Experimental study of engine cam-followers

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SUMMARY. The cam-follower pair is a very complex lubricated contact because its continuous variation of load, speed and radius of curvature. Experimental verification are necessary but very difficult to perform. After a literature review of the existing test rigs for cam-follower simulation, the main aspects of a new versatile apparatus are presented. Several design variations are presented, each one with its advantages and drawbacks. The final project will take into account some of the presented design solutions and the results of dynamic simulations of the rigs currently under elaboration.

1 INTRODUCTION

Wear problems in a valve train system contact are mainly a function of contact stress, sliding velocity and hydrodynamic film thickness between the two mating surfaces. The problem of surface wear becomes severe as the oil film lubricant is broken. It is not easy to investigate the cam-follower lubricated contact because it works under transient conditions by means of changing radius of curvature, load and entraining speed. The difficulty is also proven by the fact that most studies have been addressed to stationary conditions in the past. During the last decades the studies of non-steady lubricated contacts have been increased, mostly thanks to the improvements in experimental techniques and instrumentations for the experimental investigations and to the software and hardware for the theoretical/numerical studies, as reported for instance in [1, 2]. Despite that very complex models of the lubricated contacts have been recently developed, including mixed lubrication conditions and thermal effects, real contacts remain very difficult to simulate and experimental studies are of fundamental importance.

Friction and film thickness are the most important quantities to be investigated. Some friction measurements using a cam-follower system are reported in [3, 4]. The total friction torque is measured and all parasitic losses of the apparatus must be calculated in order to evaluate friction losses in the cam-follower contact. A modified version of the apparatus that allows the follower rotation and the measurement of its frequency is shown in [5]. An apparatus with three load cells that allows the direct measurement of the contact force components is used in [6]. Attempts of measuring oil film thickness with a capacitance transducer are made in [7], while electrical resistivity is used in [8]. Film thickness and temperature measurements are performed with thin film micro transducers in [9]. Friction measurements and some first attempts of film thickness and shape evaluation using optical interferometry are reported in [10].

Not many experimental studies on cam-follower contacts have been carried out during the recent years. Most studies are addressed to friction and wear measurements for investigating the influence of lubricant additives and surface coatings, finish and texture [11-16]. The friction force (or torque) is often calculated by subtracting the contributions of other components and of the inertia actions from the measured values [14, 17]. Film thickness measurements are very seldom performed, most probably because the big difficulties in measuring this quantity in a sufficiently detailed manner. Optical interferometry has been proven to be the most powerful and detailed method for measuring film thickness and shape, but the continuous variation of the working conditions and therefore of the interference images during running of a cam has made image recording critical till the today availability of high speed cameras. Attempts of using optical interferometry for investigating non-conformal lubricated contacts under transient conditions are reported in [18-23]. The main limitation of these experimental works is that only variable speed conditions are simulated, while the geometry and load variations, also typical of a cam-follower contact, can not be realised with the experimental rigs used. Ball on disk contacts are usually employed.

Based on the experience in friction and film thickness investigations ([19-24]) made also under transient working conditions with the apparatus shown in Figure 1, authors intend to investigate non-conformal contacts typically working under elastohydrodynamic conditions with variable speed, load and geometry. The different interference images shown in Figure 1, obtained for the same values of the entraining speed u when increasing or decreasing it, clearly indicates the importance of taking into account the transient effects.

In this paper the conceptual design steps for possible modifications of the existing experimental apparatus and for the realisation of a new test rig are reported. The apparatus should be able to simulate valve train system as well as gear teeth contacts.

