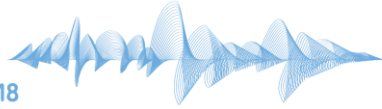




Noise and vibration
emerging methods

The 6th conference, 7 – 9 May 2018
Ibiza – Spain



A CASE STUDY OF DRIVELINE CLUNK NOISE AND DEVELOPMENT OF VISCOUS COUPLING

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ABSTRACT

One of the most important prerequisites in a vehicle design to satisfy customer is perception of vehicle quality. However, the requirements and obligations might corrupt its quality. Local and international law makers increasingly demand low-floor area in public transport vehicles to improve the accessibility for disabled and elderly people. On the other hand, the length of buses, in public transport, cannot be designed long enough to provide sufficient volume to place the powertrain longitudinally due to necessity of decreasing turning radius etc. in the cities with narrow streets and crowded populations. Therefore, laterally placed rear powertrain is appeared. While the lateral placement of the powertrain, with automated transmission and angle drive gearbox, improves the low-floor area in an eight-meter length low-floor bus design, it consequences driveline oscillations during launch and parking manoeuvres, due to the stored energy of additional sub-systems. This paper outlines an overview of a case study in order to resolve the driveline oscillations, which is caused by the stored energy in powertrain, perceived as clunk noise and vehicle fore-aft, to improve customer satisfaction.

1 INTRODUCTION

The number of low-floor buses, which improve the accessibility for disabled and elderly people in public transports, is rapidly increasing due to the necessities and obligations. In conventional low-floor buses, powertrain is placed in rear and longitudinal to allow low-floor front bus entry and increase efficiency. However, decreasing length of the vehicle and longitudinal placement of the powertrain eliminate nearly all of the low-floor area, therefore placement of the powertrain should be lateral such as in the eight-meter length low-floor bus applications.

The additional angle drive gearbox or transmission gear set is appeared in the lateral powertrain placement. In driveline with manual or automated transmission, these added parts increase stored potential energy which causes driveline oscillations during launch and parking manoeuvres. This phenomenon is also perceived as vehicle fore-aft and clunk noise by customers.

This paper describes a case study conducted on laterally placed powertrain with an automated transmission and angle drive gearbox in an eight-meter length low-floor bus. This driveline placement consequences this issue, affected customer perception of vehicle quality, due to the stored energy during launch and parking manoeuvres. This paper also indicates that the development and verification process of the viscous coupling to solve this phenomenon.

2 LITERATURE

There have been always such problems which are induced from unintended interactions of serial connected components in an assembly and case studies which try to solve these problems. For instance, Schwerdlin and Eshleman carried on such studies at mechanical couplings in earlier 80s [1, 2]. A great deal of these unintended interactions is caused from driveline oscillations in automotive powertrain systems. One of the earliest studies on the subject is Boedo and Freyburger's study, which focuses on reducing driveline torsional vibration in vehicles equipped with continuously variable transmissions [3].

On following years, lots of studies have been carried on about driveline oscillations which cause NVH problems like clunk noise. Guo et al explain how vehicle shuffle occurs in drivelines as well as building its theoretical model and stating its some influence factors [4]. Crowther et al research occurrence of clunk under typical driving conditions and its possible factors by building a reduced model of an automatic transmission powertrain [5]. A similar study examines possible nonlinear factors that cause clunk phenomenon with an analytical model [6]. Another research group studies on occurrence and possible preventive factors of clunk induced from static engagements [7]. Moreover an experimental research investigates factors and parameters of clunk such as friction, impact effect and damping by setting up a test mechanism in a laboratory [8].

Further studies generally focus on clunk in specific circumstances or new technologies. For instance, Sweeney examines unintended consequences of interacting components that form a torsionally flexible coupling and their descriptive solutions despite each component are robust on its own [9]. A more recent study clarifies how booming noise occurs at propeller shaft and what actions can be taken to reduce it [10]. Another interesting study is about dynamic driveline NVH issues including clunk in electric vehicles [11] which means clunk phenomenon will also be present in near future.

