

Innovative Torsional Vibration Reduction Devices - Vehicle-Related Design and Component Strength Analysis

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ABSTRACT

Downsizing and downspeeding are currently important development approaches of the automobile industry to improve fuel efficiency and to reduce emissions. Decreased operational speeds in combination with higher combustion pressures lead to an increase of the excitation of torsional vibrations by the combustion engine. Torsional vibrations in powertrains can cause strength and NVH problems as well as lower driving comfort and reliability of the vehicle. Currently, conventional systems for reduction of torsional vibrations are increasingly reaching their limits.

In cooperation with several institutes of the Technische Universität München (TUM) innovative concepts for an improved reduction of torsional vibrations in automotive powertrains have been developed. Several of those concepts have been realized as prototype assemblies engineered by the Gear Research Centre (FZG). ([6], [7], [8], [12], [13], [14])

During the design process, different challenges with regard to mass, mass moment of inertia and space demands have to be considered to ensure system performance and to meet vehicle-related requirements. Demands of prototype assemblies regarding modularity and installation interfaces to the available testing environment have to be considered as well. The demanding, partially atypical and dynamic mechanical loads of the components require both analytical and FEA-based strength analysis attending to the design process of the prototype assembly. With regard to bearings and gears with oscillating load, several steps of design and strength analysis have to be performed.

Selected systems are presented in concept with special regard to their prototype designs. Selected design steps and performed strength calculations for major components used in the developed torsional vibration reduction devices are introduced.

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TORSIONAL VIBRATIONS IN AUTOMOTIVE POWERTRAINS

The automotive industry is currently facing major challenges with regard to the reduction of emissions and fuel consumption. Requirements on fuel-efficiency and strict emission regulations have led to the development of small combustion engines with low numbers of cylinders and low operational speeds. Downsizing and downspeeding are the most important development approaches to encounter the CO₂ reduction targets.

Excitation of Torsional Vibrations

Downsizing of engines is characterized by low engine displacements and frequently by low numbers of cylinders as well. Downspeeding is characterized by low engine speeds in combination with high mean torques by supercharging in order to provide sufficient driving performance.

With downsizing and downspeeding there is an increase of the excitation of torsional vibrations by the combustion engine. High peak torques and dynamic torque fluctuation in combination with high mean torque can result in problems with NVH and component strength. Therefore, torsional vibration reduction systems are attached onto the engine crankshaft to reduce the dynamic torque fluctuation acting on the powertrain (Fig. 1).

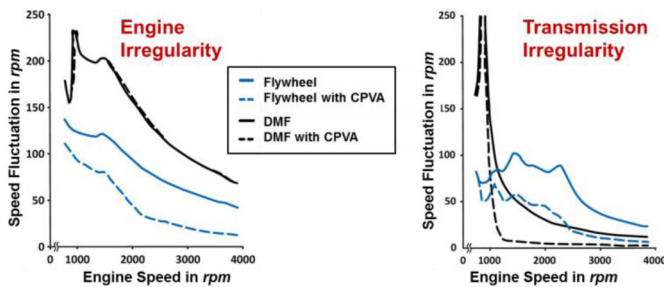


Figure 1. Effects of downsizing and downspeeding on powertrain dynamics ([1]).

Further downsizing and downspeeding is limited by the performance of torsional vibration reductions systems, especially at low engine speeds. Increasing customer demands for driving comfort can only be met with a high level of research and development.

Conventional Torsional Vibration Reduction Devices

Currently, several basic types of conventional torsional vibration reduction systems are applied to automotive powertrains. These systems feature absorber, isolation and damping effects. This subsection gives a short overview of the functional principle of common torsional vibration reduction systems.

