Universität Karlsruhe (TH)

Institut für Industrielle Informationstechnik

Zusammenhang zwischen Druckverlauf und Mengenschwankungen in einem Common-Rail-Einsprizsystem

Correlation between Pressure Waves and Fuel Mass Deviations in a Common Rail Injection System

Diplomarbeit

(in Englischer Sprache)

Von

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Erklärung

Hiermit erkläre ich, dass die vorliegende Diplomarbeit selbstständig und nur unter Verwendung der angegebenen Hilfsmittel und Quellen angefertigt wurde.

Karlsruhe, den 2. *August 2006*.

Abstract

Nowadays most diesel engines use Conmmon-Rail injection systems. These systems provide the feasibility of performing several injections per combustion stroke. As a matter of fact, up to five injections per stroke are accomplished. The fact that in a really short period of time several injections are to be performed, leads to really short fast opening and closure of the injector valves. Due to the water hammer effect, after each of the injections, a pressure pulse is generated upstream the injector nozzle thus influencing the following injection.

The aim of this work is to study the pressure behaviour and the injected fuel deviation due to the influence of neighboured injections, in order to predict this deviation and correct it, thus allowing to improve the engine performance.

To accomplish a correlation between the pressure wave generated after each injection and the injected fuel mass in the following injection, first data were obtained out of simulations from a system consisting of a single injector, the common-rail and the pipe connecting both.

After data were gathered out of simulations, both pressure wave and variation of injected fuel with the time gap between injections were fitted into damped-sinusoidal-wave models. Thus, information of frequency, amplitude phase and damping was available for both signals.

After proving that frequencies of both waves could be considered to be the same and damping could be left aside, the correlation aimed to be obtained would then consist of relations between amplitudes and phase of both pressure and injected-fuel waves.

In a first stage, a correlation was found for both this variables using data obtained from simulation were only a pre-injection and a main injection took place. A mathematical relation was obtained for both wave-phases and amplitudes were calculated by means of interpolation out of a developed look-up table. Maximum relative errors were calculated between the wave reconstructed out of the calculated parameters and the simulated wave, proving that the obtained correlation was reliable for this situation

Next stage consisted on the validation of the previously obtained correlation. Thus, it was first applied to a large group of simulated situations where three injections took place. Exactly the same correlation was then used and after reconstruction of the waves, errors between simulated and estimated waves proved the validity of the correlation for this situation.

On a final stage, the aforementioned correlation was tested with experimental data measured out of a test bench. In this case, obtained errors proved again the validity of the correlation. Hence, a way of predicting the injected-fuel deviation was finally developed.

Contents

1. Introduction

The following work is aimed to study the pressure behaviour inside a Common-Rail injection system and the effect of such behaviour when two or more neighboured injections take place.

This work is part of a study taking place in the Institute of Industrial Information Technology, University of Karlsruhe (TH) in cooperation with Siemens DVO. The target of this whole project is to accomplish an inexpensive way of knowing more accurately how pressure behaves inside the injection system close to he injector valves and therefore improving the engine management and performance as well as its fuel consumption and emissions by predicting the real amount of fuel injected.

When more than one injection per combustion cycle take place in a common-Rail injection system, the pressure waves generated by each injection have a strong influence in the subsequent injection, specifically in the amount of fuel that is indeed injected. In the following work, after describing the origination of such waves and how to measure them, a correlation between them and the injected fuel will be developed.

To accomplish this, a certain amount of working points was simulated trying to cover a wide range of the possible operating conditions. For this, a single injector model was used, and in a first approach, two injections were assumed. Out of the simulated data, pressure waves can be fitted into sine wave models against the time, consisting in the superposition of two different harmonics, thus translating the pressure values into amplitude, frequency, phase and damping parameters. As well as information over the pressure, the simulations provide values for the injected fuel. Considering the time gap between the injections as the time axis, injected fuel can also be considered a sine wave and thus be fitted into the same model as the pressure.

Once data are obtained out of simulations and transformed into wave parameters, these can be compared in order to find a correlation between them. Thus, a correlation is developed, which allows calculating the injected fuel mass out of the pressure measures and the working conditions, being: rail pressure, temperature, injections timing and gap between injections. Damping of the waves is not taken into consideration, since it would not provide information due to the short sampling time of the signals; furthermore, frequency of both waves is proved to be approximately the same. Hence, the correlation is to be established between amplitude and phase of the waves.

Once a correlation is developed, considering only two injections, more working points are simulated, this time adding a third injection. After applying the same correlation for the third injection, it is proved to be valid.

Finally, the correlation is validated using experimental measures supplied by Siemens, finding that no high relative errors occur and therefore, the correlation can be used for correcting the injection timing, thus improving the engine performance.

1.1 Common Rail and its features.

The common rail injection system is nowadays the state-of-the-art device used in most of modern manufactured diesel engines. It came out as a solution for improving diesel engines emissions with which the manufactures could reach the emission standards. In addition, it also allows noise and performance to be improved.

Once the direct in-cylinder injection systems for passenger car engines were fully developed, it was necessary to increase the pressure level of injections for better results. The previous device used in diesel passenger cars engines was the rotary-injection-pump. This was a sophisticate device; with which increasing injection pressure and controlling when injections took place was an awkward task. The answer of how this could be accomplished came from traditional petrol engines. The common-rail system is no more that an evolution of this systems. Thanks to the current developments in electronics this system could be adapted to diesel engines requirements of high pressure and direct in-cylinder injection.

Thus, instead of a complex pump that provide the required amount of fuel at any moment at the same time that it delivers pressure to the fuel, both task were separated. Now a high pressure pump provides the required pressure, reaching values up to 1800bar, to a "common rail". From this rail through thin pipes, the fuel is then driven to the injectors in the cylinders. Now this injector has also the task of being a valve that opens and closes each time an injection takes place. The injector valve is commanded by a complex electronic device, being this the central engine control unit, ECU. As high engine speed is reached the time of opening and closing of the injector valves needs to be very short and accurate. Therefore, piezo-electric actuators are used for the commanding of these injectors.

The result is a high-accuracy system, able to provide the exact amount of fuel when it is needed at extremely high pressure levels and mechanically independent of the engine. This allows engineers to enhance even more the engine's behaviour.

In figure 1, a typical arrangement of one of these systems can be seen. There are many configurations depending on the engine manufacturers. Some may use a cylindrical rail, others a spherical one; besides, one or two pressure pumps are also used depending on the manufacturer.

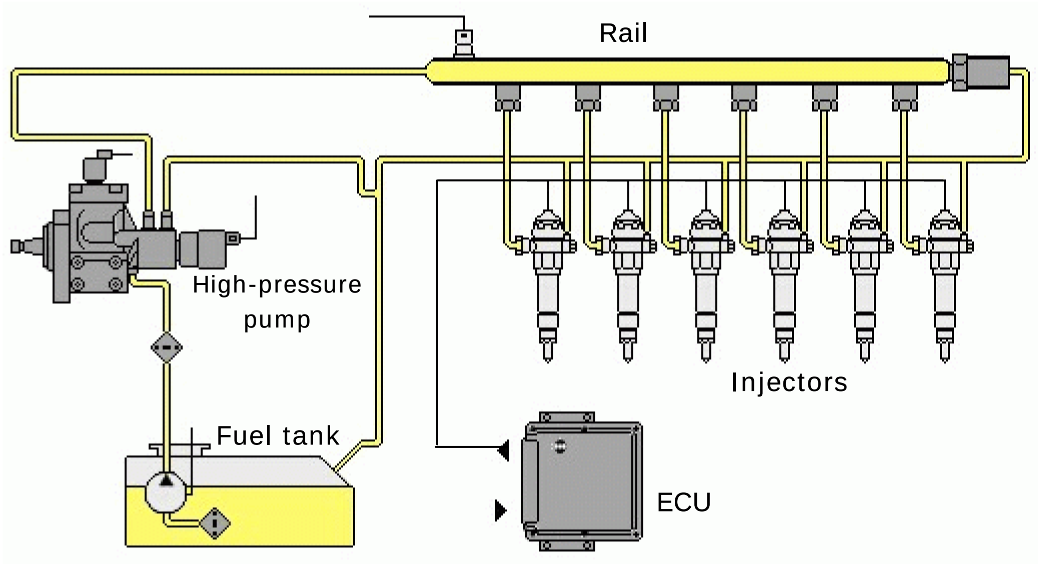


Fig. 1 Arrangement of a Typical Common Rail system.

1.2 Use of several injections

According to the field of study of this thesis, the main feature of this injection system is the flexibility it provides, which allows multiple injections to take place in the same cycle. Up to five injections per cycle is nowadays state-of-the-art, which leads to high improvements as far as noise and emissions are concerned.

The first designs of common rail systems, designed by Fiat and Bosch, injected all the fuel at once, or simply made two injections, a small one at the beginning to initiate the combustion and a longer one with the rest of the required fuel.

Unlike petrol engines, in which the combustion is due to the propagation of a flame front produced by a spark, in Diesel engines this happens spontaneously because of the high-pressure und temperature in the combustion chamber. This involves many advantages, but also some disadvantages. First of all, the fuel burns spontaneously as it is injected, that leads to a sudden pressure increase inside the cylinder and therefore, to a much higher noise and vibration levels than those in a petrol engine. Furthermore, there is an even more important problem using direct-port injection and it has to do with pollutant emissions. As fuel is injected after the compression stroke, and even though the modern combustion chambers are designed so that the turbulence of the injected flux is strong, the air-fuel mixture obtained is not homogeneous. As a matter of fact, three different areas are created: one with a high fuel concentration, near the injector nozzle; another one, far away from the injector where the air-fuel ratio is really low; and in the middle of both, an intermediate area where the air-fuel ratio is close to the stoichiometric value and hence, the combustion conditions are likely to be ideal.

The area where the fuel concentration is too high can bring onto the appearance of non-burned residuals due to the lack of oxygen in this area, which usually translates into a black smoke coming out of the exhaust pipe. On the other hand, in the area away from the injector where the amount of fuel is very low, the high temperatures and the high amount of air leads to the ionization of nitrogen and the following production of NO_x, a truly toxic pollutant.

The aim of reducing these previously related phenomena is what led engineers on their way to develop a system in where the fuel was injected more gradually into the combustion chamber.

A good way of avoiding too high or too low local fuel concentration and thus reducing emissions is trying to extend this intermediate region as much as possible. That is exactly what a scattered injection allows. On the one hand, the fuel around the injector nozzle would not be so high, avoiding the non-burnt particles to be created, and on the other hand the far away areas of the cylinder would have a higher concentration and therefore the available oxygen is used in burning of the fuel instead of in producing oxides of nitrogen.

Finally, as the fuel is not burnt all at once in a short lapse of time, but gradually in a longer time gap, the pressure inside the combustion chamber would be more stable and thus noise and vibration are strongly reduced.

In Fig. 2, an example of one of these systems against a traditional one is illustrated. Here, the most of the injected fuel is spread on three different phases. Two of these phases take place before the piston reaches TDC and the third one when it has already gone through TDC. There might also be two more injections, the first one just at the beginning of the process and the fifth one just at the end. The first one is just meant to prepare the combustion chamber, increasing its temperature, for the main injections. The late one would finally increase the temperature of the exhaust gases, which allows a better post-treatment of them later on in an oxidation catalyst.

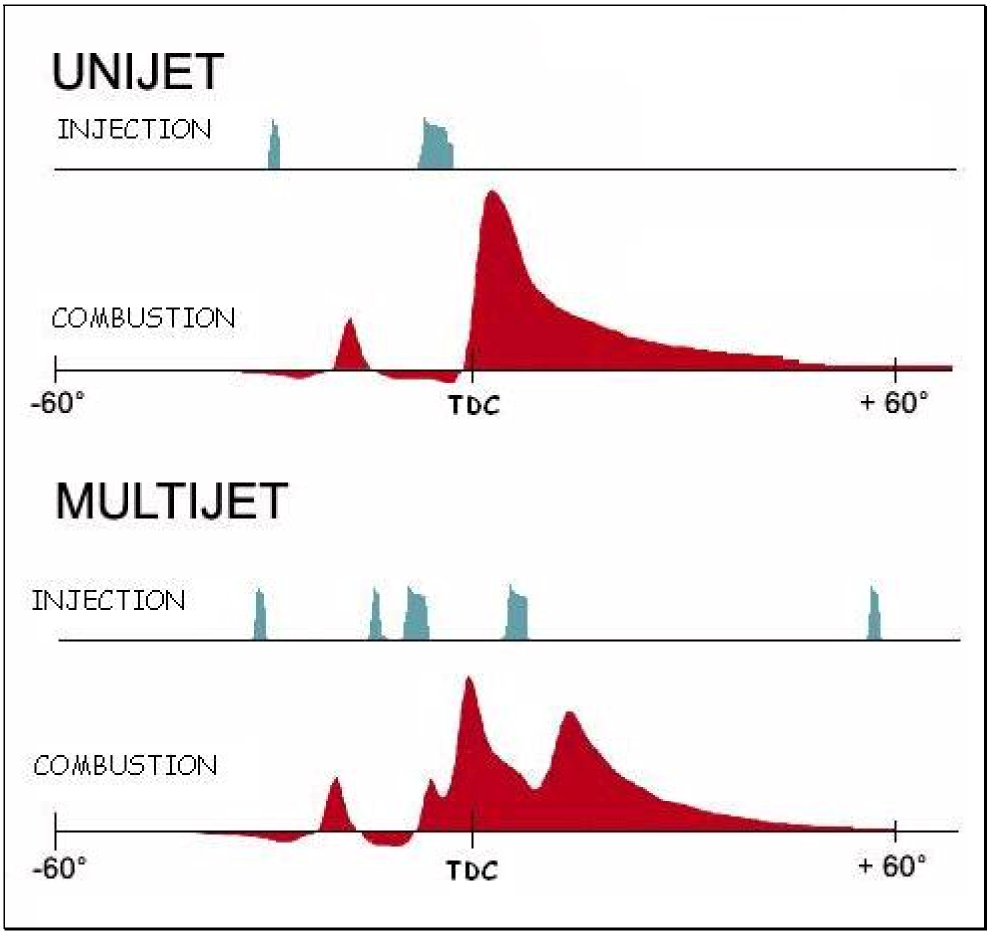


Fig. 2. Combustion process with one and five injections.

In Fig 2, it can be seen how the combustion occurs in a smoother way. This way, the fuel burning, and therefore the power that the engine extracts out of it, happen gradually resulting in a more efficient and clean process.

2. Motivation and Background

After talking about the advantages of five injections instead of one, let us think about what it physically means, and what actually happens inside the whole system each time the intake valve closes and the piston starts its way up, compressing the air up to high temperatures, getting ready for the combustion.

If a 4-cylinder engine is spinning at 3000 rpm, a combustion stroke should occur at one of the cylinder every revolution. That means that an injection procedure is to take place 50 times per second, in other words, in only 20 ms. it will start all over again. Considering that up to now pressure levels of up to 1800 bar or even more are accomplished, that the injection should occur within approximately ±60° from TDC and that we want to introduce the fuel in five stages, this leads to opening and closing of the injector, under high pressures, in time lapses of even less than one millisecond. Providing that the amount of fuel injected each time is extremely low, only a few cubic millimetres, the result is a complex system which needs to be extremely accurate as well as robust. Therefore, the main efforts of engineers in this field are focused in controlling and predicting the behaviour of such systems. It can also be noticed that the effects of this extremely short-time changes at that high pressures may lead to truly high local pressure phenomena.

2.1. Fluid Hammer.

Given the extreme working circumstances previously described, with devices such as piezoelectric injectors, the system precision requirements can be achieved. At first sight, it would be straightforward: given the rail pressure, the desired amount of fuel and the cross area of the injector nozzle, it would be easy to calculate the exact opening lapse of the injector. However, there is indeed a problem in injecting the exact amount of fuel. The problem is due to a well-known effect, occurring every time a valve suddenly closes. This phenomenon is known as *Fluid Hammer* and because of which the pressure in the rail does not remain constant at all.

The principles of this Fluid Hammer are quite simple. When a fluid, being fuel in this case, is moving down a pipe with a certain speed, this mass of fluid in movement has a certain kinetic energy. In case this movement was distorted in a relatively short time, this kinetic energy should somehow manifest. In the particular case of a valve sudden closure, the fluid just at the gates of the valve abruptly comes to a stop, but the fluid upstream in the pipe is still moving with its correspondent kinetic energy, pushing all of it against the valve. This is translated into a high rise of the pressure just at the gates of the valve. As the result of this happening almost instantly, a pressure pulse is generated. This initiates at the end of the pipe and travels upstream. This pressure wave travels up und down the pipe at the speed of sound.

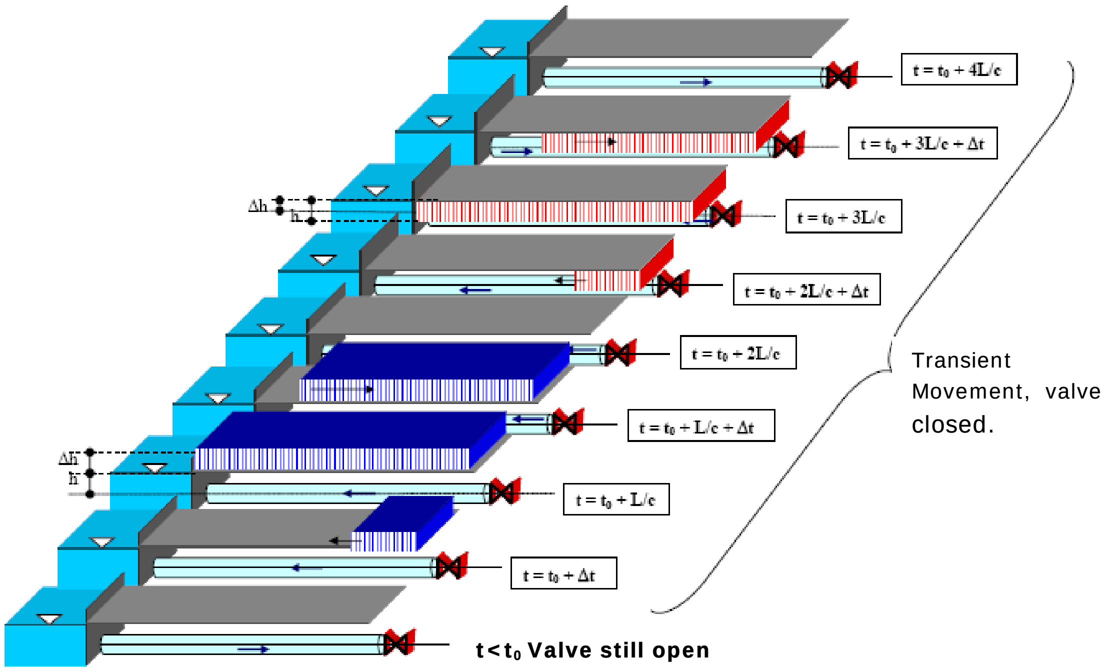


Fig. 3 . Pressure wave evolution. Fluid Hammer effect.

In figure 3, the valve closure takes place at $t=t_o$. At that time, the local pressure at the end of the pipe suddenly increases and thus the pressure wave is generated. If this waves travels with a velocity 'c' and the length of the pipe is 'L', after an L/C lapse of time, the wave will have reached the beginning of the pipe, where it is reflected. Not only a pressure wave is generated, but also the fluid tends to move up and down-stream due to this pressure wave and the reciprocal conversion between kinetic and potential energy. This way, when the fluid trends to travel upstream, after a time '2L/c', a vacuum is generated in the proximity of the valve and thus the pressure wave would now be a depression wave. This pressure pulse, positive and negative, travels once and again through the pipe until it is damped by the effects of friction and the elasticity of the fluid itself, as well as of the pipe walls.

2.1.1. Solving the fluid hammer effect.

As the fluid mechanicals theories are based in complex partial differential equations, this process above described, is not easily translated into equations. Furthermore, being the pressure increases so high, the properties of the pipe's walls should also be introduced into the equations. The equations that rule this phenomenon are those of the principle of Saint Venant. These are no more than a particular instance of the *Navier-Stokes* ones for transient flows.

Considering an oblique pipe, whose direction is *l*, the Saint Venant equations, for motion and continuity, would state as follows:

$$\left.\begin{aligned} \frac{\partial}{\partial l}\left(Z+\frac{p}{\gamma}+\frac{V^2}{2\cdot g}\right) &= -\frac{1}{g}\frac{\partial V}{\partial t}-f\,\frac{V\cdot|V|}{2\cdot g\cdot D} \\ \rho\frac{\partial V}{\partial l}+\frac{1}{c^2}\left(V\frac{\partial p}{\partial l}+\frac{\partial p}{\partial t}\right) &= 0 \end{aligned}\right\} \quad \text{(Eq.2. 1)}$$

Where:

- Z is the height at the beginning of the pipe.
- p is the pressure.
- γ is the specific weight of the fluid.
- V(l,t) is the average velocity in a given section at a given time.
- D is the pipe diameter.
- *f* is a factor depending on the friction against the pipe's walls.
- *c* is the velocity of the wave. For a thin wall it can be calculated by:

$$c=\frac{\sqrt{\frac{\varepsilon}{p}}}{\sqrt{1+\frac{\varepsilon\cdot D}{e\cdot E}}} \quad \textbf{(Eq.2. 2)}$$

Being:

- ε fluid compressibility
- ρ fluid density.
- *e* Pipe thickness.
- *E* Young's module of the pipe's material.

Directly solving these equations would be an arduous task for any mathematician and anyway, it would not drive to any useful result.

This problem has been traditionally studied under two different points of view. One point of view is the one concerning hydraulic distribution in which the only thing that matters is the highest value of the pressure, for reasons of safety in braking of pipes and other devices. For this use, an expression as the following was obtained:

$$\Delta h_{\max} \cong \frac{c\cdot V}{g} \quad \textbf{(Eq.2. 3)}$$

According to this, taking into consideration that *c* will take values between 300 m/s and 1200m/s and being g=9.81, the maximum pressure increase would be up to more than one hundred times the fluid velocity. That means that, for a fluid travelling at 1m/s, the pressure increase would be of around 100 m. For water, that is approximately 10 bars. If we considered that we are working with diesel fuel whose density is around 85% of that of the water, and that the speed of the fluid would be much higher than 1 m/s, overpressures of more than 200 bar. can be reached in Common-rail injection systems such as the ones under consideration.

This Fluid Hammer overpressure can be somehow diminished with several devices that quickly attenuate this water pressure in systems such as irrigation, water installation, and big hydraulic systems in general. Nevertheless, when it comes to the injection system of an engine, there is no choice but to cope with it.

Aware of these extremely high local pressures, engineers design all the elements of injections systems so that they can bear this pressure waves with endurance enough for the whole engine's operating life.

2.2.2 Numerical solutions.

Up to now only the scale of overpressure in the system is known, and there is in fact no problem at all in building a system capable of handling it. The real problem nevertheless lies in knowing the real behaviour of this pressure waves and how it influences the amount of fuel that is indeed being injected into the combustion chamber. That is exactly the aim of this whole work.

When studying flows ruled by equations such as the transient flow equations of Saint Venat, there are actually mathematical methods that allow obtaining a solution for these waves and thus, knowing how the pressure does really behaves.

Different methods could be applied in order to develop a computer algorithm. As a matter of fact, along history this problem has been approached through different numerical methods, among which it is worth mentioning:

- Finite differences with concentrated parameters.
- Characteristics method with orthogonal grid.
- Methods in frequency domain.
- Modal approximation
- The finites elements method.

For the current work, numerical simulations are to be made, and thus a numerical algorithm is to be used. For this task, the software used is based in a model developed in

[*1*], being this built out of the Galerkin procedure. In the mentioned work a hydraulic model for the flow in the pipe is defined. This model is to guarantee three main goals: the standardize formulation of the equations, the capability of describing all the essential phenomena and the fact of being robust and efficient.

The Galerkin's method is one of the so-called universal approximation methods. The essence of all these methods is to discretize the problem obtaining an approximate solution in a given amount of points. If the Galerkin method is to be applied, some simplifications are to be made. First, the continuity and motion equations must be linealized. Afterwards, longitudinal size of the pipe compared with transversals ones allows to simplify into one-dimensional equations. At last, the turbulent flow should be considered using the Reynolds value und thus being independent from frequency.

The basis of this method is to approximate the function by weight functions in a finite amount of points and to minimize the approximation error. The approximation functions can be polynomials or harmonic function. The result of the application of such method is the transformation of the partial differential equation in total differential equations. After the discretizing and applying of this method the result is a system of differential equations for each point. Being the equation now in total differential they can be numerically solved using numerical procedures such as finite differences. The result is finally a linear system that can be arranged into matrixes and therefore be solved. Hence, numerical solution of what is indeed happening inside the system can be accomplished.

2.2. Pressure behaviour and injected fuel.

It is obvious that for a certain opening time of the injector, the amount of fuel injected will strongly depend on the pressure upstream the valve. In a real system, the behaviour of the pressure at this location, according to the Fluid Hammer effect, will not remain steady at all. By the time an injection should take place, the injections that were previously made will have generated pressure waves that will probably remain travelling through the pipe leading to the injector. Furthermore, in a real system there would probably be four or six injectors, all of them connected through the same rail, the "common-rail". This way, although it might not be significant, there will be also some influence due to the coupling of neighbour injectors.

Trying to simplify the problem as far as possible, the pressure in the pipe following a single injection is represented in figure 4. This plot was obtained after simulating the injection process with a model that will later on be described. It represents the course of pressure in the pipe that drives the fuel from the rail to the injector. This curve is the result of a pre-injection of 0.2 ms, being the rail pressure 150 MPa. and fuel temperature 20ºC. It reveals that there is a maximum pressure increase of over 0.15 MPa, that is to say, over 150 bar, which means a pressure oscillation of over 15%.

This pressure disturbance seems to fade out after nearly 10 ms. This could be enough if only one injection took place, but in any modern system, a second injection will follow this one after a certain time, not long enough to let this perturbation disappear. According to this diagram, depending on the gap between this injection and a following one, this last one can start from nearly 1330 bar. up to over 1650 bar. This means that the amount of fuel injected in the following injection will strongly vary depending on the time gap

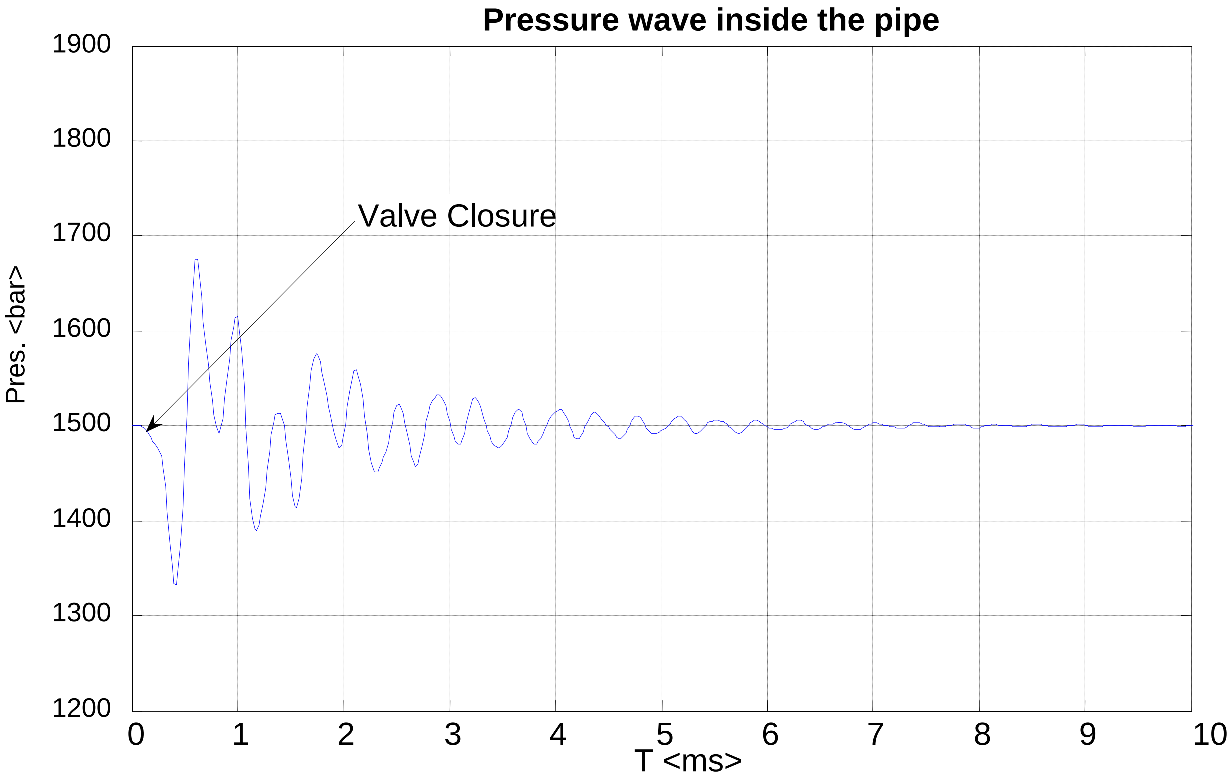


Fig. 4 Pressure wave after single injection.

Going still further, figure 5 and 6 shows what would happen, in the same conditions if a second injection goes on. Two curves are plotted for two different gaps between pre and main injections.

Both injections have the same duration, 0.25 ms. The only difference between both situations is that one takes place 0.1 ms after the end of the pre-injection and the other one after 1.3 milliseconds. Due to the difference in pressure at the start of each one, the amount of fuel will not be the same, and furthermore, the pressure waves that remains after this second injection occur, happen to be quite different in both cases. That means that the behaviour in case there is a third injection would still be influenced. Both the waves are clearly different in phase and amplitude.

