Periodica Polytechnica Transportation Engineering, 50(4), pp. 318–329, 2022

Past and Future Practical Solutions for Torsional Vibration Damping in Vehicle Industry

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Received: 01 September 2021, Accepted: 28 March 2022, Published online: 08 June 2022

Abstract
In addition to material and production costs, consumption and emission limits, the requirements for performance, efficiency and space utilization must be met when it comes to the design of today's internal combustion engines for the automotive industry. As a result, three new design trends have been emerged (based on J. Pfleghaar and B. Lohmann's paper in 2013): 1. downsizing: reduction of engine size (number of pistons and stroke) for fuel and space-saving and CO_2 emission reduction purposes, 2. downspeeding: reduction of engine speed to save fuel, which necessarily entails significantly higher torques being generated and transmitted in the engine, 3. turbo supercharging: increasing the pressure and compression ratio in the engine piston cylinder to cover the increased torque demand, which is accompanied by NO_x gas emissions. Due to these new design trends, significant transverse, axial, and torsional oscillations can occur on the engine's crankshaft. To avoid power loss and fatigue due to the torsional oscillations, a torsional vibration damper is advised to be installed on the free end of the crankshaft or integrated into the flywheel. This review paper focuses on the possible reasons for torsional vibrations, the applied methods used to dampen them, and expected future trends.
Keywords
torsional vibration damper, internal combustion engine, rubber damper, spring damper, visco-damper, magnetorheological damper, electromechanical transmission

1 Introduction

Torsional vibration is an angular oscillation caused by a torque, which is a periodic motion on the axis. The rotating crankshaft in an internal combustion engine (ICE) twists in an alternating motion around its own axis largely arising from the unbalanced gas pressure and other additional forces (see Section 1.3 for more detail). To prevent the critical failure of engine elements, related to harmful vibrations, different torsional vibration damper (TVD) solutions can be used. A TVD is usually mounted on the free end of the crankshaft or integrated into the flywheel and consists of a primary and a secondary section. The space between these sections is filled with different types of damping materials.

Since TVDs play important role in vehicle safety, they have a strong business-related and economical background: the reciprocating engines market was valued at US$ 197,803.5 million in 2017 and expected to reach US$ 271,508.6 Million in 2026, growing at a compounded annual growth rate (CAGR) of 6.5% from 2018 to 2026 (Research and Markets, 2018). Although these data were reported before COVID-19, forecasts indicate there will be a recovery sometime after 2023.

Geographically, the global TVD market has been segmented into North America, Europe, China, Japan, India, Southeast Asia, and Rest-of-the-World. Europe retains the largest portion in the global market with its portion of global revenues exceeding 36% in 2017 with China next. The worldwide market for TVD is expected to grow at a CAGR of roughly 2.0% over the next five years, and according to a new study, is expected to reach 2,360 million USD in 2024 (Absolute Reports, 2019).

Main stakeholders (manufacturers) operating in the automotive TVDs market are Geislinger GmbH, FAI

Cite this article as: Venczel, M., Veress, Á., Peredy, Z. (2022) "Past and Future Practical Solutions for Torsional Vibration Damping in Vehicle Industry", Periodica Polytechnica Transportation Engineering, 50(4), pp. 318–329. https://doi.org/10.3311/PPtr.19194

Autoparts, Winkelmann Automotive, Continental AG, and SGF. The passenger vehicle market is expected to hold a prominent share of the TVD market with the utility vehicle being the largest sub-segment, which is expected to hold a higher share while the low production of commercial vehicles makes it a relatively minor share (Transparency Market Research, n.d.).

Before addressing the main types of TVD solutions, it is important to review the reasons, nature and impact of crankshaft vibrations for high-performance ICEs in different vehicle categories. Numerous studies deal with the feature of vibrations, analysing different models and behaviour of TVDs e.g. determining the damping coefficients, excitation torque, dynamical characterization of the system (Meirelles et al., 2007; Mendes et al., 2008) or illustrate the modelling of torsional vibration, with appropriate analytical tools and torsional vibration control, focusing on some promising new research directions (Xingyu et al., 2011) or elaborating algorithms for structural optimisation (Chiliński and Zawisza, 2016; Deng et al., 2018; Lin et al., 2021; Venczel and Veress, 2019).

Besides the traditional gasoline ICEs, some publications focus on minimising the torsional vibration level of ICEs for several specified torque-order frequencies by impacting fuel injections. Common-rail fuel systems are increasingly applied in the automotive industry as well as in marine diesel engines (Östman and Toivonen, 2008).

This paper aims to provide a comprehensive description of TVDs from a historical perspective as well as of the promising future technology solutions that are already being adopted and to make predictions based on emerging trends. This paper focuses on industrial engineering applications instead of prioritizing and highlighting theoretical models.

1.1 Torsional vibration problem of ship engines

Torsional vibration problems emerged first during the intensive application of mechanical engines in ship propulsion. With the proliferation of power-driven boats, problems caused by torsional vibrations have become increasingly apparent.

According to Batrak's (2011) work, the stories about ship shaft breakages were regularly published since 1870. Great Republic steamer (Pacific Mail Steamship Company) had paddle wheel shaft breakage accident several times in 1872. Meanwhile the number of transoceanic steamers with inoperable shafts increased rapidly: 1883 – Germanic (The White Star Line), 1883 – Hellenic (Cunard Line), 1890 – Umbria (Cunard Line), 1893 – Ionic (The White Star Line), 1900 – Eturia (Cunard Line), 1906 – Poland (The White Star Line). This list reflected significant problems beyond this phenomenon. According to the detailed statistical data from the past between 1882–1885 fatal breaks of the shaft lines took place 228 times. Right after the first oceanic diesel motor ship Selandia (East Asiatic Company) was launched in 1912, the number of undesirable accidents multiplied largely due to shaft material fatigue.

