Valve motion measurements on motorbike cylinder heads using high speed laser vibrometer

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ABSTRACT

This work deals with valve motion measurements on cylinder heads of Ducati racing motorbikes, by means of high speed laser Doppler vibrometer. The experimental apparatus is described and some measurement results are presented. The results confirm that the effects of the dynamic phenomena are very important, especially at high speeds, and that the dynamic response gets worse with the increment of backlashes in the cam kinematic pairs. In addition, the measurements make it possible to analyse the valve bumping phenomena. The information retrieved from measurements provides insight into the cam system dynamics and helps the development of elastodynamic predictive models.

Keywords: valve train, laser Doppler vibrometer, motorbike engine, test bench.

1. INTRODUCTION

Nowadays tests on the dynamic performances of valve trains in reciprocating engines are becoming more and more important. In fact, this kind of devices operates at very high speed and, as a consequence, it is not possible to neglect the effects of link elastic flexibility and mass distribution, as well as the effects of backlashes and friction in joints, on the dynamic response of the mechanism. In particular, the valve motion can be so affected by the above mentioned effects, that it may fail to perform its tasks adequately, e.g. leading to alterations of the engine’s fluid dynamics. In addition, high accelerations and dynamic stress levels take place and may cause serious functional troubles, such as wear, fatigue and breakage of mechanical components (see Fig. 1 and 2).

This work deals with a desmodromic valve train of the twincylinder ‘L’ engine of Ducati racing motorbikes. This timing system has double overhead camshafts and four valves per cylinder. The schematic of the cam mechanism driving a single valve is shown in Fig. 3: the discs of a conjugate cam are each in contact with a rocker; the two rockers are then in contact with the backlash adjuster located at the tip of the valve; the two cam discs act on the adjuster, by means of the rockers, in opposite directions. With respect to the more widely-used trains with closing springs, the desmodromic trains make it possible to give very high valve accelerations, preventing the follower from jumping off the cam, without employing a very stiff closing spring; on the other hand, the mechanical complexity of the desmodromic system is justified only in high speed engines with single-cylinder heads, such as Ducati engines.

In order to improve mechanism performances, accurate valve motion measurements are necessary [1]. To this purpose, a measurement test bench has been designed and developed at the DIEM Laboratory of the University of Bologna on cooperation with Ducati.

The test system has been planned to reproduce, as well as possible, the functional conditions of the valve train; this specific request has guided to realise a test bench and to prepare a dedicated measurement apparatus which can operate for different cylinder head type, at high camshaft speed, under high temperature of the lubrication oil, and reproducing the motorbike power belt transmission. The functional requirements and the necessity of measuring high valve displacement and velocity, have suggested to adopt a high speed laser Doppler vibrometer [2 – 4]. The experimental apparatus allows the analysis of the actual performances of valve trains with several motion laws and different characteristic parameters of the mechanism.

The study makes it possible to identify the dynamic behaviour of the mechanism, even in presence of backlash, as a function of the operating speed. In addition, it makes it possible to well understand valve train behaviour and to obtain some indications about the entity of dynamic effects. Moreover, from valve acceleration it is possible to estimate dynamic forces acting on the mechanism, that are useful information to reduce component wear and fatigue. The information retrieved from measurements provides insight into the cam system dynamics and helps the development and validation of elastodynamic models able to efficiently simulate the mechanism behaviour [5, 6].

After the description of the test bench and the measurement apparatus, the paper shows some typical results of valve motion measurements, in terms of valve displacement, velocity and acceleration. The most important dynamic effects are pointed out and discussed, using proper signal processing techniques.
2. EXPERIMENTAL APPARATUS

The experimental apparatus includes a test stand, a cylinder head, an electrically powered driveline to operate the camshaft, a lubrication circuit, and measurement instrumentation. In particular, only the components required for the operation of the valve train were included into the system, that is, crankshaft, piston, cylinder, and connecting rod were excluded. As a result, no gas forces, combustion, or spurious vibrations occurred in the considered system. This means that the system response is different from typical operating conditions. However, the inclusion (or exclusion) of the forces due to compressed gases does not compromise the validity of the experimental data as a modelling tool [1].

Tests need for basic conditions: to measure high valve lift and velocity (up to 15 mm and 14 m/s, respectively), reproduce the motorbike power belt transmission, and lubricate the valve train in a similar way to that of the racing motor.

The small valve mass and its high velocity do not allow contact measurements (e.g. by means of piezoelectric transducers); on the other hand, the high frequency range and temperature do not suggest to employ proximity transducers. In addition, the valve motion measurements may be affected by vibration of cylinder head. Therefore, one has to measure the relative motion between valve head and its seat. For these reasons, a specific high speed differential laser vibrometer was used for this experimental study. This device allows non intrusive measurements, has very large dynamic and frequency range, good accuracy and sensitivity, high signal to noise ratio, as well as is applicable in many critical situations (e.g. hot surface measurements), and permits differential measurements. On the other hand, this instrument requires optical access and is expensive.

