Entwicklung und Optimierung eines innovativen Auspuffsystems für ein Ducati Motorrad

Design and Optimisation of an Innovative Exhaust System for a Ducati Motorcycle

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Abstract

This paper will show the design of an innovative exhaust system for a new Ducati bike, the 999. The bike was designed completely on CAD 3D and the time to market was very stringent. An important request of this bike was the close assembly of all the components, to ensure a very compact bike. This generates the necessity to virtually define the complete exhaust system, either the layout of the runner, or the volume of the muffler, in the first phase of designing the bike, to allow the simultaneous design of the components near the exhaust system. The 1-D simulation allows to design an innovative solution of exhaust system for high performance bike, where the innovation are: the asymmetry of the layout, the imposed reflection and the use of the silencer as compensator.

1 Introduction

The new 999 bike replaces the 998 and represents the racing image of Ducati, from which stems the Superbike. The engine of this bike is a V twin, 90° angle, that produces an asymmetry of the firing order and consequently of the mass fluxes of each cylinder in the engine.

The tasks of the exhaust system are principally two: first to take out the exhaust gases of the engine; second to reduce the noise due the energy of the gases.
The engine of this bike is designed to obtain extremely high performance (it is the most performing twin engine in production in the world, 138 CV at 10000 rpm). To reach this value, every component is designed to optimise the maximum power, that is maximize the volumetric efficiency at higher rpm. The torque of an engine is proportional to its volumetric efficiency, and this is the result of the tuning between the intake system, the valve timing and the exhaust system. Only with a well designed exhaust system it is possible to reach a volumetric efficiency of 1.15-1.2; the cause of the influence of the exhaust system is shortly explained: following the combustion event, when the exhaust valve opens, the blow down pressure in the cylinder generates a pressure wave in the exhaust runner pipe as the pistons is still travelling towards bottom dead centre. This pressure wave propagates towards the end of the pipe and is reflected as a rarefaction wave that travels back toward the exhaust

valve. If the rarefaction wave arrives during the overlap period, the combustion products scavenge from the cylinder increases; this reduces the trapped residual gas concentration at the end of the induction process. Residual combustion gases have a high specific volume which has a dramatic effect on the potential for the induction process to fill the cylinder with fresh charge.

The second task of an exhaust system is the reduction of the noise due to the energy of the gases, obtained with reactive and dissipative muffler. Reactive silencers attenuate the sound mainly due to the contractions and expansions of the fluid when travelling from one chamber to another. Combinations of the different chambers with the transfer tubes have their own resonance frequencies, which will enhance the acoustic pressure levels. The design of the exhaust system is carried out with 1D CFD code. Computer simulation programs are used extensively in the design and development of internal combustion engines. The torque of an engine is proportional to its volumetric efficiency and the predictive capability of these programs centres on their proficiency in mimicking the gas dynamic processes occurring in intake and exhaust systems.

2 Design

The tasks of the exhaust system of this new bike are:

1) same maximum power of the previous 998 bike and a torque curve without gaps at lower and middle rpm

2) fulfilling the Euro 2 pollution limitations, also taking in account to the future Euro 3, it means to minimize the modifications to reach the new homologation norms, (modify the coating of the catalyst and introduce the lambda sond)

3) new family feeling of the muffler, (Moto Gp and Superbike)

4) do not increase the weight of the exhaust system, in spite of the introducing of the catalyst

5) runner layout package, compatible with the new swing arm,

The layout of the previous 998 bike consists of two primary runner coming up from the cylinder-head; they come together in the compensator and then separate again into two tubes up to the two mufflers; the total volume of the silencer is 9 litre. The length of the primary runner is approximately the same, optimised for the rpm at maximum power (see figure1).

The new 999 bike is equipped with a double swing-arm that doesn’t allow to use an exhaust system similar the 998’s. Consequently, a new layout was designed and optimised (see figure2). The length of the tube from horizontal cylinder is twice longer as the vertical tube.