At the beginning of the 20th century, comprehensive efforts were taken to take a thorough analysis of the complex nature of the problem. Hans Lorenz's (1901) book related to crankshaft dynamics, and Hermann Frahm's (1902) published research work both investigated the steamers' shaft lines breakage events, G. W. Melville (1903) and S. P. Timoshenko (1905) made significant contribution for discussing and understanding the undesirable propulsion shafting torsional vibration issue.

The scientific papers of Hermann Frahm proved to be fundamental in the field of first analyses of propulsion system torsional vibration. He carried out torsional vibration experiments on Besocki and Radames steamers to get an explanation of the reason for shaft line breakages. He had measured the twisting angle and shaft section twisting velocities precisely and in a reliable manner. It was Frahm who drew the conclusion that the torsional vibration can presumably lead to shaft breakage (Batrak, 2011).

Besides the shaft torsional strength theoretical calculations, practical solutions were greatly needed to detect and keep under control the appearance of different torsional vibration resonances on every ship propulsion system equipped with a reciprocating main engine. In order to identify torsional vibration resonances, torsional vibration excitation frequencies are measured continuously and must be compared with the propulsion system's torsional vibration natural frequencies (Batrak, 2011).

The mathematical calculation of the torsional vibration natural frequencies meant a milestone in the reduction of propulsion shaft breakages. Nowadays, the widely used torsional vibration analyses (TVA) consist of two main parts: free vibration calculation and steady vibration calculation caused by a harmonic excitation (Batrak, 2011).

1.2 Torsional vibration problem of aircrafts' propeller system

The torsional vibration of aircrafts' propeller systems and the fatigue damage to the crankshaft have been a prominent problem since before World War I. In early aircraft designs, engine life was so extremely short that the torsional oscillations arising on the crankshafts could not be recognized, understood and controlled properly. Engineers simply assumed that the damaged engine element was not sized properly for the desired amount of torque to carry based only on gas pressure and inertia force calculations. The vibratory loads were totally neglected (Raymond, 2008).

Several factors can be identified as the sources of oscillations in an aircraft engine such as the rotating propeller itself and the practice of shortening of blades, the electromechanical interaction between the electrical power system and the aircraft's drivetrain, the intermittent combustion and unbalanced inertial forces of the crankshaft or the usage of conversed automotive engine in aircrafts. Different methods were available to mitigate and eliminate the vibration problems of airplanes driven by piston engines. The use of wood and composite (glass fiber reinforced plastic) propellers, instead of metal-blade propellers (which are perfect springs with very little inherent damping), allowed a high degree of internal damping (EPI Inc., 2014).

1.3 Torsional vibration problem of high-performance vehicle engines

The increasing requirements for fuel economy and lower emissions of modern cars have forced new driving solutions. The global original equipment manufacturer (OEM) companies in the automotive and vehicle industry highlighted optimizing the traditional ICEs and developing electrical and hybrid powertrain system concepts to meet the sustainability criteria (Pfleghaar and Lohmann, 2013).

In addition, material and manufacturing costs, consumption and emission limits, the requirements for performance, efficiency and space utilization must be met when designing today's ICEs. As a result, three completely new design trends (Pfleghaar and Lohmann, 2013) have emerged:

1. Downsizing: reduction of engine size (number of pistons and stroke) for fuel and space-saving and CO_2 emission reduction purposes.
2. Downspeeding: reduction of engine speed to save fuel, which necessarily entails significantly higher torques being generated and transmitted in the engine. However, friction losses are smaller at lower speeds.
3. Turbo supercharging: increasing the pressure and compression ratio in the engine's piston cylinder to cover the increased torque demand, which is accompanied by NO_x gas emissions.

Despite the benefits, these efforts had their disadvantages. They enhanced the unbalanced rotation of the engine due to fewer cylinders, lower operating speeds and higher torques. Consequently, the excitation of the drivetrain is multiplied, which proved an undermining factor against the increasing customer demands in noise, insulation and comfort, and led to stability issues of drivetrain components (Pfleghaar and Lohmann, 2013).

The main function of the crankshaft used in ICEs is to convert the alternating motion of the engine pistons into a rotational motion. The crankshafts of multi-cylinder engines are relatively flexible due to their greater length, and the crankshafts are sometimes equipped with minimal or no TVD (Kocsis, 2020).

Running a multi-cylinder combustion engine causes vibrations, which have a direct and negative impact on the lifetime of the engine's components in the whole propulsion system. Periodically varying gas forces and the inertia forces arising from the mass of rotating and moving engine components in the cylinders produce torque. The relative motion of the crankshaft masses occurs due to the firing interval angle of each cylinder that results in a relative change in the torque of every crank. As a result:

- transverse vibrations
- axial vibrations
- torsional vibrations

occur on the shaft which cause changeable different deformations of the flexible engine crankshaft as you can see in Fig. 1 (Homik, 2010).

Transverse vibrations result in bending deformations of the crankshaft between the main bearings. Nevertheless, the bending deformations are relatively harmless because of the crankshaft's low transverse flexibility arising from the bearing in the engine's body. Every single crank of the shaft must be supported by bearings. Due to the applied crankshaft's design method, axial vibrations have also rarely impacted the engine (Homik, 2010).

Torsional vibrations, however, are common phenomenon on the crankshaft of high-performance ICEs for the following reasons:

- a crankshaft slider-crank mechanism connecting the crank and the piston causes an alternating torque due to wear
- the cylinder pressure caused by the internal combustion process is not uniform
- the mass of the connected crank and piston generates alternating torque during movement.