Finally, the valve motion has to be referred to the camshaft position. To this purpose, the experimental apparatus includes an incremental encoder which is placed on the camshaft.
2.1 Test bench.

The test bed consists of a welded steel frame made of tubular and profiled elements (see Fig. 4). It is designed to be stiff and heavy enough to reduce possible vibrations inducted by the inertial forces, and to support the cylinder head and the mechanical transmission. Some angular stiffeners are placed as additional structure reinforcements. The general dimension of the test bed are: length 930 mm, width 720 mm, height 650 mm; the weight is about 150 kg. The upper plain is realised by C-profiled elements that support a thick steel plate, at which the cylinder head is bolted, and the slide carrying the electric motor. In particular the head is turned upside-down to permit an easy and direct access to the valve path. Moreover, the test bench is equipped with a metallic net protection and is located over a dumper rub layer.

![Figure 4 – The test bench.](image)

![Figure 5 – Schematic of the lubrication circuit.](image)
The driveline consists of a brushless motor driving an intermediate shaft by means of a timing belt; a second timing belt, reproducing the same engine belt loop, moves the camshafts. The brushless motor used is a SELEMA M4-030, SMST-T2 series, with maximum power of 4000 W and a nominal torque of 12.5 Nm at 3000 rpm. The motor speed is obtained by a properly programmed controller. The first timing belt transmission multiplies motor velocity: the ratio is 10/3, making available a maximum speed of 10000 rpm at the intermediate shaft. This shaft is fitted with a flywheel in order to reduce fluctuations of torque and velocity. The second timing belt transmission, moving the camshaft, has ratio 1/1.

Pressurized oil is fed into the cylinder head oil galleries by means of a specific circuit, in order to properly lubricate the valve train. In particular, oil pressure and temperature have to be similar to those picked up from the motor during the racing, i.e. 6 bar and 130°C respectively. A particular feature of this system is the heating device. In fact, the oil temperature is reached using an oil lamination valve that transforms pressure fluid energy into heat. This device increases system safety avoiding any possibility of oil ignition. The lubrication system (see Fig. 5) consists of an electric motor, with power of 5.5 kW, a high pressure circuit (150 bar), which includes the heating system, and a low pressure circuit, where oil pressure is reduced to 6 bar. Two thermocouples and a pressure switch, control lubricate circuit behaviour. An alarm signal is emitted in case of bad oil pressure condition.

2.2 Measurement equipments.

The measurement equipment includes the laser vibrometer, the encoders and the data acquisition apparatus (see Fig. 6). The laser equipment is a Polytec’s High Speed Vibrometer (HSV), used for non-contact measurements and high velocity applications. The HSV is a differential dual channel instrument consisting of a controller HSV–2002, two sensor heads HSV–700 and two laser units HSV–800 [7]. It can be used to measure the absolute and relative velocity and displacement up to 30 m/s and 41 mm respectively. The maximum frequency is 50 kHz. The signals are individually processed using the velocity decoder and the displacement decoder of the HSV controller.

In order to simplify the laser beams alignment, Polytec’s Alignment Kit HSV–AK 800 was used. This device permits the deviation of the laser beams emitted by the sensor heads using two 90° probes assembled on guide rails. Each guide rail allows the longitudinal movement of the probe which can also be rotated around two right axes. Those movements ensure fine adjustments in the laser pointing procedure. Raw adjustment is provided by a laser frame on which the alignment kit is mounted. In particular, a specific frame, independent from the test bench, is the support for the laser equipment and holds the laser heads. The frame is made by a large base composed of profiled steel elements from which a tubular structure rises over the test bench plane, supporting the laser optics, and is placed on a dumper rub layer.
The centre of the valve-head plane surface was chosen as measurement point. This choice makes it possible to minimize possible valve’s flexional vibration effects, which may negatively affect valve motion measurement. As reference surface, an area close to the valve was selected. The differential measurement between valve surface and reference plane, permits the elimination of raw vibration effects of head cylinder support. In order to refer time dependent valve motion measurements to the cam angular position, the camshaft is fitted with an incremental encoder. In addition, a second encoder is placed on the intermediate shaft. These devices (Elcis X59DU8 – 360) allow the measurement of the relative angular velocity between the driving shaft (the intermediate), and the driven shaft (i.e. the camshaft). This information provides insight into the dynamics of the timing belt transmission. Moreover, the encoder mounted on the intermediate shaft provides, at each revolution, a signal to reset the displacement laser decoder.

The signals were collected by means of a National Instrument PXI data acquisition system which is composed by a mainframe PXI1000B, a controller PXI 8156B, a card NI 4472 with anti-aliasing filters (8 channels, max sampling frequency 102 kHz), a counter PXI 6602 (8 counters, clock 80 MHz) and a connector block BNC 2121. The acquisition system was driven by a specific software, developed on LabVIEW 6.0.2 Full Development System, which allowed the simultaneous acquisition of analog and TTL signals. The sampling frequency was 102 kHz and the filter cut-off frequency was set to 45 kHz in order to prevent aliasing. During the tests, both valve velocity and displacement, and encoders signals were recorded. By means of the 360 notches of the camshaft encoder was then possible to refer the valve motion to the camshaft angular position. The digital signals were processed and analysed with MATLAB software.