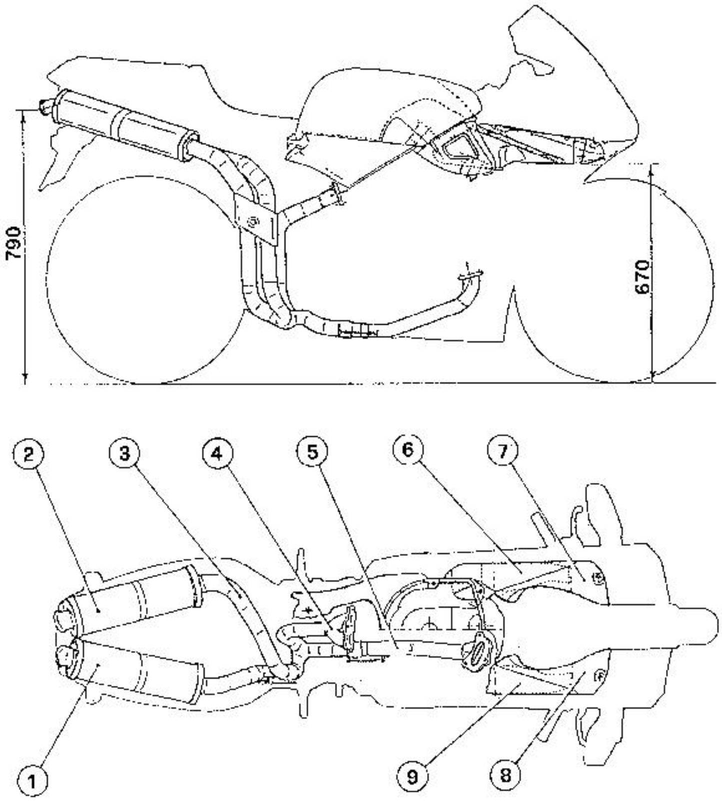

Figure 1: 998 exhaust system

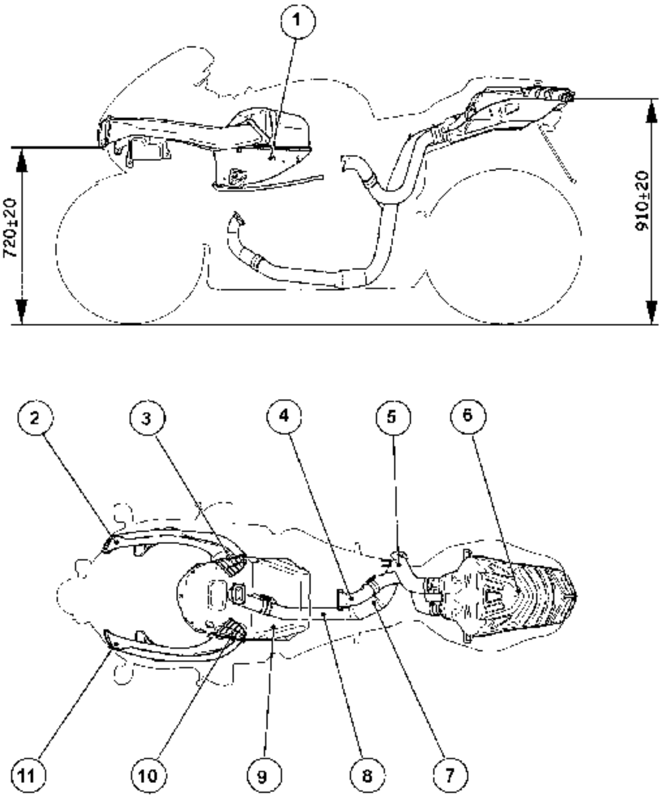

Figure 2: 999 exhaust system

The first proposal was to join the two runners before entering in the first muffler's chamber. The simulation shows that the low-pressure wave coming back in the horizontal cylinder in the overlap period is bad matched (see figure 3).

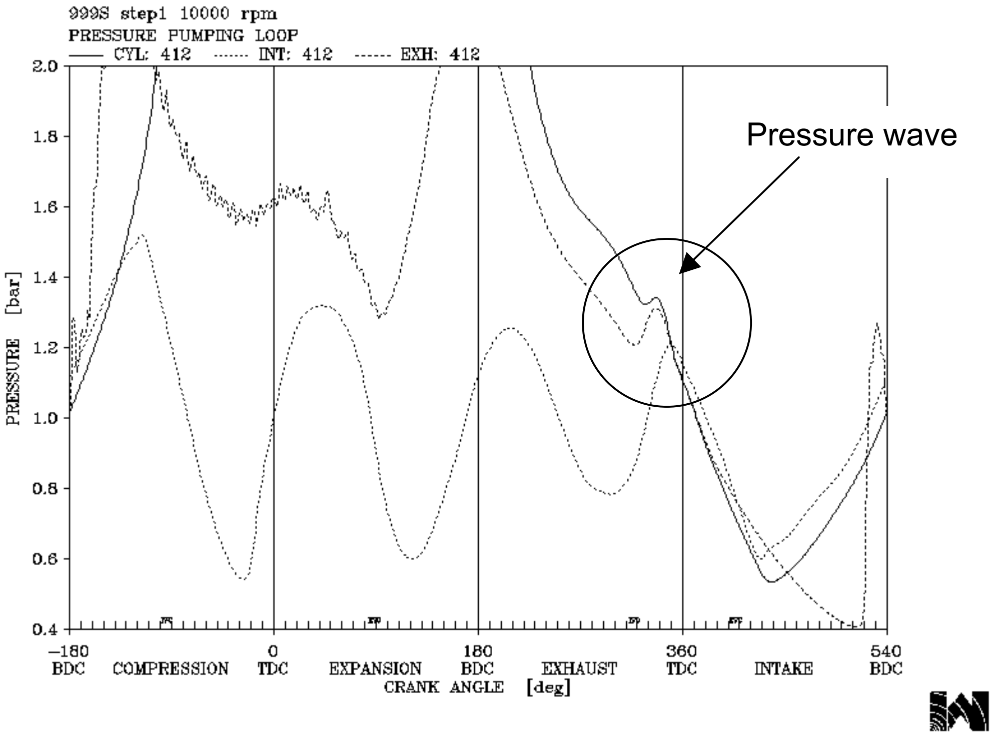

Figure 3: Pumping loop of horizontal cylinder's step 1

The first modification (step 2) is the introduction in the horizontal runner of an abrupt change of area, obtained with the join of a bigger tube. It should introduce a reflection of the wave that scavenges the combustion products from the cylinder (see figure 4-5).