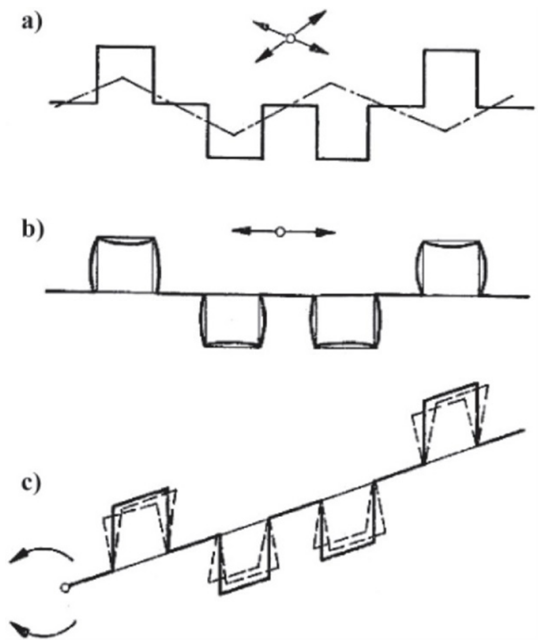

Fig. 1 Different types of vibration on the crankshaft: a) transverse, b) axial, c) torsional (Homik, 2010:p.62, Fig. 1, Copyright © 2010 by Sciendo, Reprinted by Permission of Polish Maritime Research)

Torsional vibrations can be significantly complicated to perceive compared to the previously introduced vibrations. Imposed on the rotation of the shaft torsional vibrations usually do not cause major buckling vibration of neighbouring elements, they do not mean source of noise, and therefore cannot be seen until the shaft's fatigue damage moments. Their existence can often indicate the lack of uniformity in the engine's operation, in which a timing system using a mechanical transmission (belt, chain, gear) driven by the crankshaft is loaded with torsional vibrations (Homik, 2014).

Uncontrolled torsional vibrations can cause the fracture of components, the failure of the shaft or the strap and lead to excessive wear on bearings and gear components (Kocsis, 2020).

The frequency of time changing torque of the engine raises with increasing shaft speed and with an increasing number of cylinders due to changing gas pressure in each cylinder, while the engine shaft-system has its own natural frequency of torsional vibration. In addition, when the engine system is launched, the frequencies of the excitation pass the natural frequencies of the torsional shaft in general before the target speed is reached. As a result, the torsional resonance of the shaft occurs every time it starts to operate (Vibration Database (v_BASE) Committee, 2018).

Provided that the frequency of the torsional oscillations on the crankshaft matches with the torsional natural frequency of the shaft, a torsional resonance occurs. As a result:

- The uneven running of the engine increases and its service life decreases.
- Oscillations transmitted from the drive (e.g. belt) to the driven units (compressor, cooler, generator, fuel supply) cause overload and impede their operation.
- Fatigue damage of the shaft occurs.

Detuning the excitation frequency of k^{th} harmonic far away from the natural torsional frequency of the engine's crankshaft would be a good solution for high-performance engines. However, considering engineering principles, changing the engine rotational speed (operation speed), changing the course of excitation forces, and changing the natural frequency of the entire system would be difficult to implement. Thus, engine developers continuously search for alternative ways to perform an intermediate solution (Homik, 2010).

One way to prevent damage, accidents and malfunctions is to perform vibration calculations on the shafts and design them correctly. This operation eliminates common faults such as gear wear or weight imbalance. Key information determined by calculations (Kocsis, 2020) are:

- types of crankshaft vibration and determination of natural frequency
- determination of critical speeds and resonance locations
- determination of vibration amplitudes and torsional stresses
- identifying repair options for impermissible torsional vibrations.

Another way of prevention is the usage of TVDs as the cost of a shaft breakage can remarkably exceed the price of a damper device needed to avoid damage (Kocsis, 2020).

2 Effective damping solutions

The cutting-edge TVD systems, like the commonly used Dual Mass Flywheel, have reached their limits, so new types of damping devices are being developed. The OEM companies are strongly interested in those new solutions, which are preferably passive, simple, efficient, and cost-optimised. On the other hand, active solutions should be highlighted as an active system can be used in a more comprehensive way. For example, not just to improve the damping of rotational imbalances of the engine but also the damping of oscillations related to load steps or start/

stop processes. Different active solutions usually mean remarkably better damping performance because an actuator can be used to generate arbitrary forces (Pfleghaar and Lohmann, 2013). A properly designed and installed TVD is able to reduce the resonant amplitude of torsional vibrations even by ten times. Nevertheless, every TVD decreases the engine's effective performance by a certain ratio (Homik, 2010).

Currently, different TVD types are available such as frictional, rubber, spring or viscous, but each one's common feature is that the kinetic energy of crankshaft torsional vibrations is absorbed by a flexible or degradable element and then transformed into deformation and heat. Such vibration dampers are widespread throughout the world and are widely used in high-performance reciprocating engines in the military, transportation, architectural, agricultural, and mining sectors. In the automotive and vehicle industry, the viscous version is playing a dominant role not only in aircraft engines but in heavy duty piston engines, sports cars, trucks and ships as well due to its simplicity and low maintenance costs (Kocsis, 2020).

In TVDs inertia force is used to minimise torsional vibrations. Many different design solutions have different operational characteristics. Besides the applied design solution, their technical state is crucial for the effectiveness, which is largely impacted by the operational circumstances of the engine, under which the damper is running. Since TVDs operate mainly under periodically changeable circumstances (e.g. changeable rotational speed) or changeable ambient circumstances the dampers should be regularly diagnosed to provide the proper operation of the engine (Homik, 2010).

