Prospects of Compound-Gears for e-Mobility Applications
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ABSTRACT: Electric powertrains for automotive applications bring some new challenges for design and manufacturing. New needs like lightweight design lead to new design elements for a new generation of powertrains which are optimized for the changed requirements of electric powered cars. The idea of a compound gear is to combine the advantages of plastic and steel for a gear application. For electric vehicles it is important to reduce the vehicle mass to achieve a satisfying operating distance. In addition to this the noise behaviour of electric vehicles will bring new challenges. This article will describe a compound design of a gear which combines a lightweight design with the possibility of influencing the noise behaviour as well. The concept will be explained and described. A measurement method for evaluating the influence of the design to the dynamic behaviour will be described and test results are presented.

Keywords: Powertrain, Compound, Lightweight, Gear, Noise, Vibration, Gearbox

1. INTRODUCTION

The usage of Compound-Gears in electric vehicle applications can provide two advantages which are both useful for the new challenges in electric powertrains. First, the lightweight potential of Compound-Gears can help to reduce the vehicle mass. A consistent lightweight design is important in particular for electric vehicles. Second, the reduction of the vehicle mass leads to enhanced operating range.

Due to the reduced ambient noise without combustion engine other noise sources will become more present. This especially affects the transmission. The increased engine speed of an electric engine compared to a combustion engine will cause higher noise excitation of the transmission. In addition to that the risk of exciting resonance frequencies is increased. Compound-Gears can influence the dynamic system behaviour of a transmission and thus help to improve the comfort of an electric car.

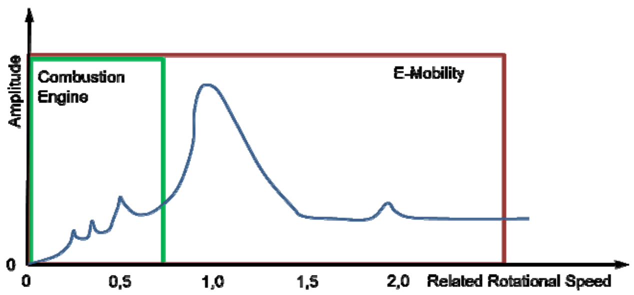


Figure 1: Comparison of the operational area of a combustion engine and an electric engine

Figure 1 illustrates the changed operational conditions of electric cars compared to conventional combustion powered cars. For this comparison a resonance curve for a gearing is shown. For the combustion engine which is usually operated subcritically only pre-resonance-peaks appear, while an high rpm electric engine may be operated around the main resonance peak.

1.1 Lightweight Design

For the Compound-Gear two different materials are used. Compared with state of the art steel gears the Compound-Gear provides an additional mass reduction. This effect is mainly caused by the lower density of the polymeric material which is with values from 1.31 g/cm³ for a 30% glass fibre reinforced blend up to 1.77 g/cm³ for a 60% glass fibre reinforced blend significantly lower than the density of steel. As a result of this low material density the overall part mass can be reduced. Compared to steel gears a weight reduction of 30% can be reached.
According to Figure 2 a massive steel gear is the basic reference for the mass and weight calculation. With a state of the art lightweight rim design the part weight can be reduced by 14% compared to the initial value. Compound-Gears can achieve a 30% weight reduction which equals an additional reduction of 16%.

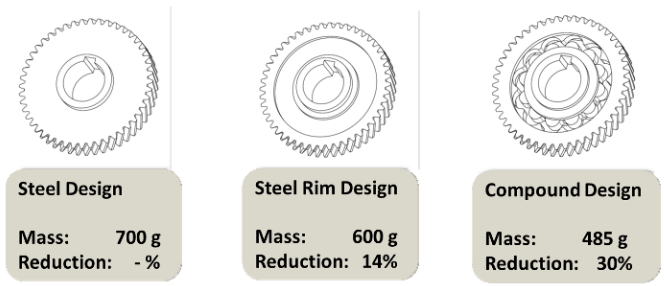


Figure 2: Mass reduction for gears with different design options

1.2 Improved Noise Behaviour

The emitted noise from a gear transmission has its main source in the gear mesh. The time variable gear stiffness causes an excitation of structure born noise. This structure born noise is transmitted through the gear body, the shafts and bearings into the housing. The housing emits the noise as airborne noise to the environment [1]. In vehicles a second transmission path is established. The mounting points of the gear box can transmit the structure borne noise into the cars bodywork. The airborne noise is emitted from the car structure itself.