3 ROOT-CAUSE STUDIES

Laterally placed powertrain with angle drive gearbox in driveline, shown in Figure 1, provides sufficient capability for an eight-meter length low-floor bus application. However, this placement and supplementary parts store additional potential energy caused sharp and uncontrolled oscillations in the driveline, when gas pedal is released especially during launch and parking manoeuvres. As the results of these oscillations in the driveline, customers are perceived vehicle fore-aft and clunk noise.

As shown in Figure 2, the oscillations in the driveline (torsional modes of driveline), are the main source of the vehicle fore-aft. Due to serial connection in the driveline, these parts reduce the total stiffness which increases the necessary duration to balance when gas pedal is released during launch and parking manoeuvres. These oscillations also introduce the clunk noise due to the gear couple backlashes which are necessary for lubrication purposes and not to be locked.

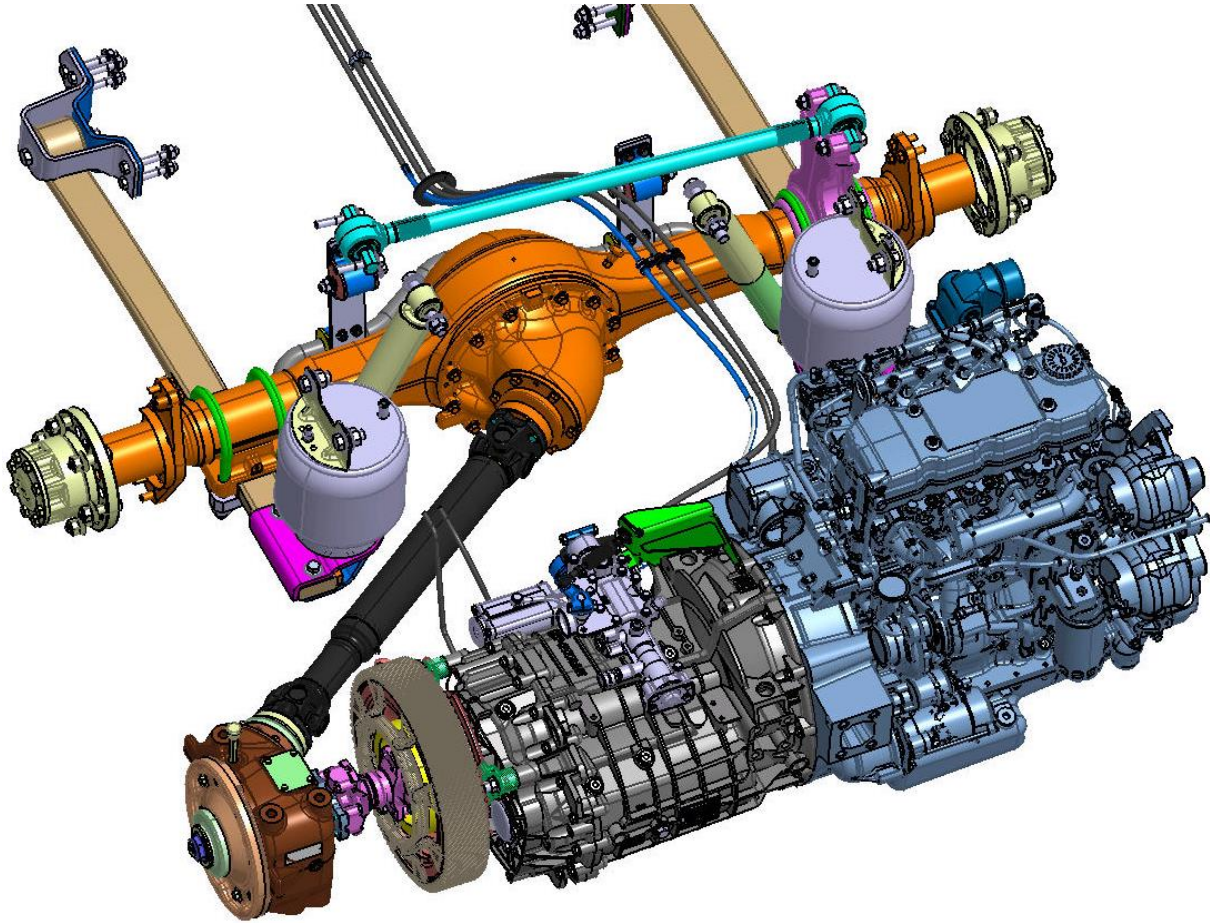


Figure 1: General View of Laterally Placed Powertrain and Driveline with Angle Drive.

