VETOR

# An overview of experimental methods for cam-tappet interactions

## Uma visão geral dos métodos experimentais para interações came-tucho

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### Abstract

In an engine, the valve train is responsible for approximately 6% to 35% of the total friction losses, with the value varying with the design and operating conditions. Even a 1% improvement in the fuel economy of a vehicle model is of great economic and environmental relevance. One of the engine systems subject to considerable friction is the control system and actuation of gas admission and discharge valves, the valve control system. Friction efforts and wear between the cam and the tappet depend on the relative speeds of the parts, the state of the surfaces in contact, the lubrication and temperature conditions, and the materials and geometries of the cam and tappet. A carefully project of the cam-tappet system is needed to preserve parts integrity and system functionality. This work presents some important experiments carried out with various cam-tappet systems, measured on engines or constructed using parts of an engine. Several important quantities are measured and analyzed by the reported experiments. The main objective of this paper is to promote a better understanding of these quantities that can be useful to engine designers to minimize energy losses or for optimize desirable mechanical characteristics of the system. Also, this paper allows researchers to plan new experiments and/or rapidly identify typical experimental results. It was possible to conclude that typical friction coefficients between cam and tappet varies from 0.05 to 0.15, that the force between valve stem-valve guide represents only about 1.5 -2% of the force acting on the valve stem, that the cam-follower friction was low for viscous oil SAE 50, compared with other lubricants, whereas camshaft bearing friction was low for lubricant SAE 5W-40 in the same engine, that the friction at the cam-follower interface decreases with increasing engine speed, that viscous oil gave greater oil film thickness as compared to the low-viscosity lubricant at the cam-follower interface, among others.

### Keywords

Experimental methods • Cam-tappet • Valvetrain

### Resumo

Em um motor, o trem de válvulas é responsável por aproximadamente 6% a 35% das perdas totais por atrito, variando o valor com o projeto e as condições de operação. Em situação de ciclo urbano as perdas são diferentes das apresentadas a plena carga. Mesmo uma melhoria de 1% na economia de combustível de um modelo de veículo é de grande relevância econômica e ambiental. Um dos sistemas do motor sujeito a considerável atrito é o sistema de controle e acionamento das válvulas de admissão e descarga de gases, o sistema de comando de válvulas. O sistema came-tucho é responsável por cerca de 7% das perdas de torque por atrito no motor. Os esforços de atrito e o desgaste entre o came e o tucho dependem das velocidades relativas das peças, do estado das superfícies em contato, das condições de lubrificação e temperatura e dos materiais e geometrias do came e do tucho. É necessário um projeto criterioso do sistema came-tucho, a fim de preservar a integridade das peças e a funcionalidade do sistema. Este trabalho apresenta alguns experimentos importantes realizados com sistemas came-tucho. Várias quantidades importantes são medidas e analisadas pelos experimentos relatados. Uma melhor compreensão dessas grandezas pode ser útil para os projetistas de motores, a fim de minimizar as perdas de energia ou otimizar as características mecânicas desejáveis do sistema. Foi possível concluir que os coeficientes de atrito típicos entre came e tucho variam de 0,05 a 0,15, que a força entre haste da válvula-guia da válvula representa apenas cerca de 1,5 -2%, que o atrito came-seguidor foi baixo para óleo viscoso SAE 50, comparado com outros lubrificantes, enquanto o atrito do mancal da árvore de cames foi baixo para o lubrificante SAE 5W-40 no mesmo motor, que o atrito na interface came-seguidor diminui com o aumento da rotação do motor, que um óleo mais viscoso apresenta maior espessura do filme de óleo em comparação com o óleo de baixa de viscosidade na interface came-seguidor, entre outros.

**Palavras-chave**

Métodos experimentais • Came-tucho • Comando de válvulas

# 1 Introduction

In an engine, the valve train is responsible for approximately 6% to 35% of the total friction losses, with the value varying with the design and operating conditions. In severe operating conditions, friction losses are much more significant in the valve train due to poor lubrication at the cam-follower interface, leading to mixed or boundary lubrication [1].

In an urban cycle situation, the losses are different from those presented at full load. For a medium-sized passenger vehicle, in this cycle, mechanical losses represent about 15% of the power provided by burning fuel [2].

