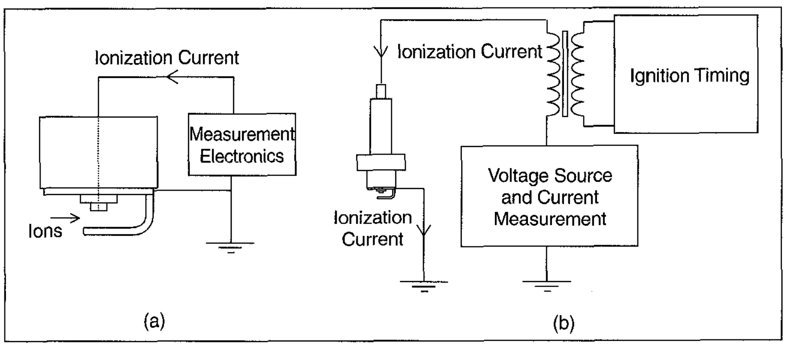


Fig. 5. Measurement of the ionization current. (a) The spark plug-gap is used as a probe. (b) Measurement on the low voltage side of the ignition coil.

The ionization current is an interesting engine parameter to study. It is a direct measure of the combustion result that contains a lot of information about the combustion, and several challenges remain in its interpretation. Parameters that affect the ionization current are temperature, air/fuel ratio, time since combustion, exhaust gas recycling (EGR), fuel composition, engine load, and several others.

Ionization Current Terminology

The ionization current typically has three phases: a phase related to ignition, a phase related to ions from the flame development and propagation, and a phase related to pressure and temperature development. In Fig. 6, the three phases of the ionization current are displayed. These phases have varying characteristics and they also mix together in complicated ways. In the ignition phase, the ionization current is large, with reversed polarity. Due to the high current in the ignition, the measured signal shown in the figure is limited. What can be seen in Fig. 6 is the ringing phenomenon in the coil after the ignition.

In the flame-front phase, the high level of ions associated with the chemical reactions in the flame produces one or more characteristic peaks. The ions generated by the flame have different recombination rates. Some ions recombine very quickly to more-stable molecules, while others have longer residual times. The result is a high peak which, after some time, decays as the ions recombine.

In the post-flame phase the most stable ions remain, generating a signal that follows the cylinder pressure, due to its effect on the temperature and molecule concentration. Ions are created by the combination of the measurement voltage and the high temperature of the burned gases, since the temperature follows the pressure during the compression and expansion of the burned gases (i.e., when the flame propagates outwards and the combustion completes). The ionization current thus depends on the pressure.

Ionization Current Modeling

The ionization current can be studied by thermodynamical and chemical kinetic modeling [10], [11], [12]. Concentrating on the pressure-related post-flame phase, an analytical expression for the ionization current has been presented. Some of the fundamental assumptions in the model are that the gas in the spark plug is fully combusted, in thermodynamic equilibrium, undergoing adiabatic expansion, and that the current is carried in a cylinder extending from the central electrode of the spark plug [10]. Given the cylinder pressure, the analytical expression for the ionization current is

$$\frac{I}{I_m} = \frac{1}{\left(\frac{p}{p_m}\right)^{\frac{1}{2}-\frac{3}{4}\frac{\gamma-1}{\gamma}}} e^{-\frac{E_i}{2kT_m}\left[\left(\frac{p}{p_m}\right)^{-\frac{\gamma-1}{\gamma}}-1\right]}, \quad (1)$$

where I is ionization current; I_m is ionization current maximum; p is cylinder pressure; p_m is cylinder pressure maximum; T_m is maximum temperature; γ is specific heat ratio; k is Boltzmann's constant; and E_i is ionization energy.

Interpretation Model

A key step in our method for deducing information is to use parameterized functions based on a phenomenological description of the ionization current, i.e., the signal consists of two com-

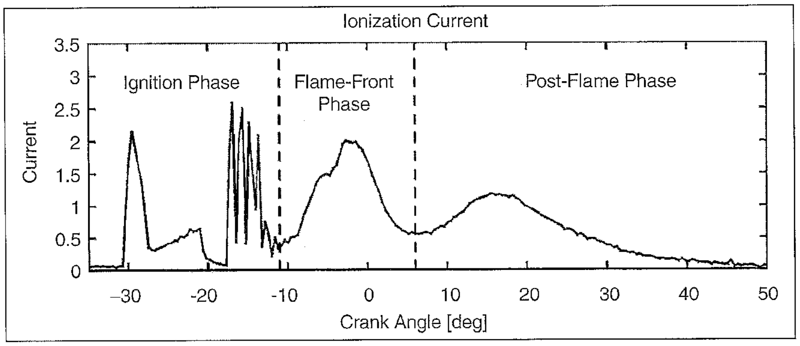


Fig. 6. Ionization current showing three clear phases, ignition, flame front, and post flame.

design phase of the engine, results in a nominal spark-advance schedule. Such a calibrated schedule is conservative since it has to guarantee good performance over the entire range of the non-measured parameters, and also be robust to aging.

