VIRTUAL PROTOTYPE OF TIMING CHAIN DRIVE

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Development of combustion engines can be characterized by continuous increase in the number of computational simulations being applied in all areas. There is a clear trend to use chain or belt drives for the design of timing drives. Computational simulation of these drives has not been developing too long due to high demands on the computational technology. The paper focuses on simulation of dynamics of the timing chain drive with the use of a multi-body system. A mass-produced four cylinder in-line engine with two camshafts and two valves per cylinder has been used as a computational model.

Keywords: *chain drive, four cylinder in-line engine, contact force, tensioner, chain stiffness*

1. Introduction

In a development history, the design of timing drives for internal combustion engines has varied widely. Depending on the demands produced by engine design, valve timing and application, the solutions for driving the camshaft, came in many different shapes and sizes. In the early days, for instance, conventional engines used gears or simple chain drives. As mass motorisation progressed in Europe, most spark-ignition and diesel engines were fitted with chain drives. Following the advances made in elastomer production with cord and reinforcing fabrics, the 1970s and '80s saw a move towards toothed-belt drives. Recent years have witnessed a trend reversal and, increasingly, chain drives are once again the favoured option, also in mass-produced engines [1].

On the basis of design and calculation work as well as economic considerations, the task focuses on changing the mechanism used in the timing drive. Employing appropriate computational tools, a concept is to be created for the function systems affected by the changes and implemented in a draft design. The basis for this is provided by a four-cylinder with DOHC four-valves per cylinder in-line spark-ignition engine with a chain drive. The design of the chain drive is optimised to the maximum extent possible. The resultant solution will then undergo final assessment on the basis of functional/technical criteria as well as from the aspect of cost.

One of the main timing drive targets is as low maintenance as possible and this forces on specific requirements. Additional demands on the timing drive arise from the loads that are caused by a multi-valve design, the valvetrain DOHC configuration as well as the increased use of roller contacts in the valvetrain. These modifications produce higher levels of timing drive loads. Higher injection and combustion pressures in DI engines also result in increased levels of oscillating torque in the timing drive.

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The timing drive and valve train generate approx. 20 % of overall engine friction losses depending on the engine speed [1]. The friction caused by chain and guide or sprocket rails is mostly higher than in the case of the toothed-belt timing drive.

Toothed-belt drive systems do not normally require measures to reduce noise; however the chain drives cannot reach the same noise level as the toothed belt. It is caused by the impact of the chain links on the sprocket wheels. This is one of main chain drive disadvantages if compared to toothed-belt timing drives.

Comparing the life prediction of the two drive mechanisms, the chain timing drive brings the biggest advantage. Chain damages can occur very rarely during engine life and also the chain timing drive maintenance is not demanding. Regarding timing drive installations there are no high differences associated with using a toothed belt or chain drive.