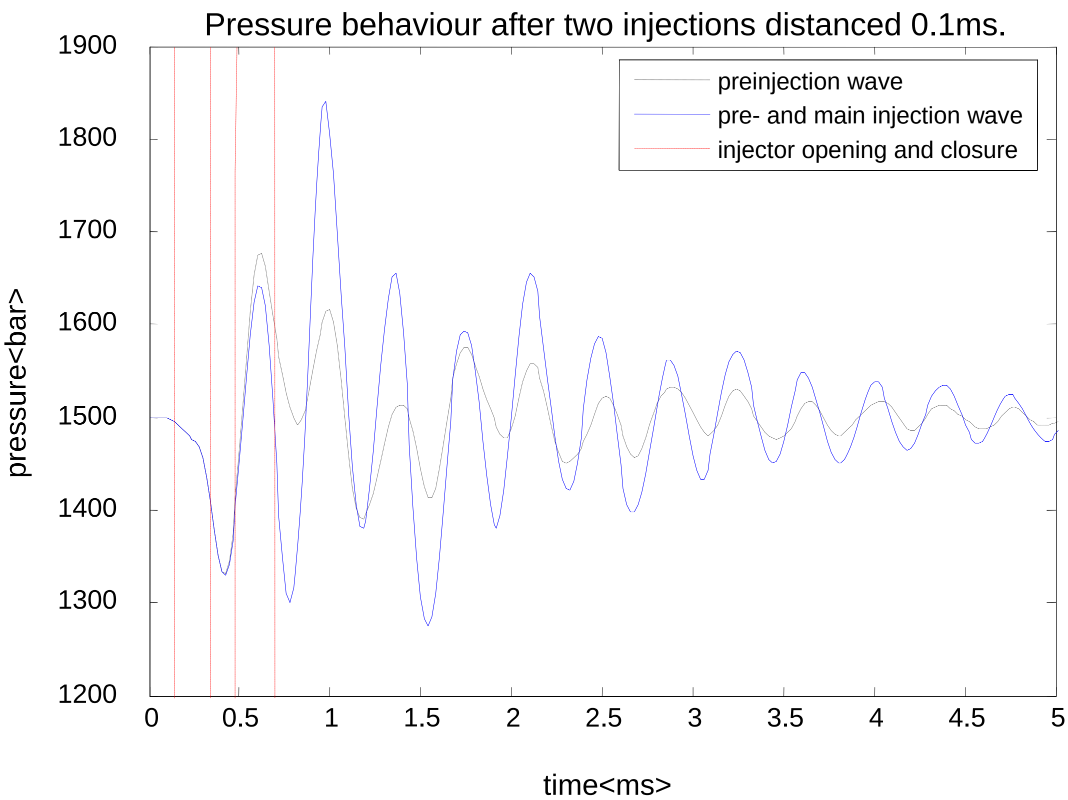


Fig. 5 Example of a situation with two injections gapped 0.1 ms.

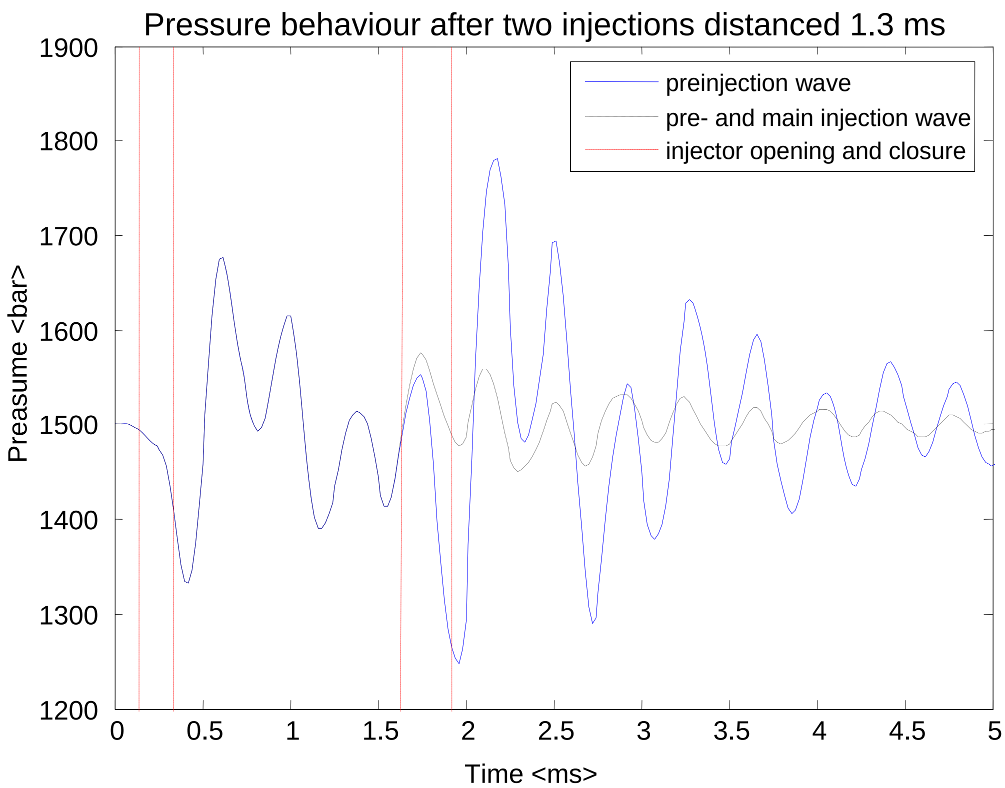


Fig. 6 Example of a situation with two injections gapped 0.1 ms.

In figure 7, the injected fuel is represented versus the time gap between pre- and main-injections, for the same working conditions as before.. The durations of both pre- and main injections remain unaltered, changing only the gap between them. The injected mass difference is over 5 mg. which implies over 20% of relative variation regarding the mean injected mass.

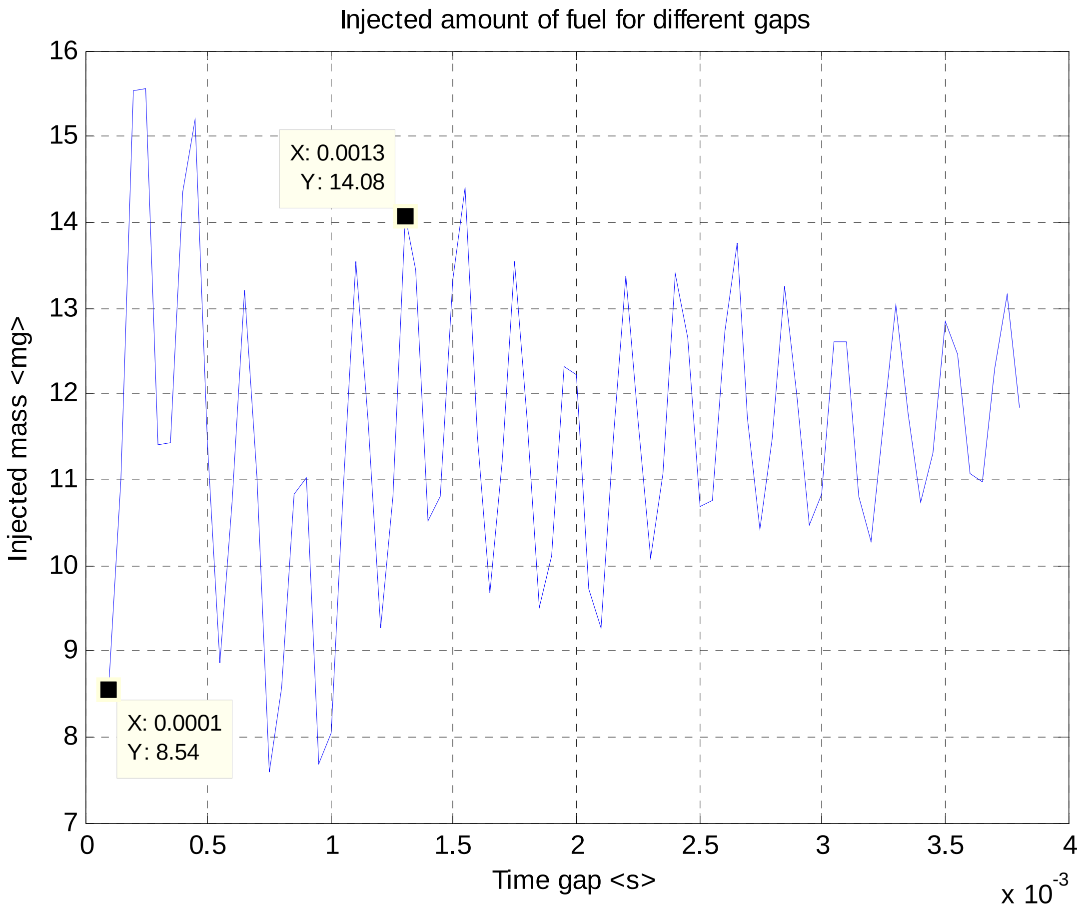


Fig. 7. Injected fuel mass depending on time gap

This behaviour is only considering the presence of two injections, being the first a tiny one. It will obviously get even more complex when more injections come into play. Thus, for a fifth injection, the effect of four previous injections will be present, varying substantially depending in the wide possible range of time gaps which in turn depend on the working conditions.

2.3. Measuring pressure waves inside the system.

It has already been explained how the pressure course in the pipe leading to the injector, and therefore the previous condition for any injection, vary in a way that makes it quite difficult to predict with accuracy how much fuel its actually being injected.

The current algorithms for solving the fluid hammer effect in pipes are not useful either. The amplitude and frequency of the generated waves depend not only on operating parameters but also on the varying fluid properties and even on the injectors' tolerance, which may vary during the engine's lifetime. Even if we could introduce all of this in an algorithm, it would be no use. The lapse of time in which everything occurs is so small that there will not be enough time to calculate it. In a word, there is no other way than measuring this pressure.

The rail pressure sensor is no use for this purpose, since it is mounted too far away from the injectors and has limited dynamic features. Therefore, a high-dynamic range sensor should be placed on each pipe just before the injector. Conventional sensors with such features, the ones based on piezo-resistive effects, are actually unaffordable for mass use in passenger cars. This way, a new, inexpensive sensor had to be developed.

2.3.1 Magneto Elastic sensor.

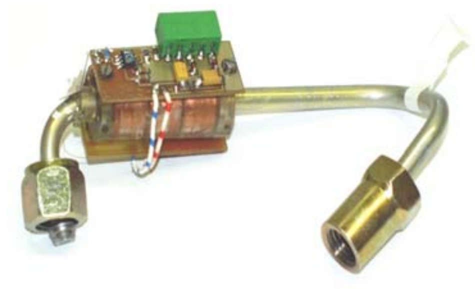
In the Institute of Information Technology, University of Karlsruhe (TH), a new sensor, based on magneto-elastic effect was successfully developed.

The appearance of this magneto-elastic effect is an inherent feature of all ferromagnetic materials. The atoms of these materials have constant magnetic dipoles, which arrange in parallel in certain areas, the so-called domains. Under no perturbation, these domains arrange themselves randomly, resulting in a null overall magnetic moment. When an external magnetic field is applied, these domains will try to re-orientate following the field's direction. Thus, due to the atoms' rearrangement, the material experiments a deformation that will depend on the kind of material. This is known as *magnetostriction* and is characterized for each ferromagnetic material by a constant λ_s, as the relative increase of length when applying an external magnetic field.

The opposite effect is what is known as the magneto-elastic effect and in which this new sensor is based. This phenomenon explains how the orientation of the domains changes as a ferromagnetic material is exposed to mechanical stress. Changing the domains arrangement translates into changing of the hysteresis curve of the material and therefore in its magnetic permeability, μ_r.

When fuel is running with certain pressure through a pipe, the pipe walls are exposed to a certain mechanical stress, σ. If this pressure changes, the stress will also vary and according to the ME-effect the magnetic permeability of the pipe walls will therefore be altered. This way, a change in pressure will translate into a varying magnetic flux density. According to Faraday's law, a time-varying magnetic flux will induce a voltage in a coil eventually mounted in the pipe, which could be taken as an output signal for a sensor and thus, measuring the pressure inside the pipe in a non-invasive and inexpensive way.

The sensor itself consists of three coils wound around the pipeline. The middle one is the measuring one, out of which the voltage inducted by the change of magnetic flux is obtained. The other two windings are pre-magnetization coils, whose task is that of generating an external magnetic field being supplied with a direct current.



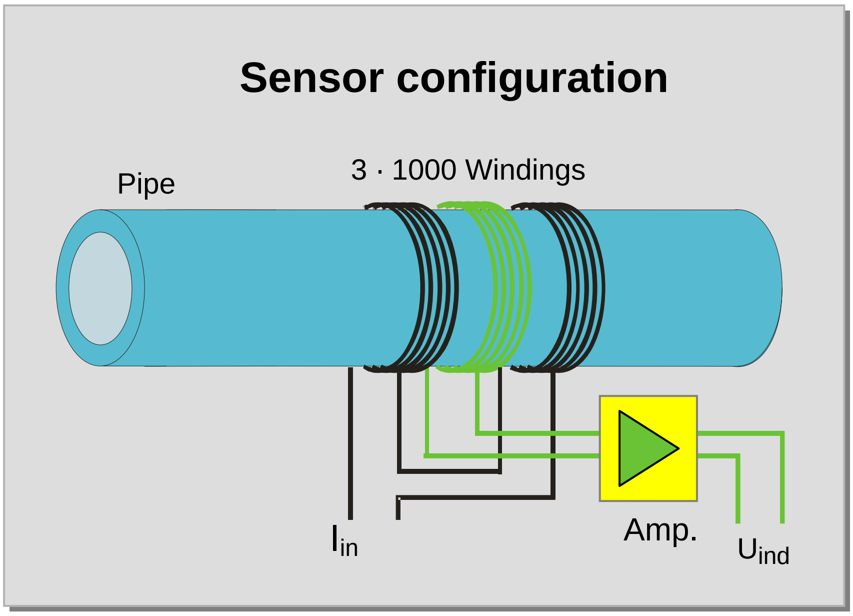


Fig. 8 Magneto Elastic Sensor

From the voltage signal coming out of the sensor, pressures waves inside the pipe can now be reconstructed. Although in most cases the pressure wave can be measured with relatively high accuracy, for low rail pressures it is possible to obtain relative errors of up to 18%. Nevertheless, it shows a high accuracy when measuring frequency of the waves. No matter if low or high-pressures, the error keeps always under 0.5%. Being able to accurately measuring the frequency makes a big deal when trying to compensate the influence of neighboured injections as well as it makes possible to establish a correlation to get to know the fuel temperature.

Hence, this sensor represent a feasible, and somehow essential, starting point for being able to predict and correct deviations in the injected fuel mass due to pressure disturbances caused by neighboured injections.

3. Model and Simulation.

In order to accomplish the goal of establishing a correlation between pressure waves and deviation of the injected fuel, a certain amount of data are required. To obtain these data, there are two ways of proceeding, on the one hand performing measures in a real test-model and on the other hand, numerically simulating with the help of hydraulic-simulation models.

Although real measures are always necessary for validation, computer simulations offer an inexpensive way of obtaining data, as well as other advantages. This way, simulating with a simple desktop computer in a relatively short time, a wide quantity of data can be gathered. Performing measures in a real system, apart from its high cost, leads to the appearance of stochastic and signal-noise errors due to the data acquisition equipment. These rrors although might not be significant are not easy to quantify. When obtaining data by means of numerical simulations, as models are not other than approximations to the real systems, some errors will appear. Nevertheless, the scale of these errors can be predicted.

Hence, even though simulated data means an abstraction from the reality to be studied, they can be used in terms of obtaining useful results as long as real measured data are afterward available for the validation of these results.

3.1 Modelling the injection system

In order to obtain the required amount of data necessary for the ongoing work, a model based in the mathematical method briefly described in section 2.2.1 is used. This model is implemented in simulating software developed by Dr-Ing. Fredrik Borchsenius in 2005[1]. The software is called HSSIM and allows building a model of the whole injection system, providing fast and reliable results.

As far as this diploma thesis is concerned, the modelling of the system into the mentioned software has no more interest than knowing that it provides indeed reliable results. It had previously been achieved and thus, provided for the direct performing of simulations. As well as any model in engineering, it starts modelling each individual element of the system and afterwards assembling all of them by adding constrains. Thus, every tiny element should be defined with its own features, as for instance length and diameter in case of a pipe. Next step will be to define nodes connecting every element and containing information relating to the interaction between neighboured elements.

How this modelling is performed can be seen in figure 9 where the injector model is shown. As the behaviour of the pressure just upstream the injector valve is under study, the model of this element is to be the more detailed and intricate. More elements are to be modelled but, since the behaviour of the fluid inside them is not so relevant, there is no need to use elaborate models.

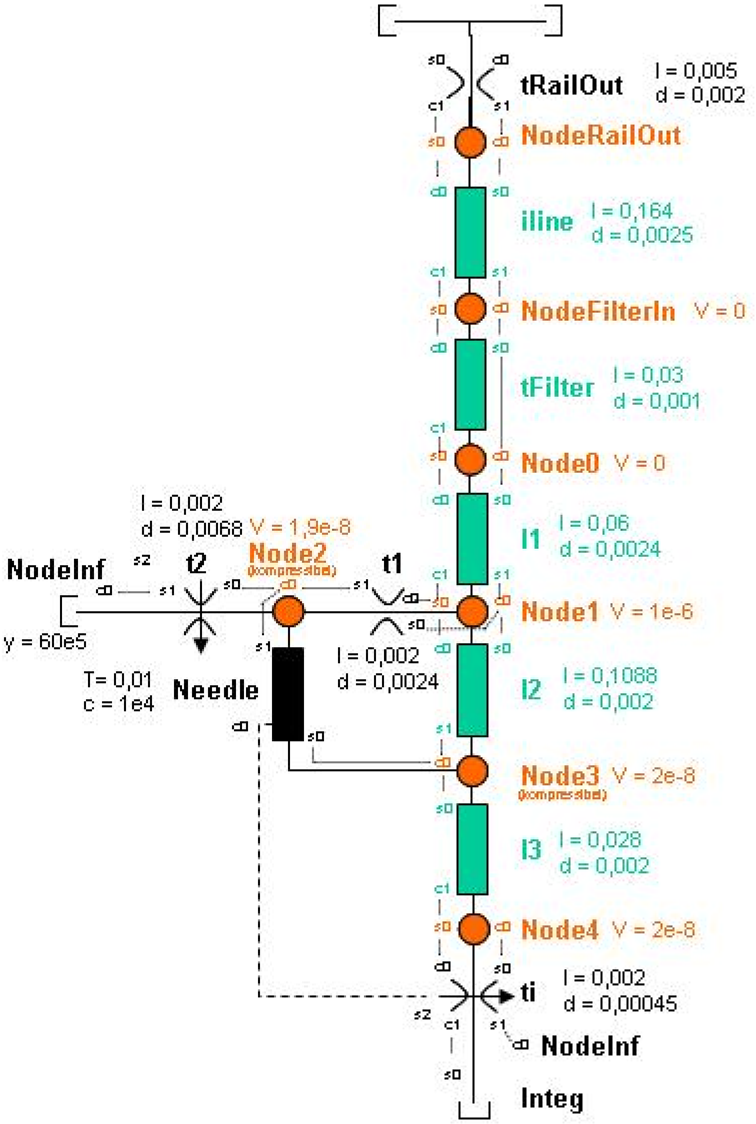


Fig. 9 Scheme of the injector model.

In the illustrated injector model (Fig 9), everything is represented using valves, pipes and nodes. At every point where there is a significant change or considered to be crucial, a node should be introduced. This way, after running a simulation, the results at this point will be available.

The injector is commanded by a leakage valve in t2. The opening and closure of the injector itself will be performed by the needle. When valve t2 opens, the pressure in *node 2* will decrease resulting in the needle going up because of the higher pressure in *node 3*. The needle will open the injection valve as it goes up.When valve t2 closes, pressure in *node 2* will now become higher as that on *node 3* and therefore the needle will go down and close the injector nozzle.

The study of the influence of neighboured injections is for what the results will be used, therefore, detailed modelling of rail and pump are not necessary. The pressure on the rail, due to its size compared with the pipe and injector, can be considered to remain steady. This way, the whole system upstream the beginning of the pipe could be simply introduced as another system where pressure keeps a constant value and which does not interact with the injector-and-pipe system, therefore being the place where pressure waves are reflected.

HSSIM software runs under MS-DOS command line providing the results of every simulation in numerical format. It allows up to three injections to take place. As input arguments, rail pressure, injections timing and gaps between injection as well as the fluid properties are used. The outcome after each simulation is a numerical array containing all calculated data. The software is set up so that a solution is provided up to an elapsed time of 40 ms. Since the process into consideration takes place in less than 15 ms,. only a part from those data will be needed. The results are arranged into columns, each one representing the value of a certain parameter at a certain time.

In order to analyse data obtained out of HSSIM, the engineering software Matlab™ was used. Simulations where then run inside Matlab environment and obtained data stored into own Matlab data-files so they could later be used.

To help performing the simulations, HSSIM was called from Matlab scripts that repeatedly varied input arguments as well as stored the results. Working points to be simulated were presented in Excel spreadsheets, containing all the required parameters from each point. Out of these spreadsheets, Matlab routines would read data and use it for running HSSIM. This way, continuous simulating could be achieved.

Although, the result of each of the more than seventy points out of every working condition are stored into a Matlab data-file, in order to the latter gathering of the results, the relevant values are also stored into a single Matlab variable, called *ergebnis.mat*. The values stored into this variable for each working condition are:

- Time
- Injected fuel mass of every single injection (pre- main and second)
- Time-gap between injections
- Pressure
    - at the end of the pipe
    - at two different points along the pipe (145mm. and 175mm.)

Also depending on whether two or three injections are performed, there will be different situations where only one injection is performed or all of them, or only two of them.

As a result, all the obtained data are organized into folders, each for every working point, containing a file with the important values to be later used and also including an excel file with the working conditions so that later everything can be automatically loaded in Matlab for further operations.

3.2 Selecting and simulating Working Points.

Given the fact that the correlation aimed to be obtained must be reliable for all engine operating range, the selection of the working conditions to be simulated happens to be one of the crucial steps in this work. The result of it is meant to have its application in passenger cars in which driving circumstances will depend on many different factors, therefore engine operating conditions will widely vary. It is obviously not possible to cover the wide range of situations under which the injection system will operate. Hence, a reasonable number of points should strategically be selected in order to describe as much of the operating range as possible.

Simulations were performed in two different stages. On a first one, only two injections were to take place. The data obtained out of these earliest simulations were meant to be used as the starting point for studying the pressure behaviour and this way, obtaining a first correlation for the injected fuel mass. On a second stage, a third injection was introduced. This way, the initial correlation could be tested in a more complex and close-to-real situation.

3.2.1 Working points performing two injections

Two injections per combustion stroke is the initial approach when studying the influence between neighboured injections. The situation in this case is the performing of a pre-injection followed by a main one. The pressure would be measured after pre-injection takes places and by means of the here in search correlation, the injected fuel mass during this last injection would be predicted.

The injector-needle position will resemble the one in figure 10, although the opening and closure will not obviously be instantaneous.

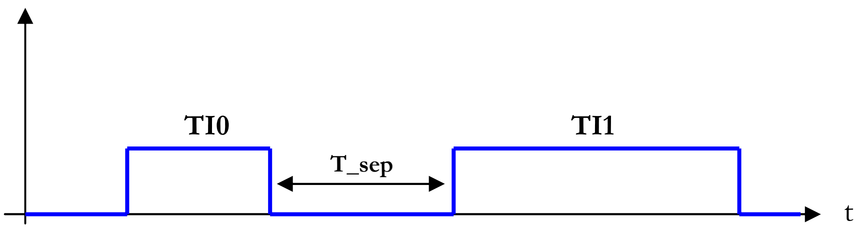


Fig. 10. Scheme of the two injections timing.

The varying working parameters that are remarkable from the point of view of the desired correlation are in principle:

- rail pressure (FUP),
- fuel temperature (T)
- pre-injection duration (TI0),
- main-injection duration (TI1) and
- time gap between pre- and main-injection (Tsep).

Systematically varying these five parameters, seventy five different working points were simulated. As a matter of fact, the so-called working points are actually groups of working points. For every given combination of pressure, temperature and injection timings, the time gap between injections is varied from 400 μs. up to 4 ms. in steps of 50 μs, that implies an amount of seventy-three different working points for each of the seventy-five different situations. Nevertheless, although it would be more accurate to call them working conditions, hereafter in this work they will be referred to as *working points*.

Fluid properties depend on pressure and temperature and will obviously influence the fluid behaviour. Hence, they are also to be introduced as an input argument for the simulations. These properties are taken out from a datasheet for fuel ISO4113, which is the fuel used in the test-bench for performing the measures that will later be used in terms of validation. They are introduced in the same datasheet of working points so that Matlab will read them out of it and create a file with fluid properties for every working point.

In Chart 1 and Chart 2, the selected working points are detailed.

Working points from one to fifty-six (Chart 1) cover the range of three different pressure levels: 50 MPa, 100 MPa. and 150 MPa. For 50 MPa. and 150 MPa., temperatures of 20ºC and 60ºC are selected, and for 100 MPa, apart from those, 40ºC is as well introduced. Along each group of pressure and temperature, injection durations are also systematically varied, thus two different pre-injection timings are used -200μs. and 300μs- and for each of them, the second injection timing also changes from 250μs up to 1.5 ms.

	Simulations parameter						
Name	**FUP [Pa]**	**Temp [°C]**	**Elasticity [Pa]**	**rho [kg/m³]**	**5*nue [m²/s]**	**TI0 [s]**	**TI1 [s]**
AP1	1,50E+08	20	3,041E+09	880,9	5,21E-05	2,00E-04	2,50E-04
AP2	1,50E+08	20	3,041E+09	880,9	5,21E-05	2,00E-04	5,00E-04
AP3	1,50E+08	20	3,041E+09	880,9	5,21E-05	2,00E-04	1,00E-03
AP4	1,50E+08	20	3,041E+09	880,9	5,21E-05	2,00E-04	1,50E-03
AP5	1,50E+08	20	3,041E+09	880,9	5,21E-05	3,00E-04	2,50E-04
AP6	1,50E+08	20	3,041E+09	880,9	5,21E-05	3,00E-04	5,00E-04
AP7	1,50E+08	20	3,041E+09	880,9	5,21E-05	3,00E-04	1,00E-03
AP8	1,50E+08	20	3,041E+09	880,9	5,21E-05	3,00E-04	1,50E-03
AP9	1,50E+08	60	2,664E+09	864,4	1,80E-05	2,00E-04	2,50E-04
AP10	1,50E+08	60	2,664E+09	864,4	1,80E-05	2,00E-04	5,00E-04
AP11	1,50E+08	60	2,664E+09	864,4	1,80E-05	2,00E-04	1,00E-03
AP12	1,50E+08	60	2,664E+09	864,4	1,80E-05	2,00E-04	1,50E-03
AP13	1,50E+08	60	2,664E+09	864,4	1,80E-05	3,00E-04	2,50E-04
AP14	1,50E+08	60	2,664E+09	864,4	1,80E-05	3,00E-04	5,00E-04
AP15	1,50E+08	60	2,664E+09	864,4	1,80E-05	3,00E-04	1,00E-03
AP16	1,50E+08	60	2,664E+09	864,4	1,80E-05	3,00E-04	1,50E-03
AP17	5,00E+07	20	2,065E+09	846,8	3,11E-05	2,00E-04	2,50E-04
AP18	5,00E+07	20	2,065E+09	846,8	3,11E-05	2,00E-04	5,00E-04
AP19	5,00E+07	20	2,065E+09	846,8	3,11E-05	2,00E-04	1,00E-03
AP20	5,00E+07	20	2,065E+09	846,8	3,11E-05	2,00E-04	1,50E-03
AP21	5,00E+07	20	2,065E+09	846,8	3,11E-05	3,00E-04	2,50E-04
AP22	5,00E+07	20	2,065E+09	846,8	3,11E-05	3,00E-04	5,00E-04
AP23	5,00E+07	20	2,065E+09	846,8	3,11E-05	3,00E-04	1,00E-03
AP24	5,00E+07	20	2,065E+09	846,8	3,11E-05	3,00E-04	1,50E-03
AP25	5,00E+07	60	1,687E+09	825,1	1,22E-05	2,00E-04	2,50E-04
AP26	5,00E+07	60	1,687E+09	825,1	1,22E-05	2,00E-04	5,00E-04
AP27	5,00E+07	60	1,687E+09	825,1	1,22E-05	2,00E-04	1,00E-03
AP28	5,00E+07	60	1,687E+09	825,1	1,22E-05	2,00E-04	1,50E-03
AP29	5,00E+07	60	1,687E+09	825,1	1,22E-05	3,00E-04	2,50E-04
AP30	5,00E+07	60	1,687E+09	825,1	1,22E-05	3,00E-04	5,00E-04
AP31	5,00E+07	60	1,687E+09	825,1	1,22E-05	3,00E-04	1,00E-03
AP32	5,00E+07	60	1,687E+09	825,1	1,22E-05	3,00E-04	1,50E-03
AP33	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,00E-04	2,50E-04
AP34	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,00E-04	5,00E-04
AP35	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,00E-04	1,00E-03
AP36	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,00E-04	1,50E-03
AP37	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,00E-04	2,50E-04
AP38	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,00E-04	5,00E-04
AP39	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,00E-04	1,00E-03
AP40	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,00E-04	1,50E-03
AP41	1,00E+08	40	2,372E+09	855,8	2,29E-05	2,00E-04	2,50E-04
AP42	1,00E+08	40	2,372E+09	855,8	2,29E-05	2,00E-04	5,00E-04
AP43	1,00E+08	40	2,372E+09	855,8	2,29E-05	2,00E-04	1,00E-03
AP44	1,00E+08	40	2,372E+09	855,8	2,29E-05	2,00E-04	1,50E-03
AP45	1,00E+08	40	2,372E+09	855,8	2,29E-05	3,00E-04	2,50E-04
AP46	1,00E+08	40	2,372E+09	855,8	2,29E-05	3,00E-04	5,00E-04
AP47	1,00E+08	40	2,372E+09	855,8	2,29E-05	3,00E-04	1,00E-03
AP48	1,00E+08	40	2,372E+09	855,8	2,29E-05	3,00E-04	1,50E-03
AP49	1,00E+08	60	2,192E+09	846,8	1,49E-05	2,00E-04	2,50E-04
AP50	1,00E+08	60	2,192E+09	846,8	1,49E-05	2,00E-04	5,00E-04
AP51	1,00E+08	60	2,192E+09	846,8	1,49E-05	2,00E-04	1,00E-03
AP52	1,00E+08	60	2,192E+09	846,8	1,49E-05	2,00E-04	1,50E-03
AP53	1,00E+08	60	2,192E+09	846,8	1,49E-05	3,00E-04	2,50E-04
AP54	1,00E+08	60	2,192E+09	846,8	1,49E-05	3,00E-04	5,00E-04
AP55	1,00E+08	60	2,192E+09	846,8	1,49E-05	3,00E-04	1,00E-03
AP56	1,00E+08	60	2,192E+09	846,8	1,49E-05	3,00E-04	1,50E-03

Chart 1. Working points from one to fifty-six when 2 injections are simulated

The range that these fifty-six parameters are able to cover is a narrow one compared to the wide possibility of operating circumstances. In an attempt to describe their range more in depth, points from fifty-seven to seventy-five (Chart 2) were also introduced. These ones consisting of variations of every parameter keeping the other fixed in one or two values. Thus, pressures from 25 MPa to 125 MPa are simulated only for 20ºC, TI1 being 300μs and

TI2 adopting three different values. Temperatures from 10ºC to 70ºC are also introduced being the rest of parameters unaltered, resulting in four more points. As there was no information in the available data sheet of ISO4113 for these temperatures, in order to obtain the fluid properties for these four points, lineal interpolation had to be used. Finally, three more values for pre-injection duration are introduced, each for two different main-injection timing.