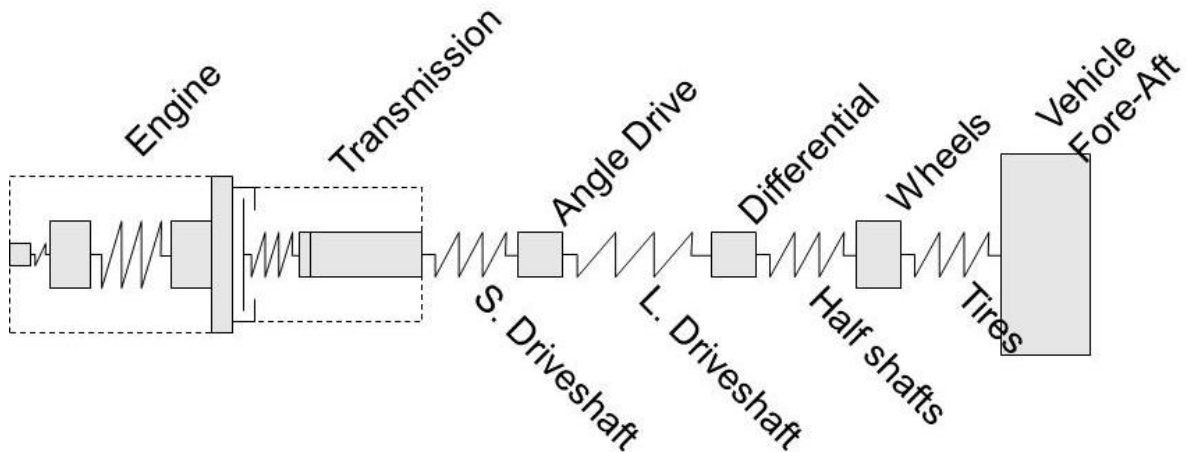


Figure 2: Torsional Representation of the Powertrain and Driveline.

Driveline system backlash values are measured as shown in Figure 3 and Table 1. Static loaded and dynamic backlash values are higher than the vehicles with longitudinal placed powertrain. However, static backlash values are proper like longitudinal placed powertrain & driveline. This situation states that this driveline configuration is suitable to store potential energy. Therefore, clunk noise, caused by driveline oscillations, is appeared when gas pedal is released during launch and parking manoeuvres.

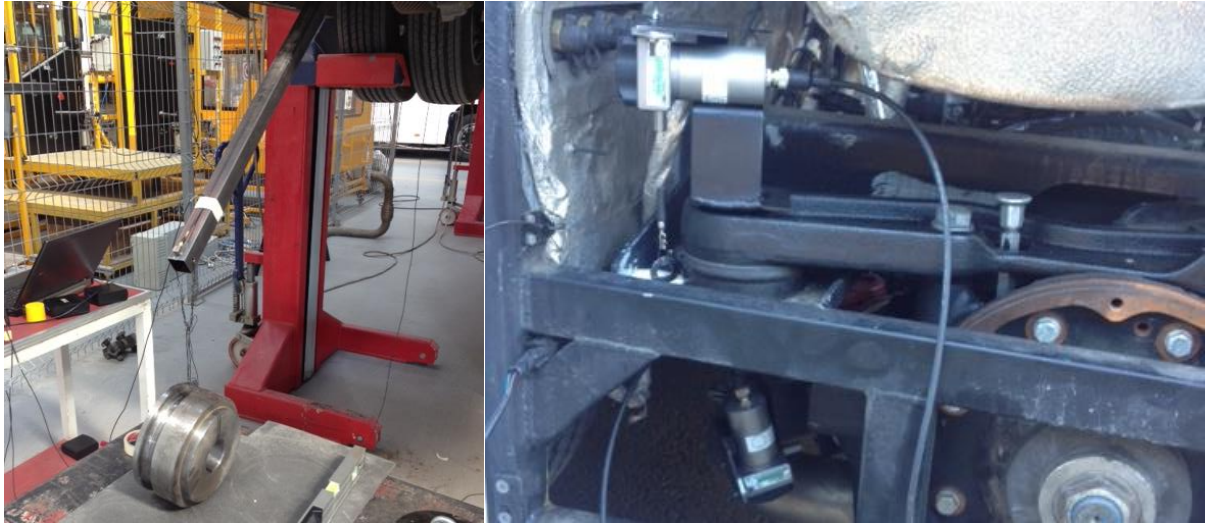


Figure 3: Driveline Backlash Measurement.

