Pressure Oscillations during Rapid HCCI Combustion

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ABSTRACT

HCCI-operation is limited to lean air/fuel mixtures in order to keep the combustion rate low. Using richer mixtures will cause rapid combustion accompanied by unacceptably high pressure derivatives. The rapid combustion and high pressure derivatives trigger an oscillating pressure phenomenon within the combustion chamber. The oscillations may consist of inhomogeneous pressure waves traversing the cylinder or they may be of a structural vibrating nature.

These works has been focused on studying the pressure oscillations and determine what they consist of. In order to study the pressure oscillations a number of pressure transducers were mounted in the combustion chamber. The multi transducer arrangement was such that six transducers were placed circumferentially, one placed near top centre and one at a slight offset in the combustion chamber. The fitting of six transducers circumferentially was enabled by a spacer design and the two top mounted transducers were fitted in a modified cylinder head. During testing a disc shaped combustion chamber was used.

The results of the tests conducted were that the pressure oscillations experienced during rapid HCCI-combustion are inhomogeneous and show good accordance to vibration mode shapes and frequencies suggested by acoustic vibration theory.

The pressure waves manifested largest intensities for the first vibration mode, a mode suggesting radial propagation in the combustion chamber. Experiments showed that the direction of the pressure wave was stochastic and hinted absence of hot spot ignition.

Lastly, engine tests using two other combustion chamber geometries were conducted. The results showed that altering the geometry of the combustion chamber affect the resulting frequency spectrum. The two geometries being of a hill- and a bowl shape. Analytical calculations on the bowl shape vibration frequencies indicate reasonably good accordance to experimental results.

INTRODUCTION

In-cylinder pressure oscillations arise in internal combustion engines when the combustion rate becomes too high. A high combustion rate will cause high pressure derivatives and the high pressure derivatives will in turn trigger specific acoustic modes within the combustion chamber. In a HCCI engine the combustion rate is naturally very high since the entire charge is involved in the combustion process concurrently. When running a HCCI-engine the air/fuel ratio is kept lean in order to keep the combustion rate acceptable. The usage of a richer mixture will eventually result in too rapid combustion and unacceptably high pressure derivatives.

Having noticed the result of rapid combustion related to richer mixture, a further increase in injected fuel amount will cause a ringing phenomenon on the in-cylinder pressure trace. The ringing phenomenon consists of pressure oscillations from within the combustion chamber.

Experience of ringing phenomenon is not unique to HCCI-engines. SI-engines show similar behaviour too. This phenomenon is known as knocking and is a result of the fuel auto-igniting. Knocking is a highly unwanted phenomenon, which may cause engine damage. The cause of knock may be a row of factors; e.g. the usage of fuel with a too low octane number, a too lean mixture, too early ignition timing or in the case with turbocharged engines, too high boost pressure.

Knocking in SI-engines consists of a non-uniform pressure wave traversing throughout the cylinder at the speed of sound. That means that the frequency of the noted ringing depends on the cylinder bore. A passenger car sized SI-engine will show first order knocking frequencies in the range of 4-5 kHz. A larger bored cylinder offers larger distances for the pressure waves to travel, and would therefore generate lower knocking frequencies.

Another cause of rippling phenomenon from within the combustion chamber is structural vibrations. The vibrations may occur if the combustion is of extremely rapid and violent nature causing e.g. compression of the connecting rod.

The easiest way to illustrate this would be to remove the cylinder head, baring the piston, and give the piston a blow with a large hammer. The ringing phenomenon created by hammering the piston would be homogenous oscillations manifesting uniform pressure development throughout the combustion chamber.

Finally, the ringing phenomenon experienced in HCCI-engines, could be any of the two alternatives listed:

- Inhomogeneous oscillations, characterized in the text by SI-knock
- Structural vibrations generating homogenous pressure oscillations

Or, even a third possible alternative:

- A combination of both cases, i.e. pressure waves overlapped with structural vibrations

MAIN SECTION

APPARATUS – The engine used for the tests was an inline six-cylinder *Volvo TD100*, converted to HCCI operation. Several modifications has been done to the engine during it's time at *the Division of Combustion Engines* in Lund. For instance, only cylinder number 6 is operational, the rest are motored and the cylinder head for cylinder 5 has been removed, and replaced with a sealing plate. The removal of cylinder head number 5 facilitates maintenance and general mounting operations of cylinder 6. A photo of the engine can be seen in figure 1 and a table containing some vital operational parameters of the *VOLVO TD100* is shown in table 1.