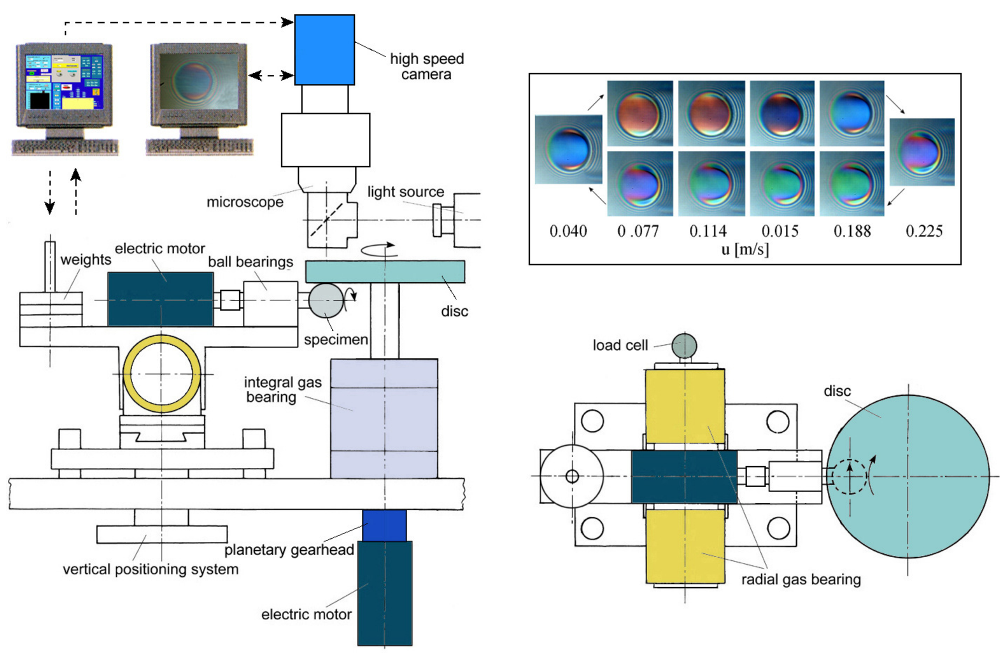


Figure 1: Schematic drawing of the existing experimental apparatus for friction and film thickness measurements. Some sample interferograms obtained under transient conditions when increasing (top images) and decreasing (bottom images) the entraining velocity u are shown in the frame (pure rolling conditions, sinusoidal variation of u with a frequency of 1 Hz).

2 MAIN CHARACTERISTICS OF THE AXPERIMENTAL APPARATUS

The experimental apparatus, both the modified version of the existing one and the new one, should be able to simulate as close as possible the working conditions of real contacts. Particularly, it should provide experimental results for cam-follower contacts at a range of engine operating conditions with different lubricant temperatures, manufacture cam materials, surface roughness, oil lubricant viscosity and contact load. Load and speed variations with different laws must be simulated. They could be generated by opportunely driven electric motors and loading systems, as well as thanks to the shape of the tested cams. Cams of different dimensions and shape as well cylindrical specimens with and without crowning should be used. Versatility must be one of the most important targets.

The apparatus is mainly devoted to direct measurement of friction and oil film thickness. The friction can be measured by a torque transducer or by opportunely designed and positioned load cells. The film thickness and shape is estimated by interferometric method using a microscope connected with a high-speed camera. Thermocouples can measure the oil temperature at the inlet and outlet of the contact, while the bulk temperature of the specimen can be estimated by imbibed thermocouples where the signals are exited up using an electrical collector.

Based on literature data and taking into account the necessary presence of a glass body in contact with the cam when optical interferometry will be used, a maximum normal load of 1500 N, a friction force along the entraining direction of 200 N and a possible lateral force of 100 N have been estimated. Dynamic forces will surely play an important role in values of the contact forces and this will influence the maximum rotational speed that has been preliminarily estimated of 2000 rpm. A recording target of one data each rotation degree of the cam is first proposed. This means 12000 Hz at 2000 rpm, not compatible with the limit of 1000 Hz of the available high speed camera that will therefore used for lower speeds and/or for lower sampling rates.

Similarly to followers of some engines, the rotation around an axis orthogonal to the plane surface of the body in contact with the cam should be possible or avoided. When the follower has the freedom to rotate, the angular velocity can be measured. The body, usually a disc, should be interchangeable in order to make possible experiments with metallic counterfaces more addressed to friction and wear tests.

The contact point move during the cam running. In addition, different initial positions of the contact can be used with respect of the disc axis. This should be considered for the microscope positioning. A maximum displacement of the contact zone of 30 mm can be possible.

Dynamic simulations of the proposed apparata reported in the paper are under way and the final design will take into account their results.

3 MODIFICATION OF THE EXISTING APPARATUS

The already available test rig for the simultaneous measurement of friction force and film thickness with the optical interferometry methodology can be arranged in a similar configuration to the one used in [10] shown in Figure 2. The improvements realised during the years, particularly its equipment with the computer-controlled high-speed camera for measuring the film thickness under transient conditions, surely allow better investigations of cam-follower contacts today.