In Figure 3 the structure borne noise transmission path is illustrated for an example gearbox.

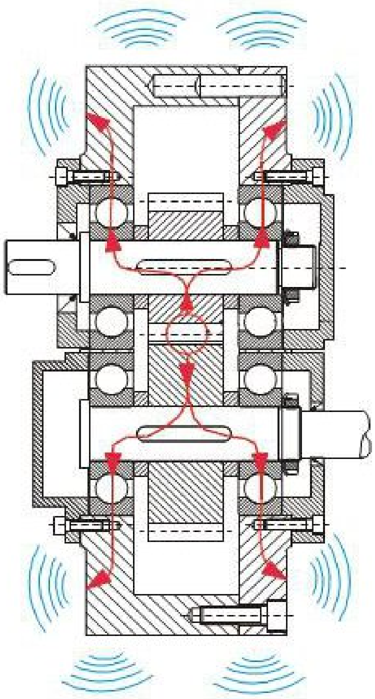


Figure 3: Structure borne noise transmission path in gearboxes.

To influence the noise which is emitted from a gearbox several methods are available. State of the art is the reduction of the excitation level. Therefore flank modifications can be used [2]. A different way is to influence the transmission path of the structure borne noise. Therefore materials with improved inner damping characteristics can be used [3].

2. COMPOUND GEARS

2.1 Basic concepts

The basic idea of a material compound is the usage of different materials to improve the part design. Unfortunately usual lightweight materials do not have the mechanical properties which are necessary for a high load carrying capacity. On the other side materials with high mechanical strength do not have high inner damping values. This conflict can be solved with compound materials. The material with high mechanical strength is used for high load areas of the part while the material with high damping values is used in low load areas to increase the parts damping characteristic.

For a gear this means a material with high mechanical strength for the gearing and shaft hub joint and a material with low density and mass for the gear body. This basic concept has already been proven in different applications [4, 5, 6].

The concept of the Compound-Gear which is used for the following analysis is different to the known concepts in following points. While [5] uses two steel parts which are still in contact with each other, within the current concept steel toothing and shafts are completely separated by the plastic material. In [4] the compound toothing and shafts are separated with Epoxyfoam which also provides an adhesive of the steel parts.

The concept of the current Compound-Gear is a steel and plastic compound which is connected with a form fitting geometry. For the plastic gearbody a high performance polymer (HPP) will be used. In contrast to a foam material HPPs can be used at temperatures over 120°C and can be manufactured in an injection moulding process.

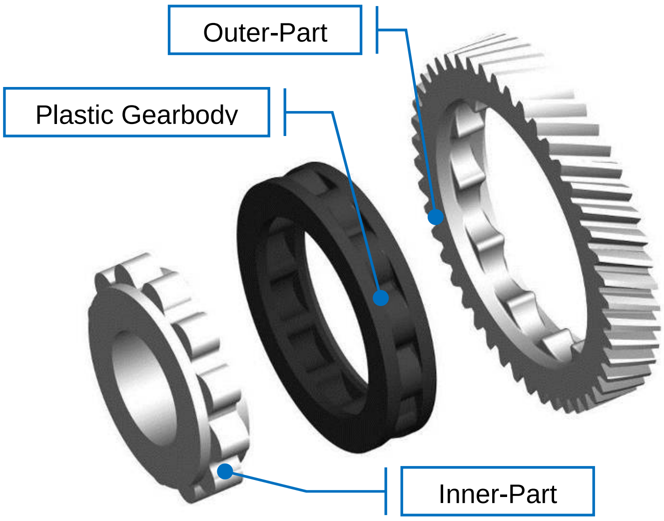


Figure 4: Basic concept of the discussed Compound-Gear with two steel parts and a plastic gear body.

Temperature stability, good mechanical properties, high resistance against automotive chemicals and an affordable price are the main demanded characteristics for a possible polymeric material for a Compound-Gear. There are several materials available at the market which can be used for the described application.

The compound concept provides the possibility to use different materials for the inner and outer part of the gear. So a material with high mechanical strength can be used for the outer part and a material with lower properties can be used for the inner part with the shaft hub joint. In Addition to that the parts can be heat treated in different ways.

