Improvement of the Noise and Vibration Behavior of an Electromechanical Brake Booster — an Integral Approach

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Introduction

The automotive world faces a tremendous change. Autonomous driving and electrification are two big topics in this context that are pushing this change. The demand for higher comfort, higher safety and tightened environmental requirements drive as well the technological change from former mechanical actuations to electro-mechanical systems in new vehicles. This can be observed especially for braking and steering systems.

One of these new arising technologies and systems in this context is the electro-mechanical brake booster from Robert Bosch (Ref. 1). This new and innovative system replaces more and more the "old" vacuum boosters; the first generation was rolled out in 2013. In the meantime, the second generation has entered the market. The iBooster can be used for all different types of drive concepts like electric, hybrid or standard vehicles. It is also a cornerstone for automated driving as it allows new driver-assisted functions to be set up, e.g. — emergency braking and traffic assist. This set of new functions and concepts results in strong requirements for good noise, vibration and harshness behavior (NVH) of the system — especially if it is used in electric vehicles and if it is activated without a driver demand by the assistance systems of the vehicle.

The electro-mechanical part of the iBooster consists of a permanent magnet synchronous motor, a three-stages gearbox with a spindle as the last stage (Figs. 1 and 2). The complete geartrain is assembled in a housing made out of sheet metal. The motor with the motor pinion is screwed to the housing. The housing of the iBooster itself is screwed to the bulkhead of the car and this screwing is the main interface to the vehicle.

The materials of the gears are metal and plastic. The motor pinion and the spindle are made out of metal, all other gears out of performance plastic materials. The plastic gears are produced by injection molding.

All components of the electromechanical drivetrain, as well as the housing, are designed accordingly to achieve the strong NVH requirements. After the start of production a project was set up to find further potential and to improve the NVH properties of the booster. This paper describes these investigations to separate the different influence factors of the system's NVH behavior and to tap possible potential of improvement.

Figure 1 iBooster Gen2 (Picture: Robert Bosch GmbH).

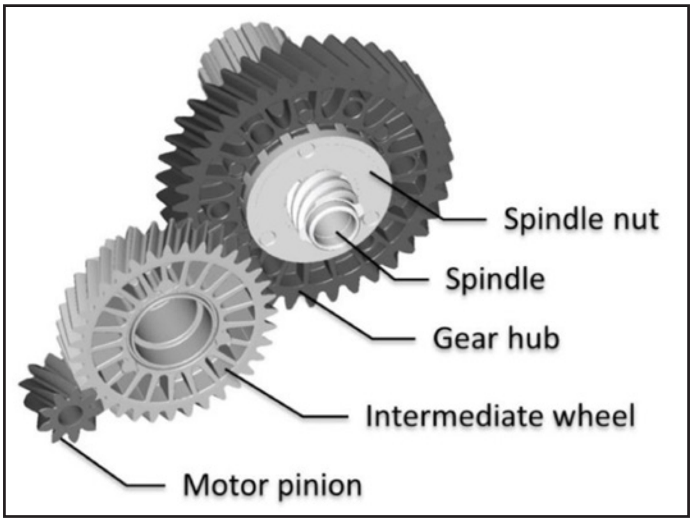

Figure 2 Geartrain.

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Approach

It is well known that the noise and vibration behavior of a system is influenced by a number of parameters and factors. An acoustical optimization of the system has therefore to follow a holistic approach and investigate all the aspects of the acoustic transfer path (Fig. 3).

The analyzed and investigated unit of the iBooster is complex, and due to this the approach of the investigation needs to be divided in four steps:

1. Definition of the system boundaries
2. Assessment of the influence factors and definition of samples
3. Definition of measurement setup and analysis procedure
4. Measurement, analysis and conclusion

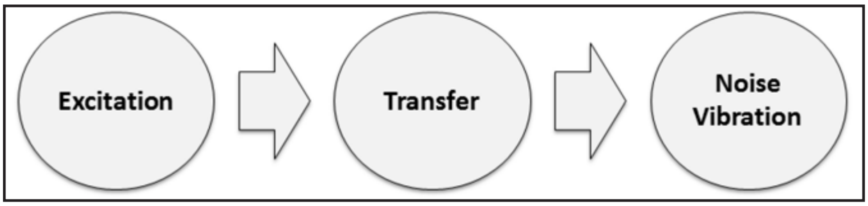

Figure 3 Acoustic transfer path.