3. MEASUREMENT RESULTS AND DISCUSSION

The valve train was operated at speeds from 1500 to 5500 camshaft rpm and with several backlash values. Some examples of the experimental data measured using the presented experimental apparatus are now shown. Various dynamic effects affecting the valve motion are illustrated and discussed, in order to demonstrate the capabilities of the experimental equipment.

Figure 7 – Theoretical (dashed line) and experimental (solid line) valve displacement; 5500 camshaft rpm.

Figure 7 shows the comparison between the theoretical and actual valve displacement at 5500 camshaft rpm. The differences are quite important, especially at the beginning of the valve rise, around the maximum valve lift and during the closing phase, where bouncing phenomena take place. The effect of the inertia forces – that act on the valve stem, rocker arms, camshaft and others valve train components – causes a delay when the valve leaves the seat, an increment of the valve lift and a lead angle at the end of the fall. As a matter of fact, during those phases the acceleration takes the maximum absolute value.
These dynamic effects are expected to increase with the camshaft speed, due to acceleration increment. In fact, Fig. 8, which reports an enlarged detail of the measured valve displacement for three different speeds (3000 rpm, 4500 rpm, and 5500 rpm), shows that maximum valve lift grows with the cam angular velocity. Moreover, Fig. 9 shows that, at the valve closure, the valve collides more abruptly on its seat and that bumping phenomena become more important as the camshaft speed increases, due to the higher impact velocity. The differences between actual and designed valve lift can be considered in assessing the actual gas flow dynamics, heavy affecting the engine performances. In addition, the bounces and toss of the valve and the actual impact velocity, are critical parameters for wear and fatigue valve design.
Just as in the case of valve displacement, the experimental valve velocity differs from the theoretical one. In particular, Fig. 10 shows that the differences mainly involve the starting and closing phases, and the camshaft angular positions where the absolute velocity takes the maximum values. In Fig. 10 the velocity is made dimensionless with reference to the theoretical maximum value.

Obviously, the deviation of the actual valve motion from the theoretical one is more evident taking into account the acceleration, as reported in Fig. 11. The valve acceleration is not directly measured, but obtained by means of numerical
derivative and the acceleration scale is made dimensionless with reference to the theoretical maximum value. In particular, in Fig. 11 actual and theoretical valve acceleration are reported for low [Fig. 11(a)] and high [Fig. 11(b)] backlash at 4500 camshaft rpm. It is clearly visible that the dynamic response of valve train gets worse with increased backlash values. In fact, when acceleration reverses, the bigger the backlash is, the more abruptly the valve adjuster and cams collide with the rocker arms. In addition, Fig. 11 shows that the amplitude of the acceleration peaks, due to the valve collision against its seat, increases according to the backlash increment. These impacts excite the natural frequency of the valve, rockers, and other mechanism links, determining damped oscillations of the valve acceleration. It is worth noting that acceleration graphs may give useful information in assessing the actual stresses and loads, in order to properly design the mechanical components.

Finally, the wavelet analysis of valve acceleration is presented in Fig. 12, in the case of 4500 camshaft rpm and in presence of low backlash. The analysis is performed in the frequency range 5 to 45 kHz, including the most important natural frequencies of the mechanism. The wavelet transform is a good means of studying how the frequency content changes with time and is able to detect and localise short-duration phenomena [8, 9]. Since impacts have a high frequency content, their localisation is particularly easy at high frequency range. The most important impact is the one between the valve and the seat occurring at about 185 camshaft degrees. Fig. 12 also shows other transient phenomena, such as the shocks at 35 and 155 camshaft degrees (due to the impacts of the “positive” rocker), the impacts of the “negative” rocker (at about 80 degrees), and a second collision between valve and seat at 240 cam degrees. Due to their broadband frequency content, the impacts excite the mechanism resonances leading to damped oscillations each having different frequency. In particular, the oscillations excited by the valve-head collisions mainly concern the frequency range 35 to 45 kHz, while the other shocks cause vibration at about 7, 13, 17, and 22 kHz.

**Figure 12** – Wavelet analysis: 4500 camshaft rpm; low backlash. Normalised valve acceleration (a) and its wavelet transform amplitude (b).

### 4. CONCLUSIONS

Measurements of the valve motion have been obtained on cylinder heads of Ducati racing motorbikes, by means of a specific test bench equipped with a differential laser Doppler vibrometer. The measurements make it possible to analyse the dynamic behaviour of the system as a function of the operating speed, identify the dynamic effect of backlash values in cam kinematic pairs, and analyse the valve bumping phenomena. The collected data may be a useful tool for identifying causes of various dynamic effects, assessing the actual stresses and loads of mechanical components, and pointing out design improvement in order to reduce wear and fatigue. Moreover, experimental results help the development of elastodynamic predictive models.
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REFERENCES