	Simulations parameter						
Name	**FUP [Pa]**	**Temp [°C]**	**Elasticity [Pa]**	**rho [kg/m³]**	**5*nue [m²/s]**	**TI0 [s]**	**TI1 [s]**
AP57	7,50E+07	20	2,324E+09	856,5	3,56E-05	3,00E-04	5,00E-04
AP58	7,50E+07	20	2,324E+09	856,5	3,56E-05	3,00E-04	1,00E-03
AP59	7,50E+07	20	2,324E+09	856,5	3,56E-05	3,00E-04	1,50E-03
AP60	1,25E+08	20	2,811E+09	873,4	4,60E-05	3,00E-04	5,00E-04
AP61	1,25E+08	20	2,811E+09	873,4	4,60E-05	3,00E-04	1,00E-03
AP62	1,25E+08	20	2,811E+09	873,4	4,60E-05	3,00E-04	1,50E-03
AP63	2,50E+07	20	1,798E+09	835,9	2,68E-05	3,00E-04	5,00E-04
AP64	2,50E+07	20	1,798E+09	835,9	2,68E-05	3,00E-04	1,00E-03
AP65	2,50E+07	20	1,798E+09	835,9	2,68E-05	3,00E-04	1,50E-03
AP66	1,00E+08	10	2,682E+09	870,3	6,50E-05	3,00E-04	1,00E-03
AP67	1,00E+08	30	2,472E+09	860,6	3,17E-05	3,00E-04	1,00E-03
AP68	1,00E+08	50	2,282E+09	851,3	1,89E-05	3,00E-04	1,00E-03
AP69	1,00E+08	70	2,114E+09	842,4	2,04E-05	3,00E-04	1,00E-03
AP70	1,00E+08	20	2,572E+09	865,3	4,05E-05	1,50E-04	5,00E-04
AP71	1,00E+08	20	2,572E+09	865,3	4,05E-05	1,50E-04	1,00E-03
AP72	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,50E-04	5,00E-04
AP73	1,00E+08	20	2,572E+09	865,3	4,05E-05	2,50E-04	1,00E-03
AP74	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,50E-04	5,00E-04
AP75	1,00E+08	20	2,572E+09	865,3	4,05E-05	3,50E-04	1,00E-03

Chart 2. Working points from one to fifty-six when 2 injections are simulated

3.2.1.1. Simulation and results

Once the working points are carefully selected, simulations are ready to be performed. The Matlab routine runs first a simulation where only the first injection takes places. This is the one out of which the pressure data will be studied since the pressure wave remaining after it is the one out of which the correlation should be developed. After this pre-injection, another simulation where only the main injection is taking part is to be performed; as a result, information about what would happen in case there were no pressure pulse will be also available. After these two simulations, the rest of the performing simulations will consider both of the injections indeed, varying for each case the time-gap between injections.

After the simulations are achieved, relevant data are now stored and available for further operations. The relevant values to be considered will be the injected fuel mass during the main injection and the pressure wave remaining after the pre- injection. The last one is available at different points, nevertheless values in the so-called "Bridenadapter", -in English, bridal adaptor- will be used. This point lays at the leading pipe to the injector, around 3 cm. upstream the injector entrance, that being the place where the sensor would be mounted in the real system.

An example of the results obtained for two different points are represented in figure 11 where two different working points are shown. The working conditions in both of them are reasonably different, occurring in the first one a tiny main injection at a high rail-pressure and in the second one, a long main injection with at a low pressure level. The duration of the pre-injection is also different for both points. In both of them, the amount of fuel injected by main-injection depending on time gap is plotted in the upper diagram and the results are two respective wave-like curves. The value marked with a circle in the y-axis is the amount of fuel that would be injected in case there were no pre-injection. It is remarkable that both injected fuel curves appear to be waves but their shapes are in fact different. Pressure waves remaining after pre-injection are also shown in both cases, and they as well present wave behaviours although resembling dissimilar shapes.

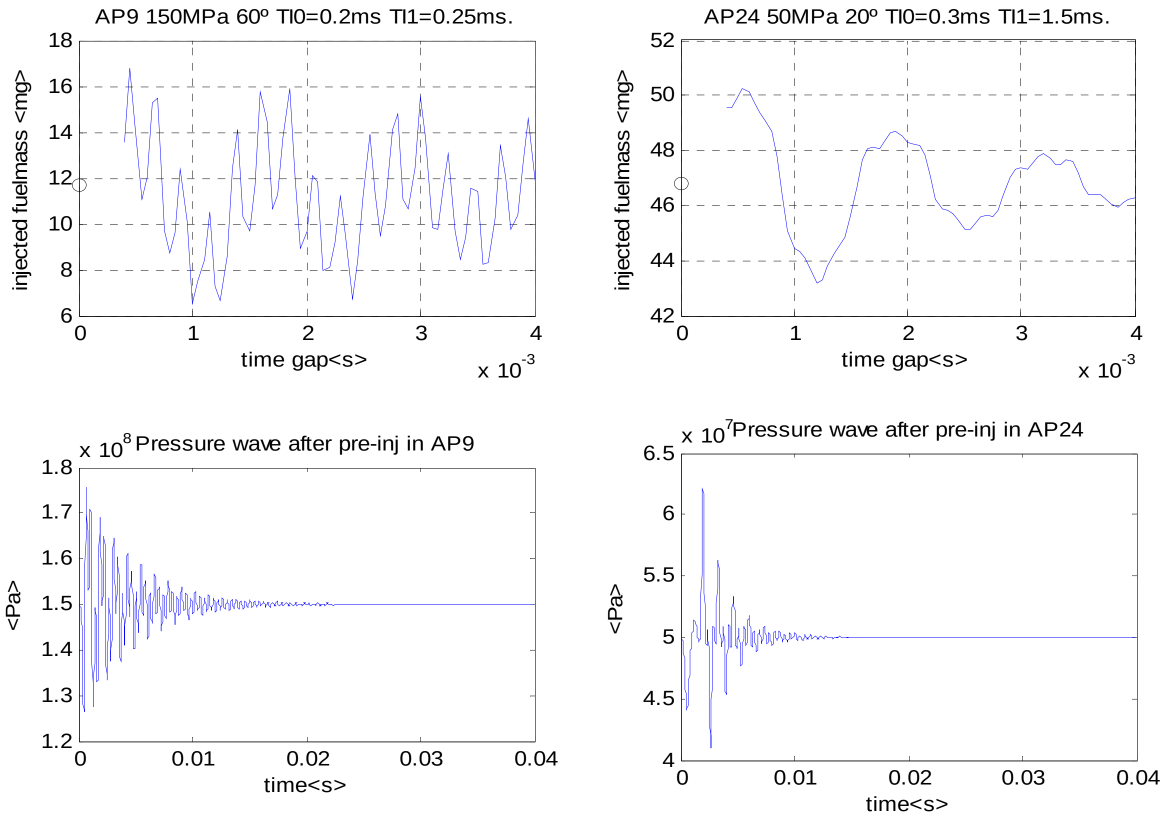


Fig. 11 Example of obtained data for two working points

3.2.2 Working points performing three injections

In a later stage on this work, working points performing three injections were also to be simulated in order to go still further in the development of the correlation. The way of proceeding for the selection of these points is the same as when only two injections took place.

Occurring three injections instead of two, results in more parameters to be selected and consequently in a higher number of possible combinations of them. Hence, the amount of points to be simulated will now be larger. A scheme of the injector-needle behaviour and time parameters is shown in figure 12.

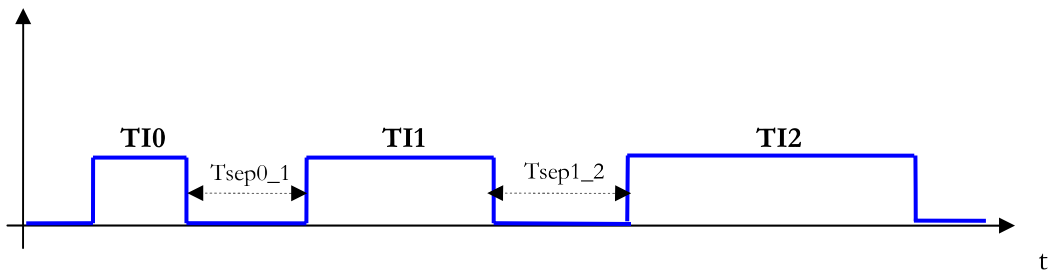


Fig. 12 Scheme of the 3 injections timing.

In the previous section, simulation where only two injections occurred were already performed, therefore the information that is interesting to be obtained this time is the behaviour after the first main-injection is performed.

In order to select the working points to be simulated, apart from those of pressure and temperature, the relevant parameters are shown in figure 12. The aim of the correlation that is intended to be proved is to relate the pressure just before the second main injection takes place with the amount of fuel injected during this last injection. Therefore, the time gap to be varied is the one between the first and second main injections, Tsep1_2. For every working point, simulations will be performed for this Tsep1_2 taking values from 0.8 ms. up to 4ms. in steps of 50 μs.

Given the larger amount of possible situations, and provided that temperature has no great weight in the results, temperature was not varied during the simulations, all the working points being at 20 ºC. On the other hand, pressure influence can not be ignored; hence, working points are the result of the varying injection timing for three different pressure levels: 50 MPa, 80 MPa and 100 MPa. For each of these pressures, three different values for each pre- and first-main-injection were combined, along with three different time gaps between them. Selected values for both injections are 0.2ms. 0.4ms. and 0.6ms, with time gaps of 0.5ms, 0.8ms. and 1.2ms. Besides, for each of the resulting combinations, three timings for the second-main-injection are to be performed, being 0.4ms. 0.6ms. and 0.8ms.

	Simulations parameter					
Name	FUP [Pa]	Temp [°C]	TI0 [s]	TI1 [s]	TI2 [s]	Tinj0_inj1 [s]
AP1	5,00E+07	20	2,00E-04	2,00E-04	4,00E-04	5,00E-04
AP2	5,00E+07	20	2,00E-04	2,00E-04	4,00E-04	8,00E-04
AP3	5,00E+07	20	2,00E-04	2,00E-04	4,00E-04	1,20E-03
AP4	5,00E+07	20	2,00E-04	2,00E-04	6,00E-04	5,00E-04
AP5	5,00E+07	20	2,00E-04	2,00E-04	6,00E-04	8,00E-04
AP6	5,00E+07	20	2,00E-04	2,00E-04	6,00E-04	1,20E-03
AP7	5,00E+07	20	2,00E-04	2,00E-04	8,00E-04	5,00E-04
AP8	5,00E+07	20	2,00E-04	2,00E-04	8,00E-04	8,00E-04
AP9	5,00E+07	20	2,00E-04	2,00E-04	8,00E-04	1,20E-03
AP10	5,00E+07	20	2,00E-04	4,00E-04	4,00E-04	5,00E-04
AP11	5,00E+07	20	2,00E-04	4,00E-04	4,00E-04	8,00E-04
AP12	5,00E+07	20	2,00E-04	4,00E-04	4,00E-04	1,20E-03
AP13	5,00E+07	20	2,00E-04	4,00E-04	6,00E-04	5,00E-04
AP14	5,00E+07	20	2,00E-04	4,00E-04	6,00E-04	8,00E-04
AP15	5,00E+07	20	2,00E-04	4,00E-04	6,00E-04	1,20E-03
AP16	5,00E+07	20	2,00E-04	4,00E-04	8,00E-04	5,00E-04
AP17	5,00E+07	20	2,00E-04	4,00E-04	8,00E-04	8,00E-04
AP18	5,00E+07	20	2,00E-04	4,00E-04	8,00E-04	1,20E-03
AP19	5,00E+07	20	2,00E-04	6,00E-04	4,00E-04	5,00E-04
AP20	5,00E+07	20	2,00E-04	6,00E-04	4,00E-04	8,00E-04
AP21	5,00E+07	20	2,00E-04	6,00E-04	4,00E-04	1,20E-03
AP22	5,00E+07	20	2,00E-04	6,00E-04	6,00E-04	5,00E-04
AP23	5,00E+07	20	2,00E-04	6,00E-04	6,00E-04	8,00E-04
AP24	5,00E+07	20	2,00E-04	6,00E-04	6,00E-04	1,20E-03
AP25	5,00E+07	20	2,00E-04	6,00E-04	8,00E-04	5,00E-04
AP26	5,00E+07	20	2,00E-04	6,00E-04	8,00E-04	8,00E-04
AP27	5,00E+07	20	2,00E-04	6,00E-04	8,00E-04	1,20E-03

Chart 3. Working points from 1 to 27.

In Chart 3 the first twenty seven points are related. These are the combination of timings resulting for 50 MPa. and a pre-injection of 0.2 ms. When the pre-injection increases its duration, time gaps of only 0.5ms. between pre- and first-main-injection are not practicable. According to this fact, for higher pre-injection times, this value will not be considered resulting in fewer working points. In Chart 4 and Chart 5 the working points increasing pre-injection length to 0.4 ms. and 0.6 ms. are shown.

	Simulations parameter					
Name	FUP [Pa]	Temp [°C]	TI0 [s]	TI1 [s]	TI2 [s]	Tinj0_inj1 [s]
AP28	5,00E+07	20	4,00E-04	2,00E-04	4,00E-04	8,00E-04
AP29	5,00E+07	20	4,00E-04	2,00E-04	4,00E-04	1,20E-03
AP30	5,00E+07	20	4,00E-04	2,00E-04	6,00E-04	8,00E-04
AP31	5,00E+07	20	4,00E-04	2,00E-04	6,00E-04	1,20E-03
AP32	5,00E+07	20	4,00E-04	2,00E-04	8,00E-04	8,00E-04
AP33	5,00E+07	20	4,00E-04	2,00E-04	8,00E-04	1,20E-03
AP34	5,00E+07	20	4,00E-04	4,00E-04	4,00E-04	8,00E-04
AP35	5,00E+07	20	4,00E-04	4,00E-04	4,00E-04	1,20E-03
AP36	5,00E+07	20	4,00E-04	4,00E-04	6,00E-04	8,00E-04
AP37	5,00E+07	20	4,00E-04	4,00E-04	6,00E-04	1,20E-03
AP38	5,00E+07	20	4,00E-04	4,00E-04	8,00E-04	8,00E-04
AP39	5,00E+07	20	4,00E-04	4,00E-04	8,00E-04	1,20E-03
AP40	5,00E+07	20	4,00E-04	6,00E-04	4,00E-04	8,00E-04
AP41	5,00E+07	20	4,00E-04	6,00E-04	4,00E-04	1,20E-03
AP42	5,00E+07	20	4,00E-04	6,00E-04	6,00E-04	8,00E-04
AP43	5,00E+07	20	4,00E-04	6,00E-04	6,00E-04	1,20E-03
AP44	5,00E+07	20	4,00E-04	6,00E-04	8,00E-04	8,00E-04
AP45	5,00E+07	20	4,00E-04	6,00E-04	8,00E-04	1,20E-03

Chart 4. Working points from 28 to 44.

Name	Simulations parameter					
	FUP [Pa]	Temp [°C]	TI0 [s]	TI1 [s]	TI2 [s]	Tinj0_inj1 [s]
AP46	5,00E+07	20	6,00E-04	2,00E-04	4,00E-04	8,00E-04
AP47	5,00E+07	20	6,00E-04	2,00E-04	4,00E-04	1,20E-03
AP48	5,00E+07	20	6,00E-04	2,00E-04	6,00E-04	8,00E-04
AP49	5,00E+07	20	6,00E-04	2,00E-04	6,00E-04	1,20E-03
AP50	5,00E+07	20	6,00E-04	2,00E-04	8,00E-04	8,00E-04
AP51	5,00E+07	20	6,00E-04	2,00E-04	8,00E-04	1,20E-03
AP52	5,00E+07	20	6,00E-04	4,00E-04	4,00E-04	8,00E-04
AP53	5,00E+07	20	6,00E-04	4,00E-04	4,00E-04	1,20E-03
AP54	5,00E+07	20	6,00E-04	4,00E-04	6,00E-04	8,00E-04
AP55	5,00E+07	20	6,00E-04	4,00E-04	6,00E-04	1,20E-03
AP56	5,00E+07	20	6,00E-04	4,00E-04	8,00E-04	8,00E-04
AP57	5,00E+07	20	6,00E-04	4,00E-04	8,00E-04	1,20E-03
AP58	5,00E+07	20	6,00E-04	6,00E-04	4,00E-04	8,00E-04
AP59	5,00E+07	20	6,00E-04	6,00E-04	4,00E-04	1,20E-03
AP60	5,00E+07	20	6,00E-04	6,00E-04	6,00E-04	8,00E-04
AP61	5,00E+07	20	6,00E-04	6,00E-04	6,00E-04	1,20E-03
AP62	5,00E+07	20	6,00E-04	6,00E-04	8,00E-04	8,00E-04
AP63	5,00E+07	20	6,00E-04	6,00E-04	8,00E-04	1,20E-03

Chart 5. Working points from 46 to 63.

This pattern is repeated along the other two pressure levels, resulting in a total amount of one hundred and eighty-nine points to be simulated.

3.2.2.1 Simulation and results.

As well as when two injections were to be performed, once the working points are carefully selected, simulation stage takes place. This time, automatic simulation routines are also developed via Matlab.

The simulating procedure for three different injections is essentially the same as for two. The main difference is that now the pressure wave that should be studied is the one remaining after the second of the three injections. For this purpose, a simulation where only the two first injections occur should be performed. As a matter of fact, this one and those happening only one of the three single injections are performed, although only the one with the two pre-injections will be useful.

As the relevant injection this time is the third one, in these simulations it is to be considered the main-injection, being the first and second injection both considered as pre-injections.

In figure 14, results for two different points are presented. In AP13, left, the conditions are 50MPa and timings of TI0=0.2ms. TI1=0.4ms TI2=0.6ms. and Tsep1_2=0.8ms. Conditions for AP159 are 100MPa, TI0=0.4ms. TI1=0.2ms. TI2=0.8ms. and Tsep1_2=1.2ms.

As well as in the example proposed for two injections, the results are wave-like curves which nevertheless present dissimilar shapes.

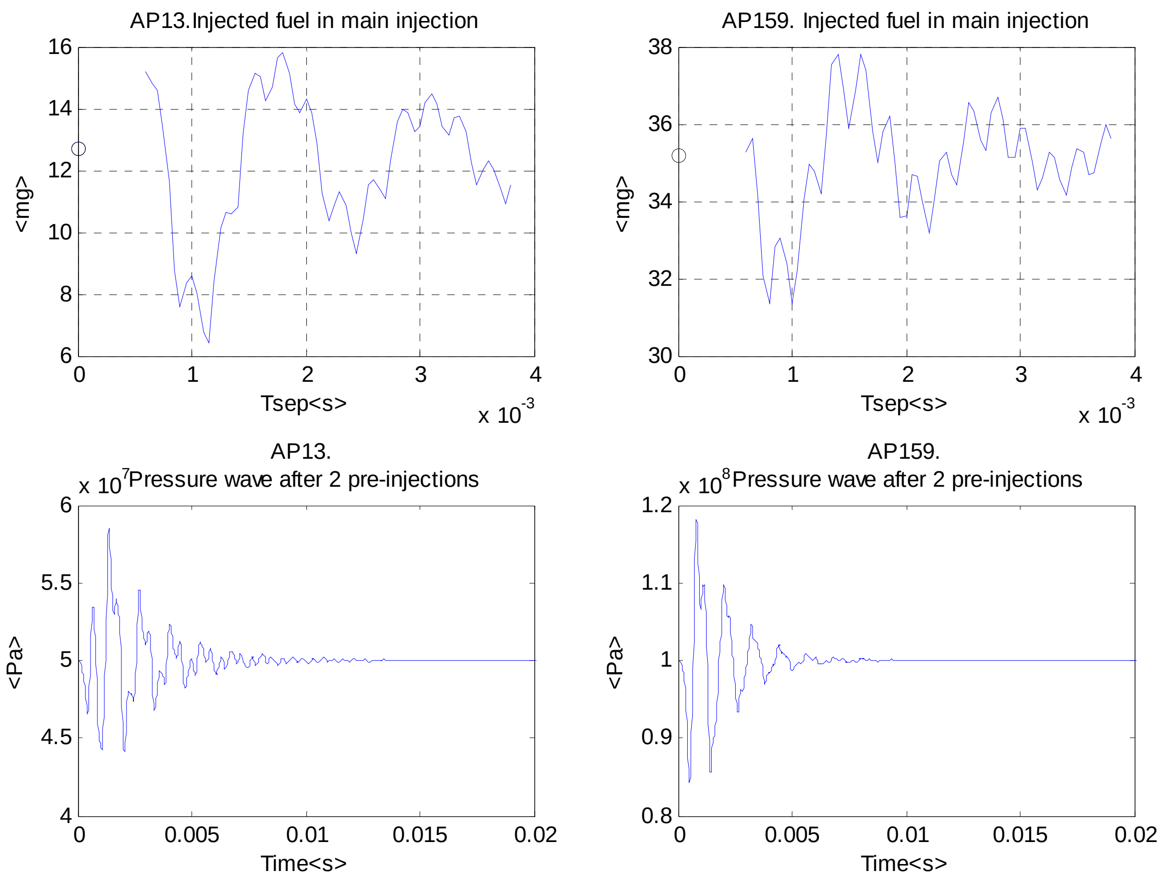


Fig. 13. Example of data obtained for two different points.

3.3 Fitting data into wave models.

Once the simulating stage is over, a great amount of data are available as numerical arrays conveniently stored. In order to study the relationship between pressure and injected fuel-mass, this data need to be fitted into a mathematical model that allows calculations to be performed.

In the previous section, plots from different working points where shown as an example of the achieved simulations. As it was then remarked, these result resembled a wave-like shape. When the rest of the working point's solutions are plotted, even though different values and shapes appear, in all of them both pressure and injected fuel share some type of wave-like resemblance. Hence, if they can both be fitted into alike mathematical wave-models, their relationship could be studied in terms of the wave parameters.

The similitude of both wave-forms with a sinusoidal wave is evident. According to the mathematical theories of Fourier, every wave can be represented as the addition of an undefined number of waves. This is the basis of the Harmonic Analysis of waves which studies the representation of functions or signals as the superposition of basic waves, the so-called harmonics. In line with this, in this work the resulting waves will be fitted into sinusoidal waves consisting of a fundamental or ground wave and its harmonics. As the results will later confirm, the fundamental wave and its first harmonic will represent a fine approximation of the real wave. Furthermore, for the aim of this whole work, the sole reconstruction of the ground-wave of the injected fuel will provide an important improvement in engine control.

The model into which the data will be fitted will consequently consist of a damped sinusoidal wave and its first harmonic, as shown in equation 4.

$$y(t)=A_1 \cdot \sin\left(2\pi \cdot f_1 \cdot t + \varphi_1\right) \cdot e^{-\gamma_1 \cdot t} + A_2 \cdot \sin\left(2\pi \cdot f_2 \cdot t + \varphi_2\right) \cdot e^{-\gamma_2 \cdot t} + K \qquad \textbf{(Eq. 4)}$$

The parameters of the wave model are, therefore:

- A_1, A_2 amplitudes of both ground wave and first harmonic.
- f_1,f_2 frequency of both waves.
- φ_1, φ_2 wave-phases
- γ_1, γ_2 wave-damping.
- K offset of the wave.

Although both signals can be fitted into this model, it is important to notice that the time axis for both of these waves is not the same. The time used for the pressure wave, the current elapsing time, would not make sense in the injected fuel mass deviation; the time that should here be used is the *time gap*. This last one should be considered as the one between the end of the first injection and the starting of the following. However, both times can be directly related.

3.3.1 Fitting procedure. Least Squares.

In order to fit data into the aforementioned two-harmonics-wave models, several procedures were used, all of them based in the Least Squares procedures.

The least squares technique is commonly used in curve fitting, being a mathematical optimization technique which, when given a series of measured data, attempts to find a function which closely approximates the data (a "best fit"). It attempts to minimize the sum of the squares of the ordinate differences –the so-called residuals– between points generated by the function and corresponding points in the data. The least squares technique is known to minimize the expectation of the squared residual, with the smallest operations (per iteration). But it requires a large number of iterations to converge.

Essentially the algorithms for curves fitting in the least squares sense try to minimize de residual, being these calculated as in Eq.5.

$$S = \sum_{i}^{n} \left(y_i - f(x_i)\right)^2 \qquad \textbf{(Eq. 5)}$$

Being:

- *yi* Every of the source point attempted to be fitted.
- *f(x$_i$)* Value of the last approximation for every x_i

In order to fit data into the wave model, each of the parameters (phase, amplitude, frequency and damping of both waves) should be identified individually.

Two different ways of fitting both pressure and fuel mass were tried; the first one based on a Matlab fitting function and the later one, directly implementing the least squares algorithm into a Matlab script. In both cases, frequency was estimated using the *Fast Fourier Transformation* algorithm. As a matter of fact, frequency was calculated only for the pressure signal and later on used on the fuel mass fitting. It will further on be proved that both pressure and fuel mass frequency can be assumed to be the same.

Matlab has at its disposal a non-linear fitting function based on the least squares theories, the *lsqcurvefit* function. This function was used for the identification of amplitude, phase and damping from both waves. A script that called first a frequency calculation and then the least squares identification was used for this purpose. Due to the slow convergence of the non-linear least squares method, the starting values, needed for the initiation of the algorithm, had to be carefully selected. Here lied the main disadvantage of this first method. For every group of similar points, parameters had to be selected manually, with a trial and error method, until the method showed convergence for all of the points.

Once the starting values were carefully adjusted, the results of this first fitting procedure were satisfactory. Afterwards, another script was used where another algorithm for the least squares method was implemented.

This second way consisted of the separate identification of the low frequency (fundamental harmonic) and the high frequency (first harmonic). After, the frequency is calculated using the FFT method, amplitude, phase and damping are to be calculated for each one. First, in order to determine the phase, a recursive LS estimator is used to determine a time-varying-amplitude and the phase. In a second LS estimator, out of the previously time-varying-amplitude, constant amplitude and damping are obtained. The process described is performed for both the harmonics and the result finally added to obtain the complete wave identification.

The first of the related methods was adapted (starting parameters) and applied for the fitting of pressure and injected-fuel with both two- and three-injection simulated data. Also the second of the methods was applied for both cases but only for the identification of pressure.

Both methods provided similar results and in a first approach it was not easy to decide which one provided the best. Consequently, both results were kept so that later on results obtained out of both could be compared. In due course, the second of the methods will turn out to provide the best starting point for obtaining the searched correlation.

Also different versions of the identifications were performed, varying simply the arbitrary point where time is equal to zero. Eventually, choosing the starting time-point where the injector closes after the pre-injection, proved to be the more sensible choice.

3.3.2 Results of the curve fitting.

For each of the working points, the result of this curve-fitting for both pressure and fuel mass are the nine parameters describing the sinusoidal wave and its first harmonic as well as an offset.

These parameters are stored in each working point's folder so they can later be recalled for further calculations. They are also available in graphical format, together with the simulated data, so the accuracy of the fitting can be checked by sight.

In the following pictures - figures 14 to 17 - , some examples for both two and three injections are shown. In these illustrations, the accuracy of the fitting is patent.

