101. Lisheng Y., Akemi I., Hideo N., "A Valve Train Friction and Lubrication Analysis and its Application in a Cam / Tappet Wear Study", SAE Technical Paper 962030, 1996

102. Turturro A., Rahmani R., Rahnejat H., Delprete C., Magro L., "Assessment of Friction for Cam-Roller Follower Valvetrain System Subjected to Mixed non-Newtonian Regime of Lubrication", ICES2012-81050, ASME Spring Technical Conference of the Internal Combustion Division, May 6-9, Turin, Italy, 2012

CONCLUSION

In this thesis a development process for a new internal combustion engine (ICE) from green field to prototype is defined, through an integrate engine design. The process has been based on going General Motors – Diesel Advanced Engineering engine project and the first proto will realized after the end of this project, so experimental studies on the new engine concept are not covered in the present work.

In the first part of the thesis, I have analyzed what there are outside the engine design environment as, in particular, marketplace, hybridization and main engine components. Nowadays, the market is plenty of hybrid cars and every car manufacturer has a wide range of hybrid solutions to future mobility. The findings of the market analysis are that the best hybrid fuel economy segment for combined mobility is the sedan one. This segment could use ICE from 1.3 liter as Honda Insight 2010 to 2.5 liter as Mercury Milan Hybrid 2009. The ICE displacement depends on vehicle mass, electrification level and engine performance management. About ICE architecture there are three different strategies: simplified, de-rating, and equal. In case of simplified architecture, in comparison with the normal production one, as Honda Civic Hybrid 2009 that use smaller engine (from 1.8 to 1.3 liter) with half number of valves (from 16 to 8), the electrification level is medium - high and the net power and torque of hybrid propulsion system are in the same range of the normal production one. About de-rating strategy, ICE used is the same but the performance output is lower due to different combustion strategy in order to reduce as much as possible pollutant emissions. For instance, Toyota Camry Hybrid 2009 that use the same ICE architecture with lower performance (compressor ratio from 12.5 to 9.5) with high electrification level, so vehicle performance are the same of normal production one. The last option uses the same ICE as Chevrolet Malibu Hybrid 2009 where the electrification level is low and its function is boost offering to the customer an higher performance vehicle respect to the normal production one.

Then I have analyzed the different hybrid propulsion system architecture to find out that does not exist an universal or always better hybrid architecture but there is a proper one for every couple vehicle mass and mission. Moreover, I have studied the propulsion system features to support hybridization as electric motors, static electrical converters and batteries highlighting that only the merged design approach could lead to a competitive and overall hybrid propulsion system design that could win the challenge of future mobility. The most important hybrid propulsion systems analyzed by me are: GM Hybrid and Two Mode System, Toyota Hybrid Synergy Drive, Honda Integrated Motor Assist, Nissan Hybrid System.

The main engine components as cylinder head, engine block, liner, oil pan, crankshaft and engine balancing, connecting rod and piston are then analyzed. Finally, I have been analyzed how evaluate the vehicle performance using a simplified mathematical model that takes into account aerodynamic resistance, slope resistance and rolling resistance.

In the second part of the thesis, the integrate methodology to achieve the main goal of the Ph.D. program has been presented. The new engine concept that is complaint to the mass, weight and cost reduction has been designed starting from the determination of both operational and geometric engine characteristics. The development process based on this strategy leads to design a new engine concept that is able to satisfy pollutant emissions, fuel consumption and performance for lead cost and vehicle application. The key point of the development process is involved from the early phase of engine concept development the voice of customers and the external requirements as pollutant emissions regulations requirements. This part highlights how customer needs and external pressures can take into account through the target setting activities. Then get worked both on performance using the target deployment activities and on subsystems/components through the target achieving activities, the customers and external requirements are transferred to each subsystems/components of the vehicle. These bring to choose a dominant concept to be developed and verified. In case of ICE, the target setting requires to define the brake torque curve, fuel consumption and pollutant emissions as main parameters.

The first step I have done to achieve the previous requirements has had the definition of the engine core archetype that collects all main references to be the starting point for the engine design and, in particular, for cylinder head and engine block. First of all, the archetype takes into account of manufacturing constraints as head-block fasteners distance and inter-bore distance, in order to identify the bigger bore dimension. About the optimum stroke dimension, it has used a research activity carried on by GM R&D on bore-stroke ratio. Secondly, the engine core archetype takes into account the main structural constraints as inter-valve distance, injection and glow plug locations, wall thickness between injector and ports, and at the end, the distance between valve and cylinder wall. Then for the valve dimension I used the engine breath capacity index as tool to identify, through benchmarking activities, an ambitious but real value to implement into the archetype defined by me. After the valve dimensioning, I defined the first attempt dimension of intake and exhaust ports, in this way the archetype definition is complete.

The second step I have done to achieve the previous requirements has had the definition of mono-dimensional fluid-dynamic model of the whole engine integrating the data extract from the archetype. The scope of this model is to evaluate the new engine concept capacity to generate performance and to understand if it is able to achieve the target brake torque. In this way the new engine concept performance baseline has been defined. About the brake torque output, it strictly follows the target and the torque peak has been moved 500 rpm lower for drivability advantage. Unfortunately, there is a small torque gap between 2250 and 3000 rpm. As well, the brake power output strictly follows the target but there is a small power gap between 2750 and 3000 rpm. Anyway, the baseline performance output is very good in general and it means that the engine architecture concept selected is the right one.