Even a 1% improvement in the fuel economy of a vehicle model is of great economic and environmental relevance, as stated by Wong and Tung [3].

One of the engine systems subject to considerable friction, and which contributes to the vehicle's fuel consumption, is the control system and actuation of gas admission and discharge valves, the valve control system. This system is responsible for aspirating air and exhausting gases burned in the engine cylinders.

The cam-tappet system is responsible for about 7% of the torque losses due to friction in the engine. Friction efforts and wear between the cam and the tappet depend on the relative speeds of the parts, the state of the surfaces in contact, the lubrication and temperature conditions, and the materials and geometries of the cam and tappet. Speeds, temperatures and lubrication conditions depend on vehicle conditions and demands [4].

A cam mechanism is a mechanical system consisting of three basic components: a driving element, called the cam; a driven element, termed the follower; and a fixed frame. Sometimes, an intermediate element is introduced between the cam and the follower with the purpose of improving the mechanism performance. This element is called the roller because function is to produce a pure-rolling relative motion between the cam and the follower. Cam mechanisms are classified according to various criteria, as the relative layout of the axes of the cam and the follower, as the output type of motion, as the follower shape and layout, as the type of motion of the cam disk, as the shape of the cam disk, as the type of contact between cam and follower, and as the number of working cycles of the follower [5].

A carefully project of the cam-tappet system is needed in order to preserve parts integrity and system functionality.

This work presents some important experiments carried out with cam-tappet systems, measured on engines or constructed using parts of an engine. Pin on disk or Stribeck experiments, for example, are not covered by this paper.

Indirect tribological experiments, like pin on disk, for example, are not capable to capture a lot of typical cam-tappet phenomena, like tappet spin, tappet tilting and so on. This fact is a source of some misunderstanding about the tribology of cam-tappet.

Several important quantities are measured and analyzed by the reported experiments. A better understanding of these quantities can be useful to engine designers and researchers.

# 2 Bibliographic Research Results

In order to obtain information regarding to important quantities of cam-tappet systems, for various possible mechanical configuration, it was performed a bibliographic research.

Below, summarized information is presented for each published experimental work, in a chronological way. There's an effort to show motivation and objectives of experiments, used materials, experimental procedure, signal acquiring and treatment, and results obtained.

This paper summarizes important experiments for cam-tappet interactions, but not all of them. Other experiments can be founded through references on these described works.

*- Dyson & Naylor, 1960 [6]*

The main objective of Dyson and Naylor, in this work, is perform a study and modelling about the flash temperatures phenomena on cam-tappet contact. An important quantity in the calculation of flash temperatures is the coefficient of friction between these parts. In this work, determined by experiments.

The principle of the experimental method was to suspend a tappet supported by a guide by means of a pair of flat springs, the stresses in which were measured by piezoelectric strain gauges. These were connected in such a manner that the signals produced by the normal force between cam and tappet were canceled, whereas those caused by the frictional force were additive. The camshaft speed was only 600 rpm, reliable values could be obtained only near the nose, and only one oil was used, an SAE 30HVI straight mineral oil. This was measured in the laboratory between a steel cam and a chilled cast-iron tappet.

At low speeds the high-frequency vibrations could be reduced to a reasonable level by a low-pass electrical filter. At higher speeds the unwanted vibrations could not be filtered out successfully. The obtained coefficient of friction appeared to be constant over a wide range of loads. At low speeds the high-frequency vibrations could be reduced to a reasonable level by a low-pass electrical filter. At higher speeds the unwanted vibrations could not be filtered out successfully.

It was obtained friction coefficients with values between 0.08 and 0.12, with a mean value of 0.10.

*- W.-J. Kim, H.-S. Jeon and Y.-S. Park, 1991 [7]*

In this work, a six degree of freedom dynamic model is constructed for an overhead-cam (OHC) finger-follower-type cam-valve and experimental work is described in order to verify the predicted follower strains.