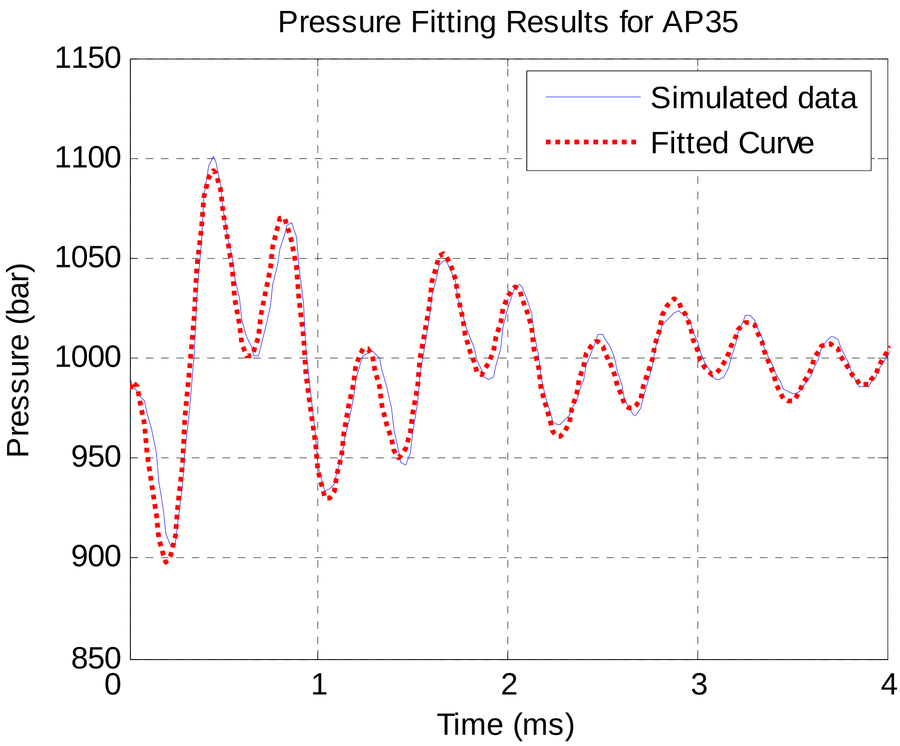


Fig. 14 Pressure for working point 35 (2 injections)

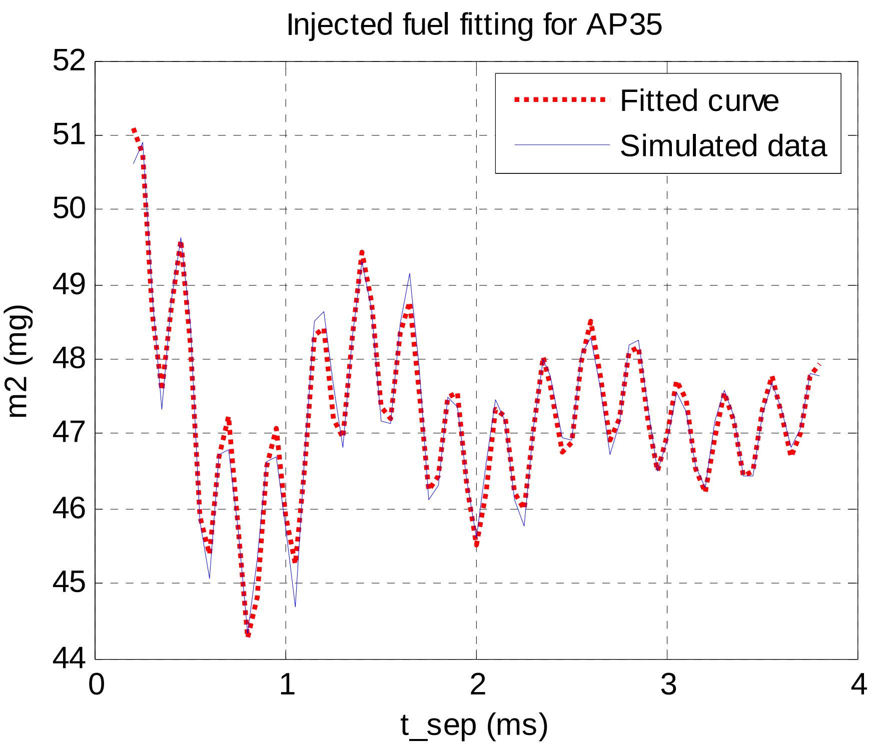


Fig. 15 Injected fuel mass for working point 35 (2 injections)

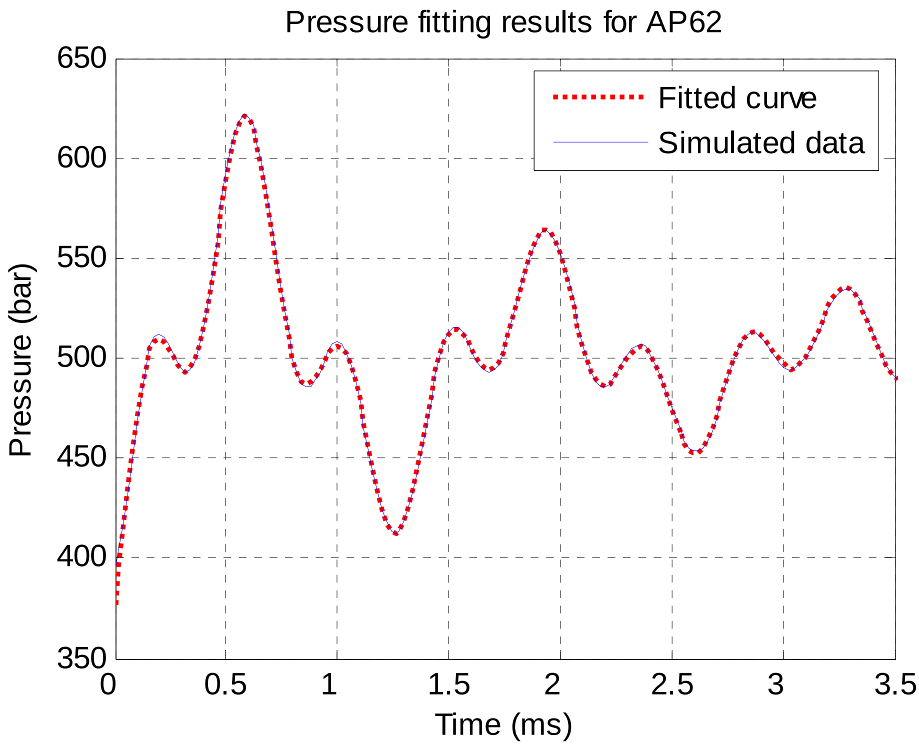


Fig. 16 Pressure for working point 62 (3 injections)

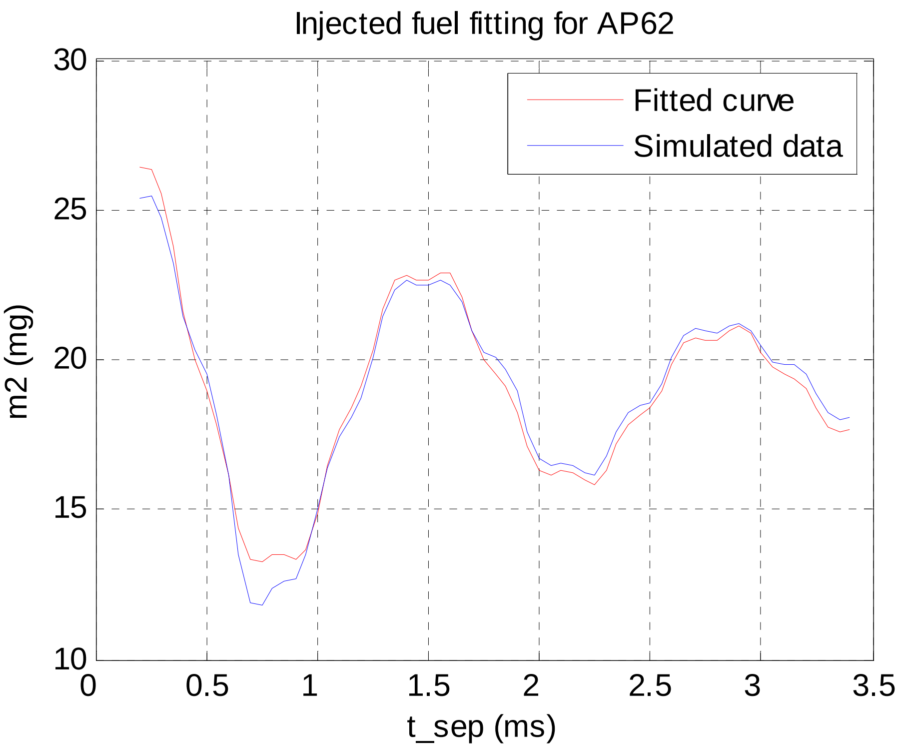


Fig. 17 Injected fuel mass for working point 62 (3 injections)

For both injected fuel and pressure fitting and both two and three injections, the maximal relative error of each points are plotted in figures 18 to 21.

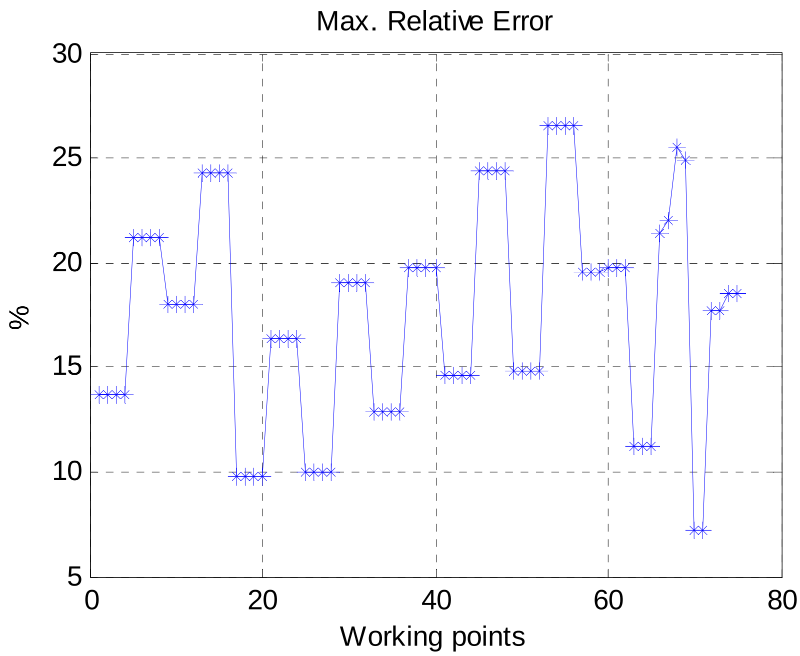


Fig. 18 Pressure Max. Relative Error (2 Injections)

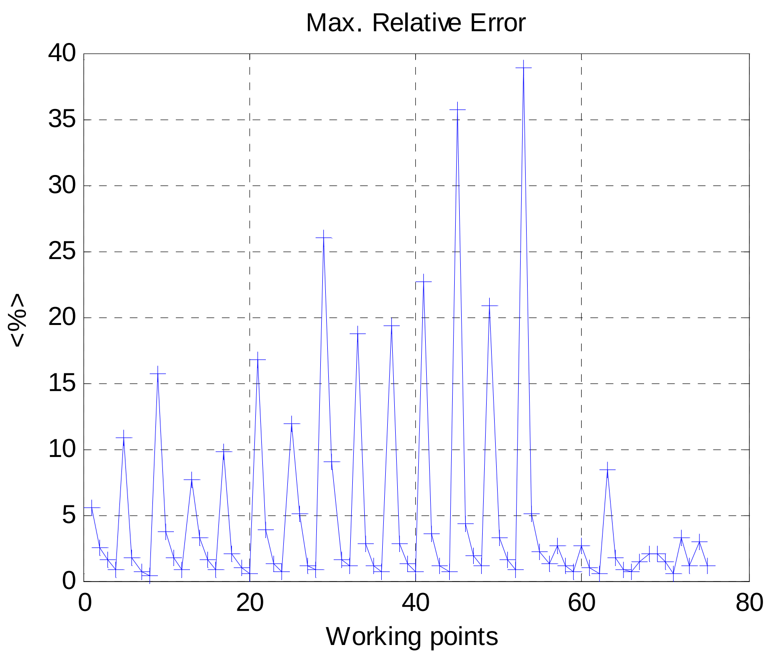


Fig. 19 Injected Fuel Max. Relative Error (2 Injections)

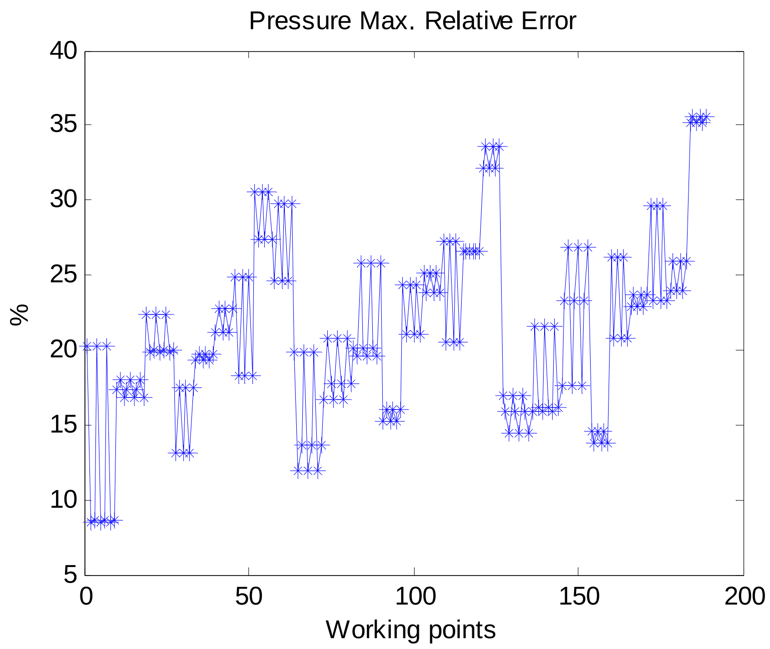


Fig. 20 Pressure Max. Relative Error (3 Injections)

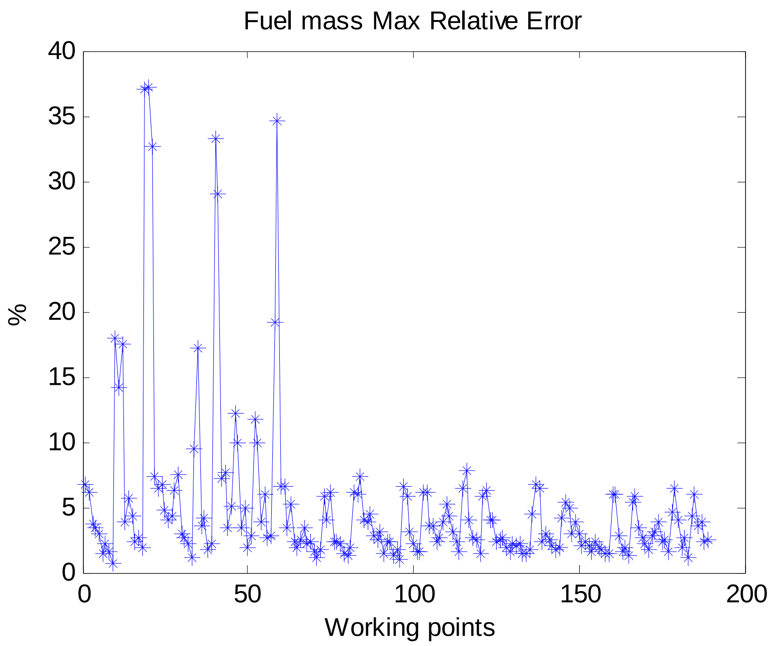


Fig. 21 Injected Fuel Max. Relative Error (3 Injections)

Although in some points these errors are even over 30%, since this is a relative error and those big errors happen for situations where the absolute value is close to zero, the reliability of the performed fitting can nevertheless be assumed.

4. Correlation between pressure and fuel mass.

Once all the simulated data are converted into wave parameters and carefully stored, it is possible to study the different parameters and their variations with the working conditions.

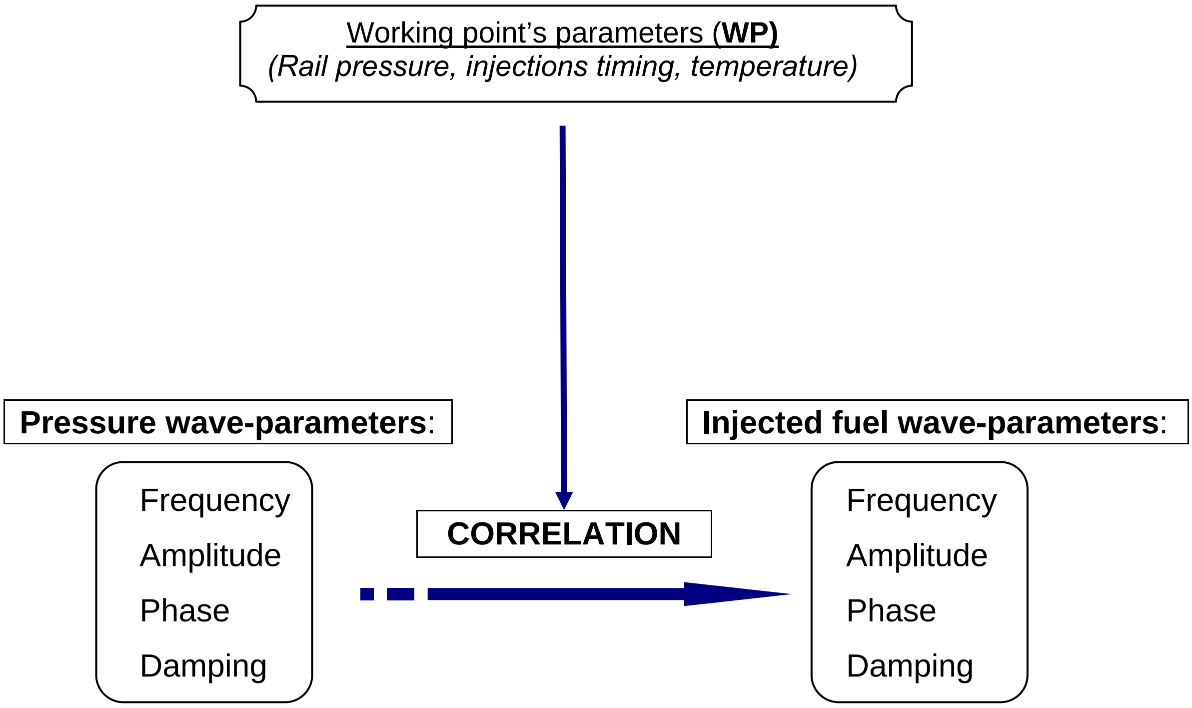


Fig. 22 Scheme of the desired correlation.

The situation at this stage is outlined in Figure 22. Up to know the information of the working conditions would be available and the pressure signal would have been obtained out of the sensor and translated into wave parameters. If wave parameters from the injected fuel mass were somehow obtained, the fuel-mass wave could be reconstructed and therefore, the exact amount of injected mass predicted.

Hence, the goal is to develop some relation between the unknown variables (from injected fuel mass*)* and the working conditions as well as the measured pressure. For that purpose, the first reasonable step is simply observing these variables and try to find out some simple connections between them that will later on lead to more exact and useful relations.

Being this the first approach to the problem, results for only the fundamental wave will be c. However, in further researches the first harmonic should also be considered.

4.1 Variation of parameters

It was already remarked that in order to make a first and simpler approach to the problem, the correlation would be developed using data from two-injection simulations, and later proved to be valid with data from three-injection simulations. Therefore, all the conclusions that will here be reached are obtained considering that only two injections are taking place.

Each of the four wave-parameters will be studied separately together with pressure parameters and working conditions. In figures 23 and 24, it is shown how the four of the parameters from the fundamental fuel wave vary and how do working points conditions and pressure parameter also change. In this first approach it is interesting to see how they qualitatively vary. Therefore, variables are conveniently scaled so they can be plotted in the same graphics.

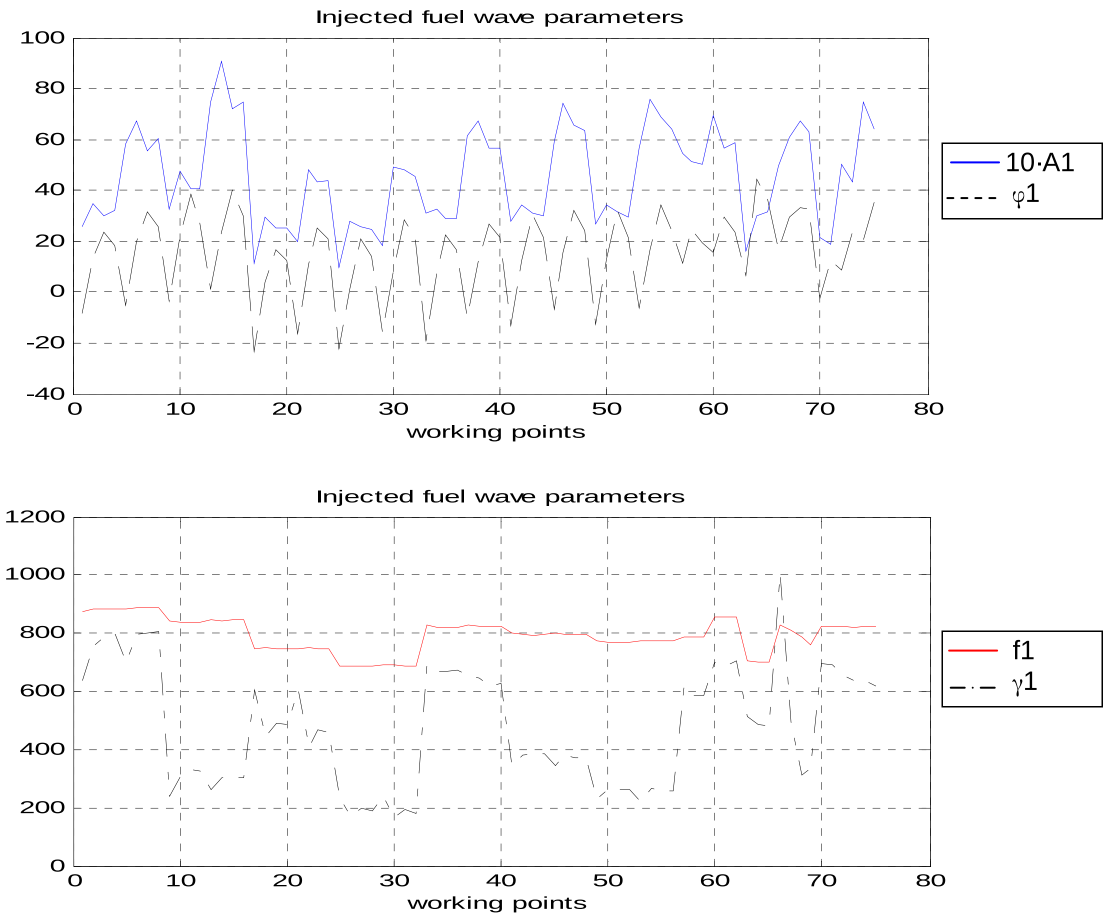


Fig. 23 Variation of fuel mass wave parameters

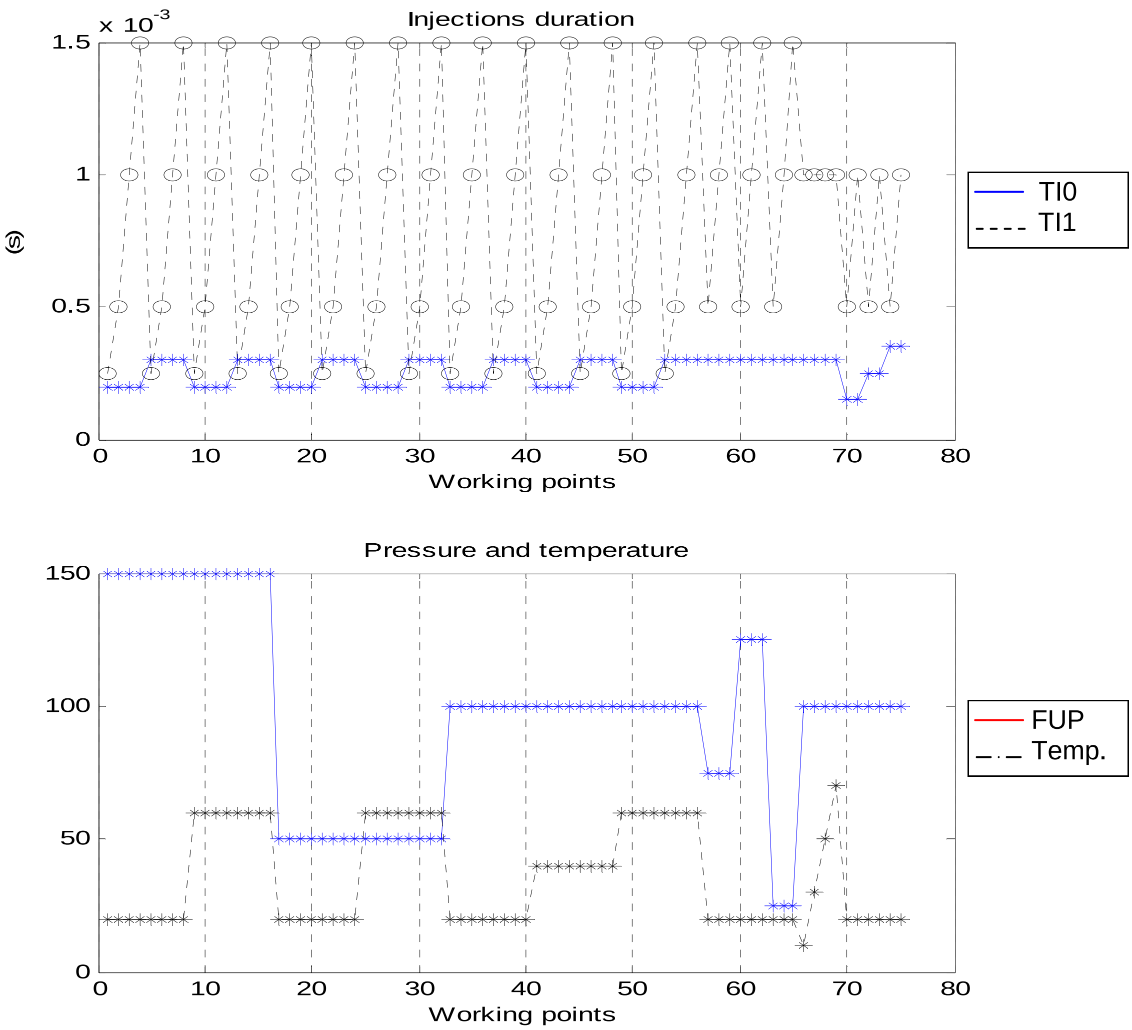


Fig. 24. Variation of working points parameters.

Observing these plots, some first conclusion can be stated. The first of them is that the damping γ presents no apparent relation with working parameters. On the other hand, for both amplitude and phase, there seems to be a strong relation between them and the duration of the injections, with pressure and temperature there is also some relation.

This provides a starting point for the further study of inter-relations between all variables. In next sections, more detailed plots are to be made, together with calculations, so as to perform a more thorough study for each of the four wave parameters.

4.2 Frequency

Frequency could be considered as the most important information when describing any wave. Therefore it is the first variable to be studied.

Thanks to the FFT (fast Fourier Transformation) algorithm, the frequency of both waves can be calculated without great computational effort. This FFT algorithm is already implemented in Matlab and, given the simulated data, provides the spectrum of the wave. In figure 25, an example of one of these spectrums is shown.

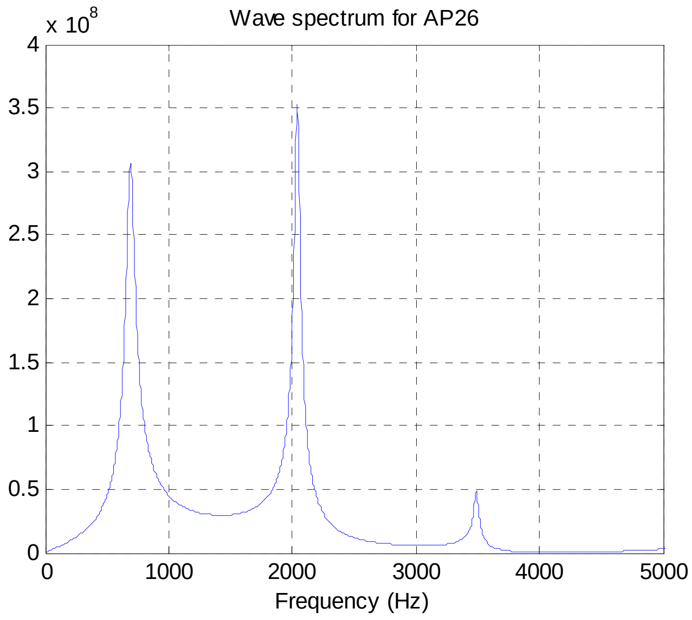


Fig. 25 Example of a pressure-wave spectrum

The wave spectrum describes the amount of frequencies present in a wave after it is decomposed into harmonics with a Fourier transformation as well as the weight of each of those frequencies. In other words, the wave is represented in terms of frequency instead of time. For every working point, obtained spectrums resemble the one shown in figure 25. There are noticeably three main frequencies and hence three main harmonics composing this wave. The peaks in the aforesaid spectrum are in fact the main frequencies in the wave and therefore the frequencies indeed of the harmonics. The third of the harmonics is noticeably tinier as the two first ones and besides, it would have no great influence as far as the injected fuel mass is concerned. Therefore, only two harmonics are to be considered. In fact, this decision was already adopted when choosing the wave model and now it is confirmed that no significant error is introduced.

4.2.1 Windowing selection

When obtaining the spectrum of a wave, a finite lapse of time is to be considered, in other words, a time-window is to be used. There are different forms of time-windows, each of them more suitable than others for certain applications. Due to the so-called *leakage error*, some time-windows can lead to wrong results. Furthermore, the selection of one or other type of window can affect the results of the spectrum analysis.

For the current application, the Hann Windowing seemed to be a good choice. The application of a time-windowing is made by multiplying data by the window values, thus neighboured fundamental frequencies will not interfere each other.

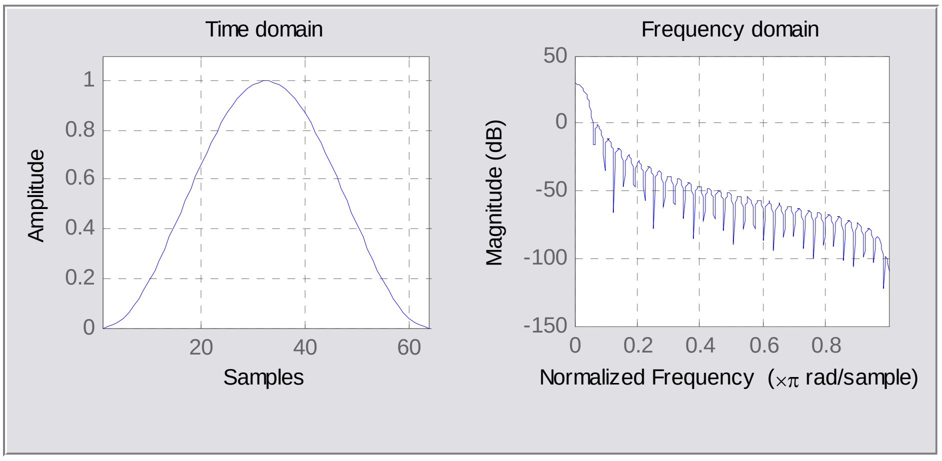


Fig. 26 Hann Windowing

The Hann window is one of the most commonly used. Nevertheless, in order to prove the suitability of this windowing, other windows were in addition used to recalculate frequencies and results were compared. After calculating the frequency applying also Gauss, Hamming and Bartlett-Hann windowings, the results were compared with those of Hann windowing. In Chart 6, the average relative differences between Hahn windowing frequency results and those obtained using other windowings are presented.