The friction force measurement is possible thanks to the connection of the load cell in an eccentric position to the disc shaft, supported by a very low friction gas bearing. Some modifications should be made to meet the requirements, particularly the maximum cam speed. Improvements related to the electric motors, the lighting system with the microscope, the load cell with its amplifier, and the data acquisition system have been considered. Technical and economical problems has been evidenced showing the inconvenience of updating some components. In addition, the big inertia of the system creates problems at high rotational speeds.

This configuration can be used in any case for tests at reduced speed and load.

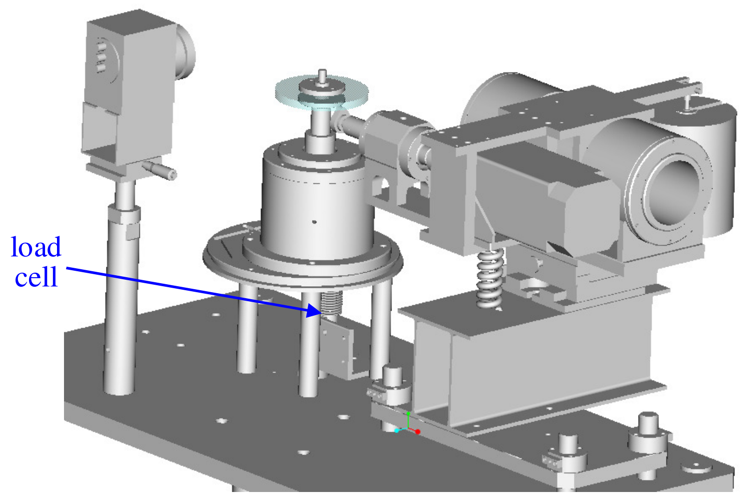


Figure 2: Configuration of the apparatus of Figure 1 suitable for cam-follower contacts.

4 DEVELOPMENT OF A NEW APPARATUS

A new test rig can be designed and built specifically addressed to cam-follower investigations. Some expensive fundamental components of the available apparatus, as the high-speed camera and the thermostatic bath for oil supply temperature regulation, can be used also for the new one. A new microscope and lightening system could be acquired for obtaining the interference images; the system should be able to overcome the optical problems of the existing stereomicroscope and the light intensity limitations, particularly critical for high speed recording of the images. New load cells with adequate full scale and more performing data acquisition system could be used.

The main problems faced during the design of the core part of the new apparatus are reported in the following. The investigation is particularly addressed to two aspects: the positioning of the microscope on the moving contact zone and the measurement of the contact force along three different directions.

The lubricated contact zone can move generally in more than one direction during running, as schematically shown in Figure 3. According to this scheme, the microscope axis must be vertical. It is not easy to give to the microscope the lateral (horizontal) movement synchronized with the one of the contact zone, both for constructive-economical problems and for the related vibration problems. Alternatively, the recording of the interference images through the camera connected to the microscope can be done by different positioning of the microscope in successive tests repeated with the same working conditions or using a reduced magnification able to capture the whole zone of the contact (the minimum magnification is obviously related to the possibility to distinguish the interference fringes). The vertical movement of the contact is related to a focus problem of the images. This could be avoided by giving a vertical motion to the microscope synchronized with the one of the cam or by maintaining the follower fixed while the cam axis is moving.

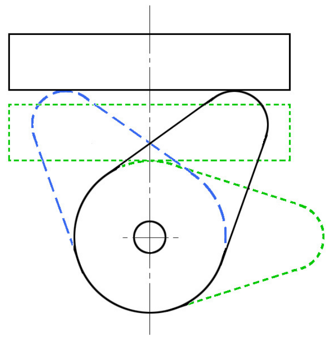


Figure 3: Schematic drawing of the contact zone displacements.

