Examination of the Friction Processes Taking Place in the
Control Mechanisms of Gas Exchange for I.C.E.

Summary of Ph.D. Thesis

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I. Information material on the results of the researches performed on the basis of the research project plan approved by the Council of Doctors of the Faculty of Transport at the Budapest University of Economics and Technical Sciences.

1. Subject and Antecedents of the Paper

By now, the number of the automotive vehicles running in the world has come close to one Billion, and the number of the vehicles produced annually is over 60 Million. In this way, it is quite reasonable to consider the vehicle fleet of the world as being the biggest and the most rapidly developing area of both the energy-consumption and the energy-supply.

At the same time, the subject of „sustainable progress" as far as the environment protection and energy consumption are concerned is more and more emphasized when the effects of progress are evaluated.

As far as the emission of pollutants is concerned, while the automotive industry has no other choice but, willy-nilly, to observe the statutes on limiting the emission values passed by the parliament and so to be on a forced trajectory, the efforts - at least in Europe - aiming at obtaining and keeping the market sectors have represented the motivation.

In the spirit of the UNO Conference on Climate held in Kyoto, Japan, the ACEA (Association of the European Automobile Manufacturers) has undertaken to reduce the fleet consumption of the vehicles produced in Europe to a value equivalent to a CO₂ emission of 140 g/km in the period from 1995. to 2008.

The undertaking, crowded with success so far, can only go on provided the efficiency of the engine can be improved using different innovative techniques in a consequent way in the future, too.
2. **Efficiency of engines, the effect of Equipment used for the change of charge on the fuel consumption**

It is in Section 2. of this paper that the elements connected with the efficiency of energy utilization and the sources of losses as well as the technical possibilities suitable for improving the motor and mechanical efficiency of the internal combustion engines have been summarized. I have made calculations in order to demonstrate what are the possibilities and the limits of decreasing the consumption through a consequent reduction of the mechanical losses.

Based on concrete engine constructions and the description of innovative engine-techniques, the paper verifies that nowadays the group of sub-systems with variable parameters has replaced the static valve timing. The efficient change of charge that meets the requirements of the engine in every condition of the operation can be ensured through the co-ordinated function of the charge and suction pipe systems of variable parameters in addition to the valve timing of variable parameters.

The once required privilege of the valve timing ceases to exist, at the same time the drawbacks, i.e. the mechanical losses that earlier had to be accepted as a compromise with a view to increasing the engine power, have survived.

The mechanical losses, caused by the valve timing, make the highest part of the losses in the operating condition of fractional load which is important regarding the consumption.

Recently special emphasis has been laid on the development of valve timings of variable parameters. Beside the phase angles of the valve timing even the systems controlling the degree of valve lift have appeared. The paper, on the one part, presents a functional evaluation of the individual equipment and surveys, on the other part, their possible effects on the motor operation.

The latest conceptions of development - e.g. the direct electromechanical valve operation - have an unlimited possibility of the setting as far as the phase angle is concerned, however, the variable valve lift has not (yet?) been resolved and the energy required by the operation is not less than it is with the conventional valve timings.
3. **Trends in the development of the valve timing mechanisms.**

In the past 10 years, it was the reduction of the mechanical losses occurring in the valve timing, the increase of useful life and the adoption of low cost production processes that have been put in the focus of the development activities. 4 main trends can be seen:

- Reducing the mass of the components included in the mechanism
- Instead of using a sliding-rolling transmission of motion, the use of roller elements
- Alternative materials for the mechanisms and alternative surface treatment processes
- Adapting the so-called assembled camshafts made of functional modules

4. **Tribology of the valve timing**

It is not any other way but the consequent application of the latest results of tribology, as a domain of sciences, for the deliberate reduction of the friction losses. The conditions of lubrication that develop during the coaction of the structural elements of the valve timing can be analysed using the knowledge of hydrodynamics and elastohydrodynamics.

