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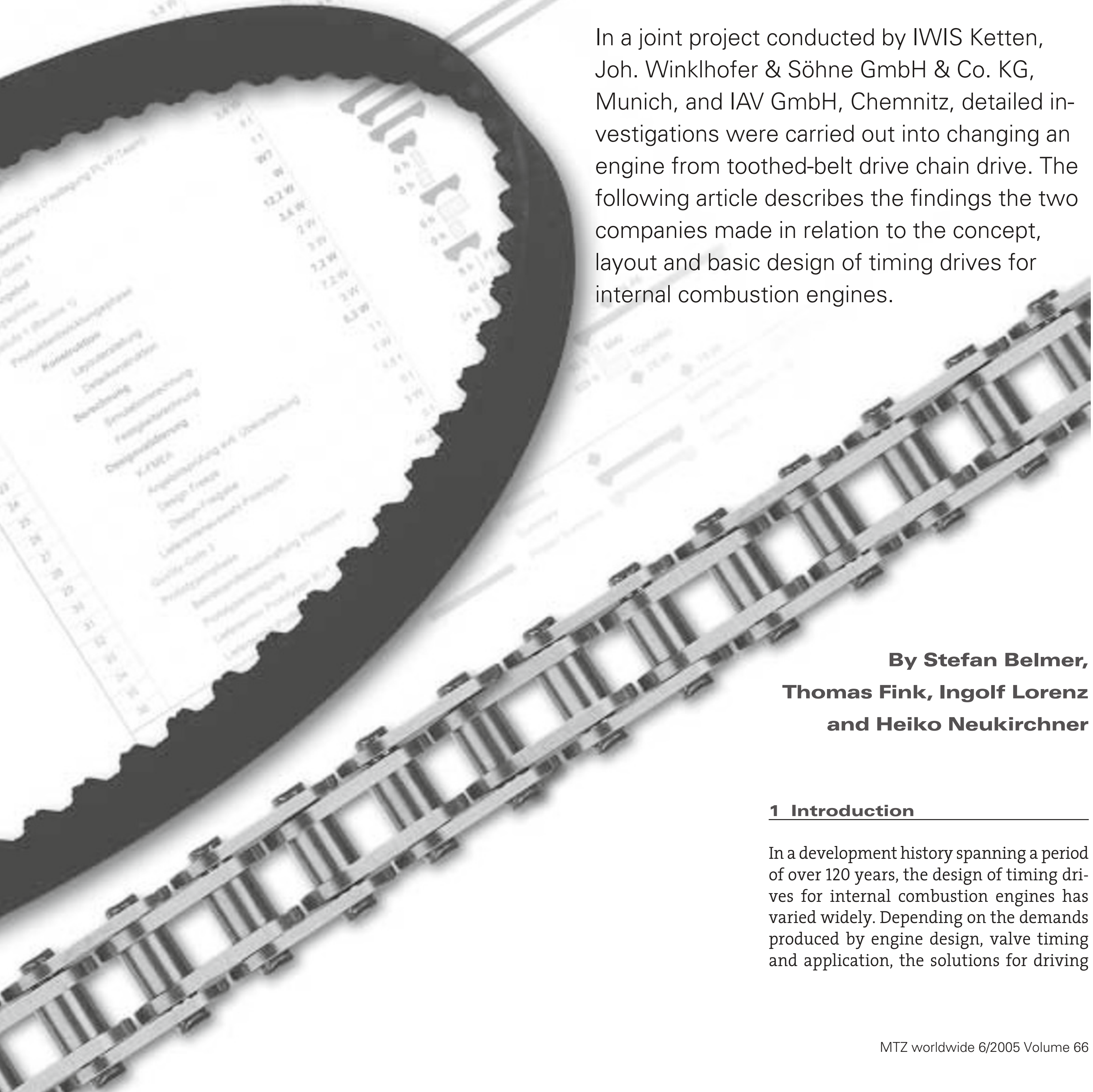
Steuertriebe für Verbrennungsmotoren – Konzeption, Auslegung und Basiskonstruktion

Timing Drives for Internal Combustion Engines

Concept, Layout and Basic Design

In a joint project conducted by IWIS Ketten, Joh. Winklhofer & Söhne GmbH & Co. KG, Munich, and IAV GmbH, Chemnitz, detailed investigations were carried out into changing an engine from toothed-belt drive chain drive. The following article describes the findings the two companies made in relation to the concept, layout and basic design of timing drives for internal combustion engines.