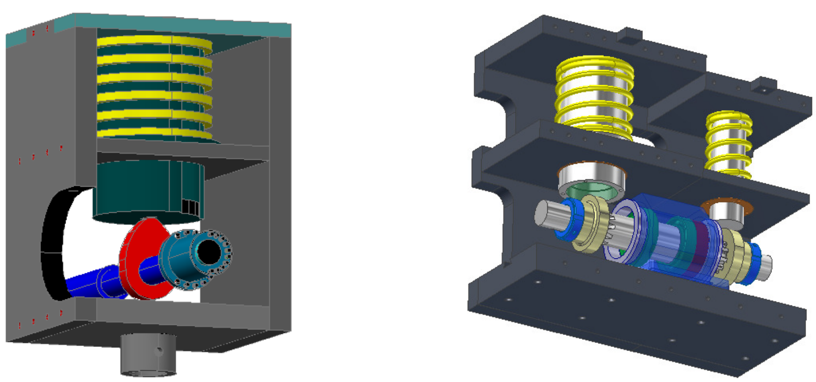
The measurement of the contact forces is not immediate. The torque acting on the cam can be measured for evaluating the friction force but, depending on the configuration or the rig, some parasitic losses can be also included in the measured values. The normal load is influenced by inertia and spring forces. In both cases a calculation is necessary to evaluate these two components of the contact force. A third force component can also arise in some cases (e.g. cam and follower with particular shape or rotating follower). A direct measurement of the three components is not easy to be realised, but is surely the best solution.

Basically, two configurations are possible: 1) cam with fixed axis and moving follower; 2) cam with moving axis and fixed follower. Each configuration presents advantages and drawbacks, as reported in the following. Autodesk Inventor 3D has been used, which allows easy modifications and combinations of the different models realised.

4.1 *Cam with fixed axis*

The cam-follower system with the cam rotating around a fixed axis works in the same operating conditions that this mechanism operates in an internal combustion engine.

The designed systems are shown in Figure 4 (some structural components have been removed for a better view of the fundamental parts).



a b

Figure 4: 3D view of the experimental apparatus with fixed axis of the cam. First version (a) and second one (b) with a duplicated cam-follower system for moving the microscope.

A slip ring collector can be used for extracting the signal of thermocouples inserted in the cam for measuring its bulk temperature (Figure 4a). Alternatively, two similar cams can be used (Figure 4b) for giving the same vertical motion of the investigated follower to the microscope by connecting it to a secondary follower (the one on the right in the figure). The follower of the investigated contact is easily interchangeable and can be made of glass for measuring film thickness by using optical interference or of metal for scuffing and pitting tests. The follower has the freedom to rotate as in real applications, but rotation can be easily avoided. The load is regulated by using springs of different stiffness; the normal force must be calculated including inertia effects. The friction force can be evaluated from the measured torque by subtracting the parasitic losses.

Possible disadvantages of this apparatus are the induced vibration in the microscope and camcorder that could also distort the interferometric images and the negative inertial effect of the added mass. The microscope should be very small to limit these effects, but, on the other hand, the dimension of the already available camera are not changeable. Finally, the distance from the microscope and the contact zone is related to the presence of the spring, so that an estimated minimum focal length of about 100 mm is necessary.

4.2 *Cam with moving axis*

This model sets the option to reproduce a cam-follower mechanism that uses a rocker as a link device between the cam follower set and the valve. As it can be observed in Figure 5, this system consists of two main sets: the rocker-arm and the follower. In the first one is installed a camshaft driven by a gear system connected to an electric motor in a manner to provide the torque to generate the coupled motion between the cam and the follower.

A plane follower type is suggested to be installed in such way to measure independently the normal contact force and the two friction force components. This can be performed using a three axial load cell, schematically indicated with a yellow cube in Figure 6. Followers of different type can be fixed in the support, but follower rotation could be also possible by using a support with angular contact bearings (Figure 7a). A configuration more similar to the one used in the cylinder head camshaft systems could also be easily installed (Figure 7b).

With this system, it is possible to evaluate the three involved forces in the lubricated non-conformal contact and to perform the interferometric measurements of the hydrodynamic film thickness using a microscopic of a 20 mm focal length. The solution with the flat follower assembled in angular contact bearings gives the follower the freedom to rotate as in real applications. As well known, this feature increases the useful life of both components under non conformal contact. Furthermore, by setting fixed the rocker-arm, the option of a cam-follower installed like on cylinder head, as shown in Figure 7b, is possible, which shows the versatility of this second model able to include also some functionalities of the solution with fixed axis.

There are also some disadvantages related to this model. The inertial effects of the rocker-arm are equivalents to developed in the real applications, which means that, at high speed, the normal contact forces developed in the nose cam because of the accelerated cam motion can reach very high values.