Table 1: Backlash Values of the Driveline.

Gear	Static Unloaded (°)	Static Loaded (°)	Dynamic (°)
1 st	15,0	44,0	97,5
2 nd	15,0	30,0	N/A
Reverse	15,0	37,0	N/A

4 TORSIONAL COUPLINGS

To improve the perception of customers against the clunk noise and vehicle fore-aft, torsional (flexible) coupling might be introduced into the driveline. The torsional coupling, which extends the oscillation time in the driveline, does not damp the stored potential energy during launch and parking manoeuvres. However, the torsional coupling decreases the amplitude of the clunk noise and vehicle fore-aft.

The average & highest transferred torque values, packaging volume and backlashes prevent applying the ready-to-use torsional couplings. Therefore, torsional coupling designs are prepared in two concepts. The main difference between concepts is including rubber or coil as spring element as shown Figure 4.

The quality perception of the vehicle can be improved by softening spring elements or controlling backlash in coupling to eliminate the clunk noise and vehicle fore-aft. However, these design selections reduce the performance of the coupling durability.

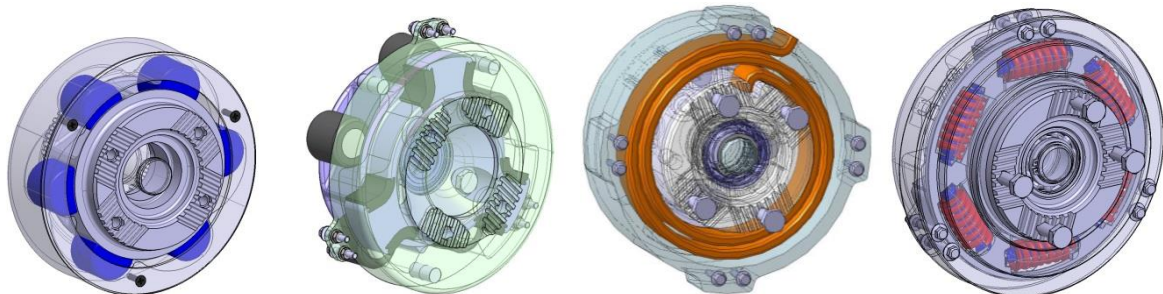


Figure 4: Designed Torsional (Flexible) Couplings.

Four different torsional (flexible) couplings are designed. First prototype is quite successful to reduce the clunk noise. However, rubber elements are failed in a short usage. Therefore, studies are concentrated on this solution by improving the rubber element

material/geometry and adding fail safe stage in the second prototype. Although these changes are improved its durability, there are still rubber failures in the early stages.

After the rubber parts failures, springs parts are appeared. Third and fourth prototypes improve the durability performance. On the other hand, they fail to satisfy the perception of the customers during vehicle fore-aft and clunk noise.

5 VISCOUS COUPLING

It is recognized that torsional (flexible) couplings will not satisfy enough durability performance in this driveline, while improving the perception of customers. Therefore, viscous coupling application has been used instead.

First of all, it is important to understand whether viscous coupling application has the potential to improve the satisfaction of customers or not. Consequently, primary prototype, sized according to torque values, backlashes and assumed damping need, is built. After it is succeeded, virtual and physical studies are initiated to size and validate.

Driveline kinematic model, shown in Figure 5, is prepared to understand damping necessity. Initially, oscillation durations of baseline status, between 5s and 6s during launch and parking manoeuvres, is evaluated. These results are also correlated with the tests, performed in the prototypes. According to achievements of primary prototype, damping value is examined and optimized in driveline kinematic model. Subsequently, oscillation durations, during launch and parking manoeuvres, are set between 2s and 3s. The amplitudes of forces, during the oscillations, are also decreased more than half.