At this point, I have been tried to optimize the dominant engine architecture, from both structural and performance point of view, working on several functional parameters as exhaust breath engine capacity index, turbocharger screening, peak firing pressure and cam profile. First of all, I analyzed the effect of exhaust breath engine capacity index in order to increase intake valve dimension, find a better location for injection and glow plug, increase volumetric efficiency, and decrease pumping losses. So two different exhaust valve dimension are implemented in the 1-D fluid-dynamic model. The findings of these analysis show that the best exhaust valve diameter is that one used in the archetype and then it is correct. The second functional parameter is the turbocharged that massively affect the engine performance and pollutant emissions. Moreover, the technology, the weight, and the dimension of turbocharger have not negligible effect on engine layout and on space managing in the engine compartment. So, seven different turbocharger are implemented in 1-D fluid-dynamic model and, in the end, I have been selected the best one, in terms of engine performance, from each technology analyzed, and in particular, waste-gate turbine and variable geometry turbine. The third functional parameter is the peak firing pressure. I analyzed this parameter because it is the main responsible about the structural load and the performance generation. Moreover, a reduction in peak firing pressure has a small effect on engine performance but a huge effect on engine dimension and mass owing to the drop of stress level of both crank mechanism and components faced on combustion chamber. So a reduction of 10% on peak firing pressure has been implemented into the 1-D fluid-dynamic model by me. About the brake torque trend follows the target but there is a torque gap between 2000 and 3250 rpm. As whole, the brake torque curve is good enough for the engine application and contains same improvements. Mainly, the low-end torque is slightly higher and is achieved at lower regime. The power brake trend follows strictly the target: it contains the advantages presented in the brake torque trend but with a small power gap in the same range of torque one. Finally, the new engine concept uses a new valvetrain system layout and due to this reason, a new cam profile has been implemented in the 1-D fluid-dynamic model. The results of this analysis show a lack of torque between 1500 and 1750 rpm, so the low-end torque profile is lower and this is unacceptable. About the brake power trend there is a power gap in the same engine regime of torque one. In the end, the torque and power trend do not follow exactly the target, so it will need to work on cam profile or on valve timing to back up the lack of torque and power.

The new valvetrain system layout uses in the new engine concept needs to be analyzed and then I defined a methodology to characterize both cinematically and dynamically and to study the friction in the cam-roller lubricated contact subjected to mixed non-Newtonian regime of lubrication. The analysis of the valve train system highlights two kinds of parameters: the first one related to the inertia components and the contact load, and the second one proportional to the engine speed. In the first group of parameters the effect of the inertia component with the increasing of the engine speed, is to raise the values in the transition area between the height ramps and the main ramps and, on the other hand, decrease the magnitude on the cam nose. The analyses confirm that partially satisfied the requirement, partially because not all the requirements are available. About the Hertzian stresses, they respect the material limit and guarantee only elastic deformation of the cam lobe-roller components.

Quasi-static model is compulsory to understand the system behavior at low speed and its results draw the lower band of the all parameters range. The quasi-static model is necessary to evaluate the first attempt parameters to set the solid-to-solid contact force feature of the dynamic model. At the end, the kinematic model built up to evaluate the tangential velocity works quite well with the main ramps but it is not able to catch properly the velocity on the height ramps. The output of quasi-static model is the fully kinematic and dynamic characterization of valve motion, Hertzian parameters evaluation of cam-roller contact, deflection and stiffness of the cam-roller contact.

The dynamic model works quite well but unfortunately it is affected from the low quality surface of the cam lobe that produces the numerical noise on its results. To avoid the numerical noise from the valve displacement and the valve velocity and then, to have a correct valve motion, the stiffness of the solid-to-solid contact force feature was increase to press the peaks of the irregularity. This approach may lead to a slightly overestimation of the lift-off velocity. In the dynamic model, it is tried to evaluate analytically the radius of curvature with different methods: the method of pole works but it does not take account of the sliding effect in the roller-cam lobe contact and, the worst point, it is not able to catch the radius of curvature of a double-dwell cam lobe which is that one used in the model. The output of dynamic model are the same of quasi-static and adds all the output about kinematic and dynamic characterization of cam-roller contact. In the dynamic model is evaluated the percentage of sliding which is negligible, then the Hertzian stress analysis was evaluated for pure rolling conditions. Moreover, the friction assessment of cam-roller lubricated contact subjected to mixed non-Newtonian lubrication has been done using 1-D elasto-hydrodynamic lubrication model. In the dynamic environment, thank to elasto-hydrodynamic model, all the lubrication output as oil film thickness, pressure on oil film and related viscosity are available. Finally, the shear stress for the lubricated contact is evaluated and then both the viscous and boundary friction force are calculated. So the power loss of the system is evaluated and compared with references and industrial report showing an overestimation of 13%. To sum up, the methodology presented is reliable but it needs to be extended to the whole engine speed range and correlated with future experimental activities on the prototype.