The strain at the specified point of the follower is directly measured and compared. An OHC type gasoline engine (1600 cc, four cylinders) is used for this experiment. The experimental apparatus was prepared as only one valve train is in operation. The speed of the cam shaft was regulated by an engine-dynamo controller. A strain gauge was mounted at a nearly flat surface area on the follower. The resulting dynamic strain was monitored while the cam shaft was driven by a DC motor. The cut-off frequency of the strain amplifier was set up at 5 kHz. The cam-shaft speeds at 600 rpm, 1600 rpm and 2450 rpm.

The maximum strains of the finger-follower were measured to be 46.646 $\mu$e, 42.657 $\mu$e and 62.311 $\mu$e at cam-shaft speeds 600 rpm, 1600 rpm and 2450 rpm, respectively.

*- Mircea Teodorescu, Dinu Taraza and Naeim A. Henein, 2002 [8]*

The paper analyses the friction in the valve train of an internal combustion engine trying to separate the contribution of the different components to the total friction losses in the valve train. The measurements are performed on a running engine in order to avoid extraneous factors introduced by simulating rigs. The experimental engine is instrumented with strain gauge bridges on the rocker arm, the push rod and the camshaft to measure forces and moments acting on these components.

The measurement of the main friction components of the valve train was made directly on a firing single cylinder diesel engine operated at different speeds and no load. The experimental engine (Deutz FIL 210) has a complex valve train including a push rod and a rocker arm. To provide the necessary information for the separation of the different friction components, strain gauge bridges were placed at selected locations in the valve train system and an accelerometer was used to determine the actual motion of the valve. In order to monitor the actual motion of the valve, an accelerometer (PCB-353B12) was mounted on the spring retainer of the exhaust valve of the diesel engine. The force acting between the valve stem and the rocker arm was measured by a half bridge of EA-060-125BZ-350 strain gauges (Measurement Group) placed on the valve side arm of the rocker arm. The force acting between the push rod and the rocker arm was measured by another half bridge using the same strain gauges and placed at the top end of the push rod. The torque required to drive the camshaft was measured by a full bridge of CEA-06-125UR-350 strain gauges (Measurement Group) placed at 45 with respect to the shaft axis. The power supply and signal take-off were assured by a slip ring assembly S 10 (Michigan Scientific). Because the signal level was low, comparable with the noise introduced by the slip rings, a pre-amplifier was built and mounted on the shaft before the slip ring assembly. The engine was run at different speeds and no load.

The measured data were sampled using a 24 channel data acquisition system (Real Time Engineering). A high precision hollow shaft encoder with 360 divisions on the optical disk (PEI-5VL670 HAZ 10) was used to trigger the sampling.

It was found that the friction force between valve stem-valve guide represents only about 1.5 - 2% of the force acting on the valve stem and only about 2% of the total energy dissipated by friction in the valve train. Due to the small relative speed and oscillatory motion, boundary friction characterizes the operation of the rocker arm bearing, the friction coefficient being about 0.15.

*- Baş, Bıyıklıoğlu and Cuvalci, 2003 [9]*

This presented method consists on an experimental study of the friction properties of the cam mechanism. In this work authors presents a torque measurement of the cam shaft and also measures the friction occurring in the journal storage.

The test apparatus consists on a driving unit, a measurement unit, a cam-follower system, a loading unit and a lubricating unit. The camshaft is driven by a 5.5 kW induction type electric motor whose speed can be changed by a speed control unit in the range of 0 - 1200 rpm. The tests apparatus is mounted on a ground plate whose surface is machined accurately. The test apparatus is lubricated by two different types in order to lubricate the working parts of system and the other is used to lubricate the region of the cam-follower.

The friction force of the cam-follower interface is measured by strain gauges mounted on a measurement beam in a Wheat-stone bridge circuit. Two strain gauges is used as active gauges while two others are used as compensation gauges. Two types of accelerators were used.

The authors obtained, experimentally, an expected trend for normal and friction forces as a function of a cam angle, as soon the friction coefficients, with a maximum of approximately 0.07 between 40-50° of cam angle and a minimum of approximately 0.05 above 90° of cam angle.

*- M. Teodorescu and D. Taraza, 2004 [10]*

This paper investigates the tribological contact conditions between a polynomial automotive cam and a flat follower. The tappet spin effect is specially considered. A presented simplified friction model is experimentally validated on a single-cylinder diesel engine. The measuring techniques are based on a redesigned engine tappet equipped with four strain gauge bridges.