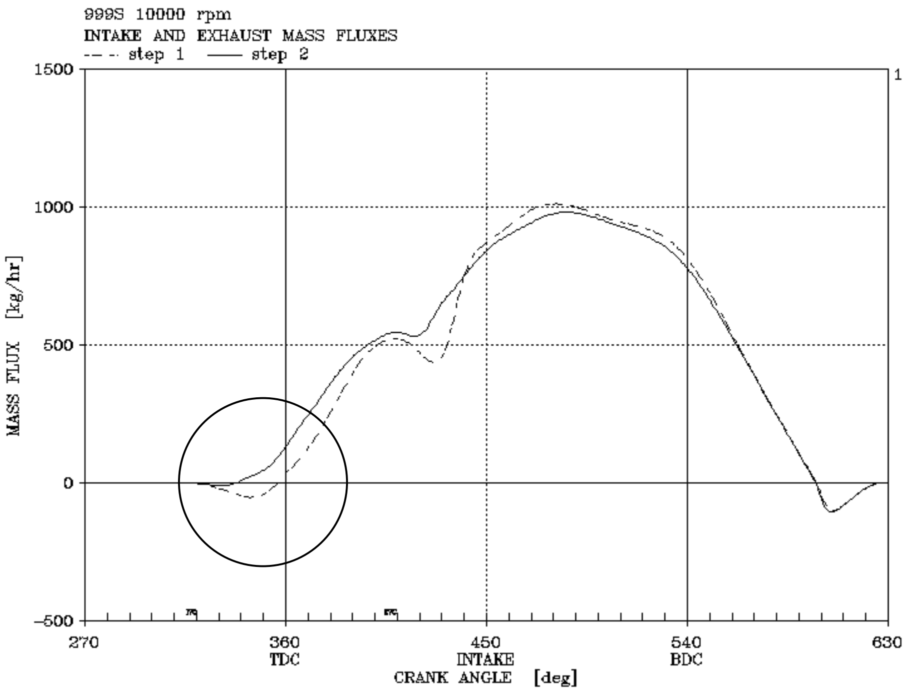

Figure 4: Horizontal cylinder's intake mass flux step 1 vs 2

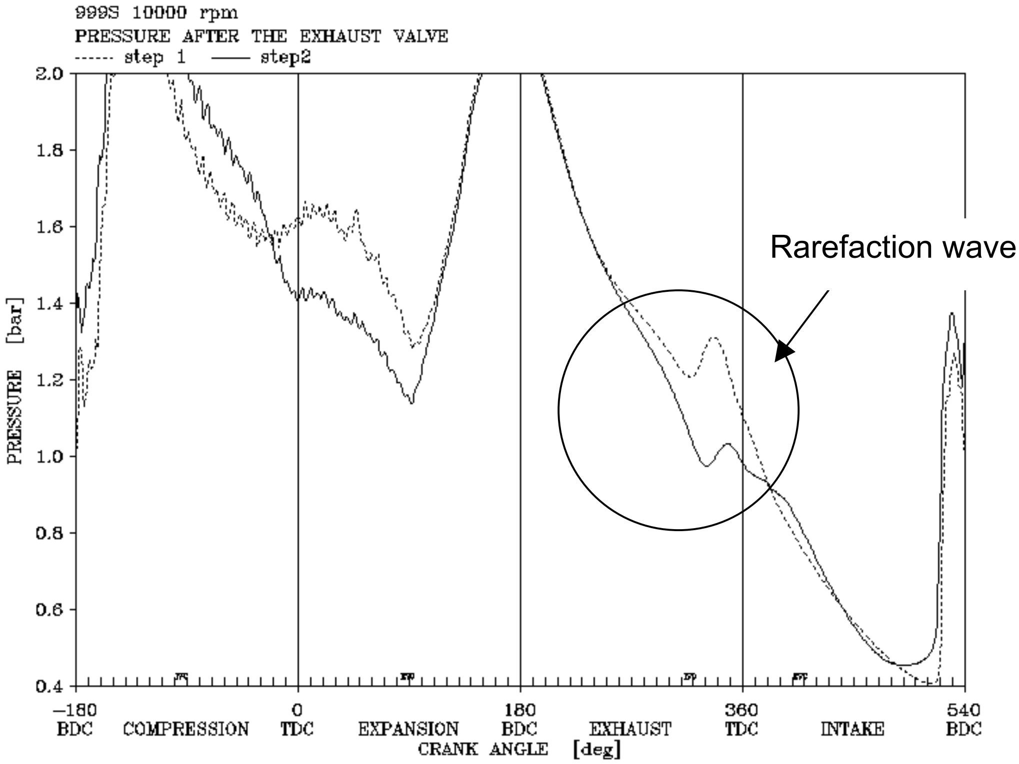

Figure 5: Horizontal cylinder's pumping loop step 1 vs 2

The distance of the biggest tube from the flange is calculated and optimised to increase the maximum power, around 1 CV (see figure 6).