2.1 Frictional damper

Frictional damper was the very first type of TVD. As shown in Fig. 2, the hub is rigidly attached to the shaft, while the inertia ring is pressed against the hub by tension springs. There is a frictional connection between the hub and the ring provided by inserts. Above a certain speed of jerking, the tension spring releases the inertia ring, which begins to move relative to the hub. Then the torsional torque of the inertia force is greater than the torsional torque due to friction. The oscillation is converted into heat by friction and dissipated into the environment.

Monitoring of TVD's friction is usually limited to checking friction surfaces' quality and holding downforce of linings with the use of the tension springs.

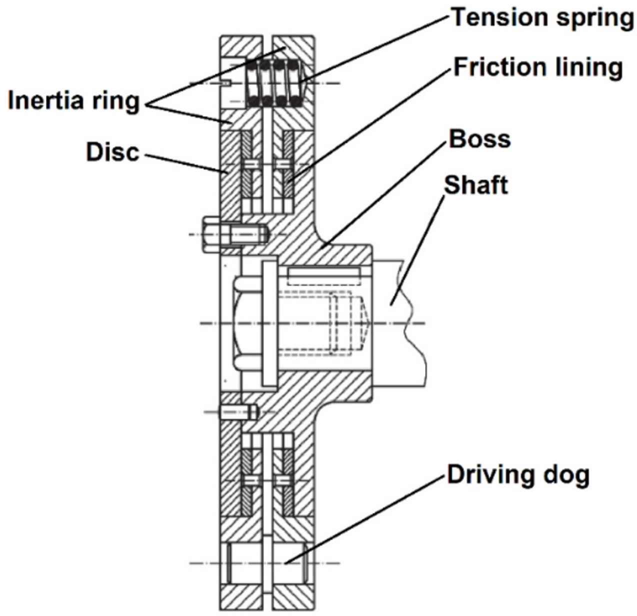

Fig. 2 Structure of a frictional TVD (Homik, 2010:p.64, Fig. 4, Copyright © 2010 by Sciendo, Reprinted by Permission of Polish Maritime Research)

The service time of this damping device is determined by the service life of the friction pads, the friction torque decreases as the pads wear. This type of damper fell short of expectations and was replaced by another type.

2.2 Rubber damper

Rubber dampers can be divided into three parts (see Fig. 3 and Fig. 4), which are separated by vibration-absorbing rubbers: one rubber dampens the torsional oscillations between the inner hub and the outer hub, and the other rubber dampens the harmonic vibrations between the inner hub and the inertia ring. The rubber TVD includes the boss and plunger connected to each other with the use of the rubber ring possessing an appropriate hardness, flexibility and internal damping. The structure itself is

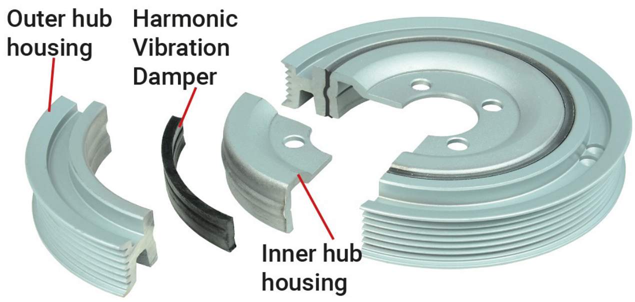

Fig. 3 Main elements of a rubber TVD (FAI Auto Parts, n.d., Copyright © by FAI Automotive Plc, Reprinted by Permission of FAI Automotive Plc)

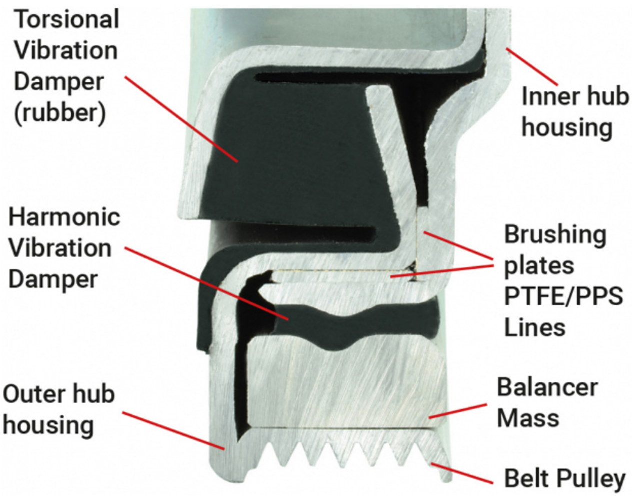

Fig. 4 Cross-section of a rubber TVD (FAI Auto Parts, n.d., Copyright © by FAI Automotive Plc, Reprinted by Permission of FAI Automotive Plc)

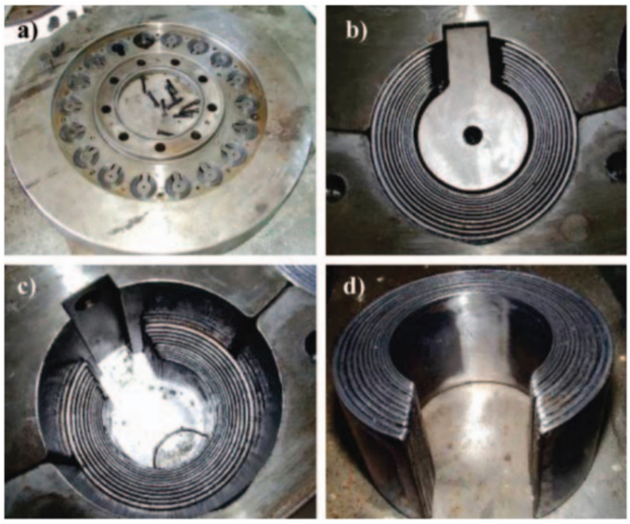

Fig. 5 Coil spring TVD: a) assembly, b) two packets of spring in a socket, c) one packet of spring in a socket, d) packet of spring (Homik, 2010:p.67, Fig. 11, Copyright © 2010 by Sciendo, Reprinted by Permission of Polish Maritime Research)