Conventional Dual-Mass Flywheel

The most common conventional system to reduce torsional vibrations is the dual-mass flywheel (DMF). The DMF is characterized by two flywheels connected by an arc spring damper device (Fig. 2). By tuning the resonance frequency of the system towards a low frequency, low-pass filtering of the dynamic torque amplitudes with frequencies above the resonance frequency of the system can be achieved. ([2])

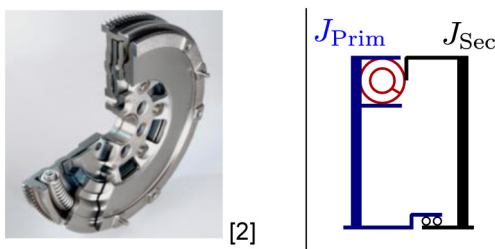


Figure 2. Conventional DMF.

The performance of the DMF is limited by the achievable torsional stiffness of the arc spring damper. For the isolation of high torque amplitudes in combination with high mean torques and low stiffnesses of the arc spring, high relative angles of the arc spring device have to be possible. But the maximum relative angle and hence the achievable torsional stiffness of the arc spring damper is strongly limited by the available installation space and the compression length of the fully torque-loaded arc spring.

Planetary Dual-Mass Flywheel

The planetary DMF consists like a conventional DMF, basically of two flywheels connected by an arc spring damper unit extended by a planetary gear set between the two flywheels (Fig. 3).

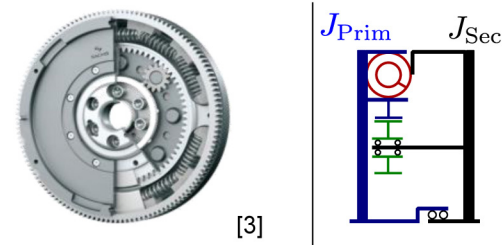


Figure 3. Planetary DMF.

Torsional vibration reduction can be improved through the inverted phase acceleration torque of the planetary gears acting against the relative movement of the two flywheels. ([3])

The planetary gear set connected to primary-sided and secondary-sided flywheel leads to an anti-resonance in the transfer behavior of the system. For vibrational excitations with frequencies near of this anti-resonance frequency a very good vibration reduction depending on the damping in the planetary gear set can be achieved. For excited vibrations with other frequencies the influence of the DMF transfer behavior dominates.

Hydrodynamic Torque Converter

The common torsional vibration reduction device for applications with automatic or continuously variable transmissions (CVT) is the hydrodynamic torque converter (HTC). The HTC is a fluid coupling and transfers the torque from drive side to driven side of the powertrain by a hydrodynamic cycle (Fig. 4). The hydrodynamic transfer itself has a damping effect with regard to torsional vibrations induced by the engine. ([4])

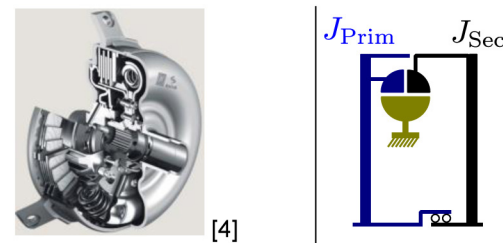


Figure 4. Hydrodynamic torque converter.

The hydrodynamic torque transfer unfortunately results in dissipation of energy because of slippage needed for the hydrodynamic torque transfer. Therefore, lock-up clutches are included in most HTS's to bypass the hydrodynamic cycle at higher engine speeds. In this case, arc spring damper devices are applied to reduce induced torsional vibrations with its

restricted performance. Recently, adding of centrifugal pendulum vibration absorbers (CPVA) or even of a planetary stage for improved vibration reduction is being considered.

Dual-Mass Flywheel with Conventional Centrifugal Pendulum Vibration Absorber

The performance of DMFs can be highly improved by adding a CPVA on the secondary-sided flywheel (Fig. 5). The CPVA enables further reduction of vibrations on the secondary-sided flywheel. ([5])

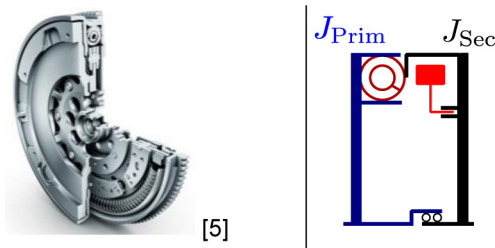


Figure 5. DMF with conventional centrifugal pendulum vibration absorber.