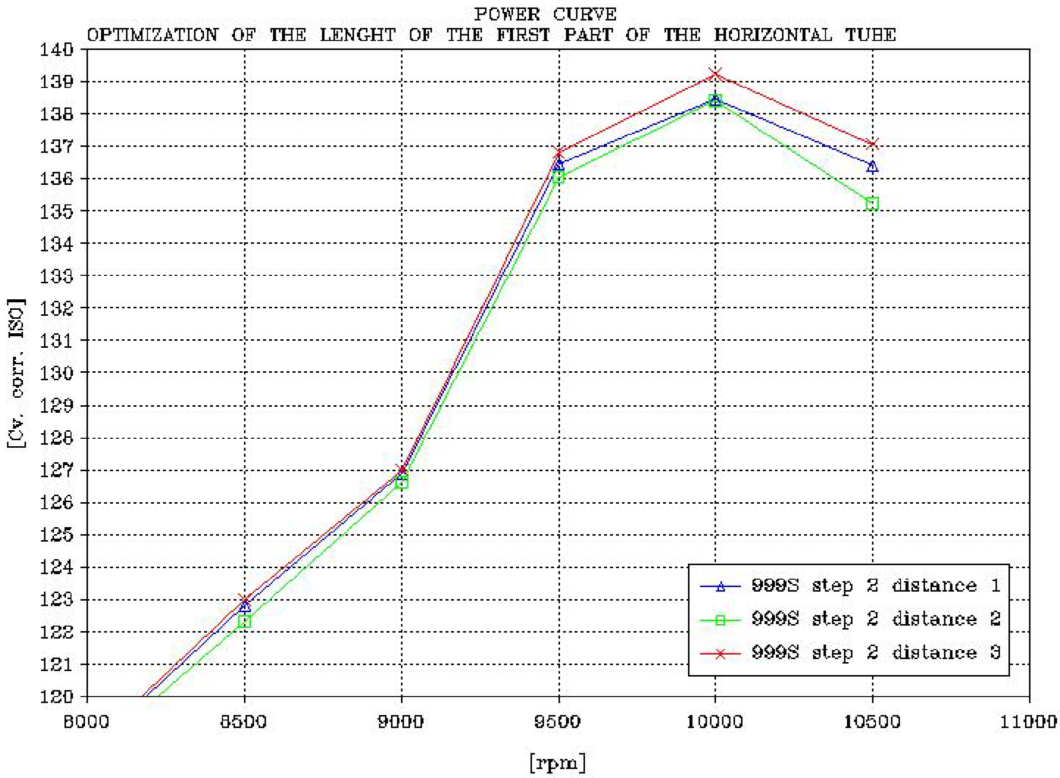

Figure 6: Step 2; optimisation of the horizontal's tube length

Subsequently the ratio of the diameters of the 2 tubes of the horizontal runner is optimised (see figure 7).