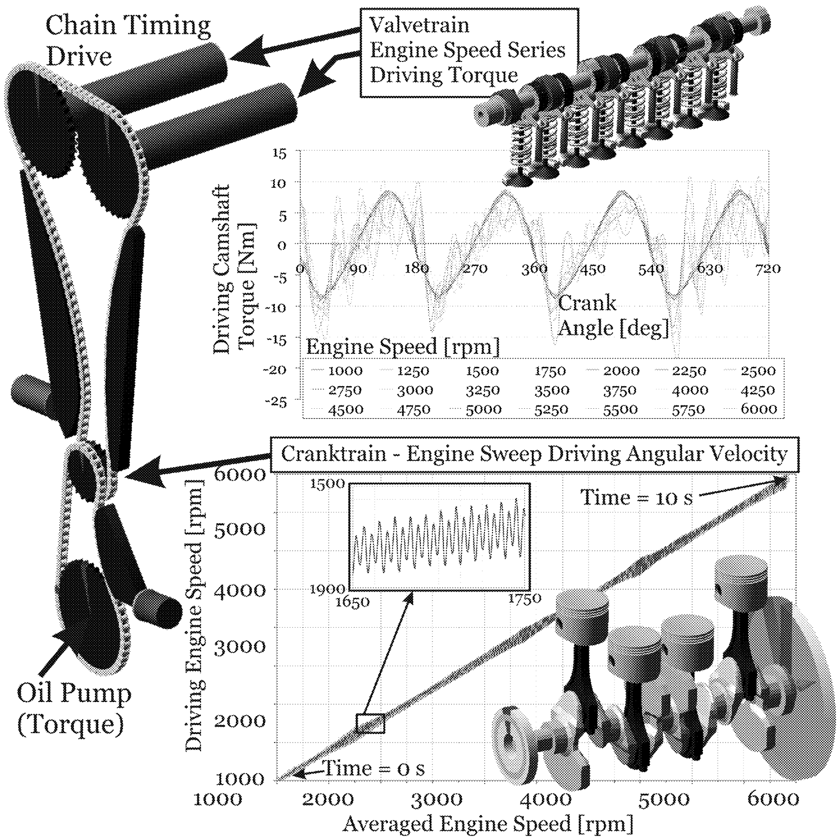

Fig.1: MBS model of chain timing drive with chain drive inputs (crankshaft driving velocity and camshaft driving torques)

2. Computational Model

2.1. Global Model

In general, the chain drive is influenced in particular by the crank mechanism as well as by the timing gear. If the model did not reflect these effects, the results would show a significant error. The most accurate seems to be creating of a whole engine model consisting of the crank mechanism, timing gear and the chain drive. Such solution is theoretically possible, in practice however it is found inappropriate due to huge demands laid on the computational technology. Thus, it is better to arrange the crank mechanism and the timing gear individually and to apply the results to the belt model as reaction torques, Fig. 1.

It has been proved that the crank mechanism in particular is only little influenced by other accessories of the engine and therefore the following reaction torques have been applied to the belt drive model:

- Driving angular velocity in the point of installation of the sprocket on a crankshaft;
- Reaction torques in place of the sprocket of suction and exhaust camshaft;
- Reaction torque from the oil pump in place of the pump sprocket.

Behaviour of the chain drive values is not a periodical one through one revolution of the crankshaft or a camshaft and that is why a so called sweep has been selected for the solution. Sweep represents a gradual increase in the angular engine velocity in the given time. In the case of the presented model, sweep is set at 1000–6000 rpm in 10 s.

2.2. Component Models

A complete computational model is composed of individual submodels. The components such as the chain guide or the sprocket are modelled as solid bodies and that is why the following aspects are sufficient: weight, centre of gravity, and the inertia tensor elements. Then, the curve defining the surface of the component is added. The crankshaft or the camshaft can be fitted by means of a hydrodynamic model of the slide bearing.

The contact force between two parts is defined by a modified impact function for a penetration larger than zero (1). The force is zero when there is no penetration.

$$F_{\mathrm{c}} = \max(k\,p^{e} - c\,v, 0)\ , \tag{1}$$

where k is stiffness, e is exponent, p is penetration, v is velocity and c denotes effective damping coefficient with a value of damping, c_{max}, for a penetration larger than penetration depth, d, as shown next figure.

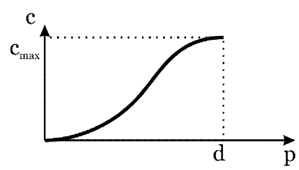

Fig.2: Contact damping characteristics

The actual stiffness values can be detected by contact FEM analysis among different parts of the mechanism. As an example can serve the contact between the pin of the chain link and the sprocket, see Fig. 2. Dependency of the force on the shift is determined in several points. Then the coefficients for equation (1) are set applying the least-squares method and with the use of Matlab software.

The chain model comprises individual parts that are being modelled as solid bodies with six degrees of freedom in general. The individual chain elements are connected by means of