For this reason it would be difficult to operate this second model in a real speed range. There could be also problems related to the three axial load cell. This kind of cells are usually manufactured with same or similar load capacity along each axis. As well known, friction forces range only about the 10% of the normal force; then the exit signals can have interference between them; in addition, the variation of the load cell output signal can be influenced when the application load point is not placed in the load cell axis, and, last but not least, they have a high cost.

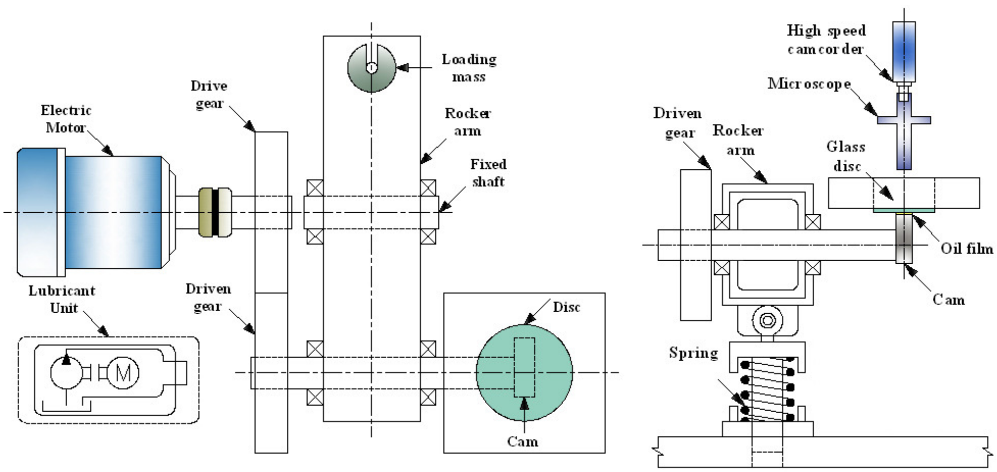


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Figure 5: Schematic drawing of the experimental apparatus with moving axis of the cam. Top (a) and lateral (b) view.

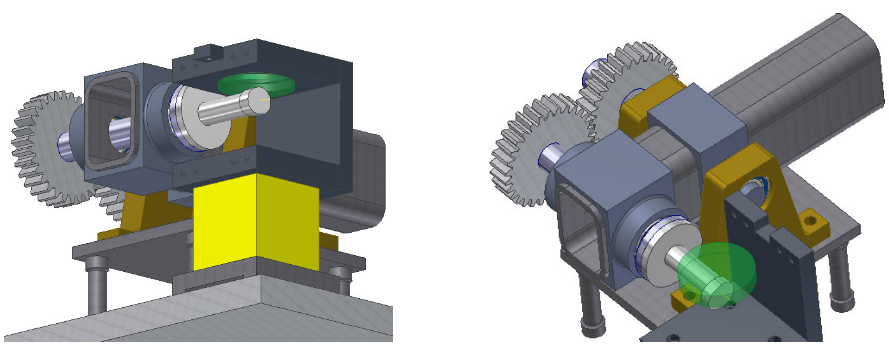

Figure 6: 3D views of the core part of the experimental apparatus with moving axis of the cam.

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Figure 7: Two additional modules of the experimental apparatus with moving axis of the cam: rotating follower (a) and cam-follower coupling similar to the one used in i.c. engines (b).

Therefore, an alternative solution with independent measurement of the normal force and of the two friction force components has been also studied. The use of three assembled frames is proposed installed on two tension-compression load cells connected in parallel with the purpose of compensating the moments induced by the eccentricity of the application force point, as shown in Figure 8. Some disadvantages of this solution are that friction forces arise in the contact points between the roller bearings and the bodies surfaces that influence the load cell measurements, and there are stresses in the Hertzian contacts that could damage the roller bearings in a few time. In addition, the link between the bodies is rigid, so that some force moments can act on the load cells.