If all parameters that affect the spark advance were measured, and their effects and interactions were properly accounted for, it would be possible to determine the best spark advance. However, such a system would be too expensive due to the measurements and testing required to incorporate it in a production car.

bustion related phases. These functions must be rich enough to capture the different variations, but they must also be such that the relevant information can be extracted. The parameterized functions are used to separate out the different phases of the ionization current, and to get an estimate of the pressure. As a model, with six parameters, a sum of two Gaussian functions is used

$$I(\theta) = \alpha_1 e^{-\frac{1}{\alpha_2}(\theta-\alpha_3)^2} + \beta_1 e^{-\frac{1}{\beta_2}(\theta-\beta_3)^2}. \qquad (2)$$

Note that this model is not based on combustion physics with respect to the flame-front phase. Even though this may seem ad hoc, the model is physically motivated in [13] with regard to pressure information. Measured pressure traces are recalculated to ionization currents using (1), and the result is shown to be close to a Gaussian function.

For ionization current interpretation, the model, (2), is fitted to the measured ionization current. Fig. 7 shows two ionization currents together with the Gaussian components of the model. The first component corresponds to the flame-front phase and the second to the post-flame phase. This second part, corresponding to the post-flame phase, is the experimentally and physically motivated basis for obtaining pressure information.

Spark Advance Control

Spark-advance control deals with determination of the engine position where the spark plug will ignite the air-fuel mixture and start the combustion. It is thus used to position the combustion and pressure trace, relative to the crank shaft motion. Engine efficiency and emissions are directly affected by the spark advance, due to its influence on the in-cylinder pressure. Work is lost to heat transfer and to the compression if it is placed too early, and expansion work is lost if it is placed too late. The optimal spark advance setting depends on several parameters, e.g., engine speed, engine load, air/fuel ratio, fuel characteristics, air humidity, EGR, air temperature, and coolant temperature. Emission regulations and engine knock also affect the best spark advance setting, but this is not a topic here.

Today, most spark-advance controllers are open-loop systems, which measure a number of parameters that affect the spark advance and compensate for their effects. Extensive testing and calibration, during the

Feedback Schemes

A different approach is to use closed-loop spark-advance control. Such a system measures the result of the spark setting rather than measuring all the parameters known to affect the spark advance. This requires measurement of parameters directly resulting from the actual combustion, such as the in-cylinder pressure or the ionization current. It is an accepted fact that the position for the pressure peak is nearly constant with the optimal spark advance, regardless of operating condition [3]. A spark-advance control algorithm that maintains a constant peak pressure position (PPP) is therefore close to optimum. Even for large changes in parameters that affect the flame speed, such a feedback scheme still maintains the optimal spark advance. This has been shown previously by using feedback schemes that utilize a pressure sensor [3], [4], [5], but these systems have not yet been proven cost effective due to expensive pressure sensors.

Spark Advance and Cylinder Pressure

The spark advance is used to position pressure development in the cylinder such that the combustion produces maximum work. Under normal driving conditions the mixture is ignited around 15-30° in crank angle before the piston has reached top dead center (TDC), and the pressure peak comes around 20 degrees after TDC. In Fig. 8 three different pressure traces, resulting from three different spark timings, are shown. Earlier spark advance normally gives higher maximum pressures and maximum temperatures that appear at earlier crank angles.

The optimal spark advance for maximum output torque is close to SA2 for the operating point in the figure, and the resulting peak pressure position lies around 17° after TDC. With too

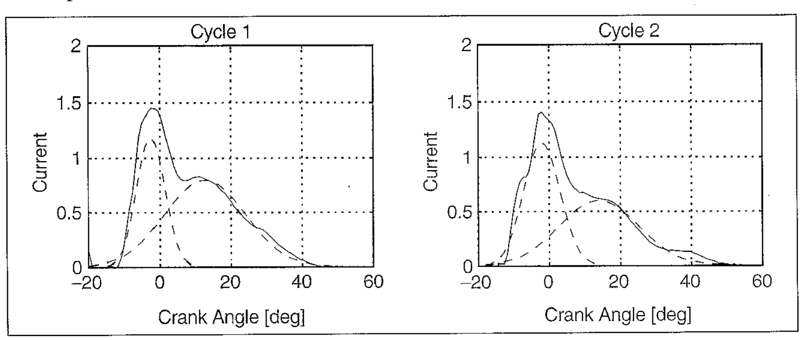


Fig. 7. Components of the model (2) that captures the appearance and the phases of the ionization current.

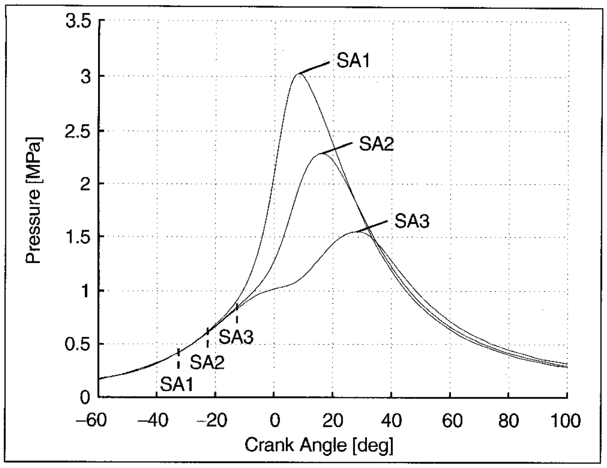


Fig. 8. Three different pressure traces resulting from three different spark advances. The different spark advances are; SA1: spark advance 32.5° before top dead center (TDC), SA2: 22.5° before TDC, SA3: 12.5° before TDC. The optimal spark advance is close to SA2.