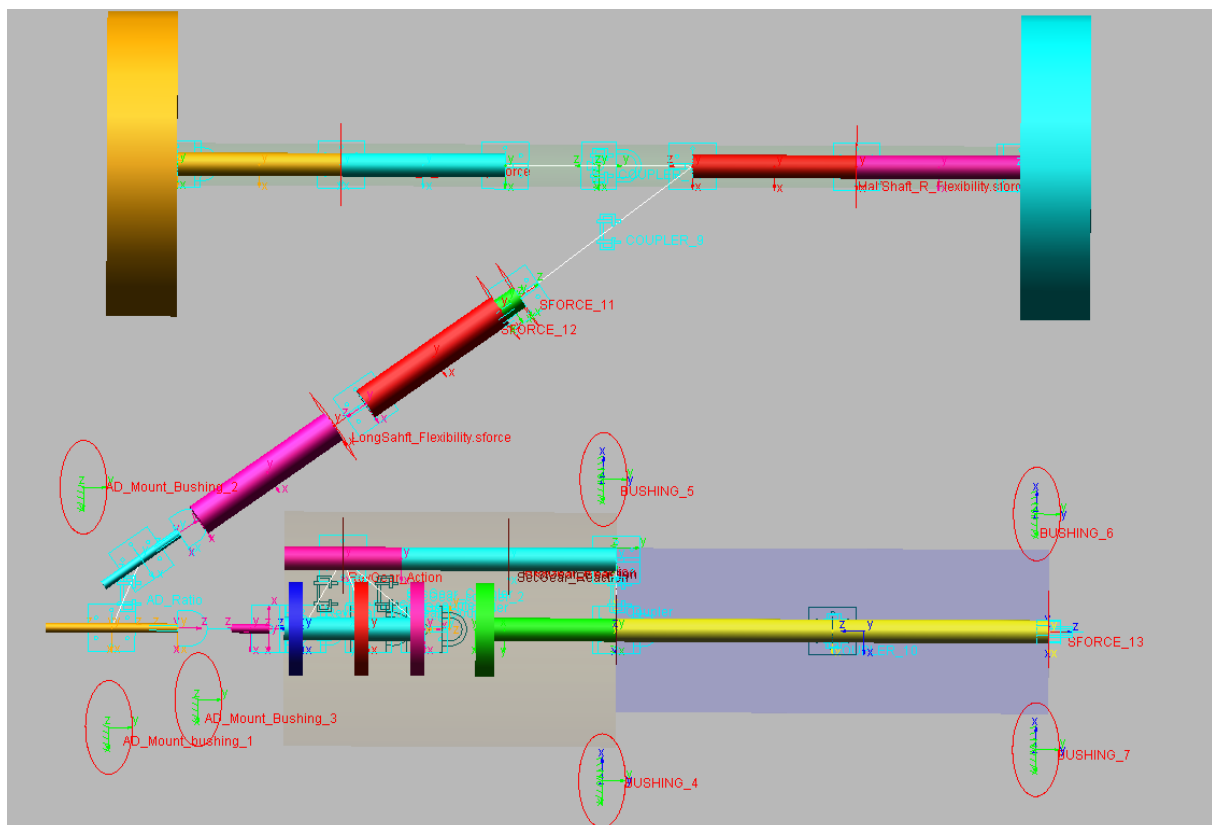


Figure 5: Driveline Kinematic Model.

After finalizing of the damping value, CFD analyses are run to size the holes between rooms and the size of the rooms itself as shown in Figure 6. CFD analyses are also run to select the fluid viscosity inside the viscous coupling.