In this section I am going to survey the most important bases of the EHD lubrication theory as well as all the instruments of calculation required to the definition of the most important parameters (\( h \) and \( h_0 \)) that characterize the lubrication condition, these parameters being linked with the names of Dowson, Higginson and Toyoda, further I am going to survey the adaptability thereof by comparing the parameters calculated using the data of concrete valve timings with the data of literature.

I have conducted an individual and detailed survey and analysis of the friction processes which take place at the edge surfaces of the components coacting within the valve timing.

The processes which take place at the edge surface of the valve lifter and the control cam and can be considered as critical and relevant as far as the scale of friction losses is concerned are highly influenced by the macro- and micro-geometry of the coacting components and the strength characteristics of the structural materials.

By combining them, the scale of the surface stress, provoked by the loading forces which emerge during the operation of a given valve timing, can be held at a level which is still acceptable for the required useful life.

The paper investigates, by taking the example of the cam-valve lifter, the importance and the manner of action of the secondary motion occurring among the coacting components.
5.-6. **Measuring the tribologic characteristics of the valve timing**

The integrating index of the friction losses emerging in the valve timing is the measurement of the driving torque required to driving the mechanism, i.e. to covering the losses.

At the Faculty of Road- and Railway Vehicles of the Széchenyi István University, a test set has been put into service for the tribologic rating of the valve timings of different constructions integrated in the cylinder head. The test set has a regulated heating/cooling system which keeps the temperature level of the tested cylinder head at a constant value.

The dynamic torque meter fitted between the driving engine of adjustable r.p.m and the camshaft ensures a highly accurate measurement.

The paper presents and analyses the results of the measurements performed on 2 typical cylinder heads. Based on the measurements, it can be stated that an optimum working temperature belongs to the operation of the valve timings, which fluctuates depending on the r.p.m.

In the future, measurements of such nature will be inevitably required to define the specification of the timing parameters for thermomanagement systems.
The test set can support even the determination of the losses caused by the individual components of the system.

The values taken by using the switch off system include important particulars for the planning and building in of cylinder head constructions including different kinds of drives or phase-angle adjusting devices.

Along with changing the material of the valve lifter co acting with the control cam, I have examined the effect exerted by the structural materials on the friction. I have got favourable results especially when I applied alternative constructional materials (e.g. silicon nitride) and alternative surface treatment processes (surface treated using the process of nitrogen-ion implantation.)

Torque reduction achieved through combining different materials, expressed in % as compared with the original execution.

B - steel, ion-implanted
C - Alu oxide
D - silicon nitride

The measurements performed changing the spring force and the mass showed the evident priority of the spring force.
8. Calculations with models for discovering the parameters having an effect on the driving torque

The main parameters of inertia, spring force and cam have an effect on the mechanical losses of the equipment. I have elaborated a program for the modelling thereof. By using this program, the driving torque of each variation can be calculated and compared. As an example, I will present the rate of loss reduction which can be achieved through reducing the masses. When calculated, the values of the driving torque belonging to the reduced masses, which have been reduced gradually at a 10% rate, have been calculated.

The negative result can be reversed to a positive direction by changing the characteristic of the valve spring and by doing so a significant loss reduction can be realized. As far as the loss reduction is concerned, it is very important how the characteristic of the valve spring (spring stiffness, degree of pretension) can be matched to the effective inertia diagram.
The value of the base circle diameter and the addendum circle diameter of the timing cam largely influences the magnitude of the losses through the acceleration. The optimum shall be determined in conformity with the variable surface stress.

It is in Section 3, that by taking the parameters of a given engine, I have calculated the effect of the mechanical losses on the fuel consumption and I have shown it in a diagram. Even the load characteristic curves of the different loss values demonstrate that the differences experienced in the consumption increase in the direction of the smaller \( w_e \) loads.

With the intention of quantifying the tendency and starting from the conchoid of the engine consumption, I have calculated for different r.p.m.s, and I have shown in a
diagram how the degree of the improved consumption, expressed in percentage, produced through the mechanical losses reduced in 5% steps, changes taken as a function of the engine load.