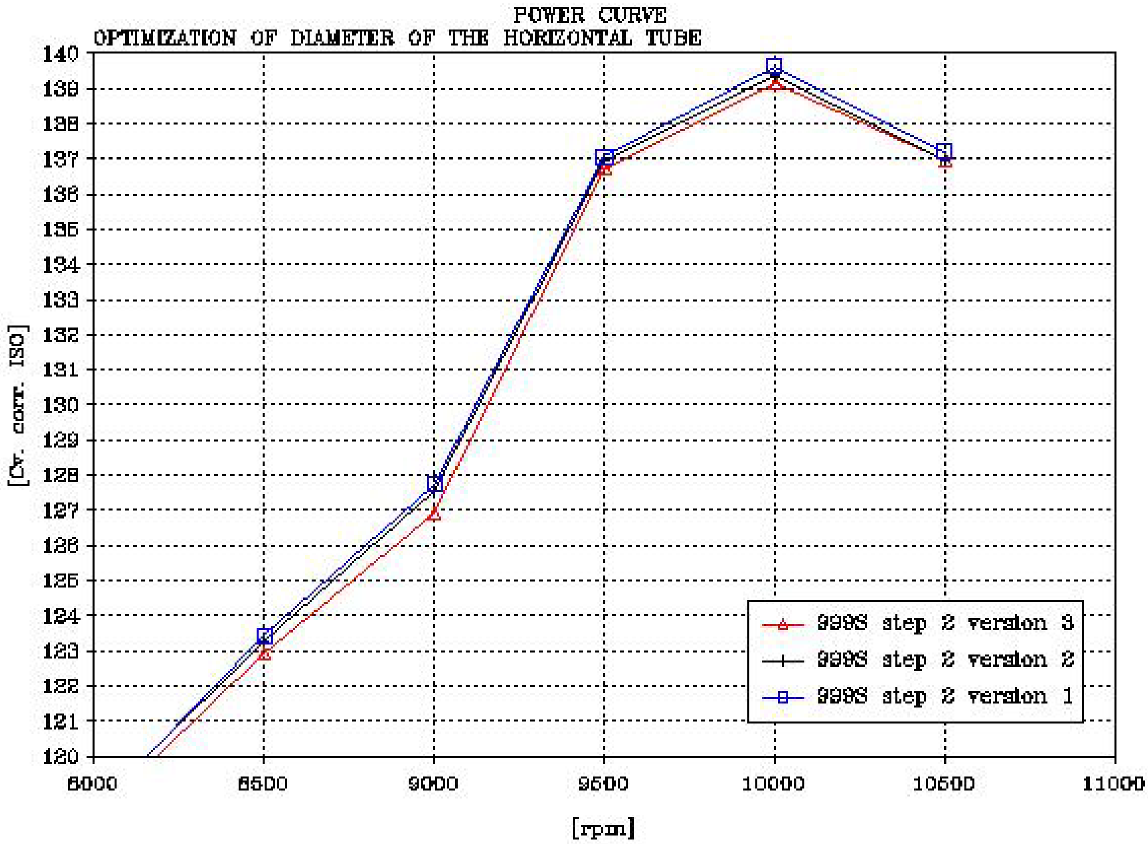

Figure 7: Step 2; optimisation of the horizontal's tube diameter

The enlarged diameter of the runner increases the power of 0.5 CV; the cause is not due to the increase of volumetric efficiency (see figure 8), but to the lower pumping mean effective pressure (see figure 9).

The behaviour of the exhaust system is very good at high rpm, but at 5500 rpm appears a dip of torque due to adverse exhaust tuning, particularly of the vertical cylinder (see figure 12). The diagram of the pumping loop of the vertical cylinder shows that during the overlap period a pressure wave travels back toward the exhaust valve (see figure 9); there is a reverse flow from the exhaust system to the cylinder.