Definition of System Boundaries

The basis of the investigations is the standalone iBooster system, requiring that all testing and analysis to be conducted on the test bench and not in the vehicle. The system boundaries are limited to the test bench to avoid any influence of the vehicle and to achieve a neutral environment for the assessment.

The investigations focus mainly on the excitation by the geartrain and the transfer of this energy to its surrounding components; surrounding components mean in this context the bearings, the housing and the interface to the vehicle. The transfer of the excitation to the position where the booster is screwed to the vehicle is of high importance. A low excitation at this interface results almost directly in a good noise and vibration ambience in the compartment.

The eigenfrequencies of the system are directly linked to its mechanical setup and design. The interaction between these eigenfrequencies and the dynamic excitations affect the noise and vibration of the system significantly.

Unfortunately the system eigenfrequencies can't be changed so easily for samples as this would mean a complete change of the mechanical setup and the system design; they therefore have to be seen as fixed boundary conditions. The eigenfrequencies of the system have been identified by an experimental modal analysis and cross-checked upfront with a finite element calculation to judge their influence on the NVH behavior. Based on these results the critical frequency bands have been determined.

The first stage of the geartrain is the main driver for the vibration. For this reason the focus lays especially on the first gear stage. The macrogeometry is changed by setting up motor pinions and intermediate wheels with different gears and helix angles.

Motor pinons with a lower number of teeth (7 instead of 9) and a higher number of teeth (13 instead of 9) are tested to see the influence on dynamic excitation by the gears itself and to change the meshing frequencies. Higher and lower numbers of teeth lead to different motor speeds at which the eigenfrequencies of the systems are met (Fig. 4); this could help to reduce the level of the excitation forces. The pairing gear of this stage also needs to be changed. The impact of the changes was simulated up front by finite element simulations.

The quality of the micro geometry of the gears is essentially given by the manufacturing process. The intermediate wheel is molded out of plastic material. Therefore the production process of the intermediate wheel was changed from injection molding to milling. It is expected that a higher quality level of the micro geometry can be achieved by the milling process.

Last but not least the transfer path between the origin of the dynamic excitation (the gears) and the housing as the

Assessment of the Influence Factors and Definition of Samples

The dynamic system has a lot of different influence factors on the acoustic behavior. Out of this plurality the following factors have been deduced for the investigation:

- eigenfrequencies as a significant system property
- Macrogeometry of the gears, i.e. — the number of teeth and the shape of the teeth
- Microgeometry and the quality of the gears, which are linked to the production process of the parts
- Transfer path itself