early ignition timing the pressure rise starts too early and counteracts the piston movement. This can be seen for the pressure trace with spark advance SA1 where the pressure rise starts already at –20° due to the combustion. There are also losses due to heat and crevice flow from the gas to the combustion chamber walls, and with an earlier spark advance the loss mechanisms start earlier, reducing the work produced by the gas. Higher pressures give higher temperatures which also decrease the difference in internal energy between the reactants and products in the combustion, thus resulting in lower energy-conversion ratios. The heat loss mechanisms and the lower conversion ratio can be seen in Fig. 8, at crank angles over 30°, where the pressure trace from the SA1 spark advance is lower than the others.

Too late ignition gives a pressure increase that comes too late so that work is lost during the expansion phase. In Fig. 8, the pressure increase for spark advance SA3 starts as late as at TDC. But work is also gained due to the later start of the effects mentioned above, which also can be seen in the figure. The pressure trace from the spark advance, SA3, is higher than the others at crank angles over 30°. However, this gain in produced work can not compensate for the losses early in the expansion phase.

Peak Pressure Concept

Thus, optimal spark advance positions the pressure trace in a way that compromises between the effects mentioned above. To define the position of the in-cylinder pressure relative to TDC, the peak pressure position (PPP) is used, Fig. 9. The PPP is the position in crank angle where the in-cylinder pressure takes its maximal value. There also exist other ways of describing the positioning of the combustion relative to crank angle, e.g., based on the mass fraction burned curve.

Engine Tuning For Efficiency

Development of an engine fine-tuner for efficiency requires experiments to describe optimal engine output. Such a description is the basis for determining the set-point values to be used in the feedback scheme. In Fig. 10, mean values, over 200 cycles, of the PPP are plotted together with the mean value of the produced torque at four different operating points covering a large part of the road load operating range for the engine. Two of the operating points have an engine speed of 1500 rpm with different throttle angles, and for the two other operating points the engine speed is doubled to 3000 rpm. The PPP for maximum output torque in the figure lies around 15° ATDC (after TDC) for all these operating points.

Note that the load and speed are changed over large intervals, and that the PPP for maximum output torque at the different operating points does not differ much. The PPP versus torque curve is flat around the position for the maximum. Therfore a spark schedule that maintains a constant PPP at 15° is close to optimum. Considering only the work produced, an optimal spark schedule maintains almost the same position for the peak pressure [3]. However, the optimal PPP changes slightly with the operating points. The efficiency can thus be improved a little bit further by mapping the optimal PPP for each operating point, and providing these values as reference signals to the spark timing controller. The peak pressure positioning principle can also be used for meeting emission standards. In [4] this question is addressed by rephrasing the emission regulations on the spark advance to desired peak pressure positions.

Principle Study of Variations

The experiments in Fig. 10 are interesting not only for determining the optimal point. They can also be used to illustrate the effect of cycle-by-cycle variations, which limits the performance of SI Engines [14], [15]. Recall that these variations are significant, as previously illustrated in Fig. 4.

The following principle study illustrates that variations in the output torque are smaller when the mean PPP is held at its optimum. In Fig. 11, a quadratic polynomial is plotted, which is the same as those in Fig. 10. The polynomial represents an idealized relation between the PPP, x_p, and the output torque, y_T. The polynomial can be parameterized as

$$y_T = -c \cdot (x_P - x_{\max})^2 + y_{\max} .$$

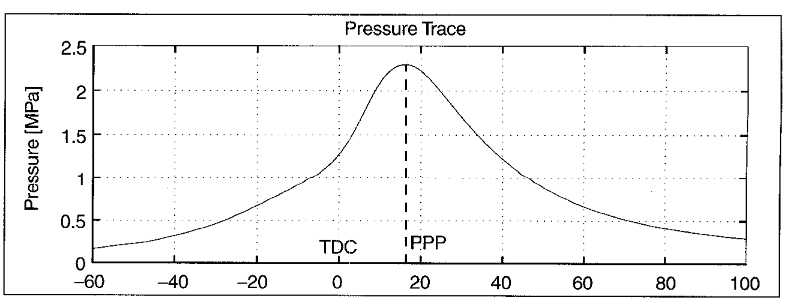


Fig. 9. The PPP (Peak Pressure Position) is the position in crank angles for the pressure peak. It is one way of describing the position of the pressure trace relative to crank angle.