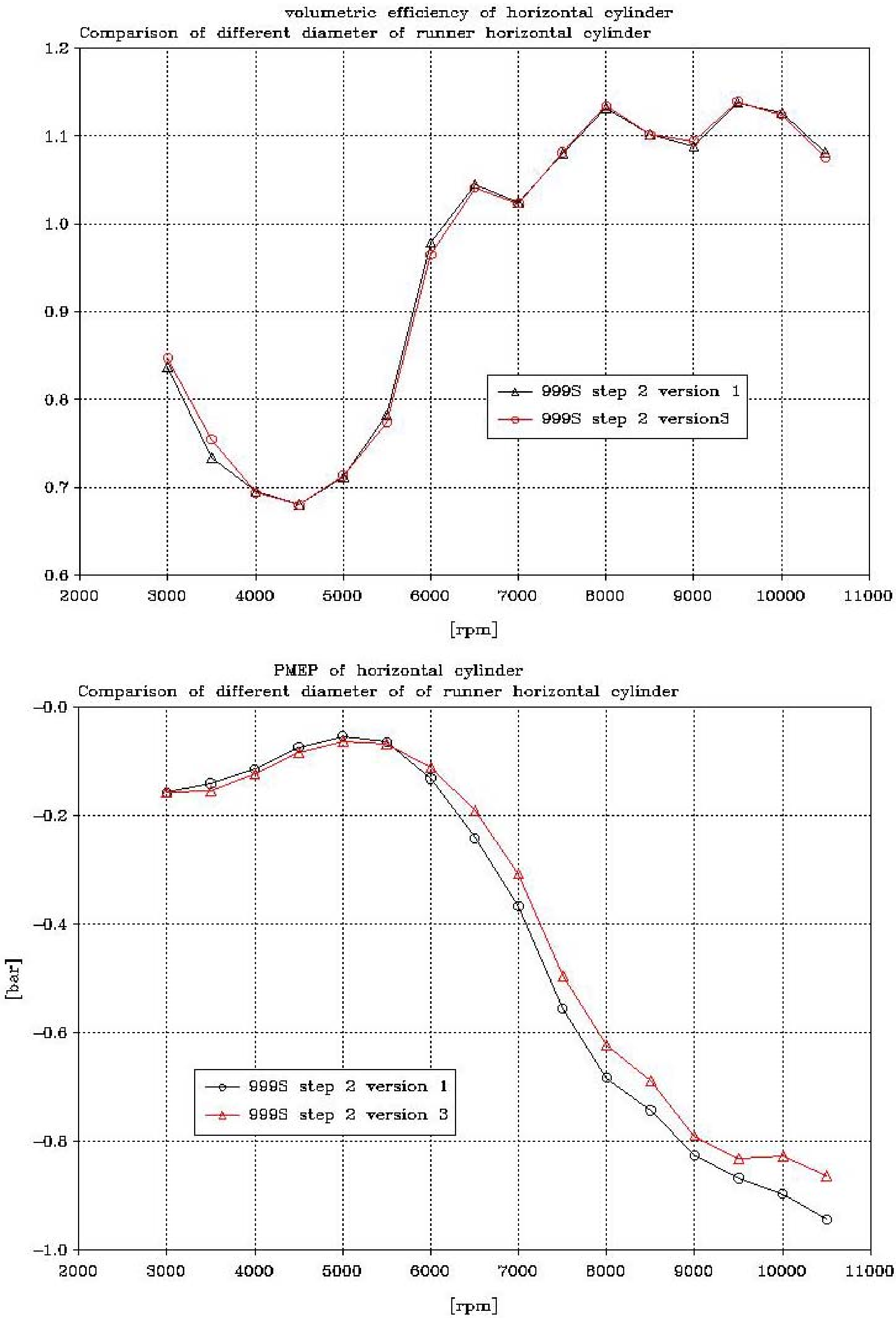

Figure 8: Step 2's PMEP; optimisation of the horizontal's tube diameter

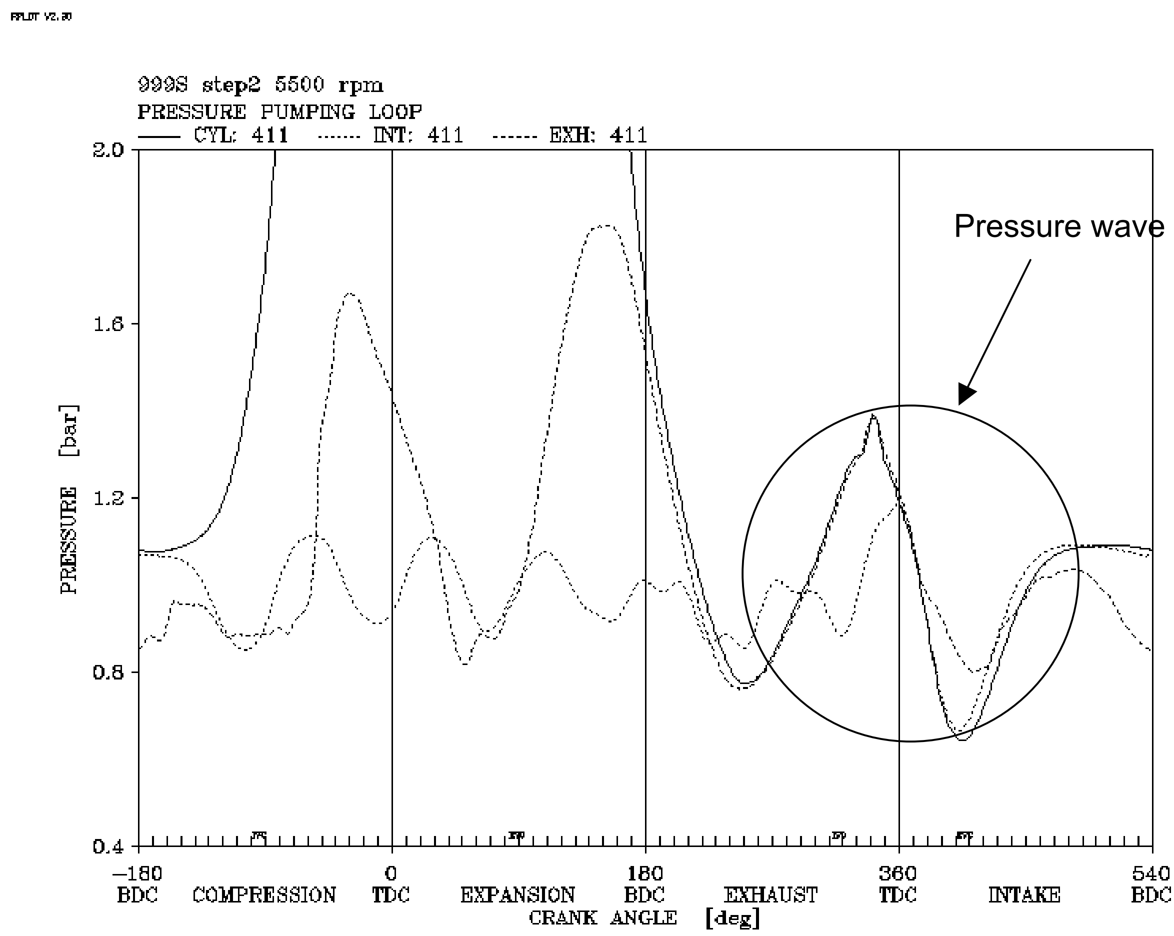

Figure 9: Pumping loop of horizontal cylinder's step 2

Moreover this induces that combustion products flow from the cylinder into the intake system at the start of the induction period, with disastrously effect on the volumetric efficiency because a part of the intake is spent in the suction of this combustion gases. To avoid the pressure wave due to the interaction of the horizontal cylinder on the vertical cylinder, it was proposed to separate the tubes up to the muffler, and to take advantage of the fluid dynamic-interaction of the other cylinder in the muffler. This solution obliges to use 2 catalysts: one after the change of area in the horizontal pipe and the other one concerning the vertical cylinder in the muffler. The advantage of this solution are: 1) the shorter distance from the cylinder head, (faster catalyst's light off, Euro3 takes in to account the cold start of the engine); 2) a lower temperature in the silencer because the overheating of the horizontal cylinder's exhaust gas, due to the catalyst reaction, is balanced from the heat exchange with the wall of the tube; 3) the thermal capacity in the muffler is halved because only one smaller catalyst is present.