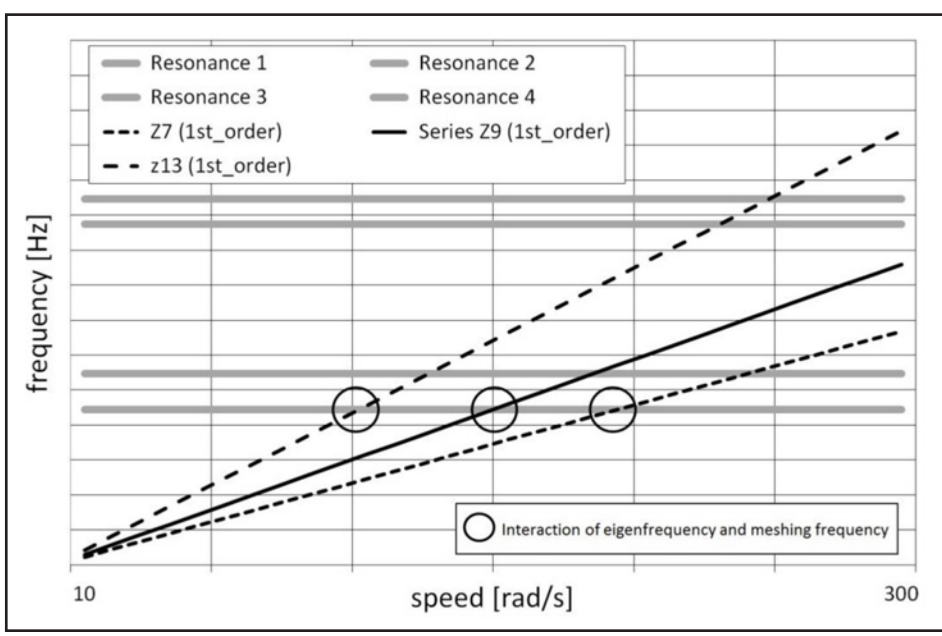

Figure 4 Critical Eigen frequencies of the system and gear meshing frequencies.

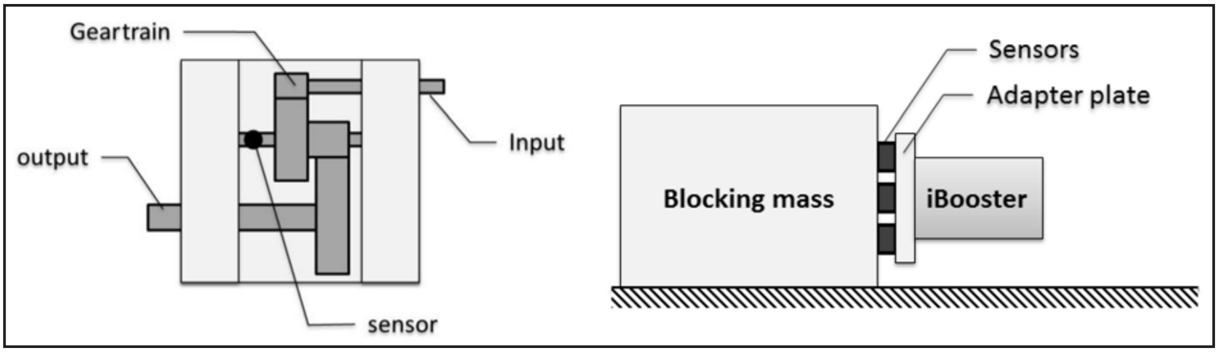

Figure 5 Test benches: geartrain, blocked forced.

interface to the vehicle is changed. It is obvious that damping this transfer path is adequate method to reduce the amplitude of the excitation.

Table 1 Investigated measures and intended influence (extract)

Measure	Excitation	Transfer path
Number of teeth (motor pinion): z = 7 vs. z = 9 (series) vs. z = 13	●	(●)
Manufacturing process (intermediate wheel): Milling vs. injection molding	●	
Additional damping element		●

A higher damping is applied by changing the bearing system in such a way that an additional rubber element is mounted within the bearing of the intermediate wheel. The vibration energy should be significantly reduced by this measure.

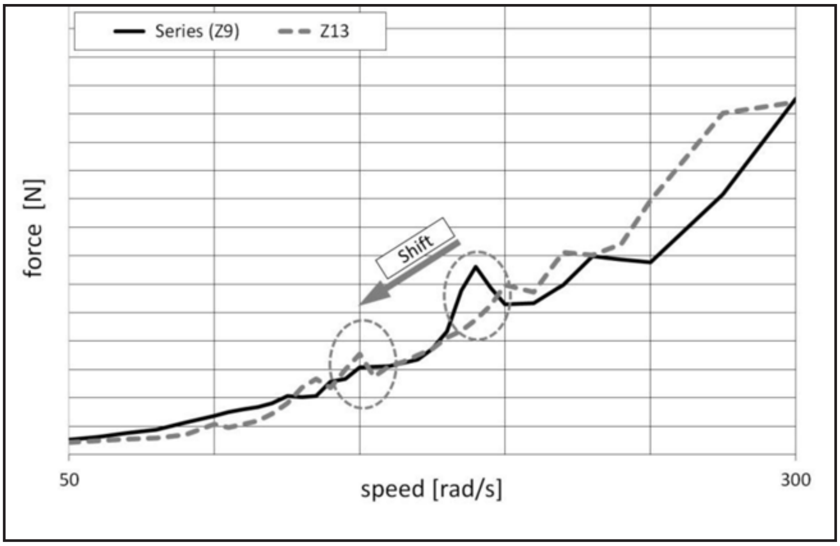

Figure 6 Number of teeth: Z13 vs. Z9 | influence on force.