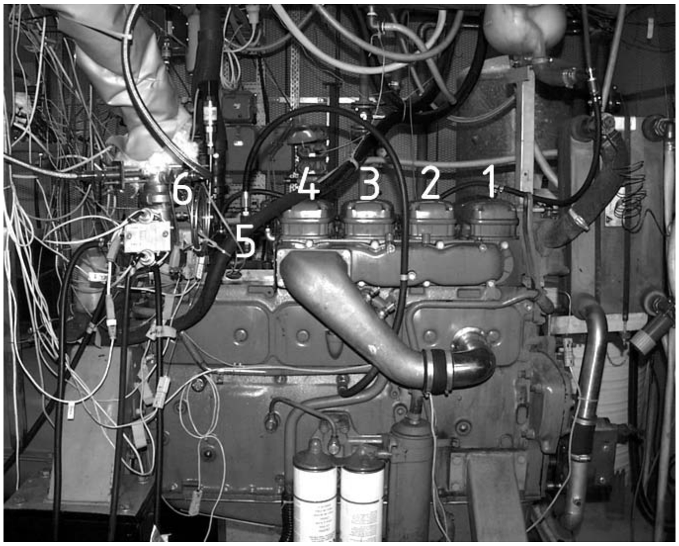

Figure 1. The modified VOLVO TD100, the engine used for all the experiments conducted.

Table 1. Geometric properties of the TD100 engine.

Displaced volume	1600 cc
Stroke	140 mm
Bore	120.65 mm
Compression ratio	*17.5:1*

METHOD – In order to monitor the oscillations within the combustion chamber, the decision fell on usage of a number of pressure transducers. The transducer itself measures pressure and strategically placed throughout the cylinder would govern a correct analysis of the oscillating process. In this case the number of transducers to be used was specified beforehand to eight. Accommodations for six of these transducers were made in a designed spacer which was placed between the engine block and cylinder head. The remaining two transducers were fitted in an existing modified cylinder head. The transducer arrangement can be seen in figure 2.

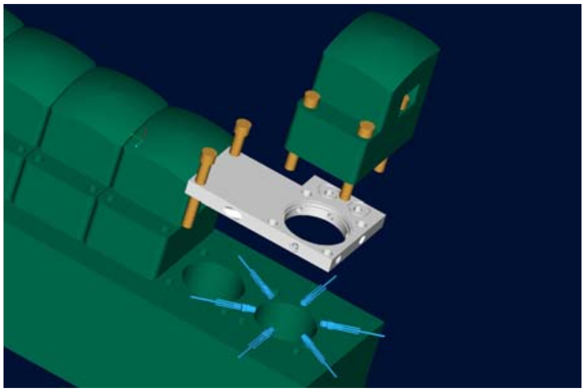

Figure 2. Picture of transducer arrangement.

The engine was, after modifications and mounting, operated at different load conditions to induce the right amount of ringing phenomenon. Thereafter, measurements were taken and data was analyzed.

An interest in investigating how the combustion chamber's shape affects the pressure oscillations developed during the project. Alteration of the combustion chamber geometry was facilitated by design and manufacturing of piston crowns. Pictures of the manufactured piston crowns can be seen in figure 3.

Figure 3.

Again, after a number of test runs data was collected and analyzed.

RESULTS 1st phase – Are the oscillations homogenous or not?

A characteristic pressure trace around TDC, the area of interest when studying oscillations caused by ignition, pressure is shown in figure XX.

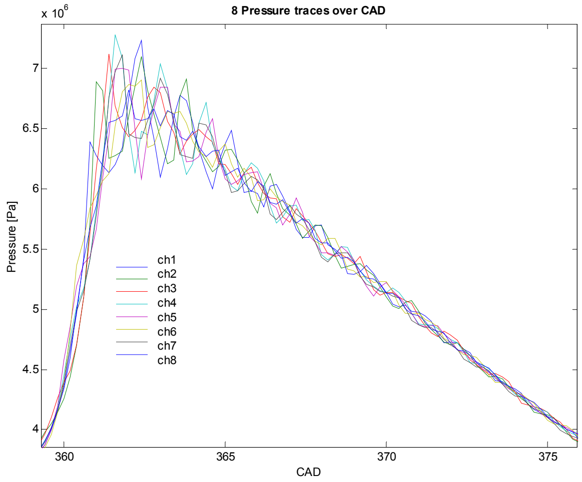

Figure 4.