The performance of conventional CPVAs is strongly restricted by design constraints. Manufacturing deviations can heavily reduce efficiency by irregular movements of the pendula. Furthermore, problems relating to strength and NVH can arise by the pendulum bodies striking on their deflection limits. ([6])

RESEARCH ACTIVITIES AT THE TUM REGARDING INNOVATIVE TORSIONAL VIBRATION REDUCTION SYSTEMS

Conventional torsional vibration reduction systems have strong limitations of performance, especially in powertrains with highly downsized combustion engines at operating points with low rotational speeds of the engine.

Therefore a network of institutes of the Technische Universität München (TUM) supported by the BMW Group Research and Technology develop new concepts for the reduction of torsional vibrations for automotive applications. Passive, semi-active and active systems with isolation and absorber effects are the subjects of current research. ([6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16])

For the development of new concepts various disciplines of mechanical engineering are needed. Deep knowledge in the dynamic behavior of mechanical systems as well as in mechanical design and component strength analysis is required.

GENERAL DESIGN STEPS

An abstract view on the basic design of torsional vibration reduction systems (Fig. 6) helps to understand parameters influencing system performance and design as well as the technical interconnection during the concept and design process (Fig. 7).

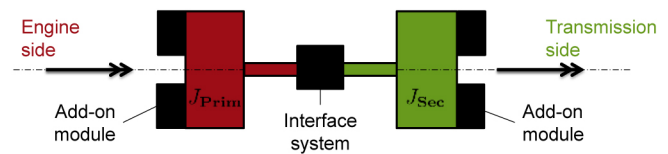


Figure 6. Abstract view of a torsional vibration reduction system.

Conventional torsional vibration reduction devices basically consist of two flywheels. The primary-sided flywheel J_{Prim} is connected to the engine crankshaft and the secondary-sided flywheel J_{Sec} is connected to the transmission input shaft. It is possible to integrate or to connect add-on modules on one or either both of the flywheels. For example, a CPVA represents an add-on module. The two flywheels are connected by an interface system. This can be an arc spring damper unit as well as a planetary gear set.

The first step (Fig. 7) is to develop a mechanical concept of the torsional vibration reduction system. Therefore, passive, semi-active and active components can be applied. Cost and technical effort have to be regarded. Therefore fully-passive concepts are favorable.

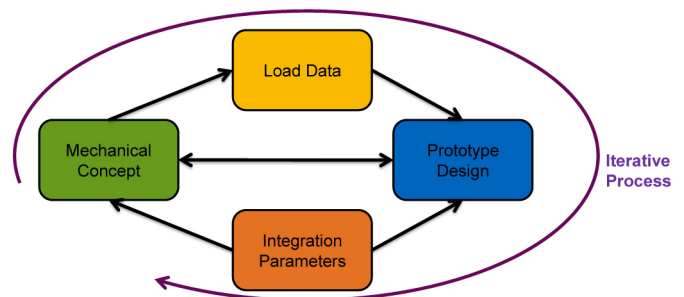


Figure 7. Prototype design process.

Depending on the mechanical concept major parameters like masses, mass moments of inertia, spring stiffness and damping parameters are preset. By first simulating the concept with simple minimal models covering the most important effects of the concept, initial estimations of component loads can be calculated.

Integration and functional parameters such as mass, dimensions and flange geometry for the integration in a test rig and/ or vehicle powertrain have to be considered for the prototype design as well (Fig. 8).