2.2 Test gears

In this article two different types of gears will be discussed. These are a reference steel rim gear and a Compound-Gear. The Compound-Gear consists of three parts: Inner part (Hub) and outer part (toothing) and the plastic which connects the parts (s. Figure 4). For the Compound-Gear a plastic blend with a fibre content of 60% glass fibre is used. For comparability reasons the rim gear is manufactured with the same mass properties as the Compound-Gear. Table 1 gives an overview of the material properties of the test gears.

Type	Material (gear body)	Tensile Modulus (at 23°C)
Steel Rim Gear	16MnCr5	210,000 MPa
Compound Gear GF 60	PPA 60 % GF	23,000 MPa

Table 1: Properties of the used test gears

Polyphtahlamid (PPA) is a plastic material which can provide all the points mentioned in section 2.1. PPA can be glass fibre reinforced to increase the mechanical properties. With a fibre content of 60% a tensile modulus of 23,000 MPa is reached. The temperature of deflection is 293 °C [7]. With these values and an affordable price the material seems to fulfil all needs for a powertrain application and therefore is used for the Compound-Gears. For the toothing and shaft hub joint carburized and hardened 16MnCr5 steel is used. This steel is a common steel for gear manufacturing.

For the connection geometry an optimized design is used with the aim of preventing high shear stress in the plastic part. Challenges like the shrinking of moulded plastics and the fibre distribution have to be considered.

Inner and outer part are machined and heat treated separately. As shaft hub joint of the inner part a spline shaft is used. The toothing on the outer part is a spur gear main geometry. A spur gear provides a high excitation level in the mesh. This is a good basis to evaluate the influence of the plastic part on the structure borne noise transmission path by measurement. The compound is established by an injection moulding process. Finally the tooth flanks are ground using a special designed mount to prevent high deviations through deflection under the processing forces.

3. DYNAMIC BEHAVIOR OF COMPOUND GEARS

3.1 Method for dynamic evaluation

To evaluate the Compound-Gear's dynamic behaviour a modified FZG back to back test rig is used. The test rig is equipped with a torsional acceleration measurement devices.

Torsional acceleration is a good indicator for a gear's noise behaviour, due to the fact that the timevariable force in the gear mesh is directly proportional to the torsional acceleration. This value can be used for an assessment of the noise and excitation level of gears.

Figure 5 shows the assembled test gear. For the evaluation of the gearbody influence two measurement devices are mounted to the gear. One device is connected with the inner part and the other one with the outer part.

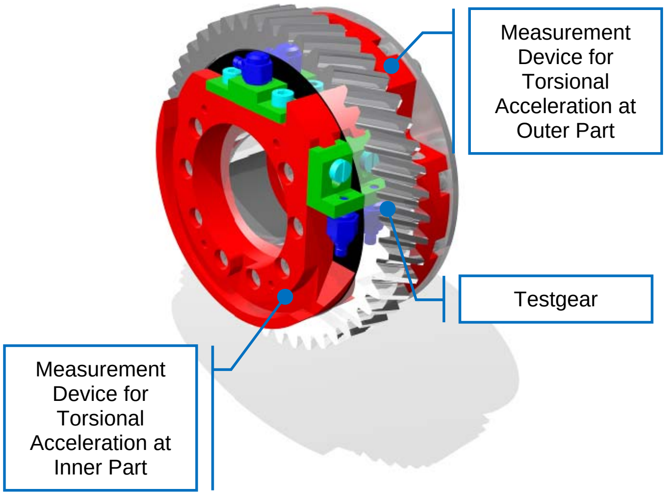


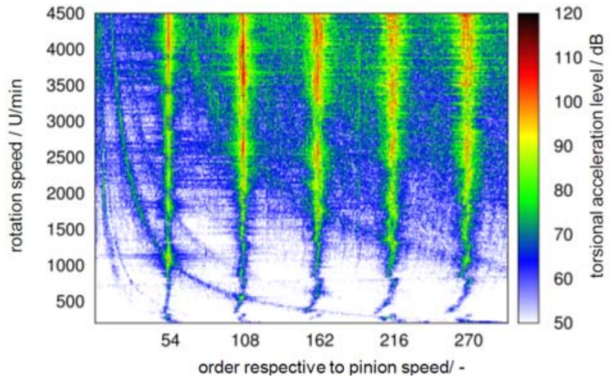
Figure 5: Exemplary assembly of test gear with mounted inner and outer measurement device for torsional acceleration measurement (displayed tooth geometry is only for illustration)

For the test gear and pinion of the test gear box are equipped with the measurement devices and the signals are recorded simultaneously during the test which is performed at constant torque and increased rotational speed in discrete steps. The speed range is 200 min^{-1} up to 4500 min^{-1} with a step of 20 min^{-1}.