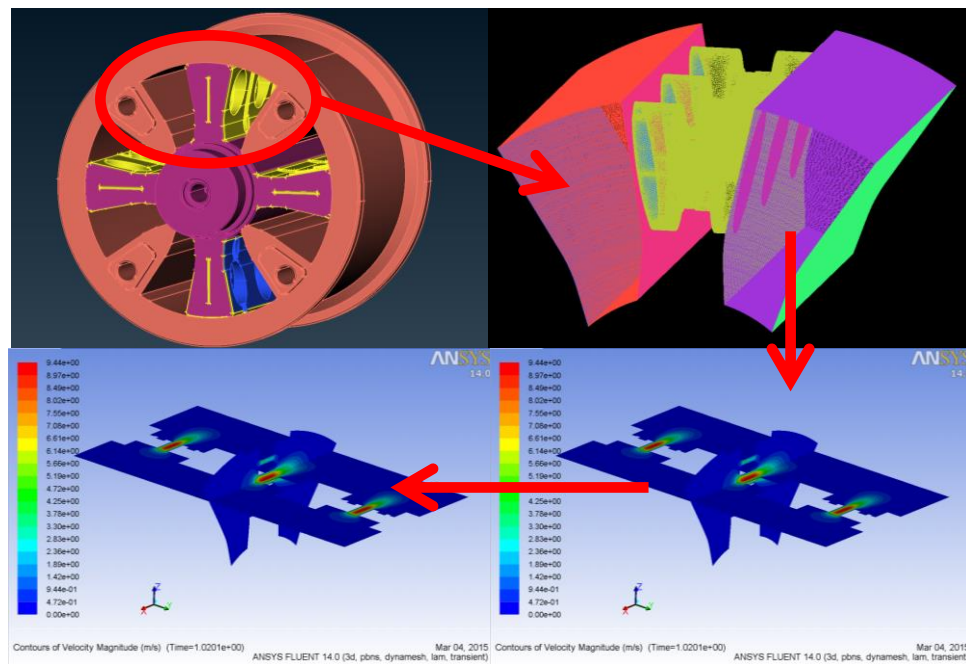


Figure 6: Viscous Coupling CFD Model & Analyses.

As shown in Figure 7, after critical sizes of viscous coupling are defined, initial CAD model is prepared.

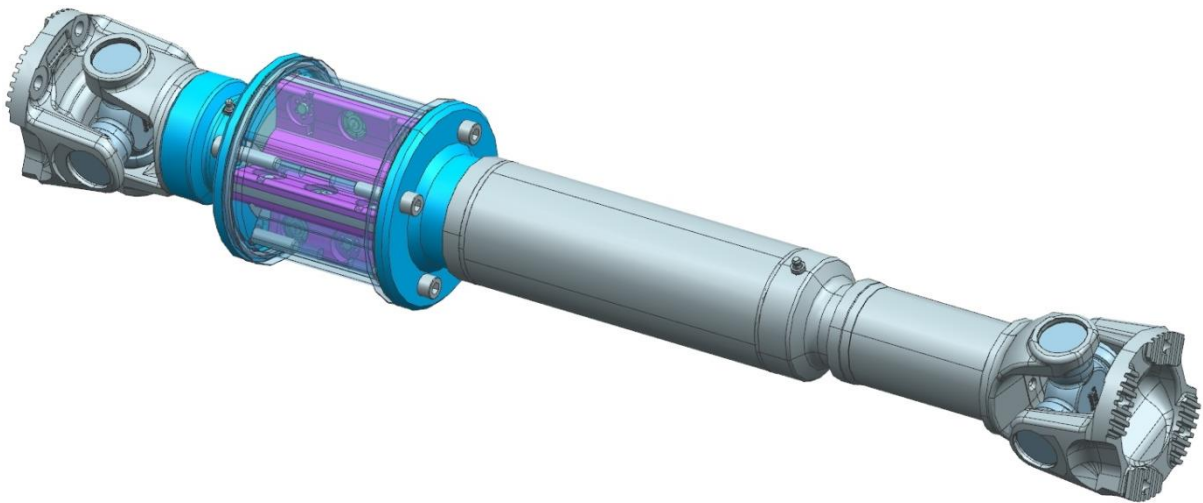


Figure 7: Long Drive Shaft with Viscous Coupling CAD Model.