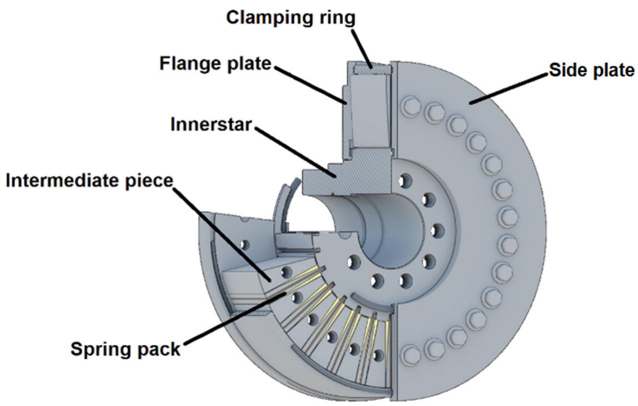

Fig. 6 Radial disc spring TVD (Geislinger GmbH, 2020:Fig. 1, Copyright © 2020 by Geislinger GmbH, Reprinted by Permission of Geislinger GmbH)

a self-contained oscillating system with its own frequency, the alignment of which is a very delicate task. The blind holes in the hub help balance the device.

Hidden fears and reluctance of many engine manufacturing companies against wide usage of rubber dampers can be related to difficulties in the design and in the instability of the mechanical rubber properties caused by manufacturing tolerances, the operating temperature range and the aging tendency of the rubber. High operating temperatures accelerate the wear process and amplify the amplitude of unwanted oscillations. Aging of the rubber occurs over time in the presence of oxygen and ozone (from the air) which make the rubber brittle.

These obstacles can be overcome with the replacement of the rubber with another suitable viscoelastic material. In the absence of stable physical properties of rubber, this type of damping has been replaced since the 1950s (Píštěk et al., 2018).

2.3 Spring damper

The first spring TVD was manufactured in 1962 and mounted on a marine engine shaft. The elastic connection between the hub and the inertia ring is provided by a coil spring (see Fig. 5) or a radial disc spring (see Fig. 6). In the latter case, the gap between the springs is filled with high-pressure hydraulic oil. They have smaller dimensions, greater resistance to mechanical failure and fatigue, longer service life, once-a-year maintenance and higher allowable operating temperatures compared to the rubber TVDs. Over time, there is no aging and the degree of attenuation does not change. Nowadays, this type of damper is mainly used on the shafts of marine engines and in power plants.

2.4 Viscous damper

Viscous TVD or visco-damper is one of the simplest solutions in damping technology, based on the usage of silicone oil – linear polydimethylsiloxanes (PDMS) – which behaves as non-Newtonian fluid responding differently to external effects compared to other conventional (Newtonian) fluids. A viscous damper, as it can be seen in Fig. 7, consists of a housing enclosing a freely moving inertia ring. While the ring spins inside the housing, the narrow gap between the ring and housing is filled with high viscosity silicone oil.

Torsional vibrations of governors of 3000 horsepower submarine engines were managed to be significantly reduced after the application of viscous TVDs in the U.S. shipbuilding industry in 1929. However, the viscosity of early silicone oils produced from organic compounds

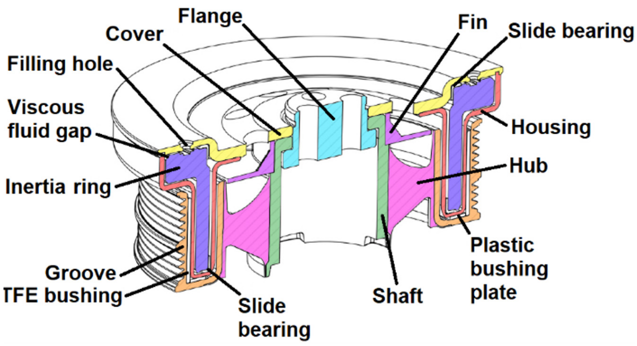

Fig. 7 Inner structure of a viscous TVD (FAI Auto Parts, 2017, Copyright © 2017 by FAI Automotive Plc, Reprinted by Permission of FAI Automotive Plc)

was dramatically decreasing by increasing the damper's operational temperature. The high operational temperature had also a decisive impact on oil aging, besides the damper's reliability and lifetime. This heavy shortcoming of the viscous TVDs resulted in reluctance from their wide usage for a long time. The negative attitude changed, when Dow Corning Corporation introduced silicone oils with higher thermal, mechanical and chemical stability on the market at the end of the 1950s, the physical features of which met all the technical parameter requirements for dampers. The "renewed" visco-damper with its enhanced effectiveness rapidly crowded out the previously used frictional and rubber dampers on the vehicle industry market (Homik, 2010). Nowadays, visco-dampers are considered primary vehicle components from the operation and safety point of view (Hasse & Wrede GmbH, 2013).

During the damping process, if the crankshaft rotates unhindered without oscillations, the inertia ring also rotates together with the housing in sync. When any minor torsional oscillation takes place, the housing and the ring begin to rotate differently from each other while circumferential shear stress emerges in the oil. The damping effect is the sum of generated shear stress on the friction surfaces between the housing/cover and the ring. The differing velocity of the housing/cover and the ring influences the viscosity and the damping characteristics of the oil: higher velocity causes higher shear stress and lower viscosity at the same time. This damping torque significantly reduces the torsional vibration amplitudes preventing the crankshaft from fatal fatigue.