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On the basis of the calculations made for the different r.p.ms, the general statement can be made that decreasing the losses will produce a higher saving of fuel just in the range of the fractional load which is the most important range as far as the operation of the vehicle is concerned.

II. Theses elaborated based on the program's scientific results

1. The test set developed within the scope of the research project as well as the developed methods of measurement enable the testing of the valve timing mechanisms irrespective of the engine but under temperature conditions that are very similar to those of the engine and the tribologic classification is possible as well. In the course of the tests, the sensitivity of the valve timing mechanisms to the temperature has been verified. An optimum temperature, which depends on the r.p.m as well – can be determined for each equipment.

\[ T_{opt} \] continually increases from the value determined at the lowest r.p.m \((90 \, ^\circ C)\) up to the max. r.p.m. \((108 \, ^\circ C)\)

The sensitivity to the temperature, as defined in the dissertation \((M_{max} - M_{min})/T\), is the strongest at the low revolutions/m. Considering the approaching introduction of the thermo-management systems, the operating temperature of the cylinder heads shall be set to the optimum temperature measured at the low revolutions/m characteristic of the partial loads for the sake of the minimum fuel consumption.

2. In addition to the design of the valve timings, the parameters of friction as well as the parameters of useful life correlated therewith depend not only on the magnitude of the arising loads but also on the combination of materials to a great extent due to the elastic deformation occurring in the EHD range.

Even the future application of the alternative structural materials in the valve timing, as a friction element, will take place. According to the results obtained during the tests performed on the test bench, the tribologic characteristics of the pairs of elements can be ranged under operating conditions.
The thermal conductivity of the individual construction materials has an increased importance beside the EHD conditions. The favourable results obtained with the components subjected to a surface treatment of nitrogen-ion implantation support the fact that in the future the development engineers shall consider the adaptation of alternative technologies even in the field of the valve timing mechanisms largely.

3. Based on the examinations published in the technical literature and on my own experiences, I have realized that a complete and uniform tribologic model, which can be treated mathematically as well, and where all the characteristics and parameters influencing the tribologic operators (friction resistance, wear) can be taken into consideration, can not be created for the valve timing mechanisms. Consequently, I have determined correlations in function equations which have a strong influence on the drive torque requirements equivalent to the mechanical losses of the valve timing mechanism.

Both the nature and the absolute values of the driving torque characteristics resulted from the calculations made by considering the construction and operating parameters of the valve timing mechanism tested show a good correlation to the characteristic curves determined on the test set.
The difference between the torque of the tested valve operating module determined by calculation and the measured equipment is under 5 5 in the whole range of operation.

4. Considering this accuracy, the applied method can be qualified as suitable for the examination of the influence exerted by the main structural parameters on the losses and based on the results obtained it is suitable for making general conclusions.

- Based on the results of the loss calculations, performed by modifying the geometric parameters of the so called harmonic cam profile which can be treated mathematically in an easy way, it can be verified that the extent of the losses can be influenced by changing the dimensions of the cam’s base circle and tip circle while the parameters of the valve timing which are relevant as far as charge change is concerned (cam angle, max valve opening) are kept at a constant value.

By reducing the value of the base circle radius from \( R_0 = 20 \text{ mm} \) to \( 16 \text{ mm} \), the value of the loss determined by calculation has reduced at low r.p.m values by 3-3% per mm on the average while the reduction was 10-10% at the max r.p.m. By gradually increasing the value of the tip circle radius from \( R_2 = 2 \text{ mm} \) to 7 mm, a loss-reduction will occur, i.e. an improvement of 3-3% calculated step by step at the low r.p.m values and an improvement of 7-7% at the high r.p.m.values, will occur.

The so called combined optimum, i.e. the calculation performed using the most favourable base circle and tip circle values, shows a loss reduction of 17 % at
the low r.p.m. value and a loss reduction of 44% at the max. r.p.m. value as compared to the base cam profile.
Based on the above results, it can be stated that the influence of the parameters discussed in the dissertation should be recommended to be included in the data used to the design of the control cam.