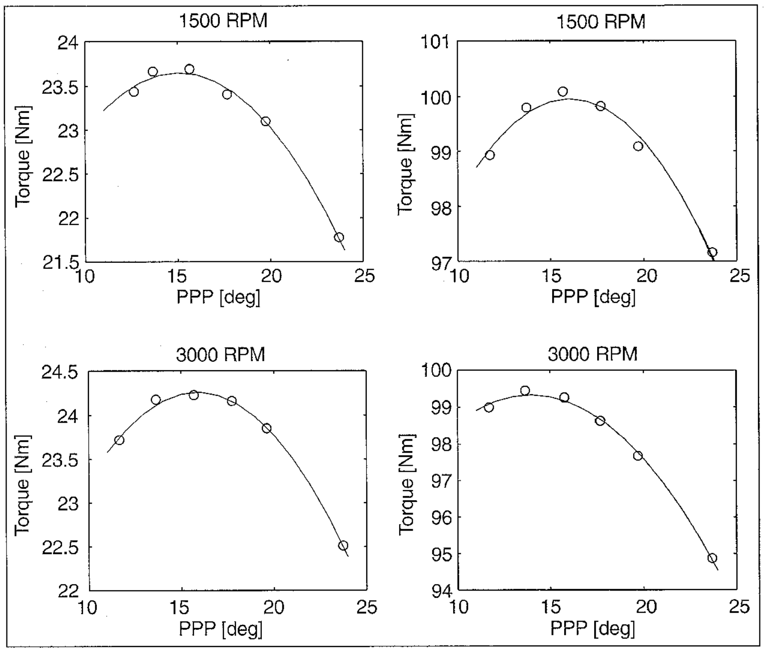


Fig. 10. Mean PPP (Peak Pressure Position) and output torque for 1500 rpm and 3000 rpm and two different engine load conditions. Each circle is a mean value from 200 consecutive cycles with the same ignition timing. The optimal mean PPP is close to 15° for all loads, even though the spark advance differs a lot.

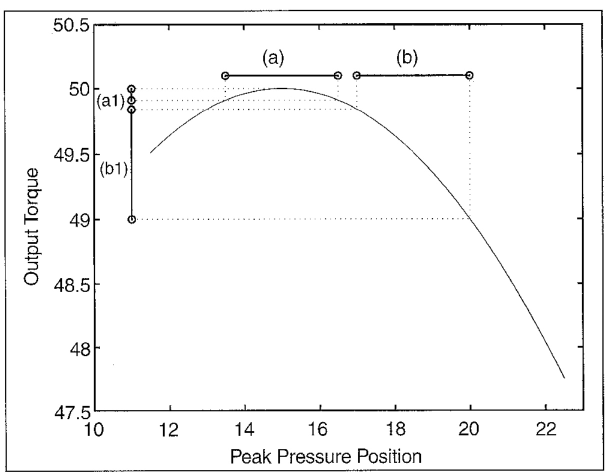


Fig. 11. The figure illustrates that when the mean PPP (peak pressure position) is at optimum the variations in the output torque are minimal. At (a) the mean peak pressure position lies at optimum which give small variations in output torque at (a1). At (b) the mean peak pressure position lies some degrees off from optimum and the resulting variations are larger at (b1).

Using this equation, the standard deviation of the variations in the output torque, σ_T, can be derived as a function of the standard deviation of PPP, σ_p, and the deviation of PPP from the optimal, d, [16]

$$\sigma_T^2 = 2c^2\sigma_p^2(\sigma_p^2 + 2d^2). \qquad (3)$$

Equation (3) gives a useful rule of thumb, and another useful quantification of the value of spark advance feedback control. The interpretation is that the influence of cycle-to-cycle variations in PPP on the output torque is minimal if the mean peak pressure position is controlled to its optimal value $d = 0$.

The conclusion is that if an engine is not kept at its optimum point then is efficiency lost. In addition, variability is increased, which leads to harsher operation, which of course is not desired for driveability reasons.

Structure and Design of Engine Fine-Tuner

The developed engine fine-tuner relies on ionization current interpretation to obtain an estimate of the peak pressure position (PPP), and it relies on the analysis above to obtain set-points and feed forward values.

PPP Estimate

The ionization current interpretation method is presented in somewhat more detail in [13]. The phenomenological model in (2) is fitted to the measured ionization current, and the model parameters $\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3$ corresponding to the flame front and post-flame phases are extracted. The second phase, the post-flame phase, is used as the estimate of the in-cylinder pressure development.

In Fig. 12, the peak pressure position (PPP) estimate from the ionization interpretation algorithm is compared to the measured PPP. For the experiments shown in the figure the engine speed and the throttle angle are held constant, and the ignition timing is positioned at six different spark timings from 35° BTDC (before TDC) to 4° BTDC. The resulting PPPs range from 7° ATDC (after TDC) to 55° ATDC as can be seen in the figure. The estimate correlates quite well with the measured peak pressure position. The correlation is best around the point of optimal efficiency at 15 degrees after TDC, which is yet another way of pointing out the increase in engine variations when moving away from optimal position. The correlation is improved by further filtering, which is discussed in the next section.

The implementation to obtain the model parameters, $\alpha_1, \alpha_2, \alpha_3, \beta_1, \beta_2, \beta_3$, can be done in different ways, but there is a real-time requirement since it is pattern recognition in a fast inner loop. The algorithm used in the real-time implementation [17] estimates bimodal functions based on the Kullback directed divergence.

