Simulation of Dynamic Stresses on High Performance Engine Valve Spring System Considering Coil Clashing Effect

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Abstract. The valve train plays a major role in the performance of internal combustion engines by controlling the combustion process and it is therefore one of the key aspects for increasing the efficiency of combustion engines. Considering the dynamics, the spring force must be high enough to reliably close the valve preventing from seating bouncing due to surge modes after the valve closure. On the other side, the spring force should be kept as low as possible in order to reduce the engine friction losses and consequently the fuel consumption. In the high-performance engines, the valve springs have to be designed and optimized for sustaining higher stresses with compact dimensions leading to critical material and manufacturing processes. This requires a reduction of moving masses and a strong focus on design and process optimization of the coil springs for reducing the mechanical load and the friction losses at low engine speed. At the same time, valve train should be reliable at high engine speed. The calculation of stresses and contact forces for moving parts under dynamic load is essential for durability analysis. A method to calculate the contact of moving masses is described and proposed to justify valve motions experimental results. To fully understand the failure mechanism of test bed reliability trials, the dynamic stresses have been calculated modeling the real springs' shape. The contact forces have been reproduced considering the coil clash effects and the dynamic behavior of the flexible spring.

Keywords: Valve train · Valve springs · Coil clash · Multibody · FEM

1 Introduction

The predictive modeling of the valve train dynamic [1] is essential for durability analysis at the highest engine speed conditions [2]. The method to calculate the complex dynamic of the valve-spring systems allows a correct representation of flexible and complex contacts under full consideration of the system dynamics. The methodology combines the multi-body dynamics modeling [3–5] and the finite element analysis (FEA) [6]. With this approach the valve dynamics, measured with laser interferometric technique

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[1], is well correlated with multibody analysis. The obtained results have been therefore used for Finite Element Analysis on the self-contacting parts such as the valve springs. In modern high-speed combustion engines progressive springs are typically used for guarantying the maximum load with a compact installation length [7]. The durability of the valve train is typically validated on monitored cylinder head test bed and valve springs are one of the most critical reliability bottle neck. Sometimes the spring breaks directly over the sharp edge of the flattened end of the last coil. In this case the failure mechanism explanation is due to high contact pressure in this area. In many cases the spring breaks between 180°–270° after this point, at a location where a breakage is least expected. Metallurgical analyses of broken springs did not indicate material inconsistencies as reason for the failure. The calculation of the stresses in the spring with traditional FE-analysis does not reveal the location of failure. Dynamic analysis using modal reduction does also not give any useful indication. To fully understand the reason of the failure, true dynamic stresses have to be calculated by considering the correct geometrical shape of the spring, contact forces due to coil clash and the dynamic behavior of the highly flexible spring. The proposed methodology based on experimental and numerical simulations allows the representation of these flexible and complex contacts under full consideration of the spring dynamics.

2 Testing Equipment

A motored cylinder head has been used for this investigation (see Fig. 1a). An electric motor connected to the end of the camshaft has been used to drive the intake camshaft controlling speed and torque. The camshaft directly operates the intake valves via hydraulic tappets. Using a laser system, the rig has also been used to take measurements of valve displacement and dynamics. This experimental measurement has been used for the numerical dynamic model validation.

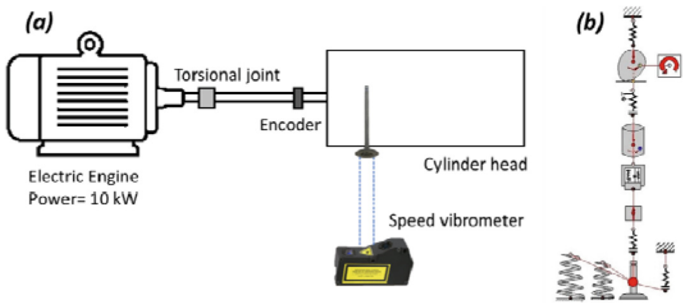

Fig. 1. Test rig and measurement system (a) and single valve-train multibody model (b)

3 Multibody Dynamic Models

A multi-body dynamic model of a single valvetrain has been developed using Ricardo Software VALDYN as shown in Fig. 1b. This valvetrain has been represented as a series of lumped mass/inertia nodes connected by stiffness and damping values. The cam node has been suspended on a stiffness element representing camshaft bending stiffness and camshaft support stiffness. The hydraulic tappet has been modelled as two mass nodes connected by a special element to account for the action of the high pressure chamber, the expansion spring and the check valve. The tappet has been connected to the valve using a lash stiffness element representing the stiffness of the valve stem between the tip and the center of mass. The valve and spring retainer have been modelled as a single mass node. The valve node has been connected to ground by another lash stiffness element representing the valve head and seat stiffness. The valve train has a double spring pack and each spring has been modelled using 4 mass nodes per coil connected by stiffness [1]. The cam profile has been designed to meet the many conflicting requirements for engine breathing, acceptable durability, high speed dynamics etc. [9, 10]. The spring pack has been designed to maintain contact between cam and the hydraulic tappet at high engine speed. Fig. 2a and Fig. 2b show the calculated dynamic valve lift and dynamic valve acceleration and against crank angle at camshaft speed of 4000 rpm. The calculation model has the capability to make calculations of valvetrain dynamic. This input, correlated with laser results from test bed experimental measurements, has been used to perform and validate a detailed Finite Element Analysis of the valve spring.