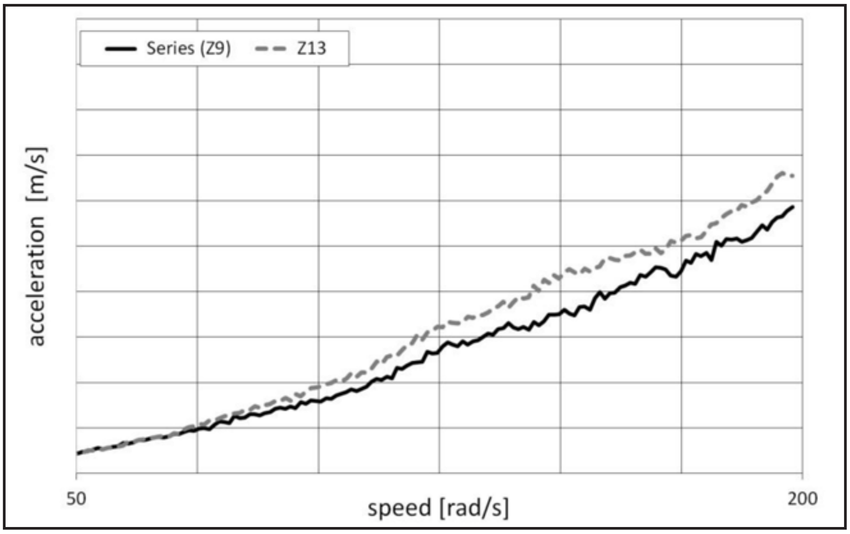

Figure 7 Number of teeth: Z13 vs. Z9 | influence on vibration.

Definition of the Measurement and Analysis Procedure

All the measurements are carried out on the test bench level. An important requirement of these measurements is that the chosen test setup needs to be as representative as possible to allow a transfer of the results to the later application, i.e. — an acoustic improvement in the vehicle. The measurements are done in two steps to reach this requirement.

In the first step the standalone geartrain without the spindle and any other system components, e.g., the housing, is measured at different speeds and loads on a special gear test bench (Fig. 5); the vibrations are measured at the shaft of the intermediate wheel. This position corresponds to the interface between geartrain and housing in the real system. The vibrations are measured by structure-borne sound sensors. The chosen setup offers a good comparison of the different defined variants on the component level.

In the next step the measured gears are mounted in a complete iBooster system and the system is measured on a so-called "blocked force test bench" (Fig. 5). This measurement procedure allows judging the impact of the investigated change on a system level. The basics and theoretical background of this measurement procedure can be found in (Refs. 3–4).

The iBooster is mounted at a huge blocking mass in this blocked force bench. The mounting is done at the same interface as it would be done in the vehicle. Force sensors are positioned between the blocking mass and the adapter plate. This test setup allows the measuring of the dynamic forces that are transferred between the booster and the environment. These dynamic forces are used for the comparison of the different variants. The investigated measurement conditions are derived from a specific use case given by a braking situation in the vehicle in respect to load and speed. Also, the frequency band that has to be improved is given by the use case in the vehicle. The tests have been carried out at motor speeds that were constantly changed from 500 to 3,000 rpm and an input torque of roughly 1.3Nm. The analyzed frequencies are within the band between 500 to 1,000 Hz.

The dynamic properties of the test benches have to be taken into account for the interpretation of the results. They limit the maximum frequency that can be measured and analyzed. These limitations have been determined before by appropriate tests to avoid a misinterpretation of the results.