Controller Structure

The controller structure for the spark timing is shown in Fig. 13. A conventional spark plug is used. The ionization current is produced by the integrated ignition and measurement system, described in [1], and the interpretation algorithm gives an estimate of the PPP. The reference value for the PPP makes it possible to have different spark schedules for different operating points, i.e., to meet other goals than maximizing the work. For example, in mid-load mid-speed ranges it is desirable to have a spark advance close to MBT, with PPP around 15°, and in high load ranges a more conservative schedule, with late PPP, for re-

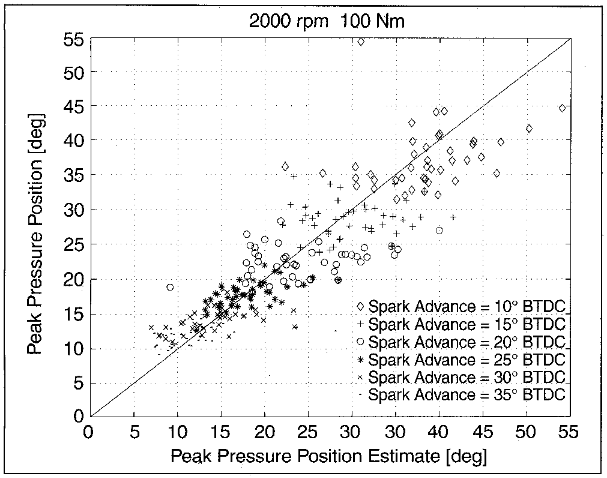


Fig. 12. The peak pressure position estimated from the ionization current compared to the measured. Each point corresponds to the estimated and true PPP for one cycle. Close to 500 cycles are displayed in the plot. One to one correspondence is indicated by the solid line.

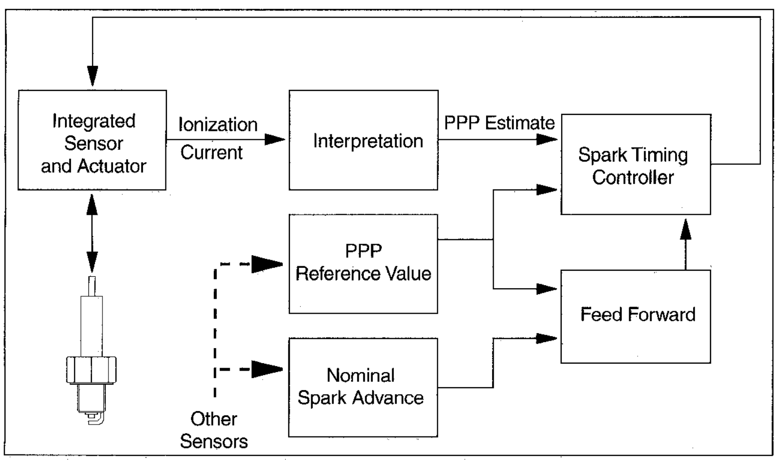


Fig. 13. The structure of the spark advance controller, where the spark plug operates as an integrated actuator and sensor. Information is extracted from the raw ionization current, and the estimate of the PPP is the input to the spark timing controller. Reference values and feed forward signals are obtained using other sensors, e.g. engine speed and load.

ducing engine noise and NO_X emissions. The feed forward structure shown in Fig. 13 incorporates information about how changes in reference value and engine transients affect the spark advance. This structure is similar to the ones used in conventional lambda controllers.

The spark advance controller measures the on-going combustion and updates the spark timing to the next combustion. Without the feed forward the spark timing update is done through the following, PI-like, control law:

$$ST[n+1] = ST[n] - C \cdot (PPP_{ref}[n] - PPP_{est}[n]), \qquad (4)$$

where ST is the spark timing, PPP_{ref} the desired peak pressure position, PPP_{est} the PPP estimation from the ionization current, and C a gain that has to be tuned.

Closed-Loop Control Parameters

The gain C in (4) is selected as a balance between attenuation of cycle-to-cycle variations and response speed. The filtering comes at the price of slowing down the feedback loop, but this can be compensated for by using feed forward schemes, shown in Fig. 13, based on a nominal spark advance table. Since environmental parameters like humidity do not change rapidly, very quick responses is not an issue. One criterion is that the spark timing shall not move more than 1° due to the cyclic variations [18]. For this engine the cycle to cycle variations for the estimate of the PPP is around 10°.

Another consideration to take into account is how well the PPP estimate correlates with the actual PPP. Moving averages of different lengths have been computed for the measured and the estimated peak pressure positions [16]. This indicates that a good choice for the gain in the feedback control law is $C = 1/10$, which is the gain used in the on-line tests.

Performance of the Engine Fine-Tuner

Experiments with the engine fine-tuner will be presented. Responses to set-point changes are presented together with measurements from an extra pressure sensor to prove that the pressure trace is correctly positioned. The highlight of the experiments is where the engine is exposed to increased humidity. There is an increase in power and efficiency when the engine fine-tuner is turned on.

Experimental Setup

The engine used for measurement and validation is a spark-ignited, Saab 2.3*l*, 16 valve, four-stroke, four-cylinder, fuel-injected, normally aspirated, production engine equipped with the Trionic engine control system. The ionization current measurement system is the production system developed by Mecel AB [1], which is used in the Saab engine. A pressure transducer and amplifier from AVL, for in-cylinder pressure measurement, is used for algorithm validation.