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1 Introduction

In a development history spanning a period of over 120 years, 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. In the high-performance engines of the 1930s and in motorcycles, vertical shafts were a popular choice, **Figure 1**.

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. Gear drives are still used in niche applications for transferring force between the camshafts or to auxiliaries as well as in high-performance engines.

As part of a joint project, IWIS Ketten, Joh. Winklhofer & Söhne GmbH & Co. KG and IAV GmbH have examined in detail the design-related and functional aspects of changing an engine from toothed-belt to chain drive.

2 Task Definition

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 layout 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 4-cylinder 2V in-line spark-ignition engine with belt drive, **Figure 2**. Allowing for existing machining sequences, the engine is to be redesigned and, at the same time, retain its principal dimensions. This rules out any change to the centre distances between crankshaft and camshaft and also demands that engine length stays more or less as it is. Layout of the chain drive is to be 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.

3 Initial Considerations

The desire for engines to require ever less maintenance is one of the main driving forces behind designing new engines. It is, therefore, necessary to examine the camshaft drive with a view to this aspect.

Additional demands on the timing drive arise from the loads that are caused by multi-valve technology, the DOHC configuration as well as the increased use of roller contacts in the valve train and lead to higher levels of oscillating torque. Furthermore, there is a move towards the use of multi-mass flywheels on the gearbox side. These, however, generate higher torsional vibrations at the damper-side end of the crankshaft and thus further add to the load. Higher injection and combustion pressures in DI engines also result in increased levels of oscillating torque in the timing drive.

3.1 Application Conditions

The design-based need to seal the chain drive also prevents the penetration of dust and water – essential from the point of view of wading ability. Normal belt covers with circulating air, however, let these media in and limit service life.

This is why engines with chain drives offer major advantages when it comes to opening up new markets characterised by the following ambient conditions:

- high air-temperature fluctuations with extreme maximums
- high air humidity levels
- dirt roads and sand tracks,
- frequently flooded roads
- high dust levels in the dry season.

3.2 Power Loss

Depending on engine speed, the timing drive and valve train generate approx. 20% of overall friction loss in the engine [1]. Resulting from the operating principle, the friction caused by chain and rails is somewhat higher than in the case of the toothed-belt. Loss distribution in the chain drive is shown in **Figure 3**.

Lubrication nozzles are capable of reducing friction at the chain rails, increasing oil throughput by about 10 per cent at nominal speed.

3.3 Acoustics

Toothed-belt drive systems do not normally require measures to reduce noise. Despite complex acoustic aids, chain drives are unable to match the level of the belt drive. This leaves a differential in the total sound pressure level which is chiefly caused by the metallic impact of the chain roller or bush on the sprocket wheel. Numerous studies show that the type of chain selected can have a positive effect on acoustics.

On many engine designs, acoustics can be improved by using inverted-tooth chains. Meaningful acoustic measures must be defined specifically for the particular engine concerned. Chain drive acoustics can be improved by using rubber-coated sprocket wheels or cushion rings and also by keeping tensioning and guide rails detached from thecrankcase .

3.4 Valve Timing

At levels of up to ± 2 °cam angle, dynamic timing variation for belt drives is much greater than for chain drives. The greater stiffness of the chain produces higher peak forces that expose the timing drive to greater loads. Wear-induced elongation of the chain causes timing to vary over the chain's life. At 2-3 °cam angle, these values are some three times greater than on the belt drive. On the chain drive, the camshaft timing is adjusted (angle advance) in order to compensate for the shift in timing.