- **The amount of the masses actuated by the control cam**
  Using the calculations performed by taking every dynamic and kinematical parameter of the valve timing equipment measured on the test set, I have examined the influence exerted on the losses through reducing the moving masses.
  The results of the calculations have proved the surprising experience, received at the tests performed on the test set, too, that reducing the mass in itself will not result in a loss reduction, on the contrary, going to the higher revolutions/m an increase of the friction loss can be observed.
  A positive change could only be realised when the spring force was matched with the changed mass force.
  The results obtained reducing the masses by 10, 20 and 30% show a 12% loss reduction for each step at low revolutions/m and this value is 13% for each step at high revolutions/m.

- **The importance of matching the valve spring in an optimum manner** has been expressly revealed during the calculations. Based thereon, I think it is reasonable to include the module enabling to change of the valve timing system during operation in the existing functions (cam phase angle, cam lift) of the valve timing systems of variable parameters.
  According to the calculations simulating this procedure show that a round 50% loss reduction can be realized in the range which is relevant as far as fuel consumption is concerned by reducing the pre-stress of the valve spring.

5. The losses occurring in the valve timing mechanisms have an influence on the mechanical efficiency of the complete engine. In order to state what extent the potential loss reduction can influence the fuel consumption of an engine I have elaborated a system of assessment.
  It is a well known fact that the consumption of I.C.Es depends largely on the engine load: for this reason, I have examined what reduction of the consumption is generated by a given loss reduction of absolute value at the different values of the engine load.
  It can be stated that
  a. the realizable fuel economy increases going towards the partial loads.
  b. the degree of the improvement in consumption depends on the initial mechanical condition of the engine. A higher reduction of the consumption can be achieved with an engine of lower mechanical efficiency than with an engine of a fully developed design.
Based on the calculations, the results of the calculation performed on the average running point of the engine taken as an example, a round 10 % reduction of the consumption, i.e. a very high reduction, could be realized through pre-stressing of the valve spring.

**Presentations published by the author on the subject**

1. Gál, P.
   Valve timing of variable parameters for I.C.E
   20 Years in Győr, Scientific Conference on the Anniversary,
   Győr, October 24-26, 1995.
   (Antal Attila Co-Author)

2. Gál, P.
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   Conference on the subject of „Fuel -Lubricants- Mechanism- Environment"
   Keszthely, 1996.

3. Gál P.
   Testing valve timing of variable parameter
   MICRO CAD 2002.

4. Gál P.
   Development of variable parameter valve timing and tribologic test

5. Gál P.
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   Ventilsteuerung
   AMMA 2002, Kolozsvár, International Conference

6. Gál, P.
   Designing and Functional Testing of a mechanically operated adjustment of
   gas exchange timing

7. Gál, P.
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   OGÉT Conference, 2002. Székelyudvarhely
8. Gál, P.
Book titled Tribology - Vehicle-Tribology
Editor and Co-Author
(Co Author: Valasek I., Auer J., Gyerő Z., Hancsók J)

9. Gál P.
Development of variable parameter valve timing and tribologic test
20th DANUBIA-ADRIA SYMPOSIUM

10. Gál, P.
Tribologic Analysis of Internal Combustion Reciprocating Engines
Conference on Fuel - Lubricant - Mechanism - Environment
(Co-Author: Dr. Valasek I.)

11. Gál, P.
Potentials and limits of reducing the mechanical losses occurring in the engine
of vehicles, with special regard to the valve timing
(Co-Author: Antal A.)

12. Gál, P.
Möglichkeiten und Grenzen der Verbrauchsreduzierung durch tribologische
Maßnahmen, insbesondere bei den Ventiltrieben modernen PKW-Motoren
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MTM 2004. Kolozsvár

13. Gál, P.
Potentials and Limits of Reducing the Mechanical Losses Occurring in the
Engine of Vehicles with Special Regard to the Valve Timing

14. Gál, P.
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