The engine chosen for the experiments is a direct injection, single-cylinder diesel engine with a pushrod valvetrain and a flat tappet. The instrumentation has been mounted on the exhaust valvetrain. The experimental engine specifications are as follows: Model Deutz-F1L 210D, Bore/stroke 95/95 mm, Rated speed 2800 rpm, Rated power 10.2 kW. To isolate and measure the friction force between the cam and the tappet, and the friction force between the tappet and the tappet bore, the engine tappet was redesigned. The instrumentation is mounted on the tappet head stem.

A tappet x tappet-bore friction forces obtained on this single cylinder diesel engine, at 1123 RPM, reaches almost 40 N peak at 60° approximately. The very low tappet bore friction force on the opening cam event was experimentally proven.

*- R. A. Mufti, 2009 [11]*

In this research work, new experimental systems have been developed that allow measurements of a number of parameters vital for evaluating the cam-tappet interface. All the three main parameters - friction, oil film thickness, and tappet rotation, have been measured for a range of engine conditions and lubricant types.

A study of HDD (heavy duty diesel) engine valve train was carried out on a Cummins B six-cylinder 5.9 l engine under motored conditions. The camshaft is driven through a set of gears from the crankshaft. As the main emphasis of this research work was the understanding of cam-follower interaction, pistons and connecting rods were removed from the engine. The engine was coupled to a 40 kW electrical motor through a Centaflex CF-X drive shaft and couplings. To understand the interaction at the cam-follower interface, only one cam lobe interaction was investigated. The exhaust cam lobe of the second camshaft unit was the cam-follower interface under study. To measure the torsion and thus drive torque, high-resistant two-element 90° torque strain gauges (Vishay Measurements EA-125TK) were installed on the opposite sides of a machined torque tube connected to the second camshaft. The performance evaluation of the engine valve train was carried out using three full formulated lubricants: SAE 50, SAE 5W-40, and SAE 0W-30 with inlet temperature of 90 °C. All the three main camshaft performing parameters, i.e., friction, oil film thickness, and follower rotation, were measured at engine speeds of 750 rpm (idle speed), 1200 and 1600 rpm.

The signal from the torque tube strain gauges and the temperature sensor was transferred from the rotating system using high-quality slip rings. A Fylde 379TA high-performance transducer amplifier was used. To use the complete range of the 12-bit analog-to-digital converter and to maintain a high signal/noise ratio, the signal from the transducer was magnified to a high level before transmission to the data acquisition (DAQ) system. The oil film thickness at the cam follower interface was measured by determining the capacitance of a lubricating oil film between the cam and follower contact surfaces. The contact capacitance was measured through the voltage drop over a known impedance. The follower rotation was measured using a miniature Eddy current sensor Kaman 2U (available from IXTHUS Instruments, UK). One of the main features of this project was the development of an advanced DAQ system for measuring camshaft friction, oil film thickness and tappet rotation simultaneously. A new DAQ system based on Pentium 4 PC and advanced high-speed DAQ hardware was developed for this research work. Thus, three different types of DAQ boards were used: National Instruments PCI-MIO-16E-1, PCI-6120, and PCI-6601.

The experimental results are presented following as approximated values. The averaged friction torque over the cam profile with an engine speed of 750 rpm are, for SAE 50, 0.283 Nm, for SAE 5W40, 0.287 Nm and for SAE 0W30, 0.299 Nm. The averaged camshaft bearing friction for SAE 50 is 0.052 Nm, for SAE 5W40, 0.048 Nm and for SAE 0W30, 0.058 Nm. SAE 50 presented camshaft bearing friction of 0.053 Nm at 750 rpm, 0.056 Nm at 1200 rpm and 0.064 Nm at 1600 rpm. SAE 0W30 presented camshaft bearing friction of 0.058 Nm at 750 rpm, 0.051 Nm at 1200 and 1600 rpm. The camshaft friction over cam profile period at various engine speeds could be found. For SAE 50, 0.28 Nm at 750 rpm, 0.251 Nm at 1200 rpm, and 0.220 Nm at 1600 rpm. For SAE 0W30, 0.300 Nm at 750 rpm, 0.275 at 1200 rpm and 0.260 at 1600 rpm. Instantaneous minimum oil film thickness was measured at the cam-follower interface for all lubricants. The averaged oil film thickness for SAE 50 was 0.8 microns at 750 rpm, 2.7 microns at 1200 rpm, and 3.7 microns at 1600 rpm. For SAE 0W-30 it was obtained 0.25 microns at 750 rpm, 0.6 microns at 1200 rpm, and 1.2 microns at 1600 rpm. The follower rotation speed data for the complete oil matrix, with 750 rpm cam rotation was obtained. For SAE 50, it could be found a 9.2 rpm, for SAE 5W40, and 7.1 rpm, for SAE 0W30, 8.5 rpm.