Results

Different number of teeth of the motor pinion. The change of the number of teeth has two targets. First, the motor speed at which the meshing frequency of the gears interferes with the eigenfrequency of the housing should be changed. Second, the macrogeometry of the teeth is changed to reduce the dynamic excitation forces of the gears; this is basically only possible by an increase of the number of teeth. A reduction often results in higher excitation forces due to a poorer contact ratio if it is not compensated by other changes like the helix angle of the teeth.

Looking at the dynamic forces measured on the blocked force test bench, it can be seen that the increase of the number of teeth of the motor pinion ($z=13$) causes a lower motor speed, at which the interference of the meshing frequencies and the eigenfrequencies happens (Fig. 6); the elevation of the force level is also diminished. A cross-comparison with the results of the geartrain test bench shows that the lever of the even higher dynamic meshing forces is not as significant as the speed shift (Fig. 7).

By a lower number of teeth ($z=7$) the interference between the meshing frequencies and the system eigenfrequencies is shifted to higher motor speeds. The higher speed means, however, high energy in the systems and hence higher dynamic forces at the interface of the booster (Fig. 8).

The increase of the dynamic forces at higher motor speeds for the configuration $z=13$ can be explained by system eigenfrequencies that aren't met with the standard configure $z=9$.

Influence of the manufacturing process. Figures 9 and 10 show the influence of the manufacturing process on the vibration and

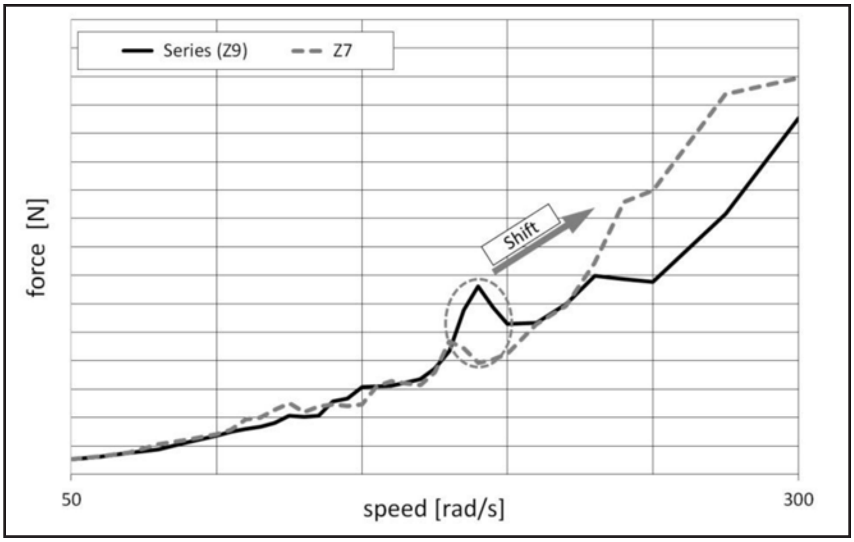

Figure 8 Number of teeth: Z7 vs. Z9 | influence on force.

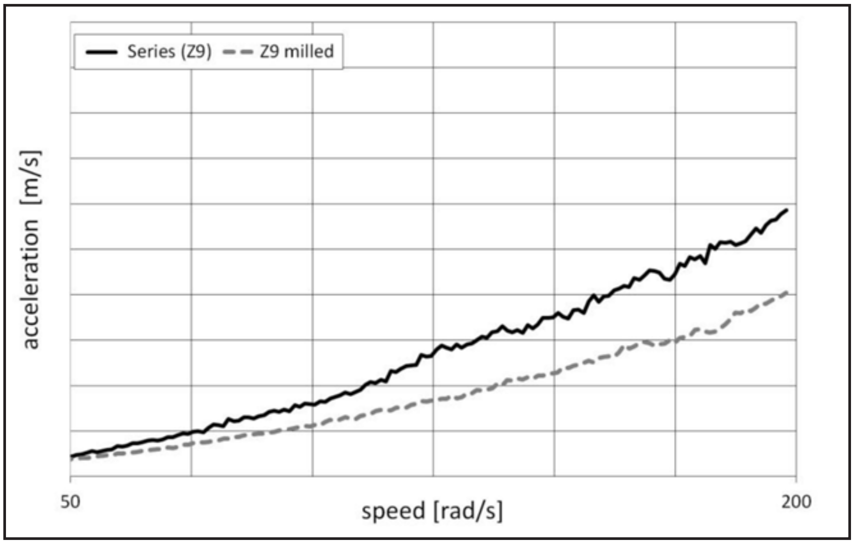

Figure 9 Manufacturing process | influence on vibration.