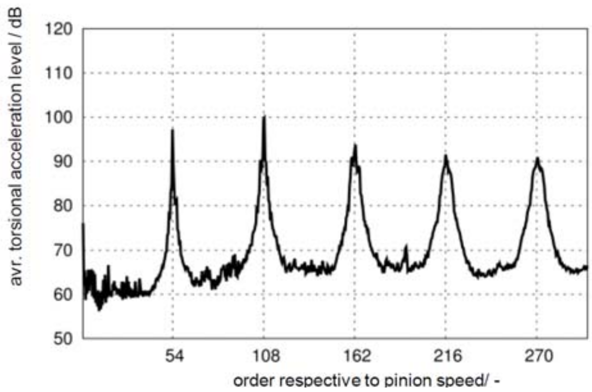
3.2 Experimental evaluation of the noise behaviour

The results of the analysis of the recorded acceleration data are shown in Figure 6 for the steel rim gear. For the following assessment the measurements for the pinion close to the shaft will be discussed. For an overview of the dynamic system behaviour Figure 6a is best to view. The Campbell diagram shows the order respective to pinion rotation speed at the horizontal axis and the rotation speed at the vertical axis. The torsional acceleration level is displayed colour coded. Vertical lines indicate an excitation of the dynamic system. In this case these lines are the excitation from the gear mesh. Eigenfrequencies will appear as hyperbolas in this diagram. If the excitation crosses an eigenfrequency resonance will appear with a raising torsional acceleration level. This effect can be observed at a rotation speed of 1100 min^{-1} where the first order meets a test rig eigenfrequency. Figure 6b displays the averaged order spectrum. This diagram is computed out of the Campbell diagram. The horizontal axis shows the order respective to pinion rotation, the vertical axis shows the averaged value for the excitation over all rotation speed steps and represents the gear's excitation.

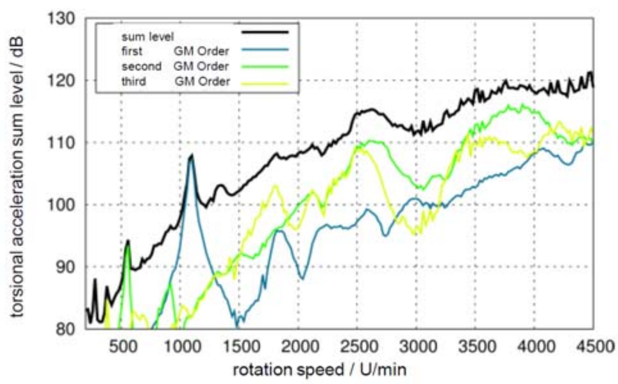
For the steel rim gear averaged torsional acceleration levels of 97 dB at the first order, 100 dB for the second order and 93 dB for the third order are measured. The levels for the fourth and fifth order are about 90 dB.



a, Campbell-Diagram



b, Averaged Order Spectrum

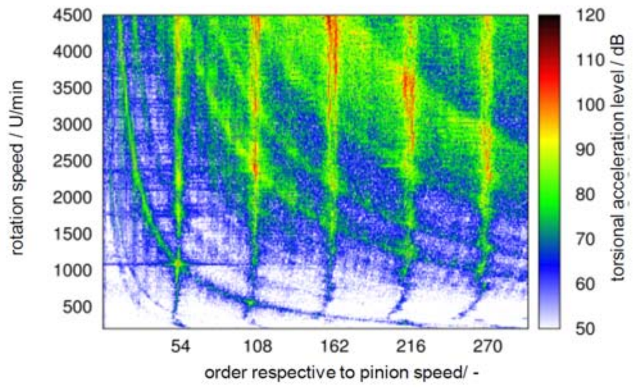


c, Sum Level

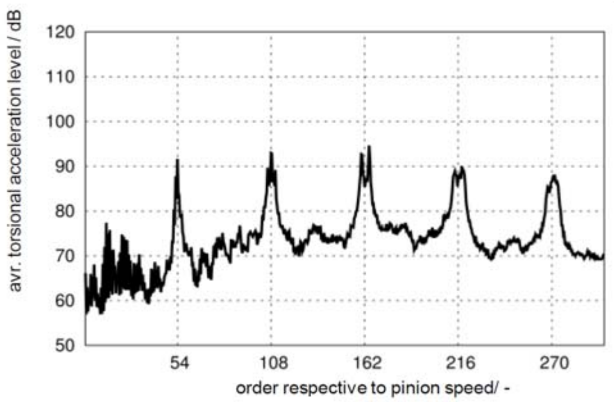
Figure 6: Campbell diagram, averaged order spectrum and sum levels for first, second and third gear mesh order (GM) for the steel rim design reference gear at a torque level of 150 Nm, measurement at shaft