Based on Andrä and Spurk's (1982) work, the damper's performance can be enhanced if the maximum level of energy dissipation is reached by applying such kind of damper where the product of damping constant and shear viscosity divided by the product of effective shear modulus and moment of inertia ring equals to one. Research revealed, when PDMS is used as damping fluid, the dissipated energy can be up to twice compared to the maximum dissipated energy with Newtonian fluids. Due to the previous facts, only visco-dampers filled with silicone oils can effectively minimise the harmful torsional vibrations in the whole frequency and operational speed ranges.

While the oscillations, as excess kinetic energy on the shaft, are absorbed by fluid damping and dissipated from the system in form of heat, the damping medium is suffering from extensive thermal load (arising from the friction and shearing of the PDMS layers), which is the main lifetime shortening factor of visco-dampers. At high temperatures, thermal degradation process occurs in the silicone oil, when its molecular structure changes, the molecular chains rupture, and the viscosity of the oil decreases permanently, making it no longer able to perform its lubrication and damping functions (Camino et al., 2002).

At the end of silicone oil's lifetime, impacted by operating time and application circumstances, a gelling phase appears. Further application of the aged oil leads to an increase in viscosity and to the formation of solid mass. Either too low or too high viscosity deteriorates the oil's damping function. The aged oil can cause serious damage to the system, which is aimed to be protected by the damper.

According to comprehensive feedback from customers, classification societies and Hasse & Wrede's business for a long time, a damper's functionality based on requirements is defined within −30% to +10% of the nominal value range of the viscosity (Hasse & Wrede, 2013).

3 Patented inventions and potential applications of torsional vibration dampers

Besides the four main damper types introduced in the previous section, patented inventions, a new application field and pioneering ideas for new types of TVD are available.

The invention of Freund et al. (2014) focuses on spring damper between driving systems and aims to dampen the input and output vibrations and balance the torque vibrations, performing excellent damping properties and enabling an angle of rotation exceeding +/−30° of the two shaft ends. Based on Fig. 8, the TVD (1) is installed between the left rotary shaft (4) and the right rotary shaft (5) which can rotate relative to each other with an axially displaceable coupling part (3) in the housing (2). The left and the right rotary shafts are connected to the coupling part by way of the left rigid coupling elements (4.1) and the right rigid coupling elements (5.1) which are mounted in

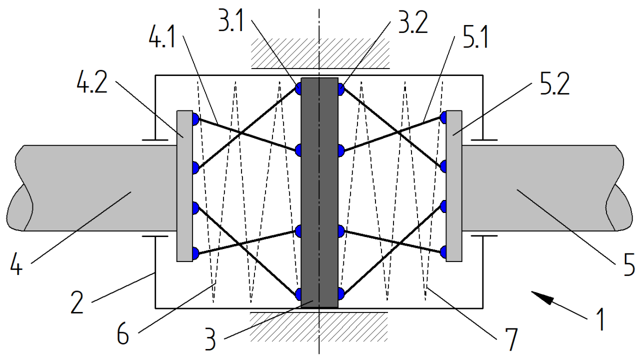

Fig. 8 Sketch of a TVD invention with compression spring and coupling part

a rotatable manner. The left rigid coupling elements are designed as ball bars and are rotatably mounted, on the one hand, with their ball-shaped ends in a left receptacle (4.2) of the left rotary shaft, and on the other hand, in a receptacle (3.1) of the coupling part. Similar to the left side of the figure, the right rigid coupling elements are rotatably mounted in the right receptacle (5.2) of the right rotary shaft and in a receptacle (3.2) of the coupling part. The left and right coupling elements can transmit torques between the rotary shafts. In order to damp the torsional vibrations, a left compression spring (6) is arranged between the left receptacle and the coupling part, and a right compression spring (7) sits between the right receptacle and the coupling part (Freund et al., 2014).

Another invention (Feldmeier, 2013) relates to a TVD for coupling two machine parts (e.g. motor shaft and pulley) disposed coaxially to each other. The goal of the patented invention is to make available simply constructed and at the same time effective TVD and advantageously mounted motor shaft. As presented in Fig. 9 and Fig. 10, the TVD (1) is built up from a multiplicity of clamping bodies (2) and intermediate elements (3) as elastic material with high internal damping (e.g. natural rubbers). The TVD is arranged between a cylindrical outer surface of the motor shaft (4) and a cylindrical inner surface of the pulley (5 and 6). The TVD permits the transmission of torques between the pulley and the motor shaft and eliminates the unwanted torsional oscillations on the shaft as well (Feldmeier, 2013).

3.1 New application field in electromechanics

Electromechanical transmission (EMT) can be an adequate response for the electric drive of heavy-duty vehicles. Torsional vibration is one of the serious obstacles in front of development of mechanical and electrical composite power train systems. During the driving process,