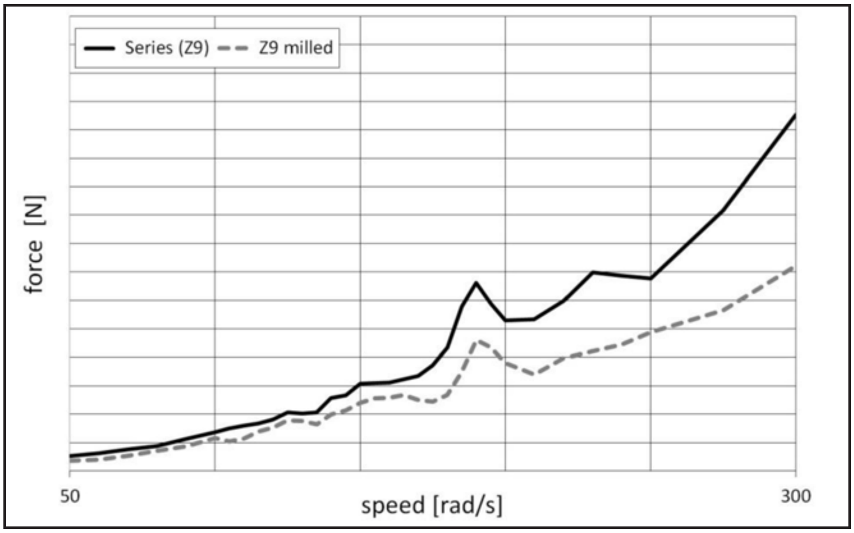

Figure 10 Manufacturing process | influence on force.

dynamic forces. All gear parts (metal and plastic) are produced in the prototype shop of IMS Gear by a 5-axis milling machine instead of the serial process that is set up for the production of high volumes.

The results of the geartrain test bench show a reduction of the vibration level (Fig. 9). This reduction can also be determined by the blocked force test bench. The characteristic of the force level over speed isn't changed by this measure. The level of the forces at the interface is lowered, but the eigenfrequency at roundabout 180 rad/s is still hit. The result can be seen as conformation of the influence of the parts quality. The better the quality, the lower noise and vibration level can be reached.

Additional damping of the transfer path. Damping the transfer path between the origin of the dynamic excitation and the position where the dynamic forces are radiated as airborne sound often seems to be a promising solution for better NVH behavior. Therefore additional rubber elements are placed in the bearing system of the intermediate wheel for this setup.

The impact of this change is impressive. The good results of the geartrain measurement (Fig. 11) can be transferred to the blocked force test bench (Fig. 12). The improvement is significantly higher compared to other measures. The interference of the meshing frequency of the geartrain stays at the same speed. It can be noted that the characteristics of the dynamic force level is kept while the height of the level is lower. The reduction of the dynamic force level is at its highest at high motor speeds.