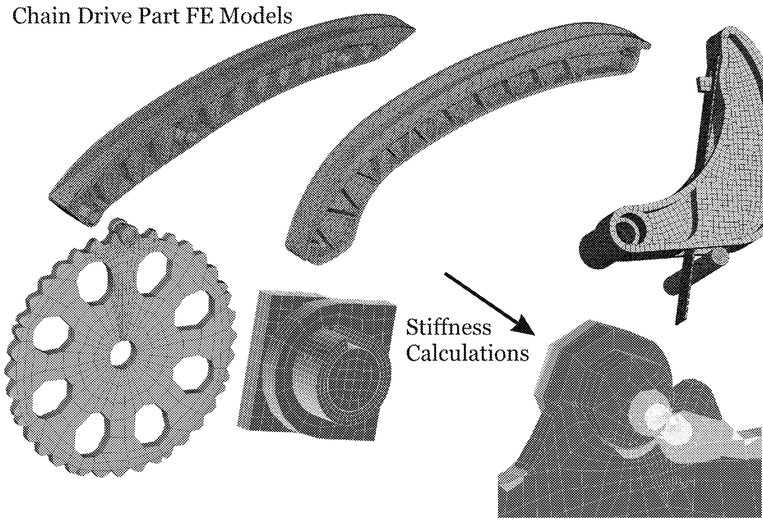

Fig.3: Stiffness calculations of chain drive components

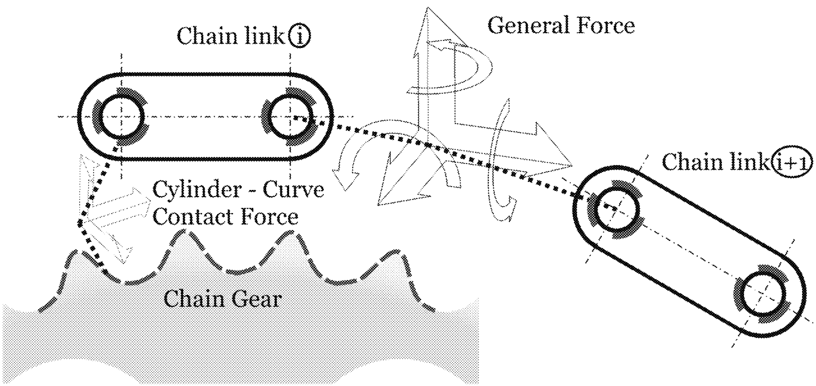

Fig.4: MBS model of chain element

general force element according to the relation:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = \begin{bmatrix} k_{TRAN} & 0 & 0 & 0 & 0 & 0 \\ 0 & k_y & 0 & 0 & 0 & 0 \\ 0 & 0 & k_z & 0 & 0 & 0 \\ 0 & 0 & 0 & k_{rx} & 0 & 0 \\ 0 & 0 & 0 & 0 & k_{ry} & 0 \\ 0 & 0 & 0 & 0 & 0 & k_{rz} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ \varphi_x \\ \varphi_y \\ \varphi_z \end{bmatrix} - \begin{bmatrix} b_{TRAN} & 0 & 0 & 0 & 0 & 0 \\ 0 & b_y & 0 & 0 & 0 & 0 \\ 0 & 0 & b_z & 0 & 0 & 0 \\ 0 & 0 & 0 & b_{rx} & 0 & 0 \\ 0 & 0 & 0 & 0 & b_{ry} & 0 \\ 0 & 0 & 0 & 0 & 0 & b_{ROT} \end{bmatrix} \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \\ \dot{\varphi}_x \\ \dot{\varphi}_y \\ \dot{\varphi}_z \end{bmatrix} . \tag{2}$$

Coefficients k or b represent the stiffness or damping in the given direction. Important is in particular k_{TRAN} that represent the chain element stiffness in the longitudinal direction, then b_{TRAN}, which is damping in the longitudinal direction, as well as b_{ROT} that includes damping moment in the chain rotation around the axis of the element pin.

Each chain element includes also the contact force between the chain pin and the sprocket or the chain guide. All contacts are of a curve-cylinder type.

Left chain guide is being stretched by a hydraulic tensioner. The hydraulic tensioner consists of a system of oil chambers with springs. The computational model has been composed according to Fig. 5. For more detailed information see references [6].