3.5 Service Life

Comparing the life expectancy of the two drive mechanisms, the toothed-belt is more likely to fail prematurely and thus cause engine damage [2]. In contrast, chain damage is rare which means that chain drives normally match engine life. This is mainly attributable to the belt material's lower ageing resistance as well as its higher sensitivity to cyclic temperature stress, **Table 1**.

3.6 Installation of Timing Drives

In terms of the applications familiar from mass production, there are, in principle, no major advantages or disadvantages associated with using a belt or chain drive. Timing adjustment as well as the work involved in fitting the sprockets and putting on the drive mechanism are comparable. The chain drive additionally demands the prevention of oil leakage which means that the cover takes longer to fit. Engine assembly times can be reduced in the case of both drive mechanisms by using pre-assembled modules, **Figure 4**.

3.7 Maintenance and Customer Service

To obtain information from practice, surveys were conducted among specialist workshops. Whereas the chain drive is completely maintenance-free, the toothed-belt must be changed at specific intervals on many engines. Using automatic tensioners, no maintenance work is required here between replacement intervals. As the water pump is integrated in the belt drive, changing the water pump is significantly more complicated. Broken belts and resultant engine damage occur far more frequently than damage to chain drives. Chain tensioners develop faults in isolated cases, resulting in complaints about loud noise levels. This allows most engine damage to be prevented before it occurs.

4 Layout and Design

4.1 Chain Drive

A number of criteria must be borne in mind when designing the chain drive. The different chain drive configurations are designed on the basis of geometric relationships as well as a wide range of empirical values. The following basic rules must be applied:

- even number of links
- free chain-run sections, ideally with 3 – 5 chain links
- inward tensioning to keep the chain wound around the sprocket wheel
- large radii on tensioning and guide rails to reduce friction
- optimised tensioning radius at the chain tensioner to take up slack in wear-elongated chain and to compensate for tolerances
- rails mounted so that they “float” on the fixing bolts to reduce noise.

The chain housing can be formed by casting on a chain channel or by means of a cast-on section with cover. Straightforward sealing concepts and the avoidance of “three-component configurations” (points where three adjacent components meet) by creating planar sealing surfaces are the principle features that distinguish optimised designs. It is possible to use the volume gained in the chain housing for the crankcase ventilation system. Low-cost, integrated underbonnet solutions can be employed to replace external ventilation concepts [3].

For assembly reasons, allowance must be made for the space required to access the camshaft fixings when defining the shape of the chain housing. Layout variations with different sprocket teeth numbers, chain pitches, chain lengths and rail geometries provided the basis for changing the engine under study from toothed-belt to chain drive.

IAV GmbH's CAE layout tool, V-CD, **Figure 5**, is ideal for generating layouts. It offers the designer practical, flexible assistance in rapidly modelling system geometry and carrying out kinetostatic calculation. The layout variants shown on a white background in **Table 2** provide favourable kinematic configurations throughout the life of the chain drive without changing the centre distances between camshaft and crankshaft.

In a second step, the DynaKet calculation program developed at IWIS is used to carry out an initial estimate of the loads acting on the chain drive [4]. By exposing the chain drives to reference excitations from the crankshaft as well as to oscillating torque from the valve train, it is possible to derive the resultant dynamic chain forces as well as other important assessment variables (e.g. torsional vibrations, contact forces, chain tensioner oil pressures etc.).

Figure 6 shows the resultant tight strand forces for a 7-mm-pitch bush-type chain as a function of engine speed revved up to 7,500 rpm. The three curves show the maximum, mean and minimum forces for the chain in different states of wear.

At just under 1,400N, it can be seen that the maximum values do not exceed the fatigue strength criterion for the chain selected (i.e. 75% of 2,000N). At no point in the speed range do the minimum forces show a zero transition and, at approx. 250N (just as in the tight strand) lie within a highly acceptable range. The effect of wear-induced elongation on chain forces is negligible in this case.