In Figure 6c the torsional acceleration sum level is shown. This value is calculated over the first three orders which are shown in addition to the sum level. The torsional acceleration sum level represents the sum level over the rotation speed which is shown on the horizontal axis.

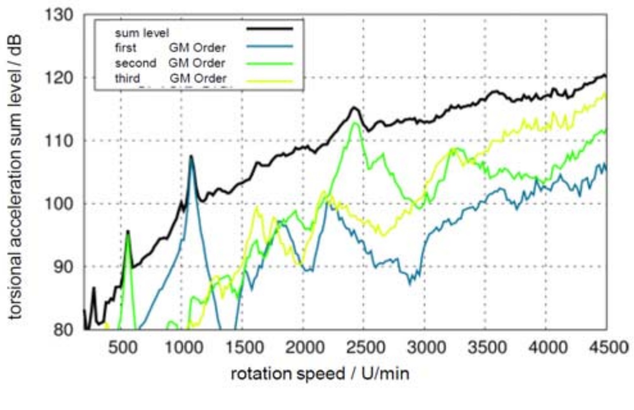
For the rim gear a sum level over 110 dB is measured at a rotational speed of approximately 2300 min^{-1} up to the final speed of 4500 min^{-1} where the sum level reaches a maximum value of 120 dB. It is well observable that at different rotational speeds different gear mesh orders contain the maximum excitation. At 1100 min^{-1} the first order is mainly responsible for the sum level while at a speed level of 2400 min^{-1} the second order is the main source for the overall sum.



a, Campbell-Diagram



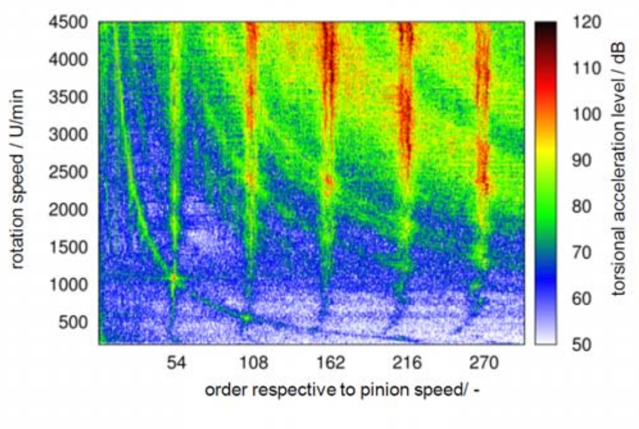
b, Averaged Order Spectrum



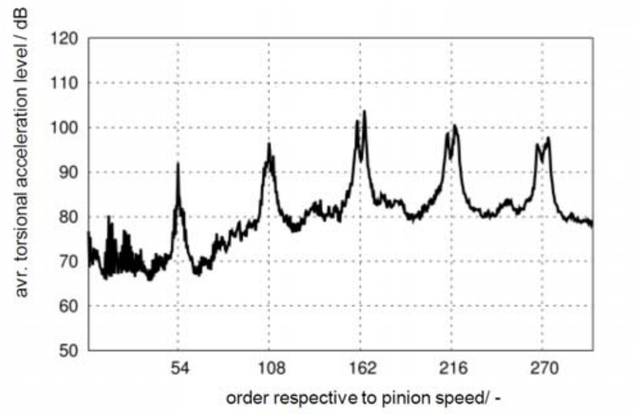
c, Sum Level

Figure 7: Campbell diagram, averaged order spectrum for first, second and third gear mesh order (GM) and sum levels for the Compound-Gear with 60% glass fibre reinforcement at a torque level of 150 Nm, measurement at shaft