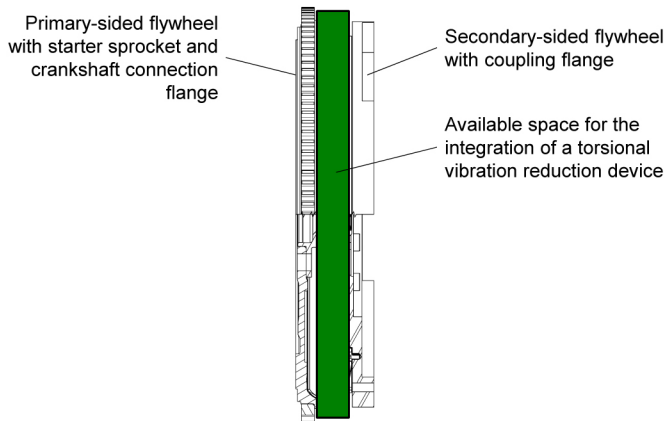


Figure 8. Integration parameters and available installation space.

During the design process, installation and manufacturing aspects have to be taken into account. The prototype design defines actual mass, mass moment of inertia, damping and gear ratio parameters. This leads to an iterative process with interactions between concept simulation and prototype design (Fig. 7). Therefore, intensive cooperation between the different special fields is required.

In the following, two concepts are presented with the performed design steps as well as with strength analysis of selected components.

ISOLATION DEVICE - PASSIVE SWITCHING ISOLATOR PSI²

In cooperation with the Gear Research Centre (FZG) and the Institute for Applied Mechanics a new concept based on a planetary DMF has been developed. The vehicle-related prototype assembly has been proven successfully through test rig trials.

Functional Concept

The Passive Switching Isolator PSI² consists of a planetary gear stage between two flywheels connected by an arc spring damper unit (Fig. 9). The hollow gear is connected to the primary-sided flywheel and the planetary carrier is connected to the secondary-sided flywheel. The planetary gears rotate according to the relative motion between the two flywheels.

The special-feature of PSI² is the switchable mass moment of inertia of the planetary gears realized by an additional sun gear with passively switchable mass moment of inertia. This leads to two anti-resonances in the transfer behavior and extends the reduction performance of the system in a wide frequency range. ([7], [8])

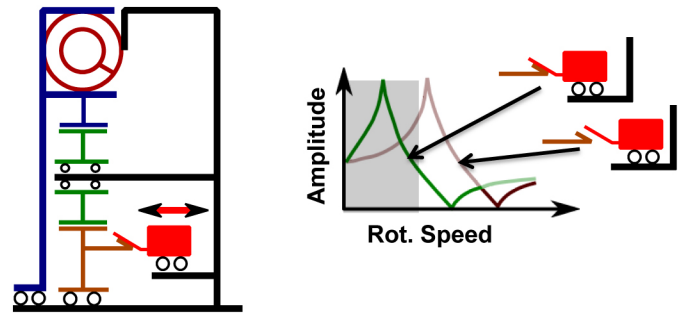


Figure 9. Concept of PSI². ([8])

Design Challenges and Conceptual Demands

The prototype assembly of PSI² has to be integrable in the test rig for torsional vibration reduction systems at the FZG described in [9], [10] and [11]. Furthermore, vehicle-related design requirements like space, mass, and mass moment of inertia of the primary- and secondary-sided flywheel have to be met.

To provide maximum performance of the system, data from the simulation with regard to mass moments of inertia like planetary gears, sun gear and the switchable mass moment of inertia have to be maintained. Additionally, the system performance is sensitive to damping. Hence, friction effects have to be minimized.

For test rig investigations of the prototype assembly under different test conditions, reliability and strength of all components have to be provided.

Design Procedure

First, a basic design of the prototype assembly is developed based on the functional concept of PSI² (Fig. 9). In conjunction with the detailing of the prototype design, strength analysis of all components has to be performed.

Regarding the concept (Fig. 9), PSI² can be divided into three main modules: ([8])

1. **Transmission module:**
Transmission of the mean torque.
2. **Planetary gear set:**
Transmission of the relative motion of the two flywheels to planetary gears and to sun gear.
3. **Switch module:**
Providing speed dependent switching of the mass moment of inertia of the sun gear and traction between sun gear and switched mass moment of inertia.