	Average difference with Hann Windowing			
	Pressure		Injected Fuel	
	F1 (Hz)	f2(Hz)	f1 (Hz)	f2 (Hz)
Gauss window	**-0,409%**	**0,039%**	**-0,068%**	**1,500%**
B-H window	**0,000%**	**-0,004%**	**-0,215%**	**0,709%**
Hamming window	**-0,476%**	**3,517%**	**0,012%**	**1,296%**

Chart 6 Difference between diverse windowing

According to these results, there is approximately no difference in the calculated frequency when using other kinds of windows and therefore the windowing selection does not seem to be a relevant parameter; the difference in the fundamental frequency is in fact smaller than 0.5% in all three cases. Hence, Hann windowing is to be used.

4.2.2 Comparing frequencies of Pressure and Fuel-mass.

Injected fuel variations will depend directly in the pressure upstream the injector at the moment the injector needle goes up. If this pressure varies along time with a certain frequency, given that time-gap between injections (x-axis of fuel wave) is directly related with elapsed time (x-axis of the pressure wave), frequencies of both waves should be the same. In other words, if one wave depends on the other and working conditions have no influence in the relation between times of both waves, in terms of time and therefore of frequency, no variation will occur.

Although it seems to be logical, such an affirmation can not be adopted without being proved. Therefore, frequencies of both waves are to be compared.

After being obtained by means of the FFT method, results were collected into a spreadsheet and relative errors between pressure and injected fuel frequencies were calculated. The results are exposed in Chart 7.

	Relative Difference	
	f1	*f2*
Average Relative Difference	**0,499%**	**0,292%**
Maximum Relative Difference	**1.575%**	**0,826%**

Chart 7 Difference between Pressure and Fuel-mass frequencies

As shown in Chart 7, the relative error is minor, especially concerning the first harmonic. Only six out of seventy-five points show relative errors over one percent in the frequency of the fundamental harmonic. Considering that relative errors of over 20% and never bellow 1% are already taking place in the curve-fitting process, adding a variation below 1% into the frequency would not suppose a major error increase.

Therefore, a first important result in the development of the desired correlation is here obtained: *both pressure and injected fuel waves frequencies can be assumed to be the same with a confidence of over ninety percent.* Hence, the frequency calculated for the pressure will be valid for the fuel mass.

As a matter of fact, this result was reached before the curve-fitting stage was achieved, and used for this identification stage. Frequency was calculated only during the pressure fitting and adopted for the identification of injected fuel.

4.3 Damping

Looking at figure 24, damping is the parameter that most randomly seems to vary. In fact, unlike frequency, phase and amplitude, it does not seem to follow any pattern that could be related with the rest of variables.

In fact, a more thoroughly glance at the whole situation will in fact lead to drop damping from the correlation.

In the real situation, where the searched correlation will have to be applied, only a part of the pressure wave will actually be measured and besides, only a point of the injected mass wave is to be calculated. This situation is illustrated in figure 27. The x-axis scaling will not be the same, since both waves are plotted against different times; in fact they are scaled so both waves match approximately, considering their difference is the pre-injection duration

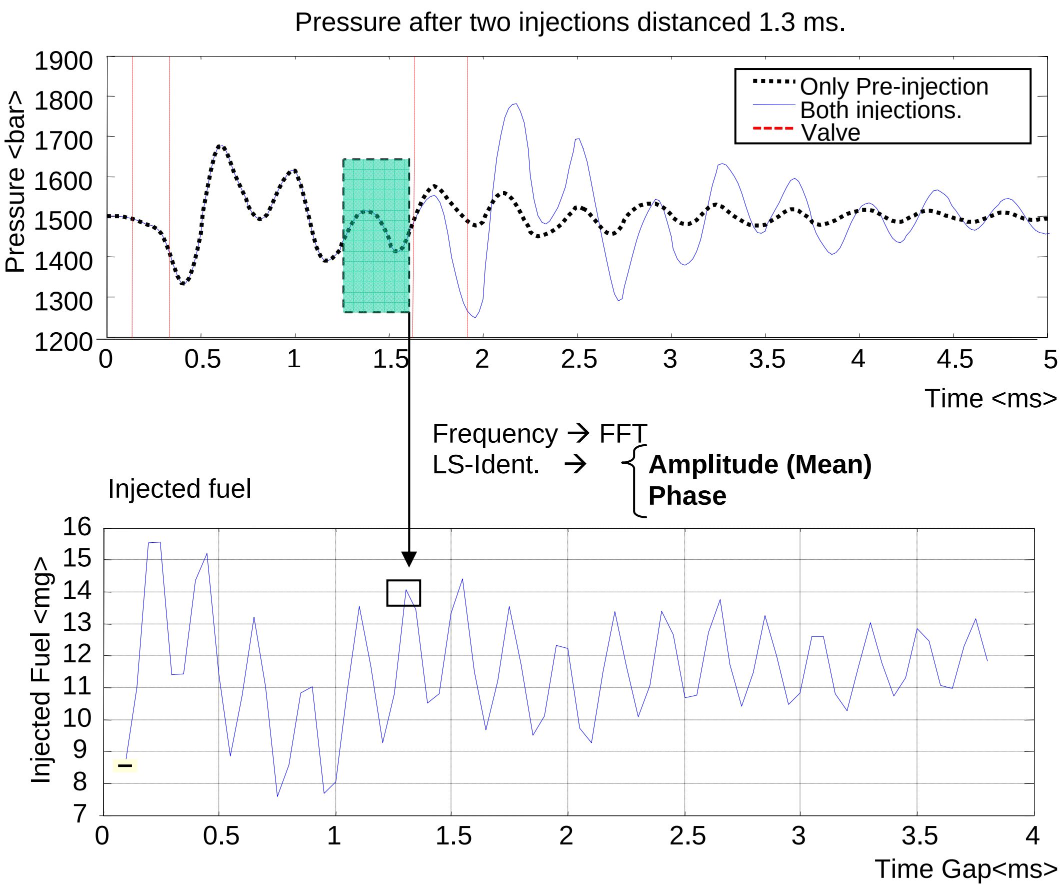


Fig. 27 Predicting fuel mass without damping information

In the real operation of the system, the sensor will measure pressure just before the injection is to take place, and due to the short lapse of time in which this measuring takes place, the amplitude provided after the corresponding signal processing can be considered as the mean value in that short interval. Being the measuring interval so brief, the attenuation of the pressure wave in it will be practically inexistent. Furthermore, what the engine's control unit needs is predicting the amount of fuel injected for that particular gapping between injections; thus, since there is no need on reconstructing the whole fuel wave, knowing frequency, phase and amplitude in this particular point will be enough.

In brief, since there is no time for the wave to be damped while the measuring takes place, the correlation can be developed disregarding damping and therefore considering a constant-amplitude wave.

4.4 Phase.

After proving that frequency can be assumed to be the same as that of the pressure wave and that there is in fact no need to consider damping, only two parameters are left in order to describe the Injected fuel wave, *Amplitude* and *Phase*.

Looking back in figures 24 and 25, wave phase seems to follow trends depending on injection timings as well as in pressure and temperature. The best way of trying to elucidate how these trends really are, is to study the dependence with each variable separately. In order to do this, phase is first plotted against each one of the variables to find qualitative dependences. Once these qualitative variations are revealed, next step is trying to convert them into quantitative relations.

It has already been explained how injected-fuel wave depends directly of the pressure wave at the leading pipe. Therefore, it is obvious that phase of this wave will also directly depend on pressure-wave phase. Due to the additive character of phase, instead of injected-fuel phase itself, the difference between phases of both waves is to be used for the present study. Thus, dependence with pressure wave is dropped and only working points influence is to be considered. The new variable will then be the phase increase, defined as:

$$\Delta\varphi = \varphi_{FUEL} - \varphi_{PRESSURE} \qquad \textbf{(Eq. 6)}$$

The so-defined variable $\Delta\varphi$ is from now on the one to be considered, bearing in mind that at the end, this variable change must be reverted in order to rebuild the fuel-mass wave. This change does not actually introduce large changes, since as can be seen in figure 28, pressure-wave phase varies a small amount compared with fuel-wave's one. Nevertheless, this change allows focusing on the working conditions by leaving the pressure wave aside.

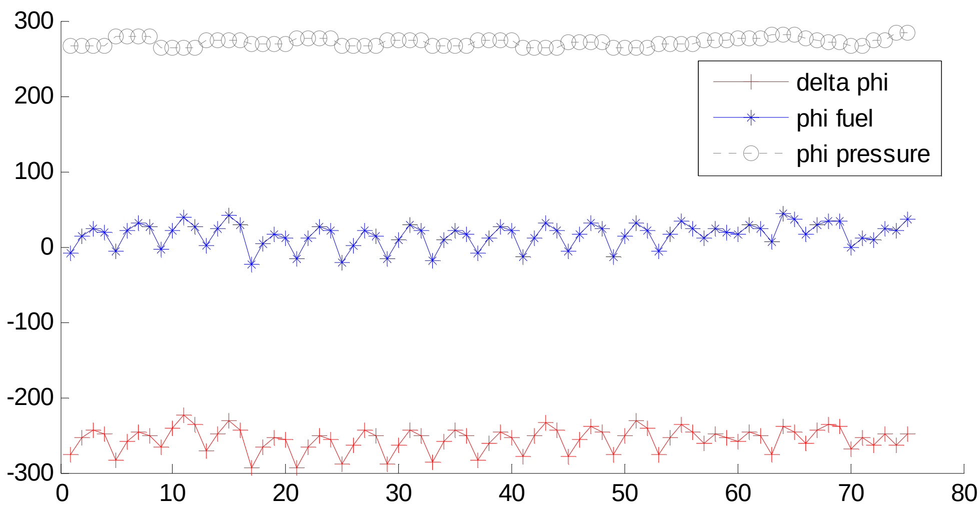


Fig. 28 Phase of both waves and their difference

4.4.1 Comparing phase increment with working conditions.

After leaving the pressure wave apart by changing the variable into an increase, the parameters influencing this new phase increase are only those of the working point conditions.

These are:

- Rail pressure ***FUP***
- Temperature ***T***
- Pre-Injection duration ***TI0***
- Main-Injection duration ***TI1***

Next, phase increment Δφ is to be represented versus all this variables in order to discover its dependence. The phase, and therefore its increment, defines where the wave will start according to an arbitrary point. For that reason, both injection durations will in some way be the parameters that more influence would hypothetically have. Fluid properties and hence pressure and temperature, will influence fluid behaviour and thus may also have some influence.

In figure 29, for different pressure and temperatures, Δφ is presented versus pre-injection length in time.

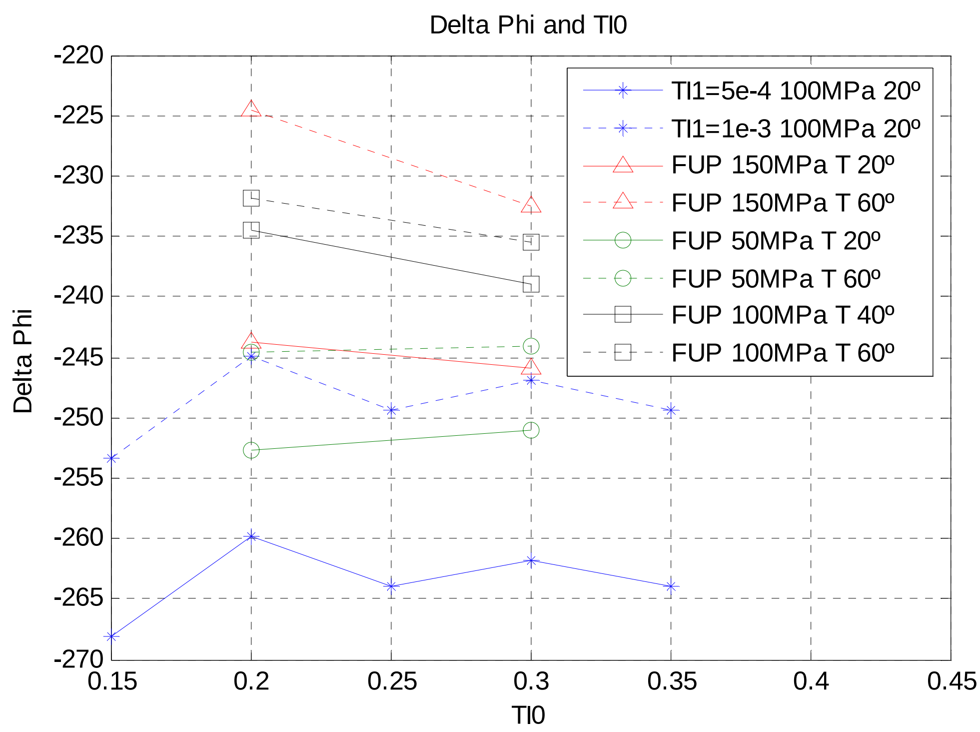


Fig. 29 Influence of pre-injection.

The influence of TI0 does not seem to be especially relevant. Considering that the arbitrary beginning of the fuel-mass wave is the end of this pre-injection, it is reasonable that this parameter has no great influence. However, it seems to have a certain weight especially when pressure is high.

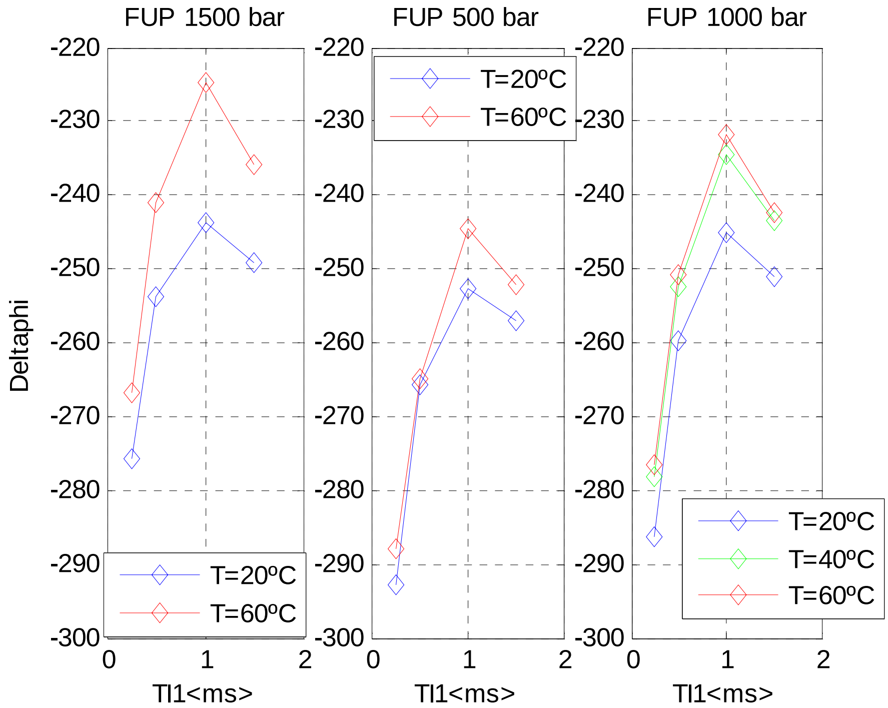


Fig. 30 Influence of main injection.

In figure 30 above, for different pressures and temperatures Δφ's evolution with main injection duration is shown. According to this graphic, the length of main injection has a large influence; moreover this relation happens to be non-linear. This variable is in fact responsible of the curly shape of the wave. Besides TI1, in this figure the influence of rail-pressure and fuel-temperature is also noticeable; in particular, pressure influence seems to be important.

In next two graphics -figures 31and 32- the influence of both pressure and temperature are displayed. As far as pressure is concerned, there seems to be a strong relation that can by no means be ignored. When pressure is low, a strange behaviour appears. The value of 250 bars will not show in this work good result, however, this operating condition will no be very frequent and besides, the sensor with which pressure will be measured shows no great accuracy for this pressure range. Finally looking at temperature, phase dependence with it does not seem to be especially important, although there is indeed some connection.

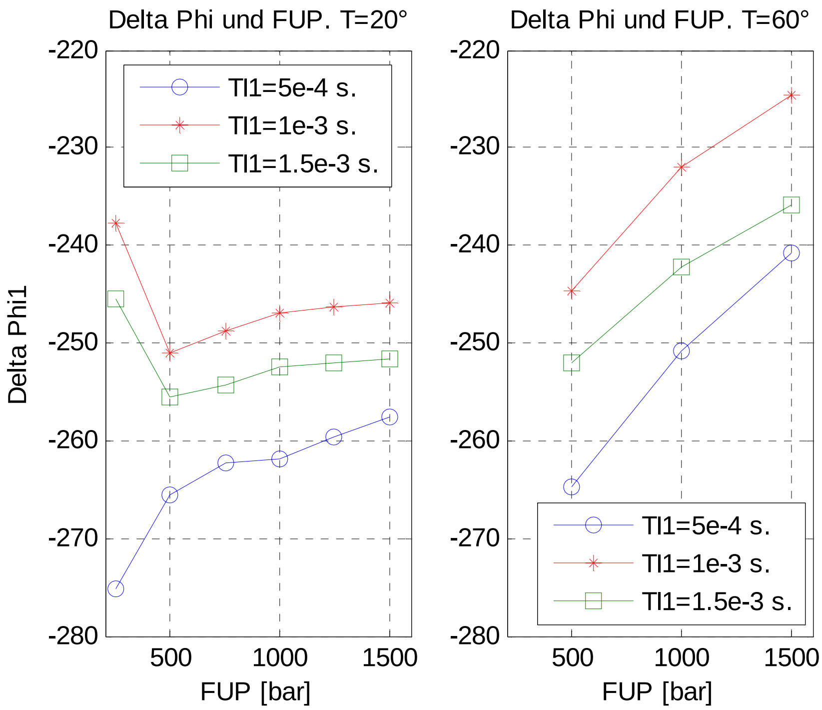


Fig. 31. Influence of pressure

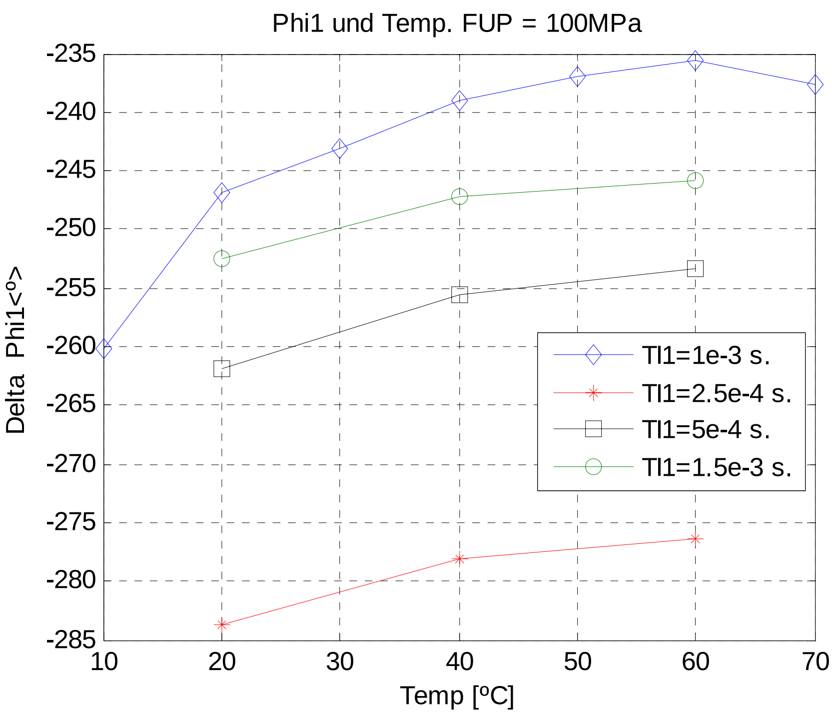


Fig. 32 Influence of temperature

After reaching some qualitative conclusion after the previous graphics, it is now time to transform those conclusions into quantitative ones.

The most important variable seems to be TI1 (*main injection duration).* The relationship between Δφ and TI1 is not linear, as a matter of fact it seems to be a quadratic dependence between them. Therefore, this dependence could be described with a second grade polynomial, and hence, the following first relation could be written:

$$\Delta\varphi = k_1 \cdot TI1^2 + k_2 \cdot TI1 + f(TI0, FUP, Temp) \qquad \textbf{(Eq. 7)}$$

Here, k_1 and k_2 are constant that should be calculated for each different system.

The dependence of Δφ with the rest of variables, represented in Eq. 7 by *f(TI0,FUP,Temp)*, considering figures 29 to 32, can be considered lineal. Thus, assuming linearity, Δφ could be obtained as:

$$\Delta\varphi = k_1 \cdot TI1^2 + k_2 \cdot TI1 + k_3 \cdot TI0 + k_4 \cdot FUP + k_5 \cdot Temp + k_6 \qquad \textbf{(Eq. 8)}$$

As far as temperature is concerned, although its influence did not seem to be ignorable, it will actually not be taken into consideration for the correlation. It was indeed considered in a first version of the correlation, but the small weight constant obtained for it, k_5, showed that its influence was not actually remarkable. As a matter of fact, eliminating the temperature did nothing but improving the results. Furthermore, being the aim of this correlation to predict the injected fuel out of measured parameters, and providing that fuel temperature in the pipe is not an easily measurable value, leaving temperature aside will be a good choice.

Hence, the function into which the phase increase will be fitted is finally:

$$\boxed{\Delta\varphi = k_1 \cdot TI1^2 + k_2 \cdot TI1 + k_3 \cdot TI0 + k_4 \cdot FUP + k_5} \qquad \textbf{(Eq. 9)}$$

The next step will obviously be to find the k_i parameters for Eq. 9 that allow fitting the phase increase properly into this function.

4.4.2 Finding correlation parameters.

In order to find the polynomial coefficients, first Eq.7 is considered. Being the TI1 dependence the more complicate, the first two parameters are to be obtained.

If points with same pressure, temperature and TI0 are set together, the results are groups of four points varying only TI1. These groups of points are plotted in figure 33.

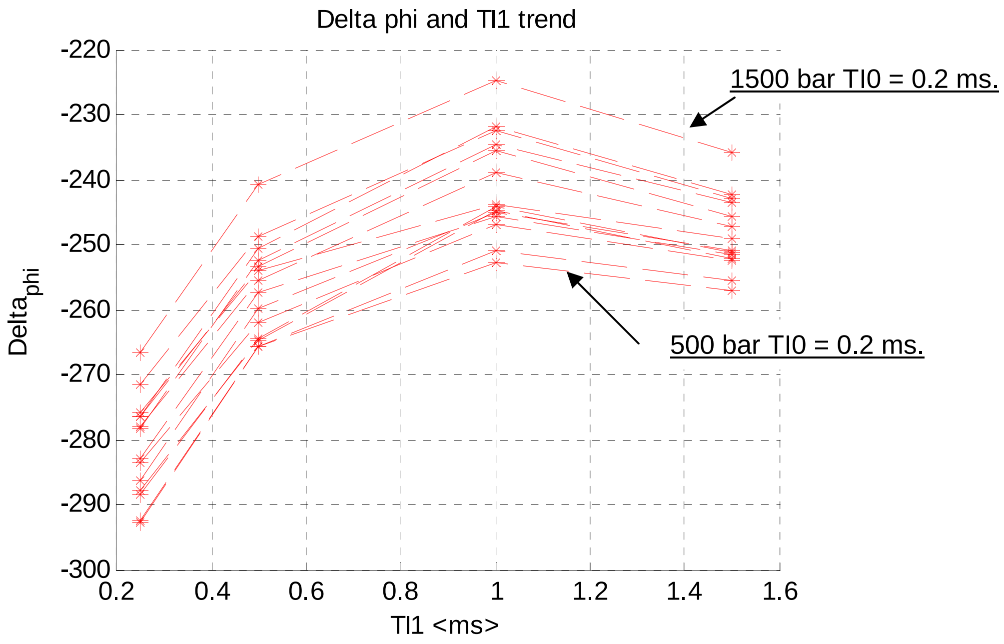


Fig. 33 Quadratic relationship of $\Delta\varphi$ and TI1.

Using Matlab polynomial-fitting function, each of these four-point groups can be fitted into a quadratic polynomial $p(x) = a_1x^2+a_2x+a_3$. The results are three parameters, a_1, a_2 and a_3 for each of the groups.

The quadratic trend of all the groups happens to be very alike. This leads to describing this tendency using the mean of all the obtained a_1, a_2 and a_3. Calculating k_1, k_2 and k_3 as the mean value of the a_i parameters, an average curve is obtained. This average curve is to describe de main trend with TI1 and thus k_1 and k_2 are to be the first parameters of the correlation.

If this average-curve is plotted without considering k_3 and together with the curves in figure 33, the result is a curve, containing the TI1 trend and whose difference with the others will be an offset, depending on rail-pressure and pre-injection duration. This result is shown in figure 34.

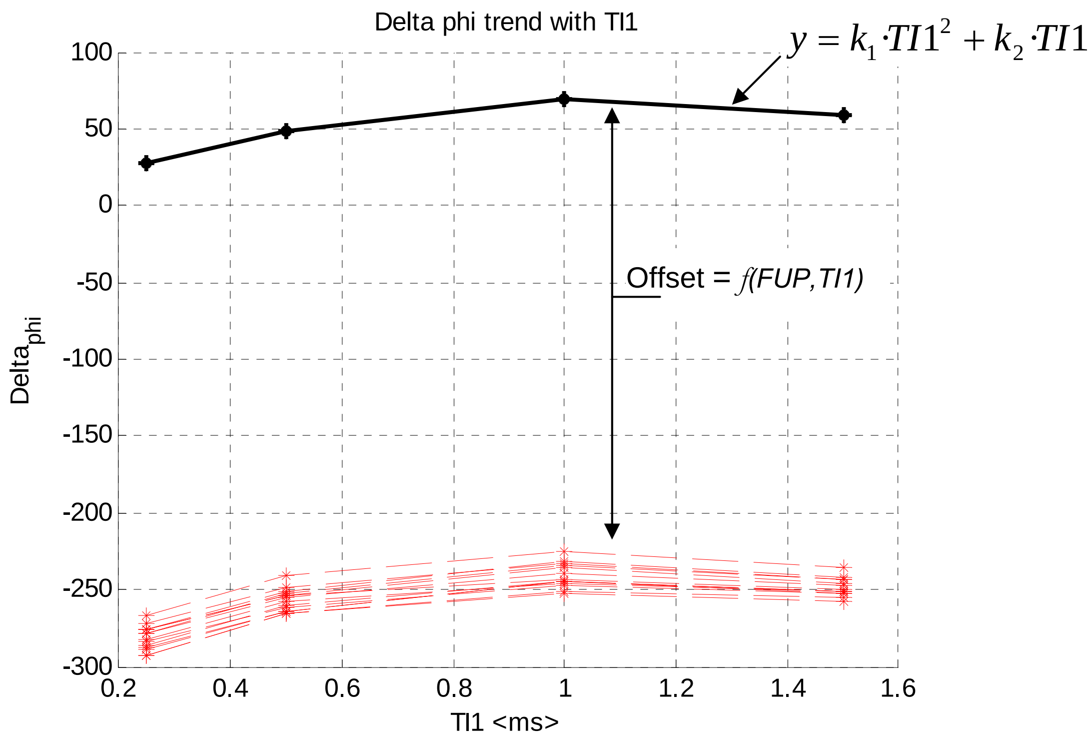


Fig. 34 Offset between average curve and the rest

Once the relation between Δφ and TI1 is settled, next step is finding the relation with both rail-pressure and pre-injection duration. In order to do this, the average offset between each group of points and the estimated trend-curve *(y)* is calculated. By means of multiple regression it is now simple to obtain the aforesaid relation.

Knowing the average offset between every group of point and the obtained average curve, as well as the corresponding pressure and pre-injection time of them, regression multiple is performed as follows. First the regression matrix is to be built. This consists of a first column of all ones and the rest of variables arranged into the rest of the columns:

$$X = \begin{pmatrix} 1 & TI0_1 & FUP_1 \\ 1 & TI0_2 & FUP_2 \\ \vdots & \vdots & \vdots \end{pmatrix}$$

If the offset, which is the variable intended to fit, is now arranged into a column vector, the parameters left can be calculated simply dividing this regression matrix by the offset vector:

$$\begin{pmatrix} k_5 \\ k_3 \\ k_4 \end{pmatrix} = X/Offset. \qquad \textbf{(Eq. 10)}$$

4.4.3 Results.

Now that all parameters are obtained, Δφ and therefore φ_{fuel} can be estimated using equation 9.

$$\Delta\varphi = k_1 \cdot TI1^2 + k_2 \cdot TI1 + k_3 \cdot TI0 + k_4 \cdot FUP + k_5 \qquad \textbf{(Eq. 9)}$$

$$\downarrow$$

$$\varphi_{FUEL} = \Delta\varphi + \varphi \qquad \textbf{(Eq. 11)}$$

Once the correlation for the phase is fully developed, results of its calculation for each working point are plotted together with the fuel phase obtained out of the identified simulations data in figure 35.