The ionization current interpretation scheme is implemented in a PC that is connected to the ECU by a CAN bus. Ionization current and pressure data are sampled into the PC synchronously with the crank shaft rotation, and a new updated spark advance is calculated and sent to the ECU using the CAN bus.

Response to Set-point Changes

In Fig. 14, it is shown that the ionization current based controller achieves the goal of controlling the peak pressure position to the desired values. The reference value (dash dotted) shifts every 250th engine cycle, from the initial value of 16° to 14° to 16° to 19° to 21° and back to 16°. The mean values for the PPP estimate from the ionization current (dashed) and the PPP (solid) are computed using a first order LP filter with unity static gain, $y[n+1] = 0.9 \cdot y[n] + 0.1 \cdot u_{measured}[n]$.

The results are very good, taking into account that the cycle-to-cycle variations of the PPP and its estimate are of the order 10°, and the actual mean PPP is controlled to within ±1° of the desired position, as can be seen in Fig. 14. It is thus demonstrated that the peak pressure position can be controlled to de-

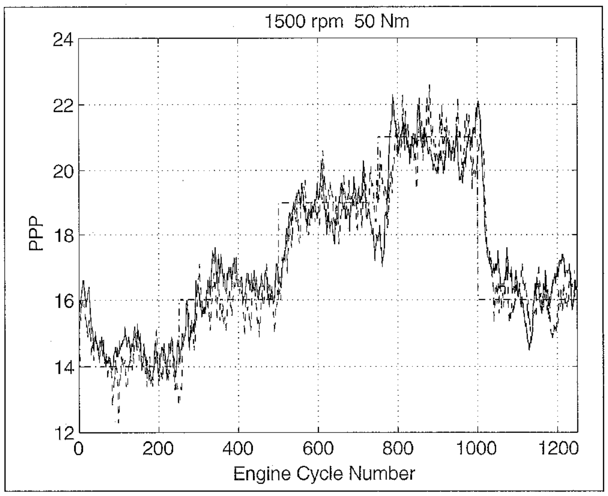


Fig. 14. Closed loop control of spark advance with changing reference value, showing that the PPP can be controlled to the desired positions (dash dotted—reference signal; solid—PPP measured by an extra pressure sensor; dashed—PPP estimated from ionization current).

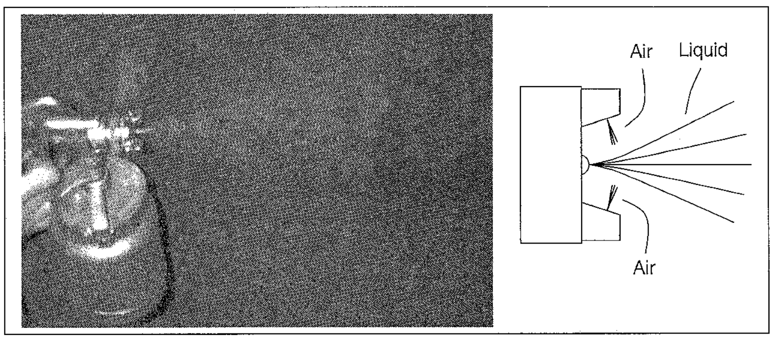


Fig. 15. Left: A picture of the sprayer spraying water. Right: A schematic figure of the sprayer nozzle with the liquid spray, pressurized air, and the atomized liquid drops.

sired positions using only information from the ionization current signal.

The response time for the controller has been evaluated using a reference square wave with a fast duty cycle, showing that the step response time is approximately 30 cycles without feed forward compensation [16]. Since no feed forward compensation is used this step response time for the reference signal will be the same as for environmental disturbances. With a feed forward loop the step response can be made faster to fit the needs during engine transients e.g., quick changes in the manifold pressure.

Water Injection Setup

To create a change in air humidity in the laboratory a water sprayer is used. The sprayer is originally a color sprayer that has a valve which delivers a liquid spray. This liquid spray is further atomized by two opposing holes that blows pressurized air on the spray. Fig. 15 displays the sprayer with the water spray. The figure also shows an enlarged schematic figure of the nozzle with the liquid spray and the pressurized air. The liquid is not fully atomized by the pressurized air but the droplets are made significantly smaller. By directing the water spray towards the throttle plate the water is drawn into the induction system by the lower pressure in the intake manifold.

The amount of water sprayed into the engine was not measured during the tests but it had no audible effect on the engine during the tests. Nevertheless, there was enough water present to change the in-cylinder pressure trace so that the mean peak pressure position moved to a position four to five degrees later than optimal.

Humidity handled by the Engine Fine-Tuner

Humidity slows down combustion speed, leading to delayed pressure development and thus decreased power and efficiency. It is normally not possible to compensate for this; the ultimate test of the engine fine-tuner is whether it really has an effect on the overall engine output, in terms of power and efficiency, when subjected to an air humidity change.

During the water injection tests, the throttle angle, fuel injection time, and engine speed are held constant. The engine is running at steady state and the A/F ratio is tuned to $\lambda = 1$ before the test cycle starts. Then the injection time is frozen and held constant during the test cycle. A controller structure that includes a feed-forward coupling, Fig. 13, using a conventional look-up table with engine speed and manifold pressure as inputs, was used during the tests.