And the channels corresponding to the indicated channels in the figure above:

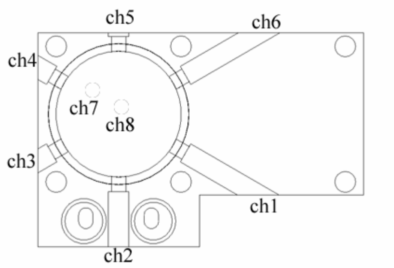

Figure 5.

From figure 4 one can clearly see inhomogeneous behaviour in the pressure trace.

Further, another phenomenon of interest which one can read from the plot in figure XX is the apparent groupings of channels. It seems that there are three different groups that show some kind of dependency between each other. The three groups are:

- Channel 1, 2 and 6. Referred to as group one.
- Channels 3, 4, 5 and 7. Referred to as group two.
- Channel 8 shows no obvious correlation to the two other groups. Although not per definition a group it is nonetheless referred to as group three.

The grouping phenomenon is shown in figure 6 through 8.

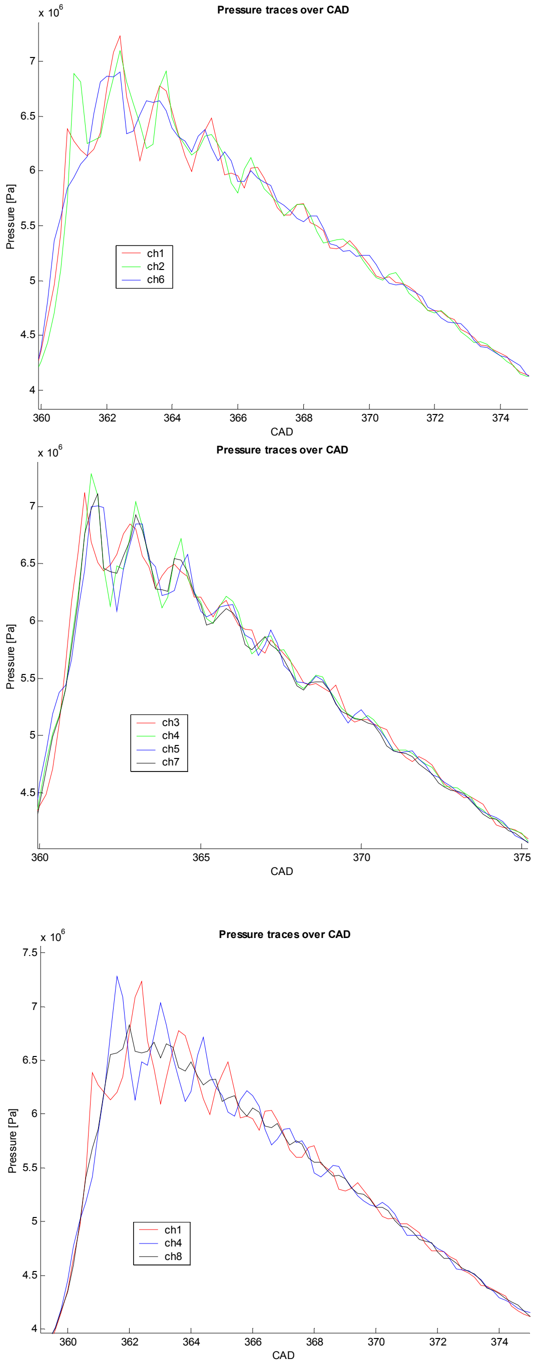

Figure 6 through 8.

RESULTS 2nd phase – A deeper look into the oscillating pressure traces reveal that oscillations within the combustion chamber are ordered into four major modes. Figure 9 shows these four modes.