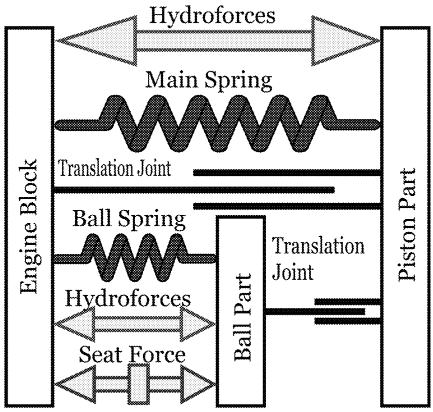

Fig.5: MBS model of hydraulic tensioner

3. Solution

A complex model of chain timing drive is assembled in multi-body system ADAMS. C++ HHT integrator is used for the solution of differential algebraic equations (DAE). The HHT integrator is based on the α-method proposed by H.M. Hilber, T.J.R. Hughes, and R.L. Taylor [1]. The α-method is widely used in the structural dynamics community for the numerical integration of second order ordinary differential equations that are obtained at the end of finite element discretization.

The chain model is very sensitive on integration scheme. The solution error has to be carefully handled otherwise high oscillations that are of no interest or parasitic oscillations that are a byproduct of the finite element discretization process can occur. See references [2] for details about a numerical solution of differential algebraic equations.

In general, chain drives consist of many components which results in models with a high number of DOF. A complete model of the DOHC timing chain drive is composed of approximately 156 chain links, 5 sprockets and 3 chain guides, which means several hundreds of contacts and thus lays high demands on the computer technology.

4. Result Discussion

The polygon effect is one of the main causes of the relatively high noise and vibration level of roller chains and bushing chains. Besides the excitation of longitudinal and transversal vibrations of the chain spans, meshing impacts between the chain links and the sprocket mesh occur. Figure 6 presents chain element contact force during one chain cycle for engine speed 1000 rpm and shows a chain element contact in sequence left guide – intake camshaft sprocket – exhaust camshaft sprocket – right guide – crankshaft sprocket. The contact between the chain and the crankshaft sprocket generates highest contact forces. Figure 7 shows contact force between the chain and a crankshaft sprocket for engine speed 1000 rpm as well. The noise excitation induced by the polygon effect usually occurs predominantly at the meshing frequency of the chain drive (= polygon frequency). If this frequency coincides with a natural frequency of the structure of the engine, resonance occurs which leads to an additional increase in the level of structure borne noise. The resulting disturbing noise is known as whine noise.

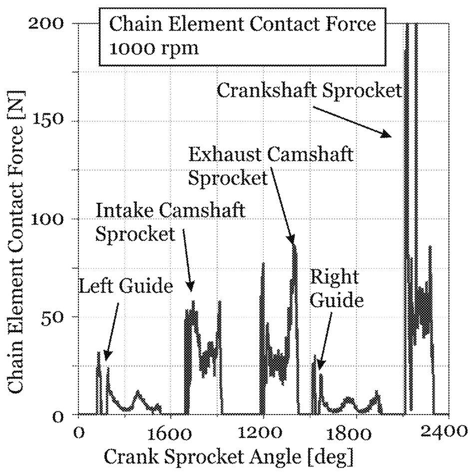

Fig.6: Chain element contact force during one chain cycle

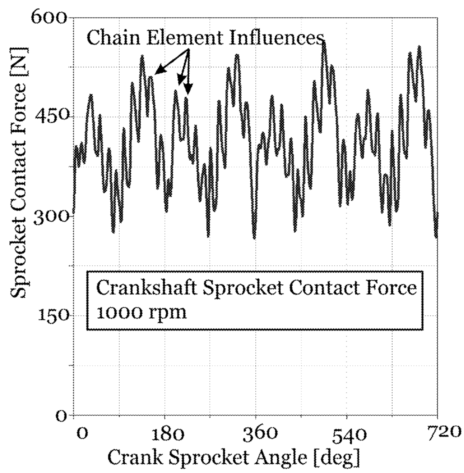

Fig.7: Sprocket-chain element contact force

Figure 8 presents chain tension force and radial force during one cycle for one chain cycle and engine speed 1000 rpm. The given chain span is located directly behind the crankshaft sprocket. The main harmonic order of chain forces bores from crankshaft sprocket vibrations.