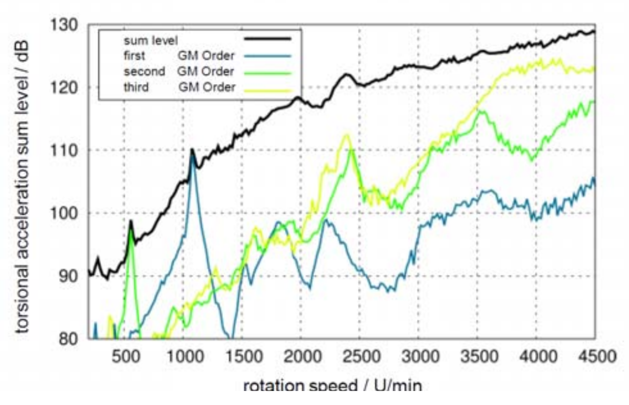
The Campbell diagram in Figure 7a for the compound gear with 60% fibre content displays significantly lower excitation levels for the first order in the whole rotation speed range.
For the second and third order the excitation levels are lower than the values for the steel gear. At the gear mesh order four and five the excitation levels are lowered as well. The effect of excitation lowering is also observable at the averaged torsional acceleration level in figure 7b. The excitation level at the first gear mesh order reaches a maximum value of 92 dB while the second order reaches a value of 93 dB and the third order a 94 dB peak. Fourth and Fifth order do not reach the 90 dB mark. In Figure 7c the sum level is displayed. Overall the sum level does not differ significantly from the sum level of the steel rim gear.



a, Campbell-Diagram



b, Averaged Order Spectrum



c, Sum Level

Figure 8: Campbell diagram, averaged order spectrum for first, second and third gear mesh order (GM) and sum levels for the Compound-Gear with 60% glass fibre reinforcement at a torque level of 150 Nm, measurement at outer part

For a better understanding of this result the results of the torsional acceleration measurement at the outer part is shown in Figure 8. In comparison of the measurement results from outer and inner part the influence of the compound structure can be shown.

In comparison with Figure 7, which illustrates the measurement at the inner part, the influence of the compound design becomes more obvious. With a closer look on Figure 8a the higher excitation level especially for the higher order values are observable. This effect can also be identified in Figure 7b and 7c. While the excitation caused by the first gear mesh order is nearly the same at the inner part as at the outer part, the excitation at second and third order is lower at the inner part than at the outer part. With a closer look at the sum level the high excitation level at the outer part is obvious. At the outer part high sum levels up to almost 130 dB are reached.

To complete the test results the measurement at the outer part of the steel rim gear is shown in Figure 9. For that design only the Campbell diagram is shown.

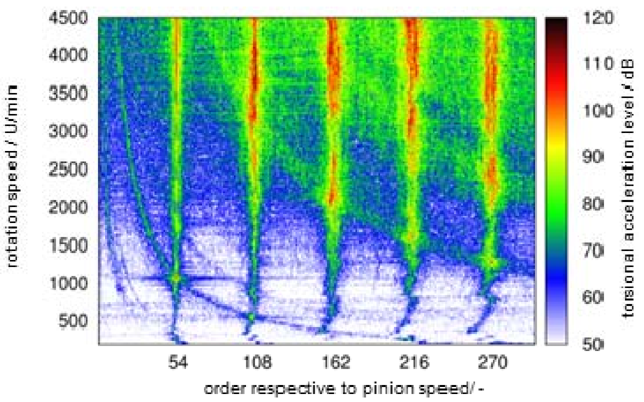


Figure 9: Campbell diagram for the steel rim design reference gear at a torque level of 150 Nm, measurement at outer part

In comparison to Figure 6 only a small decrease in excitation is observable. The acceleration levels of the gear mesh orders are similar to those of Figure 6. A slight excitation reduction effect can be seen.

4. CONCLUSION

Compound-Gears combine two innovative technologies in one powertrain component. Lightweight design on the one side provides the possibility of weight reduction with all its positive effects for electric powertrains. On the other side the possibility of influencing the dynamic system behaviour provides a chance to reduce the noise level of gearboxes. Especially for electric powertrains these two advantages can provide new possibilities for improved powertrain designs. In direct comparison with a steel gear the excitation level of a Compound-Gear is lower. The influence of the compound design on the dynamic system behaviour is obvious. The influence of a compound gear body on the stiffness properties of powertrains have to be evaluated in detail in the future. With an improved understanding of all effects caused by the compound design and a good knowledge of the powertrain`s properties it should be possible to affect the vibration and noise behaviour in a positive way.
In future the possibility of compound gears should be considered if new powertrains for alternative powered cars are designed.

5. ACKNOWLEDGMENTS

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