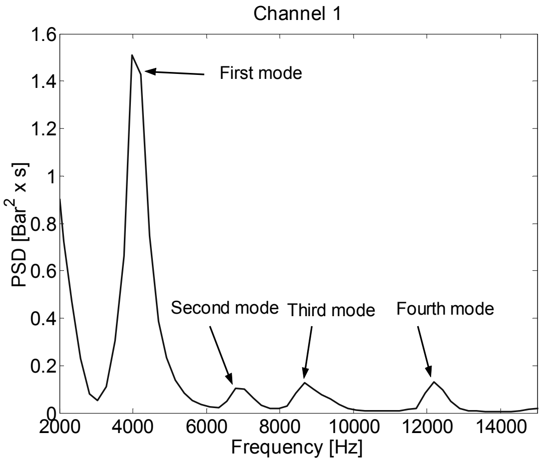

Figure 9.

Change of the combustion chamber geometry will render the following PSD-plot for the three channels 1, 7 and 8 (for the Hill- and Bowl-shape respectively).

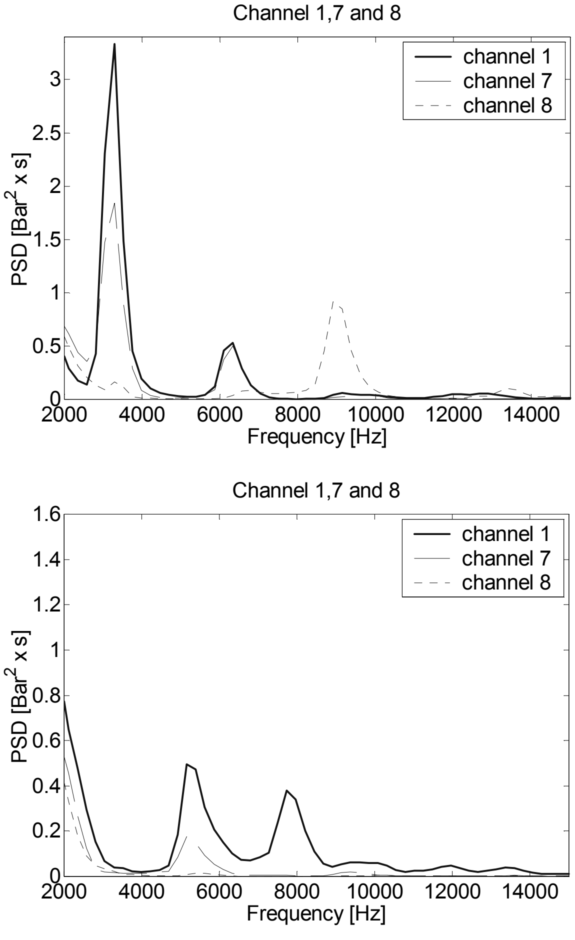

Figure 10 through 11.

A comparison to the theoretical values of the oscillation frequencies (according to Appendix A) will render the plot shown in figure 12.

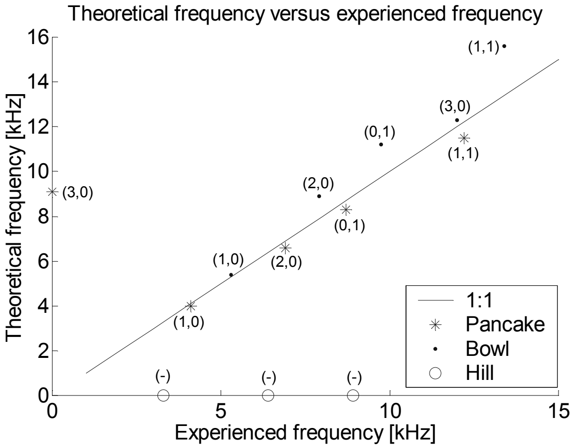

Figure 12.

CONCLUSION

Pressure oscillations during rapid HCCI combustion are inhomogeneous and, as one would expect, show good accordance with pressure wave theory. Nothing in the research indicates otherwise.

Altering the engine’s combustion chamber geometry will affect the properties of the oscillations.

REFERENCES

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A4. Magnus Christensen. *Homogeneous Charge Compression Ignition (HCCI) Engine –Mixture Requirements, Engine Load Range and Emission Characteristics.* Media-Tryck, Lund 2002

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APPENDIX

ACOUSTIC VIBRATION MODES – The frequencies at which the engine knocks are determined by the acoustic vibration modes specific to the combustion chamber.