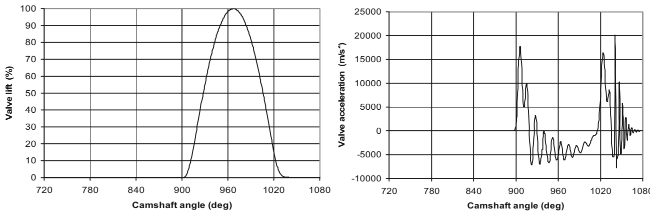

Fig. 2. Calculated dynamic valve lift (a) and acceleration (b) at 4000 rpm camshaft speed

4 Finite Element Dynamic Model

The simulation output obtained by multibody modelling have been used as dynamic input for a Finite Element model. In particular the valve springs (inner and outer spring) model is generated considering a discretization on section (QUAD 4 element). From the 2D section mesh it has been created an expansion on the valve spring helix with esaedric element. The considered FE model consists in the valve spring system composed by inner and outer spring both in contact with the upper retainer that impose the motion and with contact definition between each coil [11] (Fig. 3).

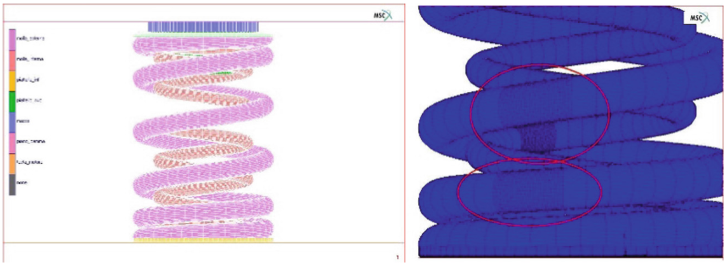

Fig. 3. Finite element model of the valve spring system (a) and details of the high density mesh region to focus on coil clash issues (b)

5 Results

The aim of this work is to show the phenomenon of coil clashing and the dynamic behavior of the highly flexible spring. The valve train system has been tested in overspeed condition, with the camshaft speed of 4750 rpm, in order to emphasize the phenomenon.

Considering the valve acceleration calculated by multi-body model and correlated by measurement, the aim of this work is to show in overspeed conditions the phenomenon of coil clashing and the dynamic behavior of the highly flexible through the FE analysis. The phenomenon of auto contact between wires is evident on internal and external wire but the absolute entity is stronger for the inner linear spring. The higher non-linearity of the outer spring (progressive stiffness) with variable natural frequency, is acting as mitigation effects.

The analysis shows the major contribution of coil clashing contact on spring stress value, as plotted in Fig. 5.

From the experimental testing it has been shown a breakage on the inner spring (1.75 wire from the bottom side) and it was also justified from analytical point of view as consequence of coil clashing effect (Fig. 4).

Fig. 4. Valve spring after testing in overspeed condition (breakage on inner spring from bottom side).

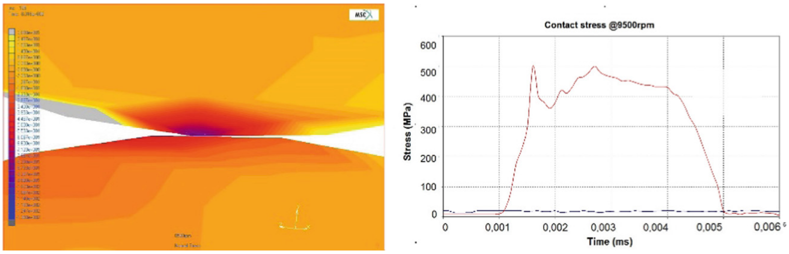

Fig. 5. Detail of area of coils clashing area. (a) and Max stress (at 9500 rpm) on outer spring (1.75 wire from the bottom side) for normal contact (blue line) and coil clash one (red line) (b).

6 Conclusion

The aim of this work has been the creation of a closed loop between modeling, analysis and measurement for a clear understanding of a High Performance Engine valve train dynamics. In particular the spring breakage phenomena have been studied with a deep analysis on the inner springs self contact "coil clashing" effect. An experimental bench has been used for testing the valve train up to overspeed conditions, to monitor the valve motion and the overall dynamics. The correlation of the experimental results has been done combining the multi body dynamics with the finite elements. Especially the capability to get stresses directly even for components which experience large deformations and high impact contacts under highly dynamic conditions such as the valve springs has been a big advantage for failure analysis and durability studies. The proposed methodological approach allows to study the dynamics of each component of the valve train, to validate the reliability and, at the end, to optimize the system by an engineering and technological point of view already in a preliminary stage of work.

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