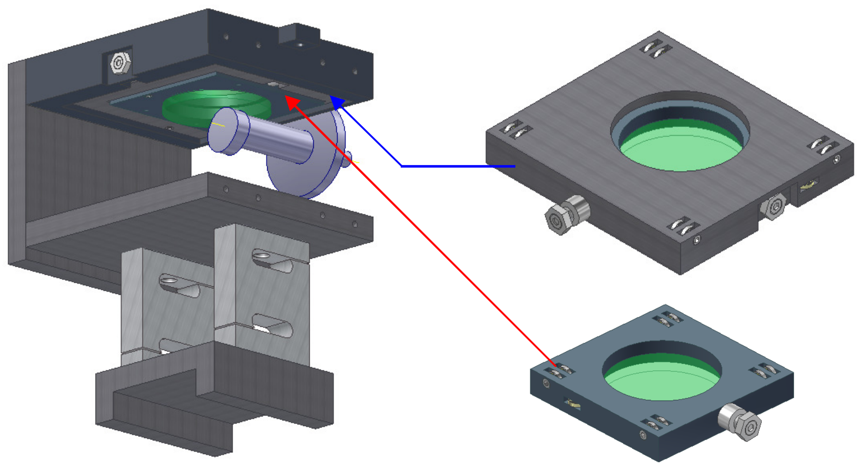

Figure 8: Details of the solution with independent measurements of the contact forces by three load cells.

In order to reduce friction and contact stress problems of the above solution, a new one using gas bearings instead of rolling element bearings is proposed (Figure 9). In addition, the connection between different parts is made by spherical rod ends which allows the rotation on three axes, so that the load cells measure only traction-compression forces. Several modular solutions are possible as in the previous version; some of them are shown in Figure 9b and c.

The disadvantages of this solution are that the manufacture of gas bearings is not economical, and requires a source of compressed air. When compared with the others alternatives, the gas bearing is larger because the load is a function of the area covered by the gas pressure. This condition increases the length of the cam shaft. The development of a deflector is necessary to avoid that the gas coming out of the bearing at high pressure divert the lubricant oil, that must to feed a constant flow in the contact area between the cam and the follower.

5 CONCLUSIONS

The cam-follower pair works usually under critical conditions due to the continuous variations of load, speed and radius of curvature that produce big variation of film thickness. The contact can range from full to mixed till to boundary lubrication conditions so that friction and wear problems can arise. It is not easy to study in depth what happen in the cam follower contact, so that experimental studies are necessary but very difficult, as evidenced by the literature review reported.

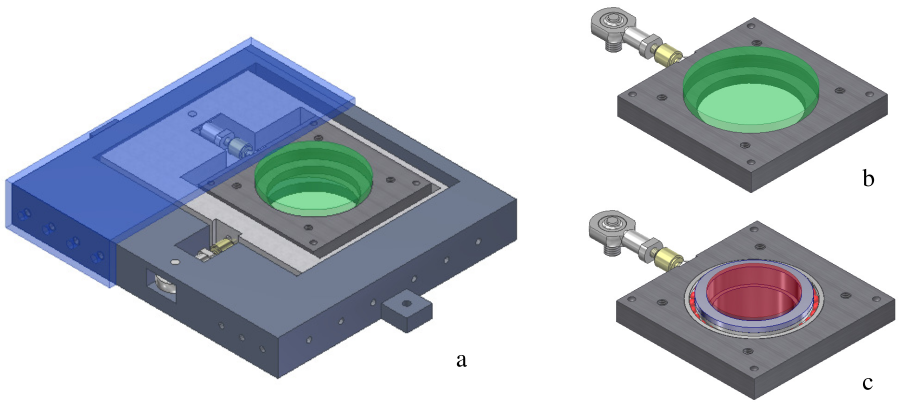

Figure 9: Alternative version of the follower support with integral gas bearing (a); details of the internal frame with gas bearing: fixed (b) and rotating (c) frame solution.

The analysis made of several design solutions for a versatile apparatus for cam-follower simulation has evidenced many important aspects that must be taken into account for developing of a final design. Particularly, the test rig should be able to measure instantaneous contact forces and film thickness for different cam-follower configurations.

A dynamic simulations of the proposed solutions is currently under way and will furnish important indications for the final design. The possibility of versions able to simulate also contact between gear teeth will be also investigated. .

The system developed will allow a deep analysis of the behaviour of non-conformal contacts under transient conditions. Useful indications for the design optimisation of cams and gears systems will be available. Furthermore, experimental results would be used to modify and develop theoretical and numeric models to evaluate cam-follower failure by pitting and scuffing.

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