When the charge ignites spontaneously a high rate of heat is released. The amount- and high rate of energy released will in its turn excite specific vibration modes.

These modes cause pressure waves traverse the combustion chamber at the local speed of sound, i.e. the acoustic velocity [A1], [A2]. The modes can be of both circumferential and of radial nature. For passenger sized engines the generated frequencies are in the spectrum of 6 to 20 kHz [A1]. Since the experimental part of this work is conducted on a large bored heavy duty truck diesel the presumed frequencies experienced by it should be somewhat lower.

To calculate the vibration mode frequencies for complex combustion geometries is quite complicated. The calculations are suitable for numerical CFD or FEM computer software. But, for a simple cylindrical combustion chamber the vibration mode frequencies can be calculated analytically using C.S. Draper's acoustic pressure wave formula, represented by equation A1:

$$f_{m,n} = \frac{C \cdot \rho_{m,n}}{\pi \cdot B} \text{ (Eq. A1)}$$

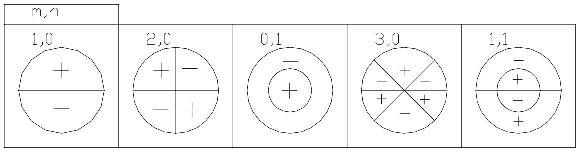
Where:

$$\gamma = \text{specific heat ratio} = \frac{C_p}{C_v} = \text{temperature dependant}$$

$$R_{Air} = \text{gas constant for air} = \left[\frac{R_{Universal}}{M_{Air}}\right] = 2.869 \cdot 10^2 \, J/kgK$$

$$T = \text{temperature} = \text{pressure dependant}$$

And further, the vibration mode number for a cylindrical shaped chamber:



$\rho_{m,n}$	1.84	3.054	3.832	4.201	5.332

Figure A1. Picture illustrating the different mode shapes with accompanying mode factors for a cylindrical chamber.

In equation A1, the Draper equation, the axial vibration modes are neglected because of the small height of the combustion chamber compared to the bore.

ACOUSTIC VELOCITY – While studying equation A1 one can note that, C, the speed of sound, is a key factor in determining the acoustic vibration frequencies. Assuming that the premixed charge behaves like an ideal gas, an assumption that is not that far fetched, it becomes well known that [A3]:

$$C = \sqrt{\gamma \cdot R \cdot T} \text{ (Eq. A2)}$$

Where:

$$\gamma = \text{specific heat ratio} = \frac{C_p}{C_v} = \text{temperature dependant}$$

$$R = \text{gas constant for air} = \left[\frac{R_{Universal}}{M_{Air}}\right] = 2.869 \cdot 10^2 \, J/kgK$$

$$T = \text{temperature} = \text{pressure dependent}$$

In equation A2 the specific heat ratio is mentioned. The specific heat ratioγ is a temperature dependent variable. It decreases as the temperature increases. But, as shown by *M. Christensen* γ can be approximated by the following expression under the assumption that γ decreases linearly while the temperature increases [A4]:

$$\gamma = \gamma_0 - \frac{k}{100} \cdot \frac{T}{1000} \text{ (Eq. A3)}$$

Where:

γ_0 = the value of γ at reference temperature, 300K
[For pure air γ_0 is 1.4,
for a lean air/fuel mixture containing iso - octane γ_0 is approximated to 1.38]
k = a constant set to 8

For a deeper understanding and further information on the approximation of the ratio of specific heats, the interested reader is referred to the work of *Heywood* [A5].

Further, needed for both equation A2 and A3 is the current in-cylinder temperature. The temperature affects the acoustic velocity C, as well as the specific heat ratio, γ. Assuming that the gas composition is constant between IVC and EVO, the following expression can be derived:

$$\frac{T_1}{p_1 V_1} = \frac{T_2}{p_2 V_2} = \ldots = m \cdot R = \text{constant} \text{ (Eq A4)}$$

Using equation A4, and information on the current volume within the combustion chamber, the temperature trace can be calculated from any given pressure data and thus, the acoustic vibration frequency.