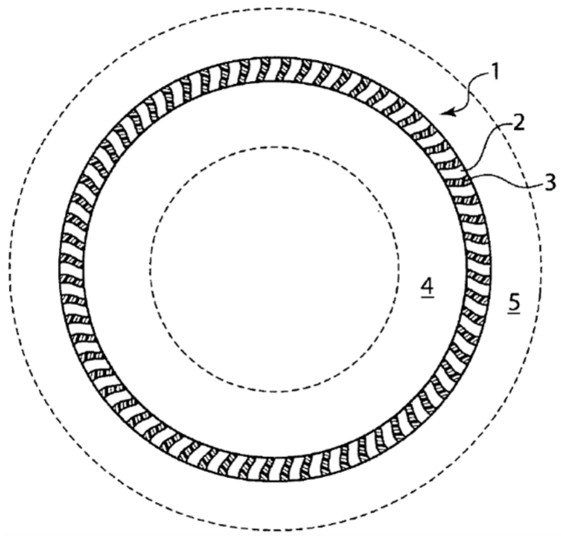

Fig. 9 TVD invention for coupling two machine parts (Feldmeier, 2013:p.2, Fig. 1, Copyright © 2013 by GMN Paul Müller Industrie GmbH & CO. KG, Reprinted by Permission of GMN Paul Müller Industrie GmbH & CO. KG)

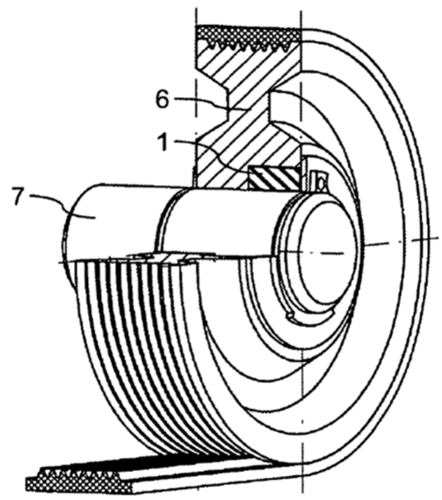

Fig. 10 TVD invention for coupling a motor shaft and a pulley (Feldmeier, 2013:p.4, Fig. 6, Copyright © 2013 by GMN Paul Müller Industrie GmbH & CO. KG, Reprinted by Permission of GMN Paul Müller Industrie GmbH & CO. KG)

the factors that cause the load changes, or the torsional vibration of the system are many and varied including the excitation force of the engine, the excitation of the pavement, and the imbalance of the wheel (Chen et al., 2016).

EMT with undesirable torsional oscillation can be found not only in Hybrid Electric Vehicles (HEV) but in Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV) and Range Extended Electric Vehicles (REEV) as well. HEV means conventional engine and a battery-powered electric motor assisting the conventional engine during, e.g. vehicle acceleration. BEV powered by a battery alone, also has a greater number of specialised components than conventional vehicles. PHEV means an electric motor and an ICE designed to work either together or separately. The onboard battery can be charged from the grid, and the combustion engine helps the electric motor when higher operating power is necessary or when the battery's state of charge is low. REEVs drive with e-motor only, while ICE & plugin (or fuel cell) is used to recharge the battery (Dziuba et al., 2018).

HEVs have been widely adopted by the automotive and vehicle industry as a solution to improve fuel efficiency and extend driving distance. The configuration is more complicated, if the design is not properly executed torsional vibration problems are more likely to occur, such as TVD damage and broken shafts, but it also provides a new means for torsional vibration control including applications of different dampers. Motor output torque fluctuations are mainly composed of electromagnetic torque and cogging torque. Due to the presence of an electric field, the magnetorheological (MR) damper, currently in the experimental (testing and validation) phase seems the most obvious solution (Zhong et al., 2019).

3.2 Magnetorheological damper

The usage of MR fluids has spread rapidly in civil engineering, safety engineering, transportation, and life science with the development of MR fluid-based devices, particularly MR fluid dampers. The MR fluid dampers could offer high performance in semiactive vibration control due to excellent dynamical properties such as quick response, environmentally robust characteristics, large force capacity, low power consumption, and simple interfaces between electronic input and mechanical output (Zhu et al., 2012).

MR fluids are smart fluids the apparent viscosity of which changes when subjected to a magnetic field, to the point of becoming a viscoelastic solid. The yield stress of the fluid in its active state can be regulated precisely by changing the magnetic field intensity and its ability to transmit force (Jilani, 2015).

The fundamental consideration of MR fluid technology is that micrometer or nanometer-size particles having magnetizing properties are introduced in the base fluid. If a magnetic field is applied to this fluid, the microscopic particles adjust themselves among the lines of magnetic flux. The resulting chains of particles restrict the movement of fluid, perpendicular to the direction of flux, effectively increasing its viscosity. Mechanical properties of the fluid in its "on" state are anisotropic. In the absence of a magnetic field, the MR fluids behave like conventional Newtonian fluids and the rheological properties of the MR fluid are similar to that of the base fluid except that it is slightly thicker due to the presence of metal particles. When a magnetic field is applied each metal particle becomes a dipole aligning itself along the direction of the magnetic field. Thus, a chain-like structure is formed along the line of magnetic flux which offers mechanical resistance to the flow. The behavior of MR fluid under the applied external field can be described by the Bingham plastic model. The chains of particles resist a certain level of shear stress and break when the shear stress exceeds a critical value called apparent yield stress of the material. The yield stress is important in many applications and depends on the volume fraction of magnetic particles, particle distribution and applied magnetic field (Baranwal and Deshmukh, 2012).

MR liquids are non-colloidal suspensions of micro-sized magnetisable particles in an inert base fluid with some additives. The three main components of an MR fluid in detail are discussed (Baranwal and Deshmukh, 2012) as follows:

1. Base fluid
   The base fluid with natural lubrication and damping characteristics, possessing low viscosity that does not change with the temperature, is an inert or non-magnetic carrier fluid in which the metal components are suspended. The most widely applied base fluids are hydrocarbon oils, mineral oils and silicone oils (Baranwal and Deshmukh, 2012).
2. Metal particles
   Metal particles are used for easy and quick magnetization. Widely applied metal particles used to be carbonyl iron, powder iron and iron-cobalt alloys with an approximate size of the order of 1 μm to 10 μm. Metal ingredients possess high magnetic saturation, and they are capable of forming a strong magnetized chain. The concentration of magnetic components in the base fluid can reach 50% (Baranwal and Deshmukh, 2012).
3. Additives
   A frequent problem in MR fluids is the tendency of the active magnetic particles to aggregate and settle down, disturbing the homogeneity of the MR fluid. Surfactants are used to eliminate or minimise this sedimentation effect. Stabilizers can also be used as additives for controlling the viscosity of the fluid, maintaining friction between metal particles and to decrease the rate of thickening of the fluid for prolonged usage (Baranwal and Deshmukh, 2012).