*- Bo Hu, Changjiang Zhou, Hongbing Wang, Lairong Yin, 2020 [12]*

Gyroscopic effect of rotary shaft and rotor should be considered in high-speed engines. The authors proposed an elastic dynamic model of a valve train system. The proposed model can effectively predict the dynamic stress, as proven by a stress experiment. In addition, idling and maximum working speeds are recommended using the predicted model and verified by a vibration experiment.

A test rig of a single-cylinder engine was built to measure the pushrod stress and housing vibration. To avoid the effects of the piston, crank shaft and connecting rod on the engine vibration, these components were disassembled from the engine. A servo motor was used to drive the camshaft by using a synchronous belt transmission. Four strain gauges were installed on element of inlet pushrod to constitute a full-bridge converter. The strain gauges were calibrated prior to measurement to avoid the influence of initial strain generated during the strain gauge installation. Engine vibration tests were conducted. Two acceleration sensors were used to obtain the three-directional acceleration of the engine housing. To verify the predicted vibration, the engine housing is subjected to a vibration test when the camshaft accelerates from 300 rpm to 2000 rpm. The vibrations vary with the rotation speed in directions x and y. The xrms and the yrms represents the root-mean-square of the acceleration in directions x and y. Unit g represents the gravitational acceleration.

The xrms (g) vary from near 0.2 at 300 rpm to almost 4.4 at 2000 rpm. The yrms (g) vary from 0.3 at 300 rpm to almost 5 at 2000 rpm. A vibration peak is observed in the measured curves when the cam speed is 500 rpm (8.3 Hz). Other peaks appear in the measured curves, such as 900, 1050 and 1750 rpm in xrms and 700 rpm in yrms. Measured stresses at cam rotation speeds of 500, 1000 and 1500 rpm were also analyzed. When the cam speed is 500 rpm, the measured stresses gradually increase during the rise phase and reach the maximum values at 180°. As the cam speed increases, two peaks appear in the curves of the measured stresses at approximately 126° and 226°.

## 3 Discussion and Conclusions

There are so many types of cam-tappet systems and designs. Regarding to experimental approaches for cam-tappet studies, it is possible to understand that it is a large variety of experimental approach of procedures, using an entire engine, or using an adapted motored engine head or constructing an entire dedicated experimental device. Some physical characteristics are often under experimental study like lubricant film thickness, friction forces or coefficients, torques, efforts, vibration information and so on.

Based on these described experiments, it is possible to summarize, for cam-tappet systems, in general:

- friction coefficients between cam and tappet varies from 0.05 to 0.15 and appeared to be not dependent of the normal loads;
- strains of the finger-follower varies from about 46.646 με to 62.311 με at cam-shaft speeds 600 rpm to 2450 rpm, respectively;
- the force between valve stem-valve guide represents only about 1.5 - 2% of the force acting on the valve stem and only about 2% of the total energy dissipated by friction in the valve train;
- a tappet - tappet bore friction forces reaches almost 40 N peak;
- the cam-follower friction was low for viscous oil SAE 50, whereas camshaft bearing friction was low for lubricant SAE 5W-40. For lubricant SAE 0W-30, both the cam-follower friction and the camshaft bearing friction were higher than the rest of the lubricants;
- the friction at the cam-follower interface decreases with increasing engine speed, whereas for viscous oil bearing friction increased with engine speed. For low-viscosity oil, camshaft bearing friction decreased with increase in engine speed;
- viscous oil gave greater oil film thickness as compared to the low-viscosity lubricant at the cam-follower interface;
- the increase in entraining velocity improves oil film thickness mainly in the cam flanks region;
- follower rotation speed is higher for lubricants SAE 50 and SAE 0W-30 and lower for SAE 5W-40;
- the gyroscopic effect apparently affects the natural frequency of the valve train system;
- reasonable idling speed setup of an engine can avoid undesirable vibrations from cam-tappet system. It can be recognized by vibration experiments;
- the behavior of engines (performance) can be enhanced when considering the component deformation in the design of cam profiles;