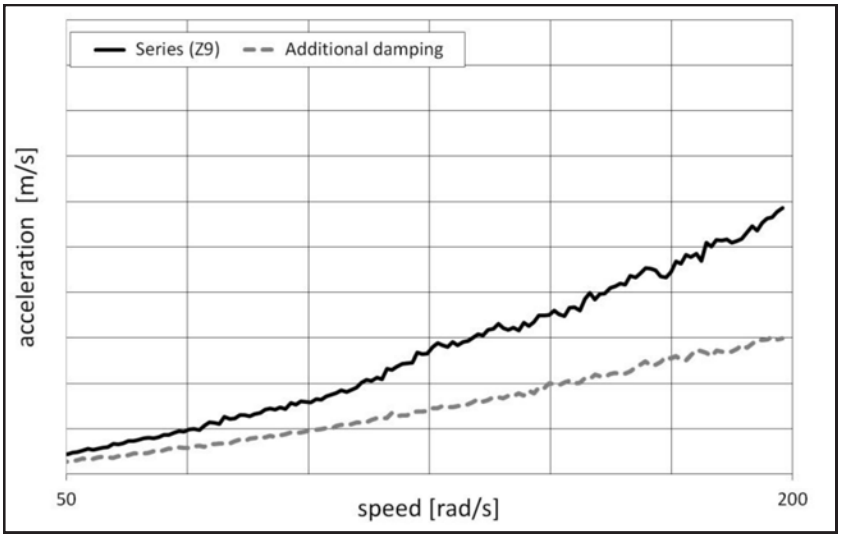

Figure 11 **Additional damping | influence on vibration.**

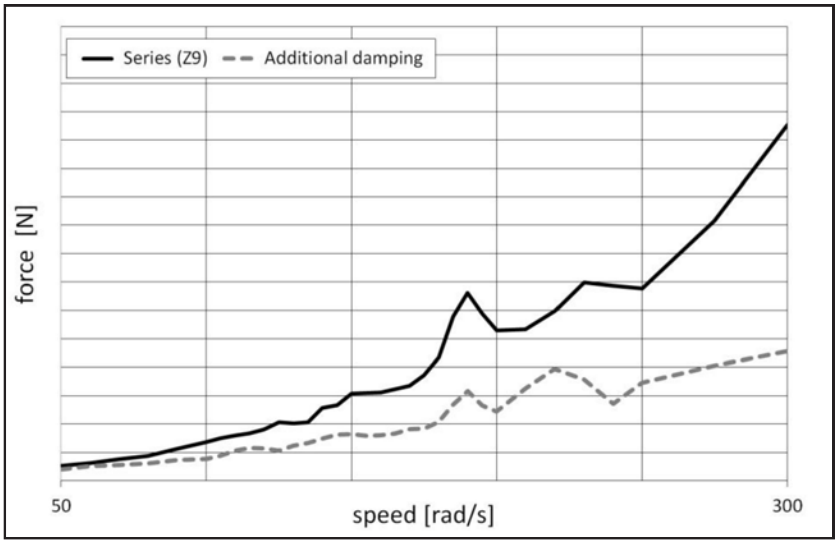

Figure 12 **Additional damping | influence on force.**

Summary and Outlook

The NVH behavior demands more and more attention in the development of electromechanical actuators — especially for electric vehicles. This article has shown how the NVH behavior can be influenced and how the tough targets can be achieved. A holistic approach that covers the complete acoustic transfer path is described.

It can be stated that it is always a number of factors that determine the "good sound" of the system. In this special case, a damping of the transfer path shows the best results, followed by the macrogeometry of the teeth and the quality of the parts. A combination of all measurements can lead to an even higher reduction.

This outcome can be different for other systems. A harmonization of all influence factors and a cross-check with other requirements like the performance, the durability and mechanical robustness is therefore essential. Solving these challenges leads to the best solution for the customer.

These investigations have been carried out through a mutual project between Robert Bosch and IMS Gear. Special thanks must be expressed to team of Robert Bosch for their support by doing the test and measurements on their test benches and for their noteworthy dedication. **PTE**

For more information. Questions or comments regarding this paper? Contact Jens Fechler at *jens.fechler@IMSGEAR.com*.

References

1. Kunz, A., M. Kunz and M. Vollert and D. Förster. Elektromechanischer Bremskraftver-Stärker und Automatisiertes Fahren für alle Antriebskonzepte, ATZ, 04/2018, p. 60–65.
2. *Impuls* 1/2018, in-house publication, IMS Gear SE & Co. KGaA, 2018.
3. Elliot, A. "Characterization of Structure-Borne Sound Sources In-situ," Ph.D. Thesis, University of Salford, 2009.
4. Trampu, L. and T. Bischof. "Improvement of the Blocked Force Method by Considering the Cross & Moment Mobilities," Kiel, DAGA, 2017.

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