Figure 7 shows the camshaft's torsional vibration amplitude in the same context. Resonance at 5,500 rpm leads to an overshoot of 0.75 °camshaft which remains unchanged even after wear-induced chain elongation. This value, too, is entirely acceptable for engine operation.

For this reason, the design of the chain drive with 7mm bush-type chain was pursued further as its resistance to wear is significantly higher than that of an inverted-tooth chain. The small chain pitch is also likely to bring about a considerable reduction in the polygon effect and significantly enhance acoustic behaviour. For these reasons and in view of the fact that an inverted-tooth chain drive is more expensive to manufacture, no further consideration was given to inverted-tooth chains in this investigation.

4.2 Cylinder Head and Crankcase Block

4.2.1 Cylinder Head/Cylinder Block and Crankcase

Unlike the belt-timed engine, it is not necessary on the chain-timed engine to seal the camshaft from the timing drive in the vicinity of the cylinder head.

The chain-timed engine incurs slightly higher costs as a result of the additional casting for the chain housing, the material required for a spraying nozzle oil duct and the need to accommodate the chain tensioner.

4.2.2 Cylinder Head Gasket

On the chain-timed engine, an additional seal is required in the area surrounding the cast-on section for the cylinder block and crankcase and for the cylinder head.

4.2.3 Cylinder Head Cover/Ladder Frame

The design of the cylinder head cover on the chain-timed engine under study is new. It has a stiffer ladder frame as well as an oil separator integrated in the cover. Furthermore, it offers a possibility to dispense with a separate cover completely. Aiming primarily to improve function, the newly designed part also incurs a lower level of costs in the “cylinder head cover/ladder frame” combination.

4.3 Auxiliary Drive

The auxiliary drive of the chain-timed engine additionally accommodates the water pump and a deflection pulley, **Figure 8**. Repositioning the water pump permits a longer design and thus allows the water pump housing to be made from plastic. This also creates a larger leakage reservoir (possibility of dispensing with the filter) and provides the option to use switched or electrical solutions. Accommodating the water pump in the auxiliary drive reduces the consequences of failure and makes replacement easier for customer service.

Integration of the water pump in the auxiliary drive and the additional guide pulley produce higher costs in the chain-timed engine. The water pump is more expensive on account of the additional hub with three fixing screws as well as the poly V belt pulley (metal or plastic). The auxiliary’s support, in contrast, has no effect on costs.

4.4 Chain Lubrication and Oil Pump

In contrast to the belt-timed engine, the chain-timed engine uses more oil as a result of chain lubrication. The aim is to ensure lubrication by using the sprayed oil and return flow of oil from the cylinder head. The use of an additional oil spray nozzle generates costs not incurred in the toothed-belt drive.

In the case under study, use of the conventionally mounted oilpump in the chain-timed engine would only necessitate a slight modification to the design of the oil-pump drive. The number of components can also be reduced by using an oil-pump drive without chain tensioner, **Figure 9**.

4.5 Base Engine

4.5.1 Engine Length and -height

Approx. 10-20mm can be taken off the length of the engine by using a chain drive. The chain runs closer to the cylinder crankcase and, transferring the same amount of power, is narrower than a toothed belt. Engine height on the timing drive side is determined by the camshaft sprockets. Toothed-belt sprockets require more space because in comparison with the chain drive a larger number of teeth must be engaged to transfer the same amount of torque.

4.5.2 Comparison of Timing Drive Mass

To compare the masses involved in the two timing drive systems under study, it is necessary to contrast absolute mass and mass moved. It becomes clear that the toothed-belt drive has approx. 2–3 times more mass than the chain drive. Even with cover or housing, the chain drive is approx. 25% lighter than the belt drive, **Table 3**.

Taking into account only the moving parts, the toothed-belt drive is required to accelerate more than twice as much mass as the chain drive. In addition, the moments of inertia for toothed-belt drives are approximately one-and-a-half times greater than in the case of chain drives, **Table 4**.

5 Customer Service

The following examines a number of potential cases for customer service.