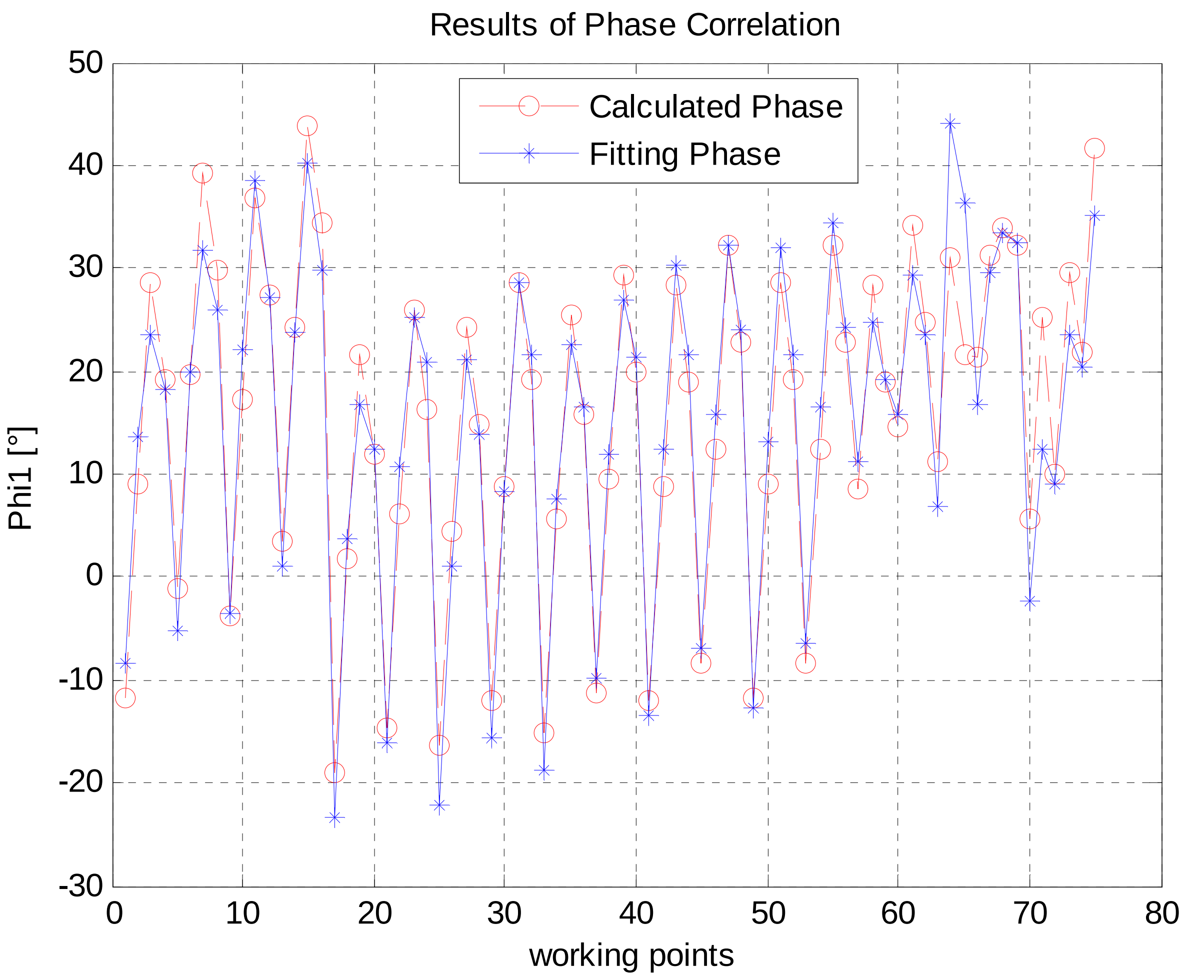


Fig. 35 Results of the Phase correlation.

The results displayed in figure 35 show how the obtained relation allows obtaining a good estimation of the fuel phase with the sole applying of Eq.9. The results qualitatively seem to match the phase obtained by the identification within a difference of less than 5º in most cases. Later on, when a way of calculating amplitude is also developed, the entire reconstructed wave error will be studied quantitatively.

After all the calculation for both φ and Δφ, results are always filtered so that they are within a -90º and 270º interval. This has no effect at all in the results, since angles will not vary when added or subtracted 360º.

4.5 Amplitude.

At this point, there is only one variable left for developing a way of reconstructing the whole injected fuel mass, this being the amplitude.

As well as it was done for the phase, the first approach to the problem of finding a relation is selecting the variables that may have any influence and studying their influence separately.

First of the parameters likely to have influence is the own pressure wave. Obviously, the higher the pressure fluctuates after the pre-injection, the more different will the injected fuel mass be depending on when main-injection takes place. In other words, there will be a straight relation between both pressure and injected fuel amplitudes. Like it was made in search of a phase-correlation, this relation can be left aside by introducing a new variable consisting of both wave-parameters, thus developing a correlation for it instead of the own fuel-mass amplitude.

Due to the multiplying nature of the amplitude, instead of subtracting both amounts, it seems more reasonable to adopt a constant factor between them, a multiplying factor. Thus, the new variable will be a constant *K*, being the quotient between both amplitudes.

$$K_{AMP} = \frac{A_{fuel}}{A_{pres.}} \quad \textbf{(Eq. 12)}$$

Once pressure influence is left aside, the rest of parameters are, as well as they were for the phase, the working conditions: rail-pressure, temperature and injection timings. Following the same steps as for the phase, the new variable K_{AMP} is represented versus working conditions in figures 36 to 39.

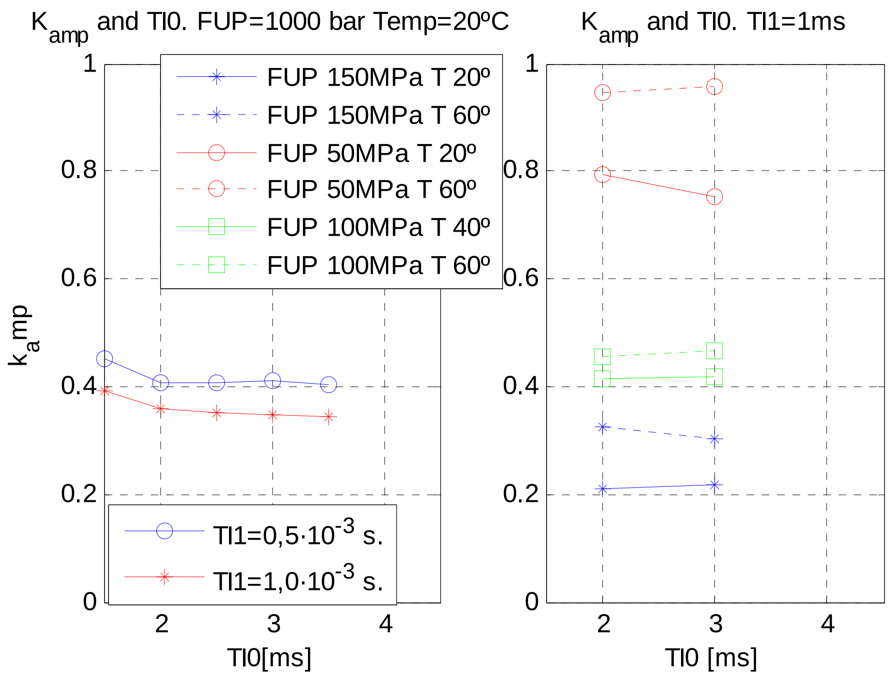


Fig. 36 K_{AMP} trend with TI0

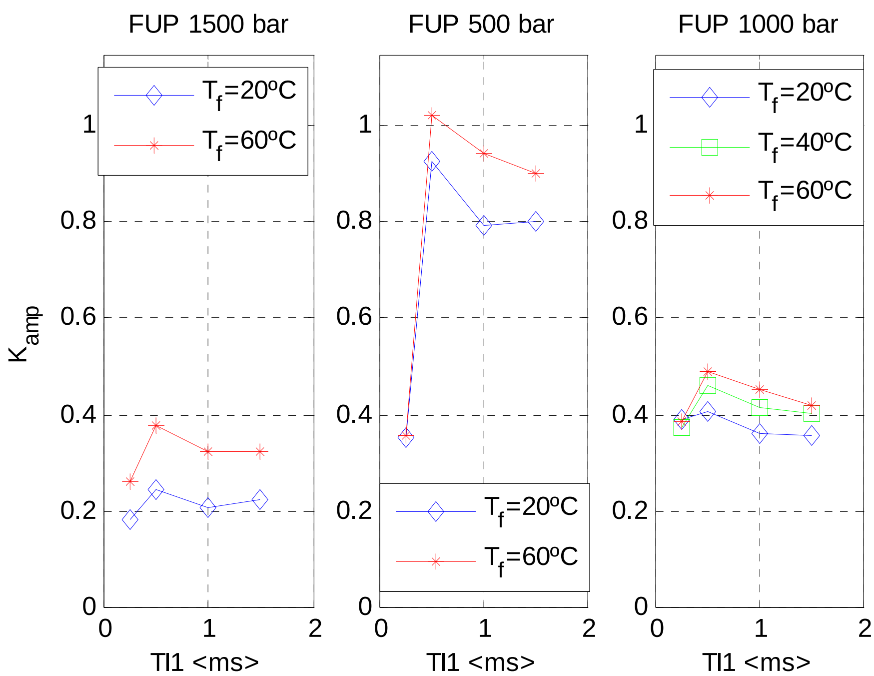


Fig. 37 K_{AMP} trend with TI1

The dependence of this amplitude-constant with TI0 does not seem to follow any pattern; however, given the few number of points available, no conclusions can be made but that it has no strong weight. Regarding main injection duration, the influence seems to be rather remarkable, but does not seem to follow a simple pattern. In an attempt to follow the same path as for the phase correlation, this relation could be mathematically described as a polynomial of third or even higher grade and later try to develop some way of introducing as well the rest of the variables (working conditions). The evolution of K_{AMP} with the working conditions is displayed in figures 39 and 40:

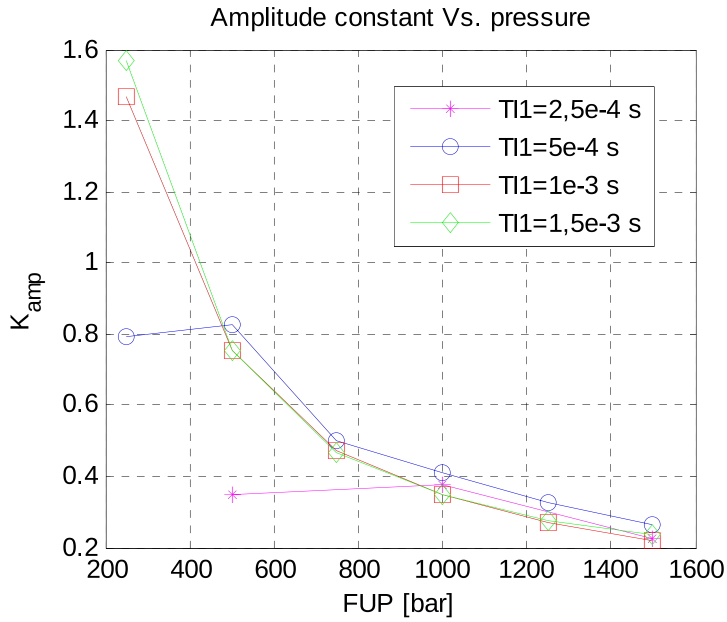


Fig. 38 K_{AMP} trend with rail-pressure

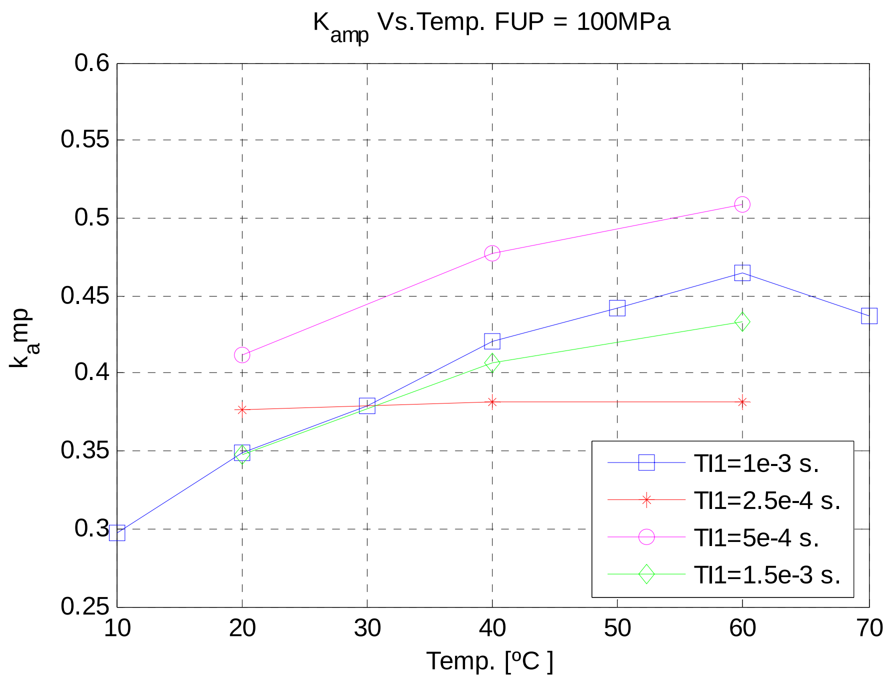


Fig. 39 K_{AMP} trend with temperature.

The evolution of K_{AMP} with working conditions does not actually provide much information. The pressure, apart from the existence of two points which values do not seem to be coherent, shows some trend alike a second grade polynomial. Regarding temperature, there seems to be a linear relation although when main injection extent is 0.25 ms it seems to be no influence.

Unlike the wave-phase, when analyzing the wave-amplitude there seems to be no simple mathematical relation that allowed calculating K_{AMP} as there was for the phase. Even if the relation with TI1 were described with a third or grater grade polynomial, still pressure follows a quadratic rather than lineal trend and could not be introduced in the calculations performing multiple regression. Besides, a high-grade polynomial is not suitable for the development of a correlation that should be valid for a large range of operating conditions because of its shape and for reasons of high computational cost.

Being this the situation, the best way of calculating the amplitude is building a look-up table, containing information of the amplitude in some points and out of which it could be calculated for any operating condition.

4.5.1 Building a look-up table.

If a look-up table is to be built, it should permit to obtain the most accurate results with the minimum amount of points.

The variable having the more complicated and important weight in the amplitude is TI1. Therefore, the look-up table should be built being careful to describe this relation. Also pressure and temperature have some weight and should be considered.

They best way it could be done is trying to describe the variation with TI1 for each pressure and temperature. For the amount of points available, there are not many different couples of pressure and temperature values, therefore the size of the thus resulting look-up table will not be large.

For the development of the look-up table only points from one to fifty-six were used. In this points, for each instance of pressure and temperature there are eight different points. In figure 40 an example of one of these cases is shown. Within these eight points there are four different values of TI1 for every two different values of TI0. Four of these different-TI1 points are to take part on the look-up table, whether one value of TI0 or the other is not yet to be decided.

Hence, the look-up table will consist of the four values of K_{AMP} for a determined TI0 and for each of the pressure and temperature possibility, as well as the average difference (as a quotient) between both TI0 values at each case. In other words, for each pressure-temperature, there will be four values corresponding to the different TI1 and another being the factor for TI0 influence. This means a total amount of points of thirty-five.

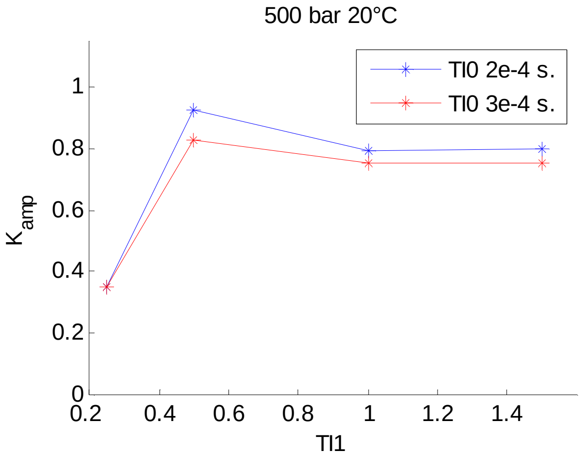


Fig. 40 K_{AMP} for 500 bar and 20ºC

There is at this point a choice left; one of the two values of TI0 should be selected for every situation. In order to decide this, two versions of the look-up table were built, one for every value. Afterwards, once the interpolation function was defined and amplitude could finally be calculated, the one that provided the best results was chosen, this being 0.2 ms.

4.5.2 Results

Once a look-up table was elaborated, in order to calculate K_{AMP} and thus injected-fuel amplitude, an interpolation script is to be developed. This consist simply of a small program that given all the parameters, chooses the appropriate values of K_{AMP} out of the look-up table depending on the pressure and temperature and interpolates or extrapolates if necessary according to the value of TI1 to obtain the corresponding K factor. Afterwards, depending on TI0 another inter- or extrapolation is done to obtain another K_b factor that when multiplying the previous K factor will provide the value of K_{AMP}. In case pressure and temperature do not match those on the look-up table, extra interpolations are to be performed to solve such points.

$$K_{AMP} = K \cdot K_b$$

Inter/extrapolating according to TI1   Inter/extrapolating according to TI0

Once K_{AMP} is known, simply multiplying pressure wave by it, the amplitude of the injected-fuel wave is then calculated. Results of this calculation together with the amplitude obtained by the identification are displayed in figure 41.

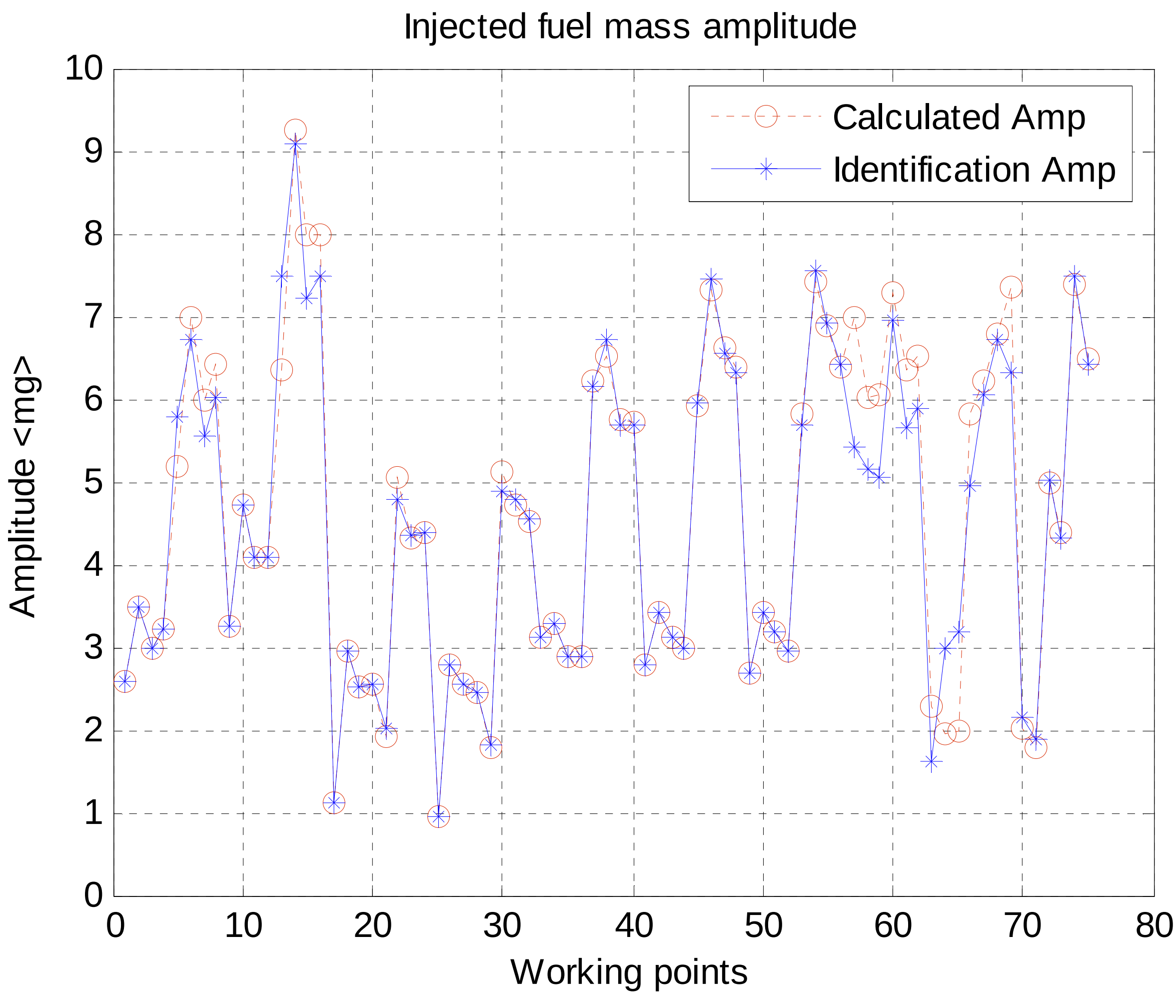


Fig. 41 Results of the amplitude correlation.

The resulting amplitude for the working points out of which the look-up table was built, are obviously the same one as provided by the fitting. For the rest of the points, the ones with different TI0, the results seem to match those of the fitting. It is especially interesting to look at working points from fifty-six to seventy-five since those are the intermediate working points which were not used to obtain the correlation.

At this stage within the work, the achieved method for calculating the amplitude is not really efficient since it uses thirty-seven points to obtain the values of seventy-five. Nevertheless, it will be later be proved that, with this look-up table and the interpolating script developed, much more working situations can be successfully described, therefore resulting in a not inefficient way of calculating the amplitude.

4.6 Reconstructing the injected-fuel-mass wave.

Up to now, a relation is developed allowing amplitude and phase to be calculated; besides, it has been proved that damping has no interest and that frequency of both waves can be assumed to be the same. At this point, the injected-fuel-mass wave can therefore be predicted.

Predicted values of phase and amplitude have already been plotted together with the identification values. This time, the whole waves are to be estimated and results compared with the simulated data. For the reconstruction of the wave, the first harmonic, as well as the damping of the fundamental wave, are taken out of the identification. Hence, only amplitude, phase and frequency are introduced for the reconstruction. This way, an error can be estimated comparing directly with data from the simulations.

Once the wave with the three estimated parameters is built, a relative error can be calculated for the difference between simulated and estimated waves. The maximum of this error for every point is plotted in figure 42.

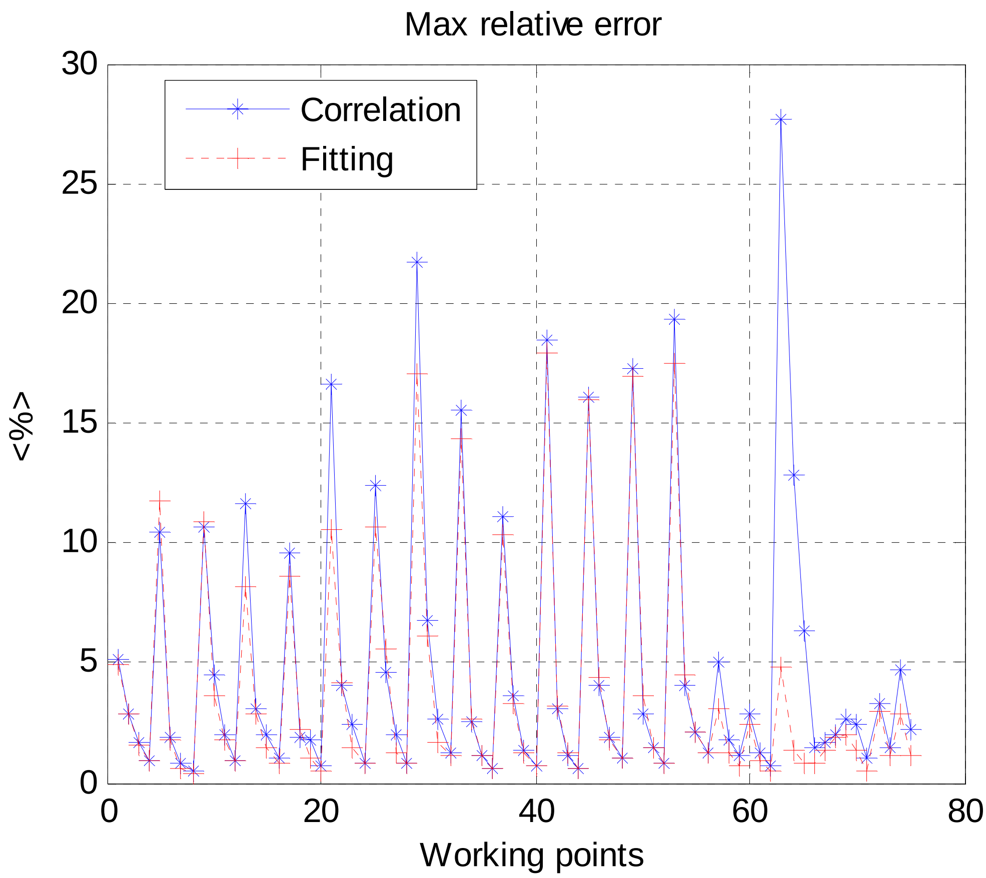


Fig. 42 Max-relative Error for calculated and identified waves

As illustrated, this maximal relative error is approximately the same as the one committed during the fitting for most of the points. In fact, there are even points where it is slightly lower. There are nevertheless three exceptions; these are points sixty-three to sixty-five, corresponding to a pressure of 250 bar. where there is an important error predicting amplitude. However, such a low pressure will not commonly occur in a real system, Consequently the error of these three points can not be considered to be decisive.

In the following pictures, figures 43 and 44, two examples of how the results look like are displayed. The accuracy of the results seems to be more than acceptable.

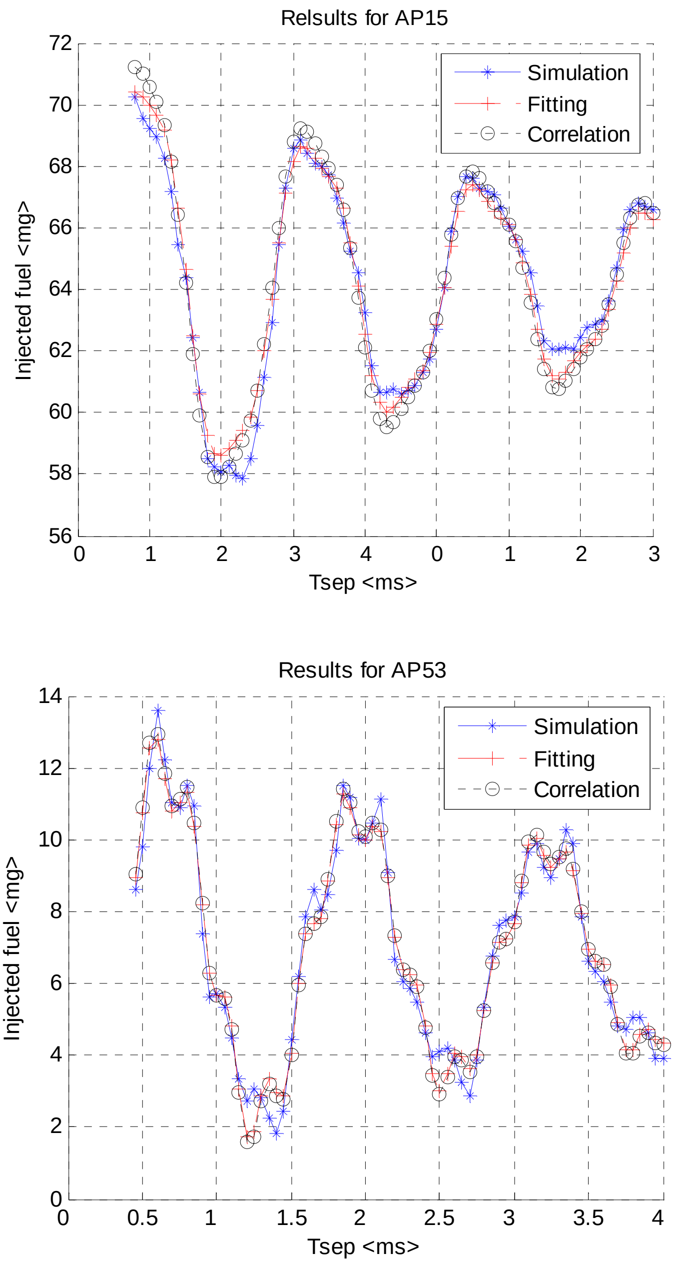


Fig. 43 Examples of the three curves plotted together

4.7 Testing results for different working points.

The results have been proved to be valid for the same working points out of which the correlation has been developed. Therefore, the fact that good results for these points are obtained does not guarantee the validity of the correlation in all the working range. For this reason, the correlation is also tested for another group of different working points. These new working points were obtained for a parallel study, using the same software and varying only the working points' parameter. Of course, in these points two injections take place.

These working points consist of a total amount of two hundred and thirty-four parameters with three different pressure (500, 750 and 1000 bar) and three different temperatures for each pressure (20, 40 and 60 ºC). The pre- and main injection durations also covers a wider range of values as the working points afore used.

After applying the correlation for these points, results for both amplitude and phase are displayed in figures 44 and 45. The resulting amplitude and phase seem to match amplitude and phase from the fitting of the simulated data as well as it happened with the seventy-five points of the previous sections. Therefore, the achieved correlation can be believed to be valid for a wide range of operating conditions.