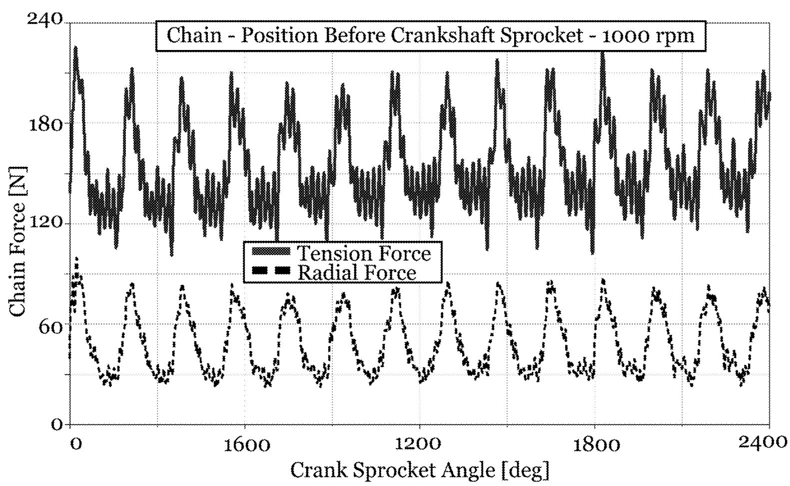

Fig.8: Chain tension force and chain radial force during one chain cycle

For left chain guide angular displacement see Fig. 9, engine speed ranging from 1000 rpm to 6000 rpm.

Tensioner lift as against the engine body can bee found in Fig. 9 presenting the Campbell signal analysis. Increased levels of vibrations are visible there. They correspond especially with the other harmonic component of the angular vibrations in the crankshaft. In the interval of 450 Hz between the engine speed of 4000 rpm and 5000 rpm, another considerable local maximum can be found. This is in accordance with the sixth harmonic component of the torsional vibrations of the crank mechanism.

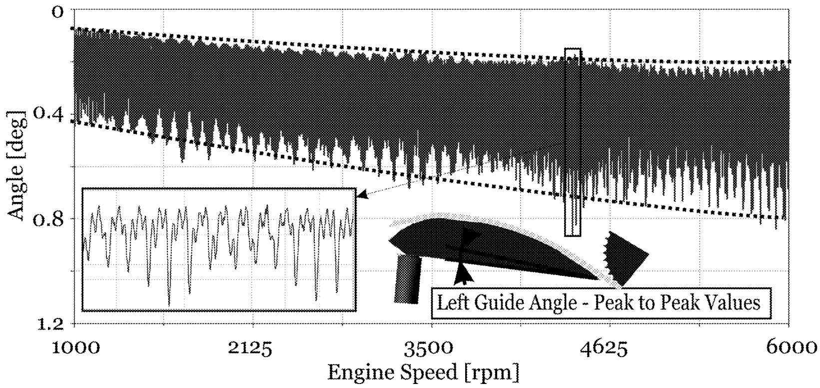

Fig.9: Left chain guide angular displacement

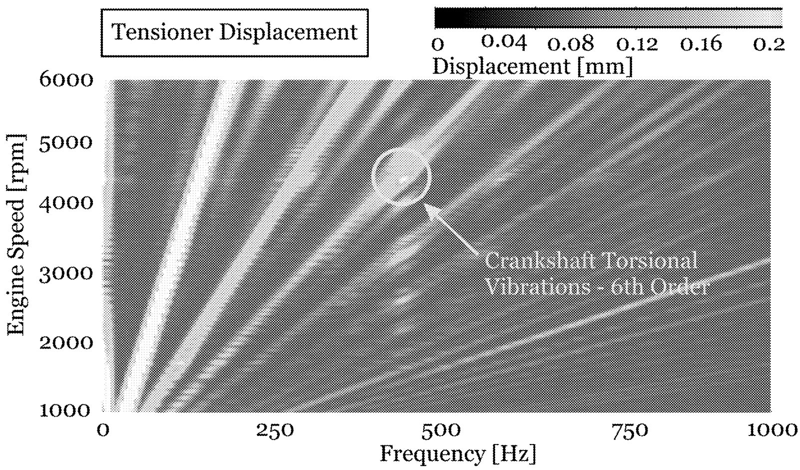

Fig.10: Campbell analysis of tensioner lift

5. Conclusion

Virtual prototypes of the timing chain drive are being created as higher-level computational models based on a multi-body system dynamics. These enable a detailed solution of the timing chain drive dynamics and can find weaknesses of the design before first prototypes are made. They will speed up the development of the timing chain drive with better technical and economic parameters.

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