The figure 10 shows the attenuation of the pressure wave in the overlap period, that strongly increases the torque at 5000-5500rpm (see figure 12); unfortunately another consequence was the loss of 1 CV of maximum power, therefore we have obtained the same power of the 998 which was the target (see figure 11).

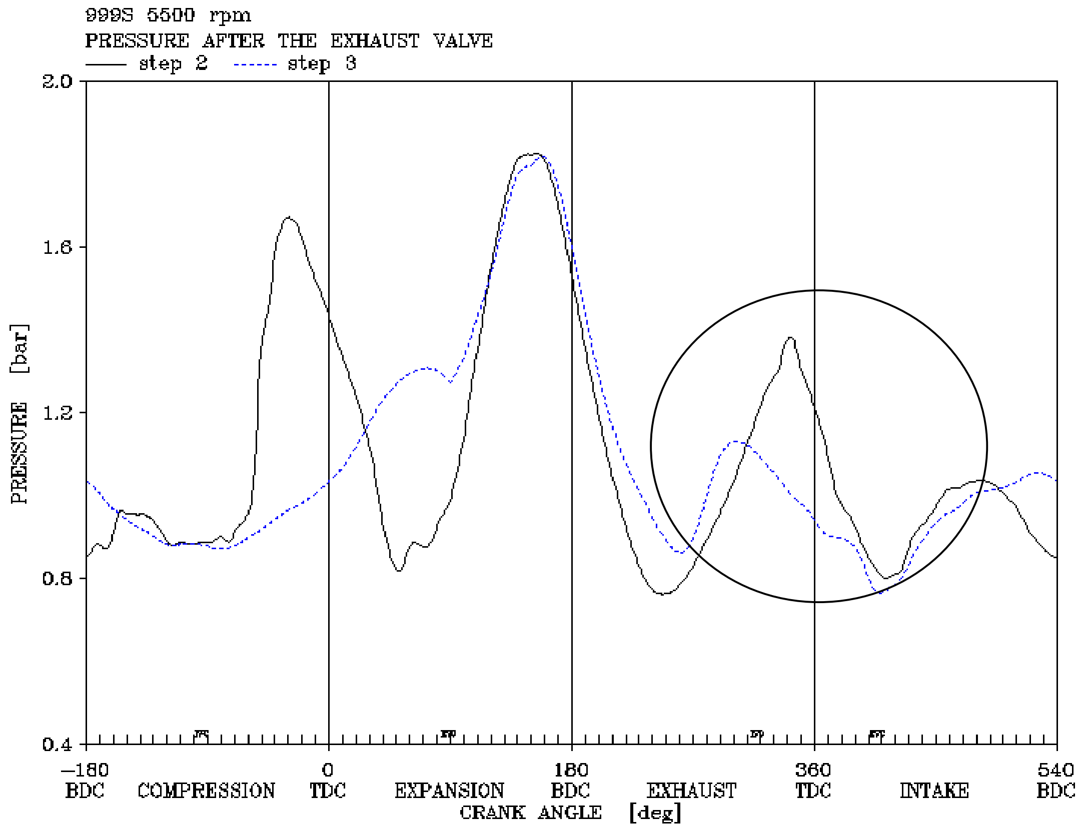

Figure 10: pressure downstream the exhaust valve: step 2 vs step 3

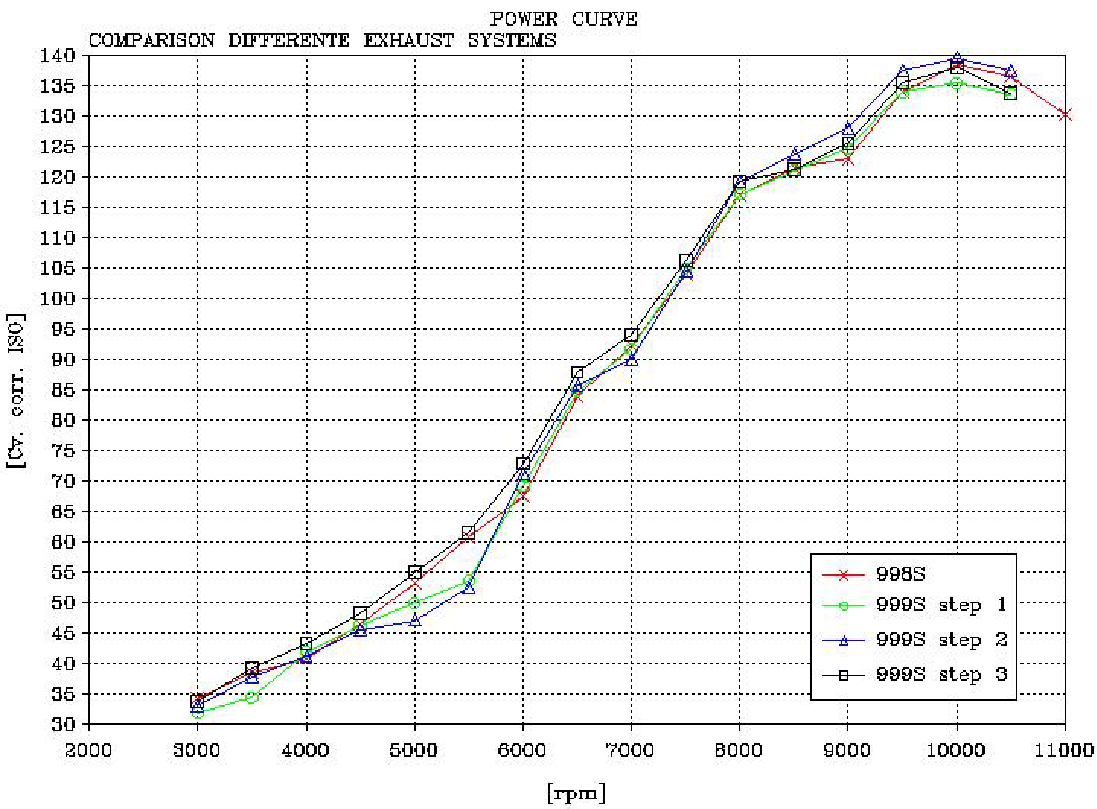

Figure 11: Power curve comparison

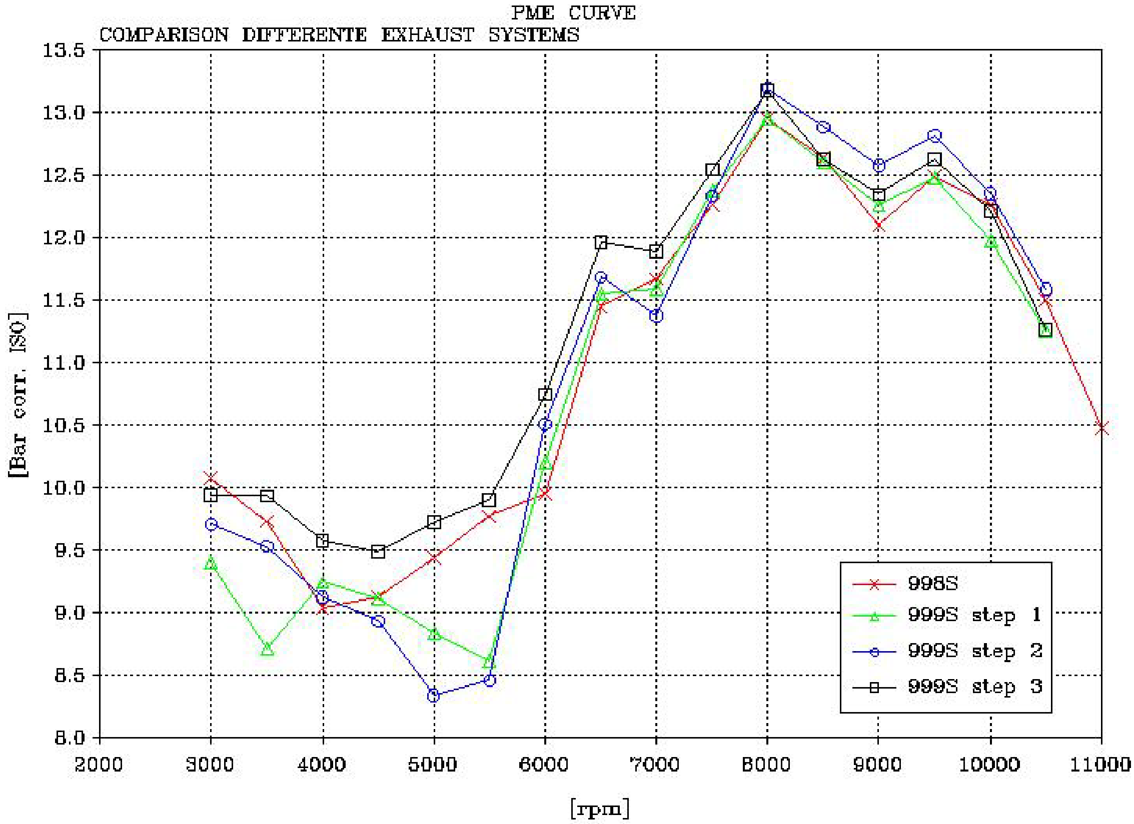

Figure 12: BMEP curve comparison

Conclusions

It has been shown the development of a exhaust system of a high performance engine. The use of predictive analysis with 1D CFD code in the early stages of complex design is of benefit in reducing the lead-time for the product development. Predictive analysis may identify early faults that would be extremely difficult to change later in the design cycle.

The main steps of the developing concerning the performance of a innovative exhaust system were shown. The innovations in the design are the asymmetry, the imposed reflection and the use of the silencer as compensator.

References

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