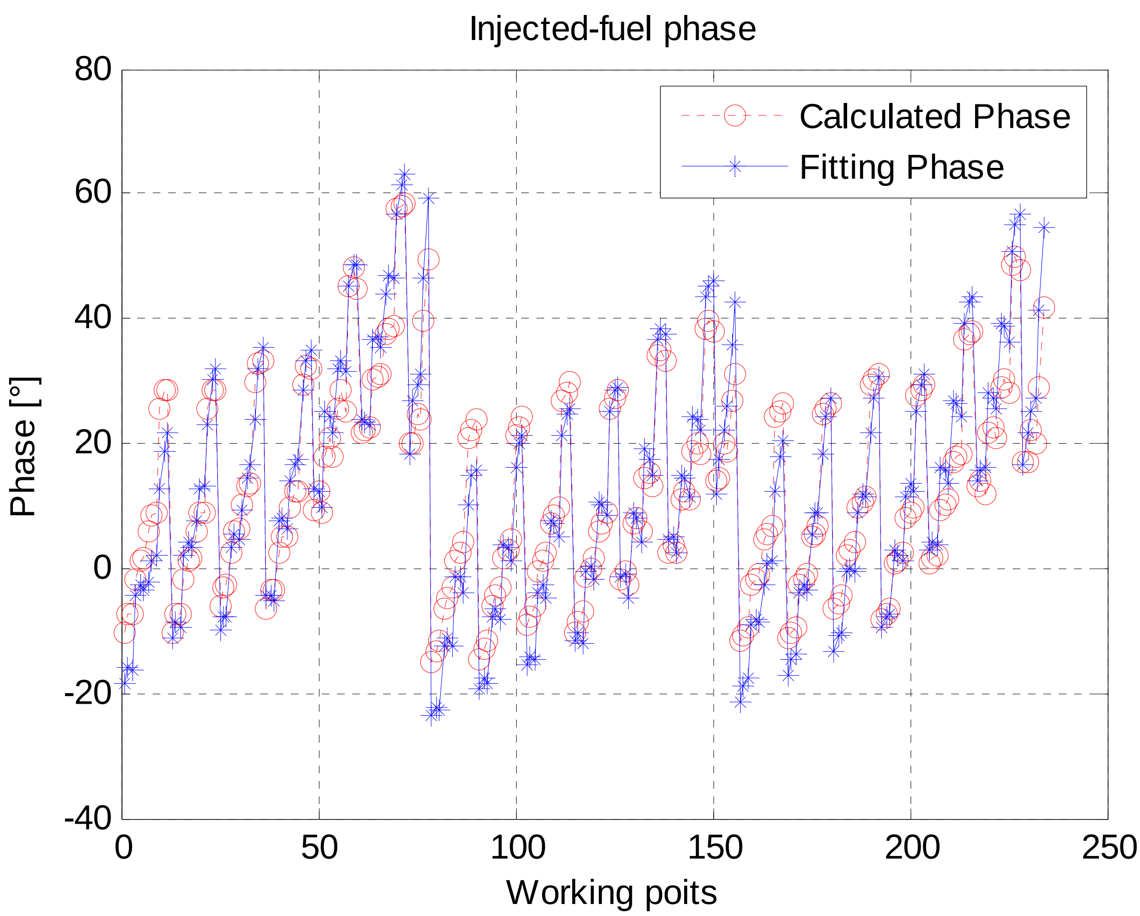


Fig. 44 Calculated and simulated phase.

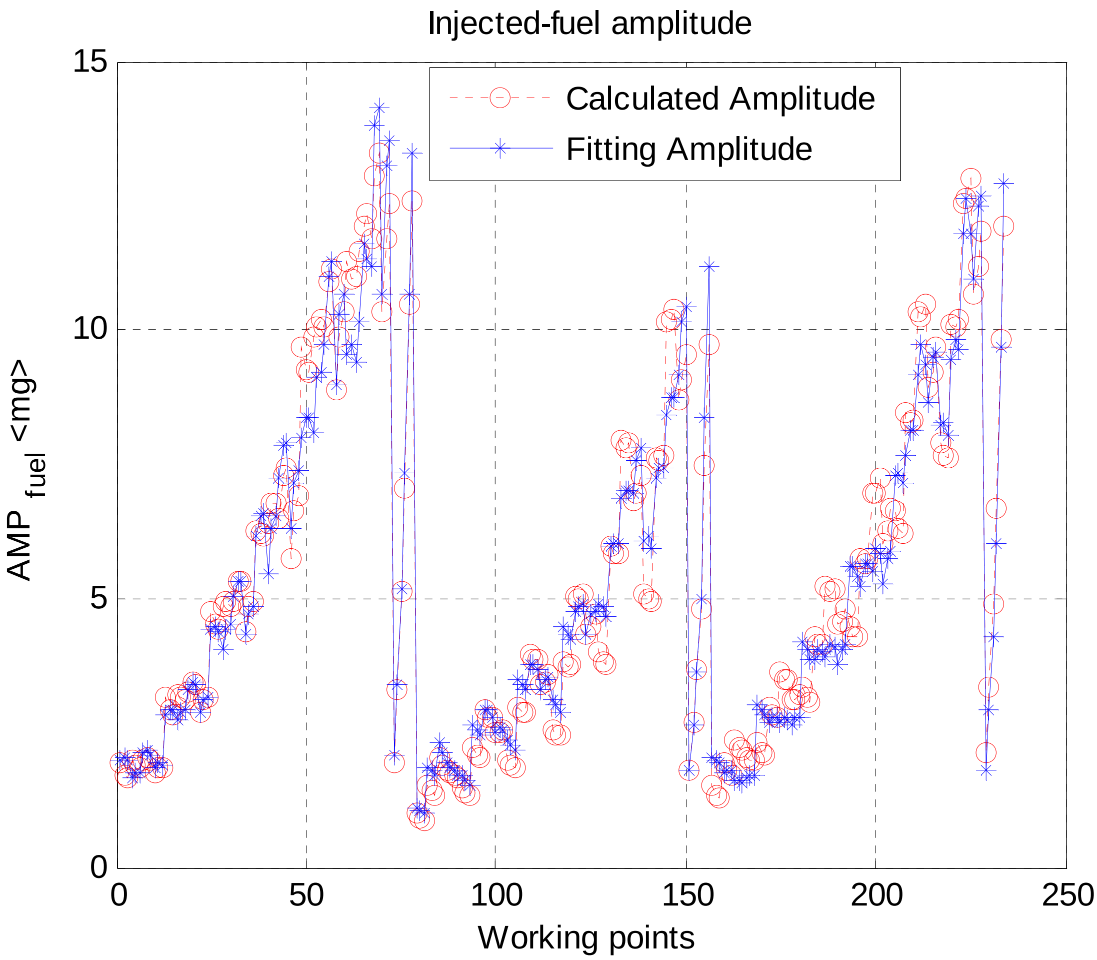


Fig. 45 Calculated and simulated amplitude.

Due to the large amount of points and the scaling of the graphics, the absolute value of the difference between curves in figure 45 and 46 is not easily to notice. Nevertheless what is important is to notice that both calculated and identified parameters follow the same tendencies.

5. Validation and results.

The developed algorithm to calculate phase and amplitude has up to now proved to provide good results for situations where two injections take place and fuel injected during the main injection is to be predicted. In this chapter, the developed correlation is to be tested with more simulated points where another extra injection takes place, as well as with real measurement data.

5.1 Validating for three injections.

In this section, the correlation will be tested with data out of the simulations performing three injections. Predicting the injection just following the pre-injection has already been proved to be accomplished. What it is now to be proved is the feasibility of predicting the injected fuel during another injection following a main injection.

The situation now is a pre-injection and two following main injections. The pressure data to be used for predicting the second main-injection injected mass are those obtained just before the second main-injection takes places. The remaining wave in the system at the moment pressure is measured is this time the result of two injections instead of one.

Exactly the same correlation is to be applied for both amplitude and phase in this three-injection case. The conclusions reached about frequency and damping are still valid, therefore only amplitude and phase are to be predicted. Nevertheless, in order to apply the same algorithm, some changes should be performed.

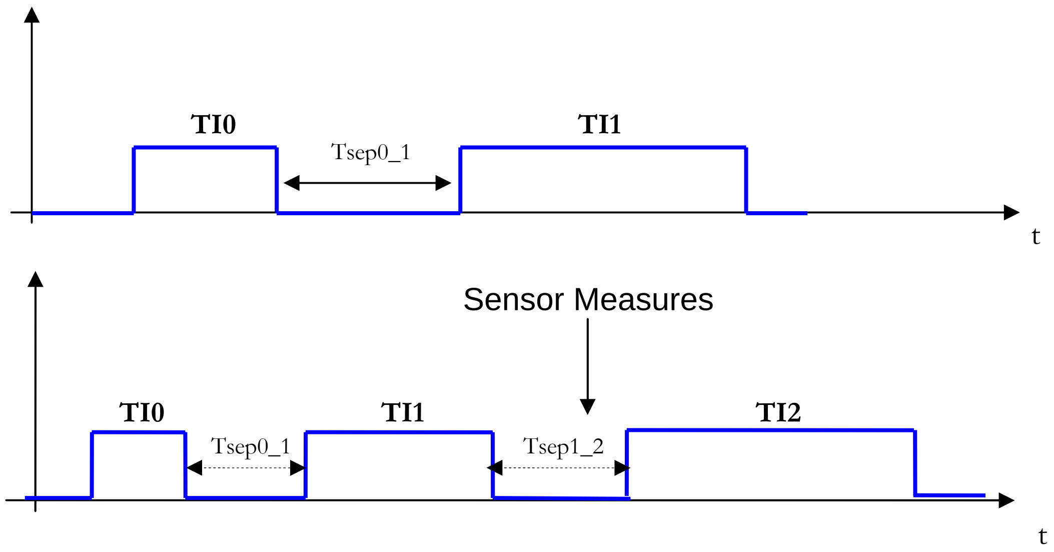


Fig. 10 and 12. Injections timings.

In the current situation, variables are practically the same as when only two injections were performed. However, in order to set clear the slight different between both situations, figures 10 y 12 are again displayed. The main difference now is how the injections are named. Now the main injection is called TI2 and the injection previous to it will be another main injection instead of a pre-injection. The pre injection, TI0 should now have no influence in the third injection TI2, because of the occurrence of another long injection in-between. When two injections where performed, TI0 proved to have some influence, thus if there is to be such influence now, it will be from TI1.

Leaving apart the influence of the pre-injection, the correlation is now to be applied with the sole change of the names of both injections. Thus TI0 and TI1 in the previous version of the algorithm should now be called TI1 and TI2.

Another difference with the previous situation is the existence of two different separation times. In fact, this means no change at all since the first of the time gaps remains fixed for every working points and the one which does vary is the gap between both main injections, and it will be then named Tsep. Nevertheless, this separation time should be carefully calculated, since the simulation software considers the separation time between the pre-injection TI0 and the second main injection instead of the one between both main-injections.

Before simply applying the correlation with this data, some improvement was thought to be necessary. The wave generated after the two injections depends on their timing as well as the separation time between both. Nevertheless, after trying to achieve some improvement looking for relations between this first separation time and injected fuel mass, no real improvements were found and therefore, the correlation is to be applied as it was developed, without any changes in the parameters or extra relations.

As a matter of fact, it seems sensible that there should be no change in the correlation between both situations. The achieved relations estimate amplitude and phase from the pressure wave before the injection as a function of fuel properties and duration of the injection itself. The fuel dynamical behaviour should be exactly the same, and therefore, the fact that a pre-injection was made before the first main-injection should no be relevant.

In order to obtain better results, a slight improvement of the correlation had actually to be performed. The reason for this correction is that when first developing the correlation, the influence of the previous injection was indeed overestimated at the amplitude calculation. The available data out of which this relation was worked out consisted of only two different values of this pre-injection. In this three injection instance there were more different values for the previous injection, now being the first main-injection. It was discovered that there was indeed no influence when this injection lasted longer than 0.35 ms. This change will have no effect at all in the previous results, because in previous situations there were no such long pre-injections. Nevertheless, when performing the correlation for the phase, this problem did not appear and thus, this correction was only to be made in the amplitude interpolation algorithm.

Finally, changing names of variables (*injection timing numeration)* and applying the aforementioned change in the amplitude, the correlation is tested for the current data and results are those displayed in figures 46 and 47.

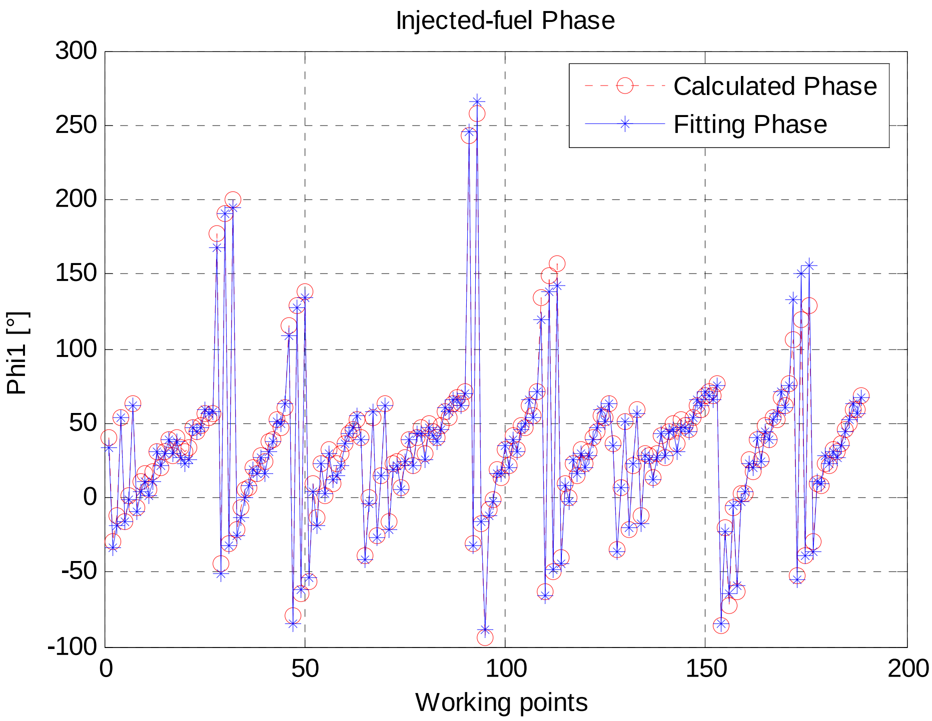


Fig. 46 Injected-fuel phase for points performing three injections.

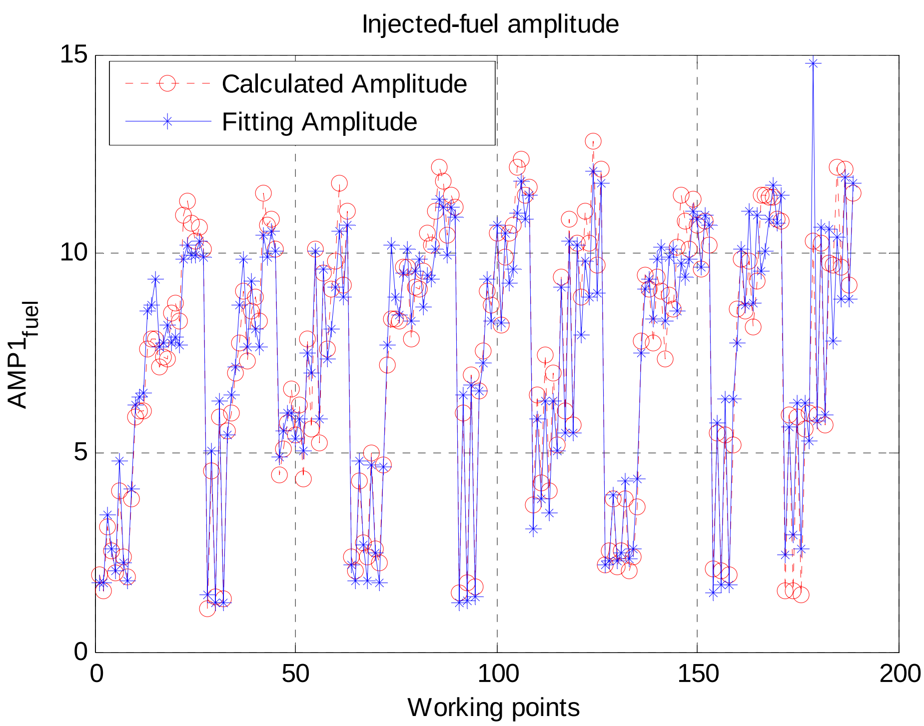


Fig. 47 Injected-fuel amplitude for points performing three injections

Both figures 46 and 47, do not allow seeing the real error between both waves due to their scaling; however, they do show how both curves have the same shape and therefore, the the correlation for the three-injection points can be assumed to match the identified parameter with noticeable accuracy. . Therefore, these results prove that the achieved algorithm allows predicting the fuel mass wave-parameter as a function of the pressure before the injection, no matter how many injections had already been performed. Later on, the total error will be displayed once the waves are reconstructed.

5.1.1 Wave reconstruction

Even though the results seem accurate at first sight, the sole plotting of them should not be enough to state their accuracy. Thus, the injected-fuel-mass waves are to be reconstructed and compared to the injected-fuel-mass data obtained out of the simulation as well as the wave reconstructed out of the fitting parameters.

As well as when two injections were performed, the reconstruction of the wave is made using the estimated values of amplitude and phase. Frequency obtained out of the FFT analysis and the rest of parameters are adopted from the wave identification. Once this wave is calculated, the relative error is calculated as the difference between this wave and the simulated data at each discrete point divided by the simulated data at that particular point. The maximum value of this error at each point is plotted in figure 48.

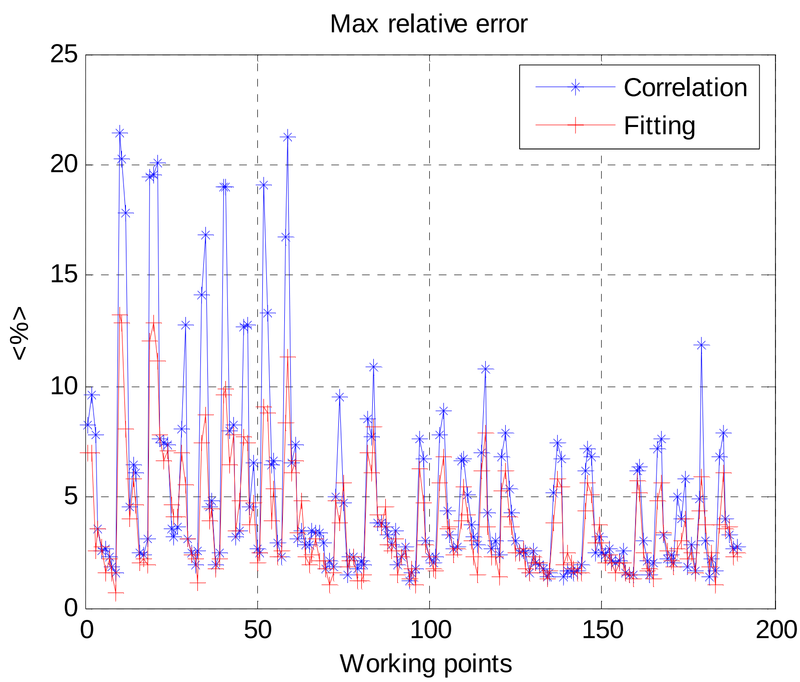


Fig. 48 Maximum relative error for the reconstruction of the fuel-wave.

As shown in figure 48, the obtained relative error of the correlated data is approximately the same as for the identified data and in some points even slighter. Compared to figure 43, where the error of the reconstruction for two injections is shown, this three-injection error happens to be even slightly smaller than that of two injections.

This results are rather encouraging since now the working points are completely different from the points out of which the parameter for the correlation were obtained and the range that they cover is also larger.

At certain points, the maximum relative error shows values relatively higher than those of the identification. If these particular points are analyzed more in depth, these errors are found not to be so significant. The reason for this is the fact that the relative error is calculated by dividing the absolute difference by the simulated value for each point. If this value is close to zero, a slight different will however mean a high relative error. If points where these errors take place are plotted, it becomes clear that the reason of these high maximum errors is that they occur in points that are close to zero. In figures 49 and 50, examples of the wave reconstruction for points where high error occur are displayed. In these graphics it is patent how these maximum deviations happen close to zero and although slight they will produce a high relative error.

Fig. 49 Example of reconstructed wave for working point 21

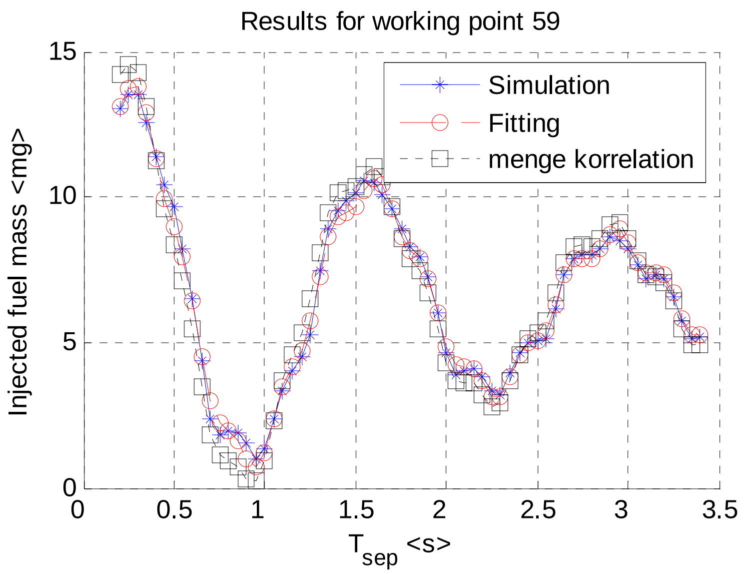


Fig. 50 Example of reconstructed wave for working point 59

5.2 Validation with experimental data.

Once a correlation is developed and proved to offer the possibility of predicting the injected amount of fuel for a wide range of operating conditions, it can not be assumed as reliable without testing it with data obtained out of a real system instead of computer simulations.

In order to do this, data obtained out of a real system were necessary. These data were provided by Siemens and consisted of measures performed upon a test bench designed to accurately measure the amount of fuel injected as well as the pressure in the pipe leading to the injector.

The provided data consisted of a total amount of one hundred and ninety-three points. In all of them only two injections, pre- and main-, were performed. Data from four different pressure levels were provided: 200, 800, 1200 and 1800 bar. All the measures were performed without varying temperatures, although it adopted several values during the measures, however, temperature has been proved to be a non-decisive variable and can be left aside. For each of the pressure levels several different injection timings were measured, but not the same ones for each of them. However, the working points provided, characterize in certain way a representative part of the possible working operation.

If the correlation was to be tested with these data, they should be fit into the same sinusoidal model into which simulated data were fitted. For this purpose, the same least-squares fitting procedure as earlier was achieved. Of course, when handling real measured data, the resulting errors are higher due to possible measuring errors as well as signal noise present in the data acquisition and signal processing equipment.

Once all the information was translated into wave-parameters and all data arranged in working points, it was then ready for the testing of the achieved correlation.

Of course, the system that was simulated was defined in order to resemble a real system but for the measures available, the topology of the test-bench where they were performed where not the same at all. As a result, the correlation with the previously obtained parameters could not simply be applied.

As the system is not the same, new parameters are to be obtained, although the same structure should be kept. Thus, for both amplitude and phase, $\Delta\varphi$ and K_{AMP} variables according to previous definitions were to be used. Thus the correlation itself will predict these values and afterwards, adding or multiplying by the pressure corresponding parameter, predict injected fuel amplitude or phase. As well as before, the correlation will only predict values of the fundamental harmonic of the wave.

5.2.1 Amplitude

Exactly the same interpolating structure is to be used for the predicting of the wave amplitude. Nevertheless, a new look-up table is to be built. The way of building this look-up table, as well as it was for the simulated data, is to store the value of K_{AMP} into a look-up table for a certain amount of points within every pressure and temperature level. As in the previous situation with simulated data, the amount of points that should be used to build the look-up table must allow describing the evolution of K_{AMP} with main injection duration.

The first results obtained after testing the interpolating correlation with the so obtained look-up table, though results were satisfactory, seemed not to describe with accuracy enough the influence of TI0, the pre-injection duration. The reason of this was obviously the lack of information concerning TI0 with which the first version of the correlation was accomplished. Simply enlarging the look-up table with more points where different values of pre-injection length occurred, this problem was solved. The amount of point at every pressure situation to be added was only one.

After the slight enlargement of the look-up table, the results obtained with it were plot together with data obtained from the identification, being the results displayed in figure 51.

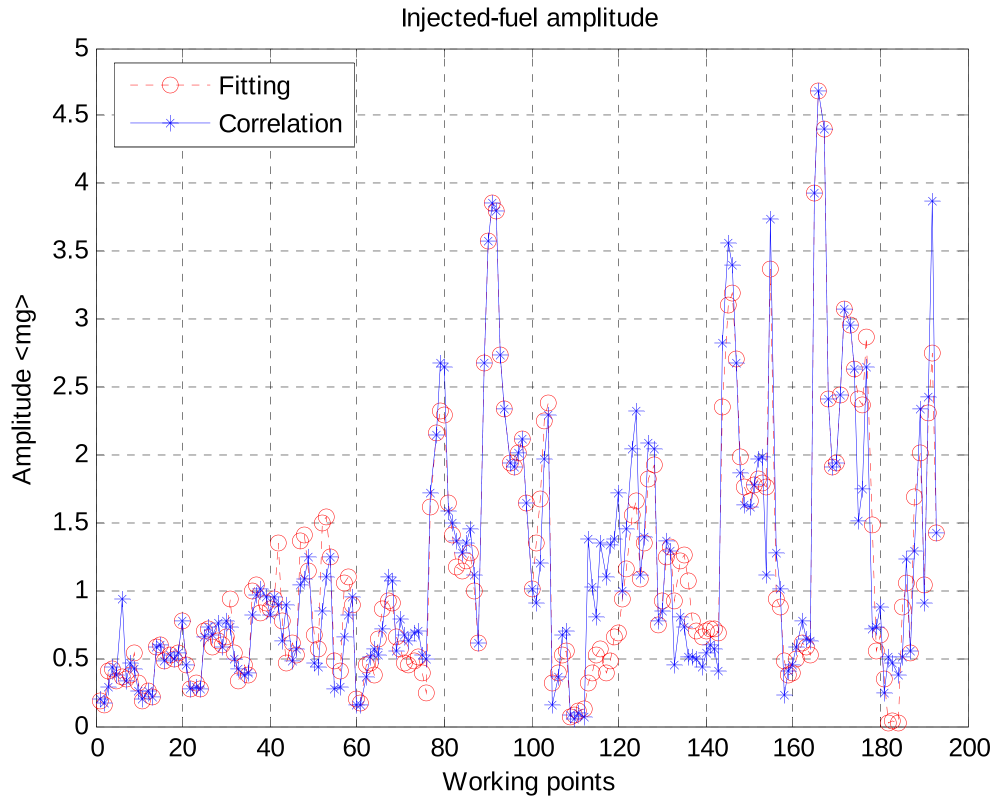


Fig. 51 Calculated amplitude after enlarging the look-up table.

Although, due to the large amount of points present in figure 51, real error for every particular point can not be differentiated, this picture does show how both curves consisting of fitting- and correlation-amplitude, follow the same tendency. Further on, the error will be studied considering the whole reconstructed wave.

5.2.2 Phase

Calculating new parameters for the phase was not as simple as for the amplitude. However, following the same scheme as for the early correlation development, a new set of parameter where obtained.

After applying the same correlation with the new obtained parameters, although the results seemed to follow the main trend of the identified phase parameters, they did not predict it with enough accuracy.

The way of solving this problem was adopting the correlation structure of the amplitude. Thus, the phase would now be calculated by means of interpolating out of values obtained from a look-up table.

The look-up table had the same structure as the amplitude's one. The phase increases from a certain amount of points at each pressure level were introduced in the look-up table.

The values kept had to allow describing the variation of phase increase with both injection timings. Once the look-up table was selected, the script developed for interpolating or extrapolating the look-up table values followed exactly the same structure of the one used for the amplitude.

Results obtained after developing this look-up table and interpolation procedure are shown in figure 52

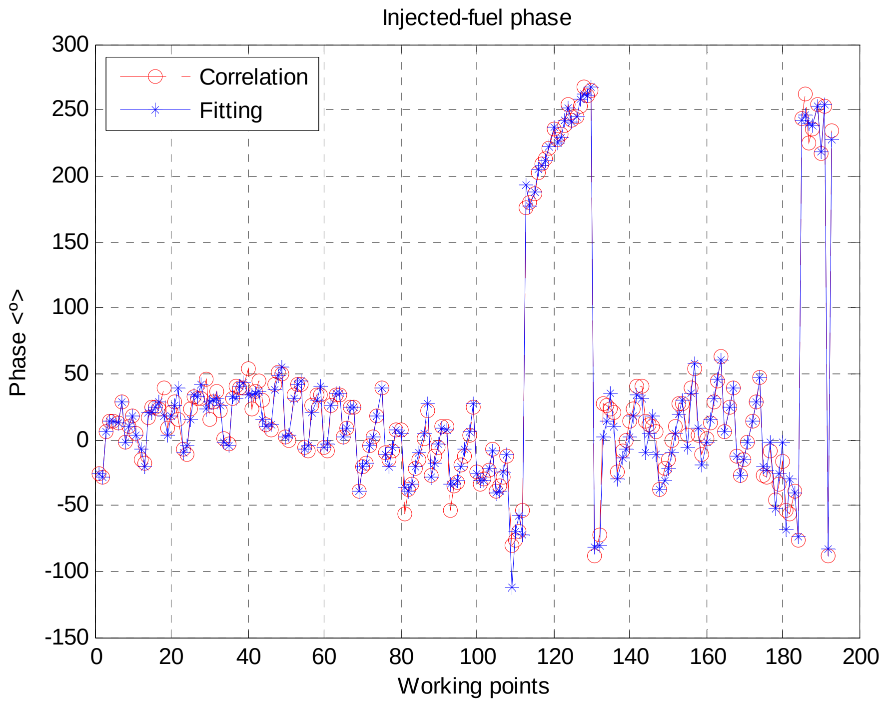


Fig. 52 Injected-fuel phase obtained out of a look-up table.

As well as before, this figure 52 only allows seeing how both fitting and correlation results resemble to each other but real errors will be considered in next section regarding the whole reconstructed wave.

5.2.3 Reconstruction of the wave.

Once the obtained correlation is adapted for its use with the measured data, as well as it was accomplished in previous sections, the injected-fuel wave is finally reconstructed using the calculated parameters. Subsequently, the maximum relative error is calculated and plotted together with the one from the identified parameters. Results are shown in figure 53.

Once more, the reconstructed wave shows values of the maximum relative error approximately equal to those of the identified wave. Hence, the validation of the correlation is finally achieved and therefore, the results of it can be assumed to be reliable.