The MR damper includes components with different material properties (one can deal with ferromagnetic or paramagnetic materials), therefore the MR damper magnetic field distribution calculation must be implemented with design, analysis and verification (Abouobaia et al., 2016).

3.3 Hybrid CPVA-MR damper

While traditional centrifugal pendulum vibration absorbers (CPVA) have been widely used in eliminating torsional vibrations in rotating machinery, MR dampers have been taken into consideration as the most promising new devices to keep under control of undesirable torsional vibration in the future. By integrating the two different damping systems, an effective hybrid CPVA-MR TVD can be achieved as reported in Abouobaia et al.'s (2016) article. According to Fig. 11, the rotor shaft is connected to the MR damper housing and they are rotating together at the same speed. The rotary MR damper is a floating disk inside the cylindrical cavity filled with MR fluid rotating unhindered relative to the housing, generating controllable damping friction torque. The magnitude of the damping torque can be regulated by the current in the electromagnetic coil of the damper.

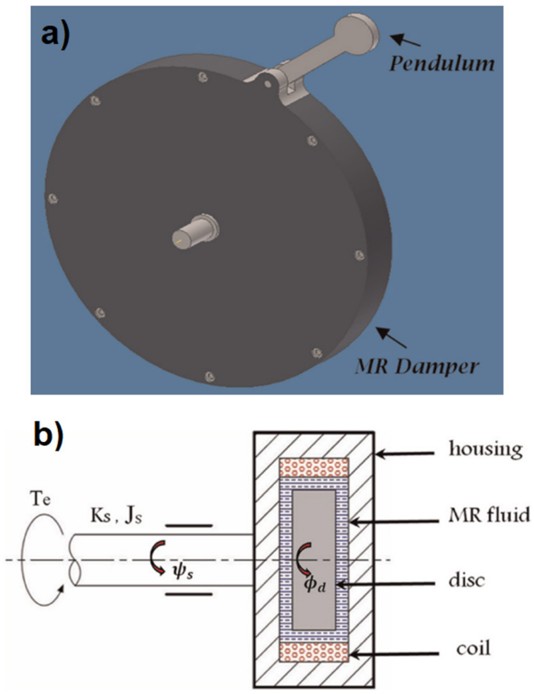

Fig. 11 Schematic a) and structure b) of a hybrid CPVA-MR TVD (Abouobaia et al., 2016:p.4, Fig. 2 and Fig. 3, Copyright © 2016 by SAGE Publications, Reprinted by Permission of SAGE Publications)

The driving shaft is directly linked to the damper housing rotating together, while the disk inside the housing is freely rotated relative to the housing. The centrifugal pendulum is attached to the cylindrical housing of the MR rotary damper by a pin that can rotate undisturbed in a plane perpendicular to the axis of rotation. Properly designed pendulum length, based on the resonance tuning condition, provides an optimum reduction in torsional vibration amplitude (Abouobaia et al., 2016).

Currently, the MR damping technology is in the experimental stage, but it can provide promising replacement alternatives for viscous dampers in the near future.

4 Conclusions

This review paper aimed to provide a comprehensive landscape about the possible reasons for emerging torsional vibrations in the vehicle engines, to discuss the applied methods and engineering devices used to dampen these undesirable vibrations and to outline the actual research fields and trends of TVD's developments and applications at the same time.

In the everyday practice in the field of automotive and vehicle industry, the emerging torsional vibration in the ICEs occurs as a consequence of downsizing, downspeeding and turbo supercharging of the engines. The reasons behind torsion vibrations are the alternating torque generated on the crankshaft during operation. These undesirable and not easily detectable torsion vibrations can lead to fatigue damage of the shaft, therefore damping of these vibrations is crucial for the stable engine operation and the prolonging of engine parts' lifecycle.

The torsional vibration is also the largest barrier hindering development of mechanical and electrical composite transmission systems. Damping technologies have become more and more mature towards eliminating the harmful oscillations of the crankshaft. During the past few decades, different TVD devices were developed and taken into practice including friction, rubber, spring and viscous dampers and each has several drawbacks along with their advantages.

When designing any TVD, it is necessary to take into consideration not only the mechanical and fluid dynamic parameters but also the thermal effects of the dissipated power in the damper. This type of dissipated power is a part of the total mechanical losses in the drive unit. Proper selection of a TVD type can lead to a comparable mechanical loss reduction.

The application fields of torsional vibration dampers are broadening as technology and material sciences allow us the usage of modern design theories in the vibration control field. A new promising field can be the application of MR dampers and hybrid CPVA-MR dampers for semi-active control of torsional vibration in the future despite the fact that the problem in MR fluids is the tendency of the active magnetic particles to aggregate and settle down, disturbing the homogeneity of the MR fluid.

Acknowledgments

The completion of the present study was supported by the Pro Progressio Foundation and has been realized with a subsidy of the Basic research project in the field of laser-beam – technologies and energy at the Edutus College, complemented by knowledge transfer and activities aimed at enhancing enterprises linkages and social engagement. Project identification No.: EFOP-3.6.1-16-2016-000.

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