# References

[1] R. Roshan, M. Priest, A. Neville, A. Morina, and X. Xia, “A Boundary Lubrication Friction Model Sensitive to Detailed Engine Oil Formulation in an Automotive Cam/Follower Interface,” *Journal of Tribology*, vol. 133, no. 4, 9 pages, 2011. Available at: https://doi.org/10.1115/1.4004880

[2] B. S. Andersson, “Paper XVIII (iii) Company perspectives in vehicle tribology - Volvo,” *Tribology Series*, vol. 18, pp. 503–506, 1991. Available at: https://doi.org/10.1016/S0167-8922(08)70168-8

[3] V. W. Wong and S. C. Tung, “Overview of automotive engine friction and reduction trends - Effects of surface, material, and lubricant-additive technologies,” *Friction*, vol. 4, pp. 1-28, 2016. Available at: https://doi.org/10.1007/s40544-016-0107-9

[4] L. A. Ratamero and V. Ventura, “Fuel Economy Sensitivity Analysis for DLC Coatings on Tappets,” *SAE Technical Paper 2018-36-0027*, 2018. Available at: https://doi.org/10.4271/2018-36-0027

[5] J. Angeles and C. S. Lopés-Cajún, *Optimization of Cam Mechanisms*. Netherlands: Springer Science Business Media, 1991. Available at: https://doi.org/10.1007/978-94-011-3572-8

[6] A. Dyson and M. A. Naylor, “Application of the Flash Temperature Concept to Cam and Tappet Wear Problems,” *Proceedings of the Institution of Mechanical Engineers: Automobile Division*, vol. 14, no. 1, pp. 255-280, 1960. Available at: https://doi.org/10.1243/PIME_AUTO_1960_000_026_02

[7] W.-J. Kim, H.-S. Jeon, and Y.-S. Park, “Contact Force Prediction and Experimental Verification on an OHC Finger-follower type Cam valve System,” *Experimental Mechanics*, vol. 31, pp. 150-156, 1991. Available at: https://doi.org/10.1007/BF02327568

[8] M. Teodorescu, D. Taraza, N. Henein, and W. Bryzik, “Experimental Analysis of Dynamics and Friction in Valve Train Systems,” *SAE Transactions*, vol. 111, pp. 1027-1037, 2002. Available at: https://doi.org/10.4271/2002-01-0484

[9] H. Baş, A. Bıyıklıoğlu, and H. Cuvalci, "A New Test Apparatus for the Tribological Behavior of Cam Mechanisms," *Experimental Techniques*, vol. 27, pp. 28-32, 2003. Available at: https://doi.org/10.1111/j.1747-1567.2003.tb00126.x

[10] M. Teodorescu and D. Taraza, "Combined multi-body dynamics and experimental investigation for determination of the cam–flat tappet contact condition," *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, vol. 218, no. 3, pp. 133-142, 2004. Available at: https://doi.org/10.1243/1464419042035935

[11] R. A. Mufti, "Experimental technique for evaluating valve train performance of a heavy duty diesel engine," *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 223, no. 3, pp. 425-436, 2009. Available at: https://doi.org/10.1243/13506501JET537

[12] B. Hu, C. Zhoub, H. Wang, and L. Yin, "Prediction and validation of dynamic characteristics of a valve train system with flexible components and gyroscopic effect," *Mechanism and Machine Theory*, vol. 157, paper no. 104222, 2021. Available at: https://doi.org/10.1016/j.mechmachtheory.2020.104222