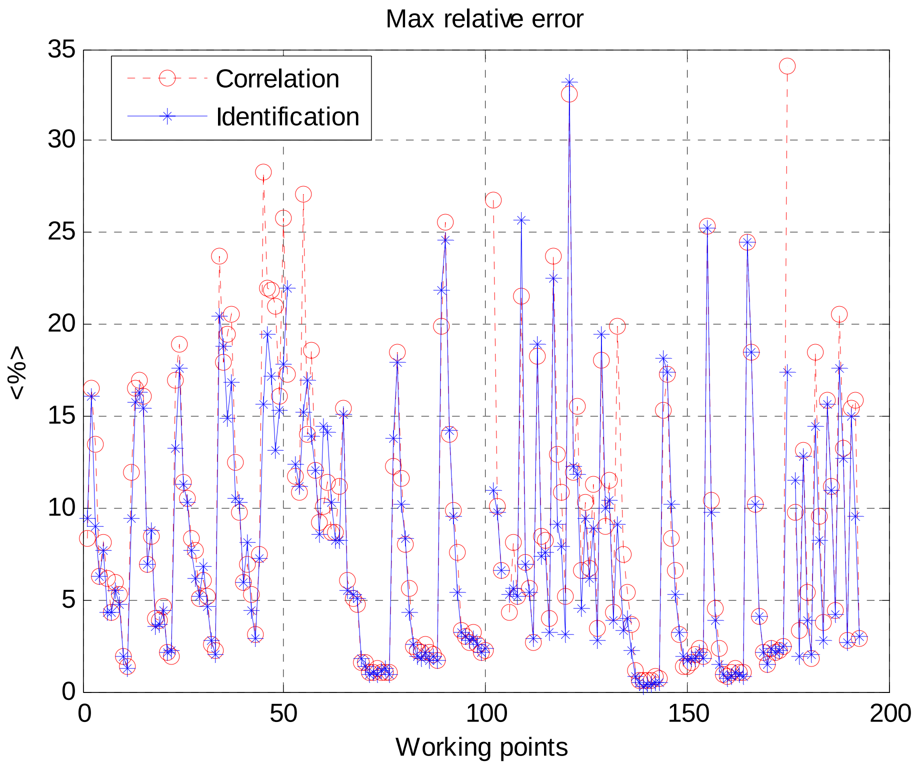


Fig. 53 Maximum relative error

After the final validation of the results has been achieved, the aim of this work is now considered to be accomplished. Hence, it can be affirmed that injected fuel mass can be predicted out measured pressures and thus, as in next section will be explained, deviations on injected mass be accurately corrected.

5.3. Results

The fact that injected-fuel mass can be predicted with certain precision means an important improvement in the field of engine control and implies the possibility of further improving of fuel consumption an emissions.

Perhaps the most important feature of this prediction is the fact of being accomplished out of information of what is happening inside the system in real time. Up to now this prediction could only be performed by the use of large data-maps stored in the engine's control unit obtained out of experiments in testing engines. However, injected fuel would be predicted without any information about the real behavior of the pressure.

The predictions made out of standard look-up tables are inaccurate because they are not obtained for each particular injection system but out of models. Moreover, features of the system, like injector tolerances, vary along operating time, not to mention fluid conditions. Therefore, the feasibility of obtaining real data and thus predicting the injected fuel provides a great improvement as far as engine control is concerned.

Being able to predict the injected fuel deviations depending on the pressure wave in the injector leading-pipe, allows correcting such deviations by varying the injector opening-time.

When the injected fuel that would indeed be injected is known, a correction on the injection duration can be performed. Thus, a *corrected time* can be calculated for the duration of the injection to be performed.

This corrected time can be defined as

$$t_{corr} = \frac{|m_{inj} - m_t|}{slope}$$

Being m_{inj}- m_t the difference between the predicted injected fuel and the amount of fuel that should indeed be injected and *slope*, the slope of the injected fuel mass for the given pressure and injection duration. The value of this slope should be obtained out of another look-up table developed for the injector itself.

This corrected time can be calculated just after the injected fuel mass is predicted and thus readjust the injection extent so the variation in fuel mass is corrected. In figure 54, an example of how this correction would affect the injected fuel is shown. This was obtained by means of simulating again the working points with this corrected time after it was calculated.

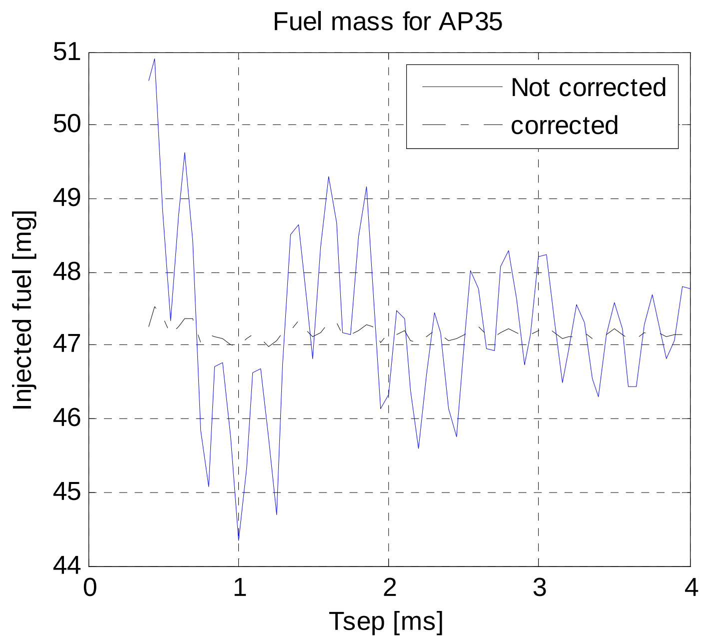


Fig. 54 Injected fuel mass before and after applying the time-correction.

As can be seen in the graphic, though there is still a slight variation in the injected mass, the deviation occurred without this correction is practically corrected.

5.3.1 Future developments.

Once the feasibility of predicting the fuel deviation due to neighbored injections has been established, next step will be the implementing on a control unit in order to practically correct this deviation.

However, future works will also have to deal with the first harmonic parameters. All the results obtained during this work concerned only the fundamental wave, but as the feasibility of predicting these values was obtained, a similar correlation could be developed for the prediction of the first harmonic.

The required sensor together with its data acquisition equipment are already developed and proved to supply reliable measures of the pressure inside the leading pipe.

With this work, the possibility of predicting the real injected-fuel-mass out of this pressure data and out of it being able to correct the fuel-mass deviation has been also stated.

As a result, future research and development efforts should lead to the final implementation of a control algorithm in the car’s engine-control-unit that out of the given measures and previously developed look-up tables, corrects automatically the fuel mass deviation.

6. Conclusions and Outlook

6.1 Conclusions

Common-Rail injection systems are nowadays one of the most popular injection systems in passenger-car diesel engines. The system itself consist of a high pressure pump that provides pressures of up to 1800 bar to the so-called rail, from where the fuel at such high pressures is driven to the injector. Unlike all diesel injection pumps, where the pump itself provided pressure and delivered fuel at high pressure to the injector, in common-rail systems both tasks are separated. The fact that the device controlling when the injection should take place is not anymore the fuel pump, allows a more efficient controlling of the system. Injectors now have the twofold task of acting as valves at the time they provide the right diffusion of the fuel.

The starting of the injection is now determined by the injector itself, which will open and close its needle valve, electronically commanded by the engine's control unit. Nowadays, thanks to the development of extremely fast actuators such as piezoelectric valves, the opening and closure of the injector can be achieved in extremely short lapse of time. This constitutes the higher advantage of these systems, apart from the high injection-pressures that are able to be achieved. With the described features, more than one injection during each combustion stroke are feasible, thus achieving a smother and more complete combustion In order to reduce fuel consumption emissions and noise, in modern injection systems, up to five injections per cycle are accomplished, this number tending to increase.

The fact that several injections per cycle are to take part, together with the high pressure of the whole system leads to deviation on the intended injected-fuel mass due to the influence of neighbored injections. Several injections in such short time laps will lead to the appearance of pressure waves upstream the injector nozzle due to the well-known water-hammer effect. This perturbations will remain in the system long enough to affect the following injection and thus being this last one performed from a different pressure as the rail pressure.

Hence, if this deviations are somehow predicted, they could be corrected and thus engine performance be improved. Up to know devices such as magneto-elastic sensor have proved to be able of providing reliable real-time information of the pressure in the pipe leading to the injector. As the pressure behavior upstream the injector is the responsible of the aforementioned deviations in the injected-fuel mass, if this pressure can be measured, predicting of these deviations should somehow be feasible. The aim of the present work is therefore the development of a correlation that allows calculating the fuel-mass that is indeed being injected out of information from pressure in the leading pipe and working conditions. If this is achieved, valuable information for improving engine performance will hence be available.

In order to obtain the desired correlation, information of the behavior of these systems was needed. The first step was therefore obtaining those data. As in most of engineering researches, data were obtained out of computer simulation.

From the point this work was started, a model of a typical Common-Rail system had already been developed. This model consisted of a single injector and its leading pipe and was developed into hydraulic simulating software able to provide numerical solutions for transient flows based in a finite elements model. With the assistance of this software, numerical simulations of a pre-defined injection system could be performed and thus data be obtained for the later development of a correlation. This software provided numerical values along time for the pressure at several pre-defined points as well as the injected fuel mass injected through the injector nozzle, allowing up to three injections to take place. All data are obtained as arrays that could be stored in Matlab formatting so they could later on be analyzed.

In order to obtain a relation between pressure evolution inside the system and injected-fuel-mass, working points should be carefully selected in order to obtain useful data describing most of the possible operating conditions.

If the obtained results are to be used by the engine-control-unit to predict and correct the injected-fuel deviations within the tiny available time between injections, apart from its accuracy, the main feature of the required correlation should be its simplicity, then allowing performing fast calculation. The parameters should therefore be reduced as much as possible and the simplest situation been studied. This led to developing the correlation out of the simplest situation, the performance of only two injections. Of course, the obtained relation based on data from two-injection simulations can not be decisive and should be tested and improved if necessary with further data.

Therefore, in order to develop a simple correlation a group of working points, where two injections were performed was selected and, for the further testing and improvement of it, another group of points performing three injections was as chosen. The number of points of the first one of the groups was seventy-five. Regarding working points performing three injections, as the number of parameters to be varied was superior, a larger amount of points were selected, one hundred and eighty-nine. Each of these points consist of a different situation regarding rail-pressure, fuel-temperature and duration of injections

The parameters meant to influence the injected-fuel deviation, apart from duration of the own injections, were fluid properties as well as duration of injections and time-separation between them. Fluid properties are a function of pressure and temperature, so they could be described with these two variables. However, the main variable influencing the injected-fuel mass is clearly the effective separation between injections. Thus, for every working point it was varied in tiny steps and a simulation for each of the values performed so that, for the given working-point conditions, the evolution of injected-fuel mass with time-gap between injections was obtained.

Once the working points to be simulated where selected, simulations were to be performed and data out of them conveniently stored for its later study.

The results obtained out of the simulating phase of points performing two injections, were then studied. Pressure after the first pre-injection showed a damped wave form, as it was already expected. Regarding injected-fuel mass along different separation times, the results happened to resemble some wave-like form as well. That led to the idea of describing both variables as being waves and thus being able to analyze it using wave properties.

Therefore, next step was to somehow fit the available results of both pressure and injected-fuel into wave models. For that purpose a typical model of a sinusoidal damped wave consisting in two harmonics, the fundamental and first harmonic was to be used. The wave model would be the same for both waves with the only exception of the time reference being different for each of them. The pressures waves are fitted in a wave along elapsed time while the time reference of the injected-fuel waves is the separation time.

By means of procedures based on the least-squares algorithms, and after finding proper staring values for them, the fitting of both signals into the aforesaid wave model were successfully accomplished. Now, both pressure and fuel signals were translated into wave parameters (frequency, amplitude, phase and damping) and these could be studied one by one.

As far as frequency was concerned, after calculating it by means of the FFT method, frequencies of both waves proved to be approximately the same. As a result, frequency could be yet dropped from the study in order to focus on the rest of variables. On the other hand, due to the short time in which the pressure wave measure will take place and the intention of predicting only one point of the injected-fuel wave in a real case where the correlation was intended to have its application, damping of both waves had no interest at all and was therefore left aside. As a result, the predicting of the injected fuel was no reduced to the calculation of two variables, amplitude and phase of the injected-fuel wave. A relation of those variables with working point parameters as well as pressure waves was then to be developed.

In order to predict the wave's phase, a new variable was defined. These variables consisted of the difference between phases of both waves, therefore being able to eliminate the influence of the pressure wave of the calculations. This phase increase was then represented versus the rest of working parameters. Finally it was found to present a square relationship with the duration of the main injection (second one) as well as linear dependences with pressure and duration of pre-injection. Temperature also seem to have a slight linear influence, but after developing the correlation both with and without considering it, it was decided to be left aside since its influence was very slight and however, it is not a variable that can be measured with precession in the real system.

Hence, the phase would be fitted into a polynomial depending on injection duration to square, rail pressure and pre-injection duration. The parameters of this polynomial were then to be calculated by means of applying polynomial fitting algorithms and multiple regression. First working points were arranged in groups of four points where only main-injection duration varied. The parameters regarding main-injection influence where then obtained as the mean value of the parameters obtained out of the polynomial fitting of every of this group. Once these parameters were obtained and the influence of it thus described, the mean differences between every group of points and the obtained tendency were calculated and arranged with their respective pressure ant pre-injection duration. At this point, multiple regression was performed between the mean offset of every group of points and its respective pressure and pre-injection. Thus, the rest of parameters were finally obtained.

After all the parameters where obtained, phase increase and therefore injected-fuel phase could now be calculated. Results of the calculation were plotted together with the phase obtained out of the identification and the results were proved to be accurate enough.

Once the phase could be estimated, only amplitude was left for being able to predict the injected-fuel mass. In order to obtain this amplitude as well as for the phase, a variable consisting in the difference of parameters from both waves was introduced. This time, instead of a difference a quotient between both was used, being therefore defined by a constant.

When the new constant was plotted against the difference working parameters, the mathematical relation between them seemed to be much more complicate as for the phase and therefore, trying to fit these relation into a polynomial proved to be both difficult and unpractical. The way this problem was then solved was to build a look-up table allowing calculating the amplitude-constant. This look-up table consisted of the value of the mentioned constant for a determined number of points together with another constant describing the influence of pre-injection duration. Together with the look-up table, an interpolating script had to be developed in order to calculate the amplitude-constant for whichever working conditions. Being this accomplished, amplitude of the injected-fuel-mass wave could now be calculated.

At this point, all wave parameters could be calculated and therefore the whole injected-fuel wave be reconstructed. After applying the developed correlation to all working points, results were stored and used for the reconstruction of the waves. These results were compared to the wave reconstructed out of the identified parameters and the values of the simulations and maximum relative error calculated. The thus obtained error approximately matched the one from the identification curves. Hence, up to now, for the point out of which it was developed, the correlation is proved to be valid.

Next step was to prove this recently obtained correlation with further situations in order to prove its validity. Thus, the same correlation was applied to the points were three injections were simulated. The objective now was to calculate the fuel injected in the third of the injections from values of the pressure wave remaining after the second of the injections.

The correlation should be adapted in terms of nomenclature, but the structure and parameters remained the same. After applying it to the almost two hundred three-injection points, only one modification had to be made in order to obtain better results. As for the case of having two injections only two values of pre-injection duration were available, the influence of this parameter was not accurately defined and was actually overestimated. It was proved than that for long main-injection durations the injection just before had indeed no influence.

After this slight modification on the correlation, it was successfully applied to the current working points and phase and amplitude calculated. As well as in case of two injections being performed, the injected-fuel waves were reconstructed with the calculated parameters and together with the identified ones compared to the simulated waves. The obtained maximum relative error was again for most of the points approximately the same as the one from the identification and therefore it was proved the validity of the correlation in case more than two injections were performed.

The final step of the process is to validate the correlation applying it to data obtained out of measures from a real system. This was achieved with the help of a certain amount of data provided by Siemens. After fitting those new data into wave models and applying the same correlation to them, results of the correlation could again be compared with the, this time real, measured data.

When applying the correlation to this new data, new parameters should be calculated following the same structure in order to adapt the correlation to this new and different system. No problem was found in achieving this with the amplitude, but when it came to the phase correlation, results did not show enough accuracy. The phase was then calculated with the same structure as the amplitude, building a look-up table and interpolating with exactly the same structure of the amplitude correlation. Regarding the amplitude look-up table, due to the larger amount of points with different pre-injection times, the look-up table was enlarged with one more point for every pressure and temperature situation thus improving substantially the results.

Finally, the results of applying the adapted correlation to the measured data where used to the reconstruction of the fuel-waves and maximum relative error were calculated. The result happened to be approximately the same as with the identified values and there for the correlation finally validated for real data.

6.2 Outlook.

At this point it could be now affirmed that a correlation was successfully developed and thus the feasibility of correcting the injected-fuel-mass deviations in common-rail injection system. In order to do this, research efforts should be applied in developing the necessary software to implement the obtained correlation into the engine's control unit.

RESUMEN

El sistema de inyección Common-Rail es hoy en día uno de los sistemas más comunes en motores Diesel de medio y pequeño tamaño. El sistema en sí consiste en una bomba de alta presión que suministra el combustible a presiones de hasta 1800 bar. al rail común o Common-Rail, de donde el combustible a alta presión es conducido al injector. A diferencia de los sistemas de bomba inyectora, donde la propia bomba es la que distribuye el combustible a la vez que suministra la presión, en los sistemas Common-Rail ambas tareas están separadas. Este hecho facilita en gran medida la posibilidad de realizar un control más eficiente del sistema. Los inyectores ahora serán los que tendrán una doble función, actuar como válvulas a la vez que proporcionan la adecuada forma y difusión del pincel de inyección.

El inicio de la inyección lo marca ahora el propio inyector mediante la apertura y cierre de su válvula de aguja, comandada esta electrónicamente por la centralita del motor (UCE). Gracias al desarrollo de los actuadores piezo eléctricos, es posible la construcción de inyectores capaces de realizar el proceso de apertura y cierre de la aguja en tiempos verdaderamente cortos. Esto confiere a los sistemas common-rail una de sus principales ventajas, al permitir la realización de varias inyecciones sucesivas dentro de un mismo ciclo de inyección. De este modo, se consigue inyectar el combustible deseado en varias etapas, consiguiendo así una combustión más suave y completa. Con objeto de conseguir una apreciable reducción de emisiones y ruido, en los motores modernos se llegan a realizar hasta cinto inyecciones por ciclo y este número tiende incluso a aumentar.

El hecho de que tengan lugar varias inyecciones por ciclo unido a las altas presiones a las que se realiza el proceso de inyección, conduce al fenómeno objeto de estudio en este proyecto, por el cual el combustible inyectado se desvía del teórico fruto de la influencia existente entre inyecciones vecinas. Debido al fenómeno hidráulico conocido como *golpe de ariete*, la rápida apertura y cierre de la válvula del inyector generará una perturbación en forma de onda de presión aguas arriba de la aguja del inyector. Dicha perturbación permanecerá en el sistema un tiempo suficiente como para afectar a la siguiente inyección, que tendrá lugar a partir de una presión distinta debido a la influencia de la mencionada onda.

Si las desviaciones producidas por la presencia de estas perturbaciones pudieran ser predichas, se podrían entonces corregir y aumentar como resultado el rendimiento del motor. Con dispositivos como los sensores magneto-elásticos se ha demostrado que se puede obtener información fiable en tiempo real acerca de la presión existente en la tubería que conduce el combustible desde el common-rail hasta el inyector. Dado el echo de que la presión aguas arriba del inyector es la responsable de la mencionada desviación en la masa de combustible inyectada, si dicha presión se puede medir, a partir de dicha información ha de haber un modo factible de predecir la desviación. El objetivo de este proyecto es, según lo descrito, el desarrollo de una correlación que permita el caculo de la masa de combustible que está realmente siendo inyectada a partir de información a cerca de la presión en la tubería de conducción y las condiciones de operación del motor.

Con el fin de obtener la correlación deseada, se necesita información a cerca del comportamiento del sistema. El primer paso es por tanto la obtención de dicha información. Como en la mayoría de las investigaciones en ingeniería, los datos necesarios fueron obtenidos a partir de la simulación por ordenador.

En el punto en que arranca este proyecto dentro de un proyecto mayor, un modelo de un sistema common-rail típico había sido ya desarrollado. Dicho modelo consiste en un único inyector y la tubería que llega a él desde el conducto común, definido dentro de un software capaz de proporcionar resultados numéricos fiables para un flujo no estacionario, basado en un modelo de elementos finitos. Con la ayuda del mencionado software, se pudieron simular diferentes situaciones en dicho sistema para posteriormente poder estudiarlas y desarrollar una correlación útil. El programa proporciona valores tanto de la presión en la tubería como del caudal a través del inyector, permitiendo la realización de hasta tres inyecciones. Todos los datos son proporcionados en forma matricial y guardados en formato compatible con Matlab para su posterior utilización.

Para poder obtener una correlación válida para la mayor parte del posible rango de funcionamiento del sistema, los puntos de trabajo han de ser cuidadosamente seleccionados.

Dado el hecho de que la correlación debe permitir a la centralita del motor calcular la cantidad de combustible inyectado en el corto intervalo de tiempo que transcurre entre una inyección y otra, una de las principales características que deberá poseer dicha correlación es que además de proporcionar resultados fiables, sea sencilla y permita una elevada velocidad de cálculo. Por lo tanto, los parámetros de los que dependa la relación buscada, han de ser reducidos al máximo. Así, la correlación fue, en una primera etapa, desarrollada a partir del más simple de los casos, aquél en el que solo una pre-inyección y una inyección principal tenían lugar. Por supuesto, los resultados así obtenidos no pueden considerarse decisivos y han de ser probados bajo diferentes y más complejas situaciones.

Los puntos de trabajo, teniendo esto en cuenta, fueron seleccionados en dos grupos, uno donde solo dos inyecciones tenían lugar, y otro grupo teniendo lugar tres inyecciones. Cada uno de dichos puntos de trabajo, corresponde a diferentes situaciones de trabajo, dentro de la cual varían los lapsos de tiempo entre inyecciones, dando lugar a numerosas condiciones de trabajo distintas dentro de cada punto de trabajo.

Los parámetros que en un principio son susceptibles de influenciar la cantidad de combustible inyectada, aparte de la duración de la propia inyección, son las propiedades del fluido y las separaciones en el tiempo entre inyecciones. La variable que más influencia tiene es sin duda el tiempo entre inyecciones, de modo que esta es la variable principal a variar en las simulaciones. Como resultado, tras las simulaciones se obtuvo información sobre la evolución del combustible inyectado en función de la separación efectiva entre inyecciones, para cada grupo de puntos de trabajo bajo unas mismas condiciones de presión y temperatura.

Una vez seleccionados los puntos de trabajo más convenientes, se estuvo en disposición de llevar a cabo las pertinentes simulaciones y a salvar los datos obtenidos para su posterior estudio.

Superada la fase de simulación, el siguiente paso es el estudio de los datos obtenidos con objeto de dilucidar una correlación entre el combustible inyectado y los parámetros de funcionamiento del sistema. En primer lugar se partió del caso más sencillo donde solo dos inyecciones estaban presentes. Como era de esperar, la presión remanente en la tubería tras la pre-inyección mostraba una clara forma de onda. Por su parte, la cantidad de combustible inyectada, representada frente al tiempo de separación entre inyecciones, también mostraba una forma clara de onda. De este modo, parecía lógico tratar de describir ambas señales como ecuaciones de onda y así poder analizarlas más fácilmente.

Una vez hecha esta observación, se trataba entonces de ajustar las señales de presión y masa de combustible inyectada en modelos matemáticos de onda. A este propósito se utilizaron modelos de onda sinusoidal amortiguada compuestas por dos harmónicos. Para ambas señales se había de utilizar el mismo modelo de onda, teniendo en cuanta la particularidad de que el eje de referencia de tiempos era distinto para cada señal; para la presión, el tiempo y para la masa, el tiempo de separación. Ambos ejes de tiempo están, no obstante, relacionados.

Por medio de procedimientos basados en el método de los mínimos cuadrados y tras encontrar los parámetros iniciales adecuados, el ajuste de ambas señales en el modelo señalado fue llevado a cabo con éxito. De este modo, ambas señales se reducen ahora a valores de amplitudes, fases, amortiguamientos y frecuencias, que pueden ser estudiados independientemente.

La frecuencia fue calculada por medio de la transformada rápida de Fourier, FFT. Tras comparar las frecuencias de ambas señales, la diferencia entre ellas era despreciable. Así, la frecuencia puede a priori ser desechada de la correlación. Por otro lado, dado el corto tiempo de muestreo de la señal de la presión y el hecho de querer predecir solamente valores discretos de la cantidad de combustible inyectado -no toda la onda- , el amortiguamiento de ambas ondas resulta irrelevante y por tanto también puede ser desechado. Como resultado, la predicción del combustible inyectado queda reducida al cálculo de dos variables, la amplitud y fase de la onda de combustible inyectado. Una relación entre ambas variables con los parámetros de los puntos de trabajo así como la onda de presión previa a la inyección sería suficiente para llevar a cabo la predicción.

Para poder predecir la fase de la onda se definió una nueva variable, una fase incremental definida como la diferencia de fase entre la onda de presión y la onda de combustible. Con esta nueva variable queda eliminada la influencia de la onda de presión para poder centrarse en la dependencia con las características del punto de trabajo. Finalmente, este incremento de fase mostraba una relación cuadrática con la duración de la inyección principal y relaciones lineales con la presión en el rail y la duración de la pre-inyección. La temperatura también parecía mostrar cierta influencia, sin embargo fue finalmente desechada debido a su baja influencia y al hecho de ser una variable difícilmente mesurable con precisión en un sistema de aplicación real.

Consecuentemente, la diferencia de fases podía ser ajustada como un polinomio dependiente de la duración de la inyección al cuadrado, la presión en el rail y la duración de la pre-inyección. Los coeficientes de dicho polinomio fueron calculados por medio de ajustes polinomiales y regresión múltiple. Una vez calculados los coeficientes adecuados, se puede calcular el incremento de fase buscado y deshacer el cambio de variable para finalmente calcular la fase. Una vez realizados los cálculos, los resultados se comprobaron con los datos obtenidos de los ajustes y se mostraron suficientemente precisos.

Calculada la fase, solo resta calcular la amplitud para poder reconstruir la onda. Para la predicción de la amplitud, al igual que se hizo con la fase, una nueva variable había de entrar en juego, el incremento de amplitud. A diferencia de la fase, debido al carácter multiplicativo de la amplitud, el incremento se calculó como cociente de amplitudes en lugar de cómo diferencia, resultando una constante.

Al representar la mencionada constante de amplitud frente al resto de variables y parámetros, las relaciones matemáticas existentes resultaron ser mucho más complicados que en el caso de la amplitud y ajustar estas relaciones en un polinomio arrojó ser tanto complicada como poco práctico. La manera de operar entonces fue construir un mapa de valores de la constante de la amplitud, consistente en una tabla de valores de dicha constante para determinados puntos seleccionados cuidadosamente. Además del mapa, se desarrolló un algoritmo de interpolación que permitía calcular el valor de la constante para cualquier punto a partir del mencionado mapa con resultados satisfactorios.

Llegado este punto, todos los parámetros que definen la onda podían ser calculados y por tanto la onda completa se podía reconstruir para comprobar la validez de los resultados obtenidos. La onda de presión fue reconstruida utilizando los resultados obtenidos por medio de la correlación y comparada con los resultados obtenidos a través de las simulaciones. El error relativo obtenido entre ambas resultó similar al obtenido por medio de la identificación matemática de las curvas, concluyendo por tanto la validez de esta correlación para al menos los puntos con los que había sido desarrollada.

El siguiente paso fue probar la validez de la correlación aplicándola a puntos de trabajo diferentes. Así, se aplicó a puntos donde tres inyecciones tenían lugar con parámetros de presión y temperatura cubriendo un abanico aún mayor. El objetivo en este caso era obtener el combustible inyectado en la tercera de las inyecciones a partir de la onda de presión remanente tras la segunda de las inyecciones. La correlación hubo de ser adaptada en términos de nomenclatura, pero la estructura y los parámetros se mantuvieron invariantes. Después de aplicarla a los casi doscientos puntos de trabajo, con tan solo una pequeña modificación, se obtuvieron valores de amplitudes y fases que permitían la reconstrucción de la onda como en el caso anterior. Al comparar los resultados de la reconstrucción con los de las simulaciones, el bajo error relativo probó la validez de la correlación para un rango mayor de puntos.

Una vez probada la validez para rangos mayores de funcionamiento del sistema, solo restaba probar el algoritmo con datos obtenidos de un sistema real. Un cierto número de datos fueron provistos por Siemens, obtenidos de un banco de ensayos experimental. El procedimiento a seguir era el mismo: ajuste de los datos, aplicación de la correlación y comparación con los resultados experimentales.

Al aplicar la correlación a este nuevo conjunto de datos, nuevos parámetros habían de calcularse, puesto que se trataba de un sistema distinto al teórico con el que la correlación había sido desarrollada. No hubo ningún problema en adaptar la correlación a la amplitud, sin embargo, en el caso de la fase los resultados con nuevos parámetros no fueron satisfactorios. Como consecuencia, la estructura de mapa de valores y algoritmo de interpolación de la amplitud fue adaptada a la fase y finalmente los resultados obtenidos fueron satisfactorios.

Finalmente, los resultados de aplicar la correlación adaptada a datos tomados de un sistema real fueron utilizados para la reconstrucción de la onda y el cálculo de errores relativos. Los resultados concluyeron la validez de la correlación también para un sistema real.

Perspectivas.

Tras el estudio realizado, se puede afirmar que una correlación suficientemente precisa ha sido desarrollada y queda por tanto demostrada la factibilidad de corregir las desviaciones en la inyección en sistemas de inyección Common-Rail. Para finalmente llevar a cabo esta tarea, los esfuerzos en investigación deben ahora ir encaminados a desarrollar el software necesario para poder implementar este resultado en la centralita de control del motor.

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