5.1 Changing Timing Drive Components

This is where chain timing offers greater advantages as it is designed to match engine life and thus necessitates no scheduled replacement of timing components. Belt-timed engine specifications may demand component replacement at specific intervals (e.g. toothed belt, tensioner pulley, water pump).

5.2 Changing the Poly-V-Belt

Neither engine concept demands any routine component replacement. Ultimately, however, the longer poly-V-belt (integration of water pump and deflection pulley) does give the chain-timed engine a slight edge.

5.3 Changing the Water Pump

As the water pump in the chain-timed engine is positioned in the auxiliary drive, it is easier to change. In contrast to the belt-timed engine, this has the advantage that in the case at hand it can remain untouched.

5.4 Changing the Cylinder Head Gasket

The chain housing makes it more complicated to change the cylinder head gasket on the chain-timed engine. This is where the belt-timed engine scores.

5.5 Leakages

The chain-drive is not affected by oil escaping in the vicinity of the drive housing, cylinder head/cylinder block and crankcase. As the toothed belt is sensitive to oil, conventional toothed belts may fail if they are exposed to oil leaking in this area. Although the newly designed cylinder head cover permits the use of a smaller gasket on the chain-timed engine, the sealing surface is increased to the size of the chain housing. The “three-element configuration” places higher demands on the sealing concept.

5.6 Repair-Workshop Costs

5.6.1 Changing Toothed-Belt/Chain

With the chain-timed engine, the chain incurs no costs as it lasts for life. On the belt-timed engine, however, changing the belt costs between € 100 and € 800. Depending on vehicle type, belts must be changed at intervals ranging between 60,000km and >150,000km.

5.6.2 Changing Water Pump

Changing the water pump on the belt-timed engine costs more than on the chain-timed engine with integrated waterpump because the covers and timing drive are more complicated to remove and re-install. As the water pump is integrated in the timing drive on the belt-timed engine, it is often changed unnecessarily or as a precautionary measure.

6 Cost Assessment

Figure 10 illustrates the newly designed chain drive.

Cost assessment is based on extensive component cost analyses which, however, cannot be published here in detail for understandable reasons. In essence, an assessment of costs shows that the chain-timed engine is cheaper to produce than the belt-timed engine. A further potential saving is produced for the chain-timed engine by using a chain module.

The one-piece chain drive housing is simpler in design than its multiple-component counterpart on the belt-timed engine. It increases the engine’s overall stiffness and the amount of noise it generates can, by implementing appropriate measures, be reduced to a level similar to that of a belt cover. In the engine under study, the one-piece design of the chain drive housing is less expensive than the multi-component toothed-belt guard. The chain drive housing furthermore provides the capability of integrating other components (e.g. oil filter).

7 Summary

This article examines the design, function and cost-related aspects of changing an engine from toothed-belt to chain drive. The investigations provide a comparison, as summarised in tabular form in **Table 5**. A major advantage of the chain-timed engine must be seen in its resistance to environmental influences, making it ideal for use in any climate region. In addition, the chain drive is wade-proof and completely maintenance-free. It takes up less space than a comparable toothed-belt drive and is lower in weight.

If the chain suffers excessive wear, the noise perceived by the vehicle driver serves as an “early warning” of damage. This can prevent engine failure. On the customer-service side, the water pump is easier to change on the chain-timed engine because it is accommodated in the auxiliary drive. Changing over to an electric or switched water pump is easier in design terms than with solutions integrated in the belt drive.

The design work involved in changing over from toothed belt to chain can be kept to a minimum and production can continue on existing facilities. In the example under study, the chain-timed engine offers significant cost benefits over the belt-timed engine. The prospect of reducing component numbers by using integrated solutions, such as cylinder block and crankcase ventilation system, promise further potential cost savings.

The use of well-proven layout and calculation tools at both parties provided the capability of “simultaneous engineering” at different locations. The project exemplifies the way in which component suppliers and development partners can be incorporated into the concept phase of engine development. Drawing on the wealth of experience available at the parties involved and using virtual methods, it was possible in a very short time to develop a set of decision criteria for re-designing the timing drive.

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