Fig. 16 shows a part of a test cycle where water is sprayed into the engine air intake, and the closed loop spark advance controller is switched on and off. The speed and load condition is 1500 rpm and 55 Nm. Initially in the test cycle, the closed-loop spark-advance controller is running and it changes the spark advance controlling the peak pressure position to a position close to MBT, i.e. 17° after TDC. The ionization current is used as input to the controller, and the in-cylinder pressure is only used for validation. The signals PPP and output torque have been filtered off-line with the filtering procedure with zero phase shift, which is included in the signal processing toolbox in Matlab. The filter that is used is a Butterworth filter with order 3, and normalized cut-off frequency at 0.3.

At cycle 50 the closed-loop controller is turned off and the spark advance is held constant, changing only slightly due to the measurement noise in the manifold pressure signal used for feed forward. At cycle 250 the water spraying is started, and two things can be noted at this point: Firstly, the most important point is that the PPP moves 4 degrees. Secondly, the actual spark advance changes slightly, 0.5°, in the wrong direction due to a change in intake manifold pressure. When the controller is turned off, the spark advance can be viewed as a conventional pre-calibrated schedule with a spark advance close to MBT. The parameters that affect the spark advance are, then, the engine speed and the manifold pressure. Note that a conventional scheme changes the spark advance in the wrong direction, since increased manifold pressure indicates higher load and therefore would require a smaller spark advance.

The spark advance controller is switched on again at cycle 500. The PPP is controlled to 17° ATDC by using information from the

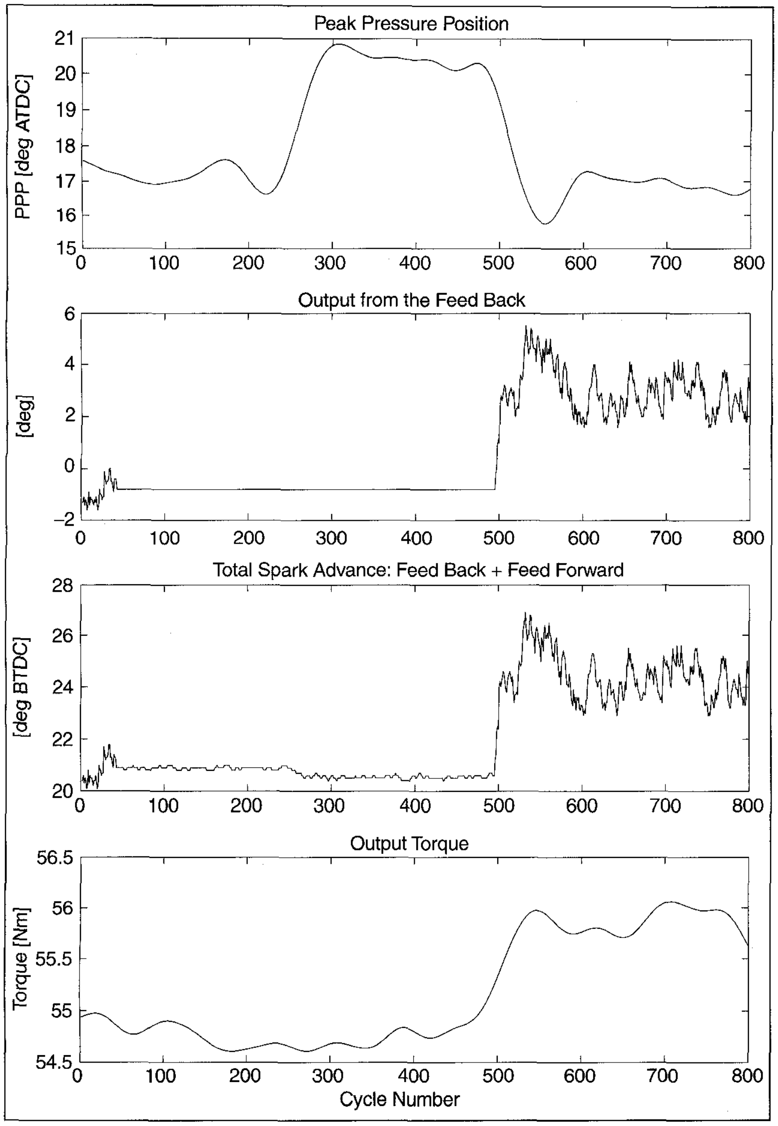


Fig. 16. The interesting part of the test cycle. The spark advance controller is switched off at cycle 50 and the water injection starts at cycle 250, which leads to increased PPP. The controller is switched on again around cycle 500, controlling PPP to MBT, which increases the output torque.

ionization current. Note that the output torque increases by ~2% when the controller is switched on. It is thus shown that the engine fine-tuner can handle external disturbances such as air humidity, and control the engine to an optimal operating condition.

Conclusions

Developments of virtual engine-doctors and virtual engine fine-tuners are trends that add to the challenges and joys of modern research in engine control. Here an ion-sense engine fine-tuner has been presented. It is a feedback scheme, not a calibration scheme, based on ionization current interpretation. The method is very cost effective since it uses exactly the same hardware and instrumentation (already used in production cars) that is used to utilize the spark plug as sensor, to detect misfire, and for knock control. The only addition for ignition control is further signal interpretation in the electronic engine control unit.

Humidity significantly changes the burn-rate in the combustion, and thus the peak pressure position, which in turn affects power and efficiency. Humidity is not easily measured, and is therefore usually not compensated for. Both experimental and theoretical studies (Figs. 10 and 16, and (3)) clearly demonstrate the value of spark advance control regarding power and efficiency. The ion-sense engine fine-tuner has a response time more than sufficient to follow environmental changes. And it was shown, as a main result, that it can control the engine back to its optimal operation when subjected to humidity in the intake air.

References

[1] J. Auzins, H. Johansson, and J. Nytomt, "Ion-gap sense in missfire detection, knock and engine control," *SAE SP* 1082, SAE paper no. 950004, pp.21–28, 1995.

[2] A. Lee and Jan S. Pyko, Engine misfire detection by ionization current monitoring, *SAE SP* 1082, SAE paper no. 950003, 9–19, 1995.

[3] M. Hubbard, P. D. Dobson, and J. D. Powell, "Closed loop control of spark advance using a cylinder pressure sensor," *J. Dynamic Systems, Measurement and Control*, pp. 414–420, Dec. 1976.

[4] I. Glaser and J. D. Powell, Optimal closed-loop spark control of an automotive engine, SAE paper no. 810058, pp. 11–21, 1981.

[5] K. Sawamoto, Y. Kawamura, T. Kita, and K. Matsushita, Individual cylinder knock control by detecting cylinder pressure, SAE paper no. 871911, 1987.

[6] Y-Y. Wang, V. Krishnaswami, and G. Rizzoni, "Event-based estimation of indicated torque for IC engines using sliding-mode observers," *IFAC Control Engineering Practice*, vol. 5, no. 8, pp.1123–1129, Aug. 1997.

[7] S. X. Chen and J. J. Moskwa, "Application of nonlinear sliding mode observers for cylinder pressure reconstruction," *IFAC Control Engineering Practice*, vol. 5, no. 8, pp.1115–1121, Aug. 1997.

[8] Y. Shimasaki, M. Kanehiro, S. Baba, S. Maruyama, T. Hisaki, and S. Miyata, "Spark plug voltage analysis for monitoring combustion in an internal combustion engine," SAE paper no. 930461, 1993.

[9] N. Collings, S. Dinsdale, and T. Hands, "Plug fouling investigations on a running engine - an application of a novel multi-purpose diagnostic system based on the spark plug," SAE paper no. 912318, 1991.

[10] A. Saitzkoff, R. Reinmann, T. Berglind, and M. Glavmo, "An ionization equilibrium analysis of the spark plug as an ionization sensor," SAE paper no. 960337, 1996.

[11] A. Saitzkoff, R. Reinmann, and F. Mauss, "In cylinder pressure measurements using the spark plug as an ionization sensor," *SAE SP* 1263, SAE paper no. 970857, pp. 187–197, 1997.

[12] R. Reinmann, A. Saitzkoff, and F. Mauss, "Local air-fuel ratio measurements using the spark plug as an ionization sensor," *SAE SP* 1263, SAE paper no. 970856, pp. 175–185, 1997.

[13] L. Eriksson and L. Nielsen, "Ionization current interpretation for ignition control in internal combustion engines," *IFAC Control Engineering Practice*, vol. 5, no. 8, pp.1107–1113, Aug. 1997.

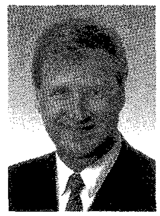
[14] D. J. Patterson, "Cylinder pressure variations, a fundamental combustion problem," SAE paper no. 660129, 1966.

[15] B. Johansson, *On Cycle to Cycle Variations in Spark Ignition Engines*, PhD thesis, Lund Institute of Technology, 1995.

[16] L. Eriksson, L. Nielsen, and M. Glavenius, "Closed loop ignition control by ionization current interpretation," *SAE SP* 1236, SAE paper no. 970854, pp.159–166, 1997.

[17] L. Eriksson, "Closed-loop spark-advance control using the spark plug as ion probe," Technical report, 1997, LiU-TEK-LIC-1997:14, Thesis no. 613.

[18] J. D. Powell, "Engine control using cylinder pressure: Past, present, and future," *Journal of Dynamic System, Measurement, and Control*, vol. 115, pp. 343–350, June 1993.



Lars Nielsen received the degrees of M.S. in engineering physics in 1979 and Ph.D. in automatic control in 1985, both from Lund Institute of Technology, Sweden. Since 1992 he has held the Sten Gustafsson Professor of Vehicular Systems chair at the Department of Electrical Engineering, Linköping University.

Lars Eriksson was born in Edsbyn, Sweden, in 1970. He received the M.Sc. degree in electrical engineering from Linköping University in 1995. Since then he has been a research assistant and graduate student at the Division of Vehicular Systems, Linköping University. His research interests are modeling and control of spark ignited engines, with a focus on spark advance control and ion sensing using the spark plug as sensor.