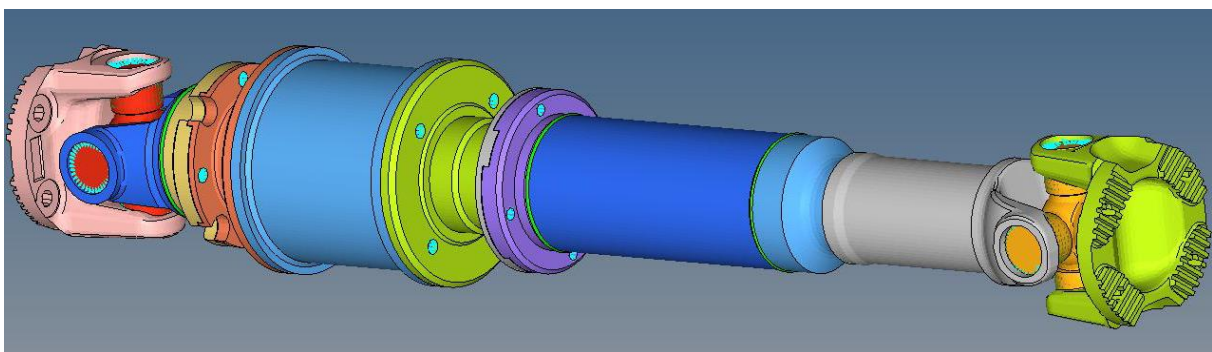


Figure 8: Long Drive Shaft with Viscous Coupling FE Model.

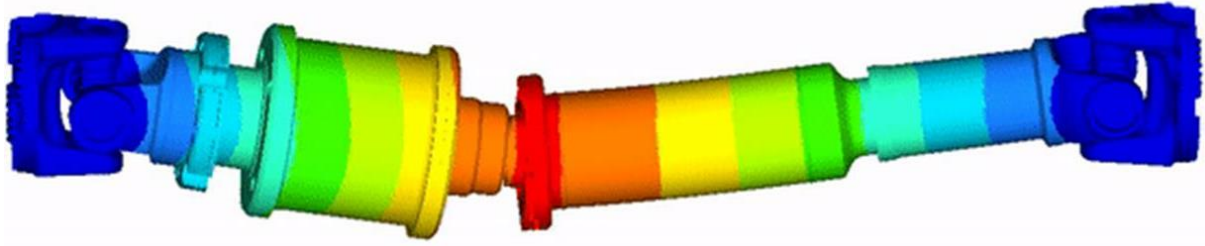


Figure 9: First Natural Mode of Long Drive Shaft with Viscous Coupling (174 Hz.).

To understand the critic shaft revaluation speed, natural mode analyses are run as shown in Figure 8 and Figure 9. First natural mode frequency is equal to 174 Hz. Critic shaft revaluation speed is 5200 rpm accordingly. Theoretically maximum shaft revaluation speed during operation is equal to 4500 rpm. Therefore, there is no issue expected due to the critic shaft revaluation speed.

Viscous coupling satisfies all requirements in static loading with high safety factor in full torque loading scenario. In fatigue analyses, it also fulfils three times longer life according to expectations in all scenarios.

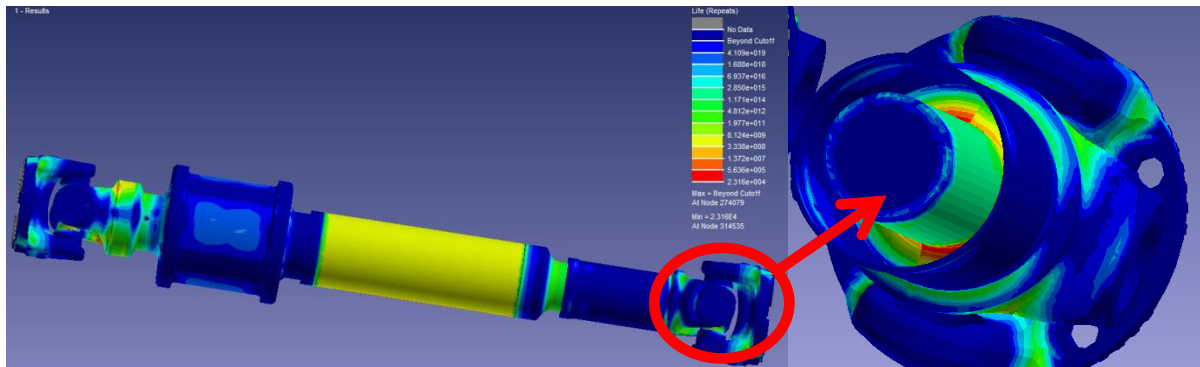


Figure 10: Static Loading Results of Long Drive Shaft with Viscous Coupling.

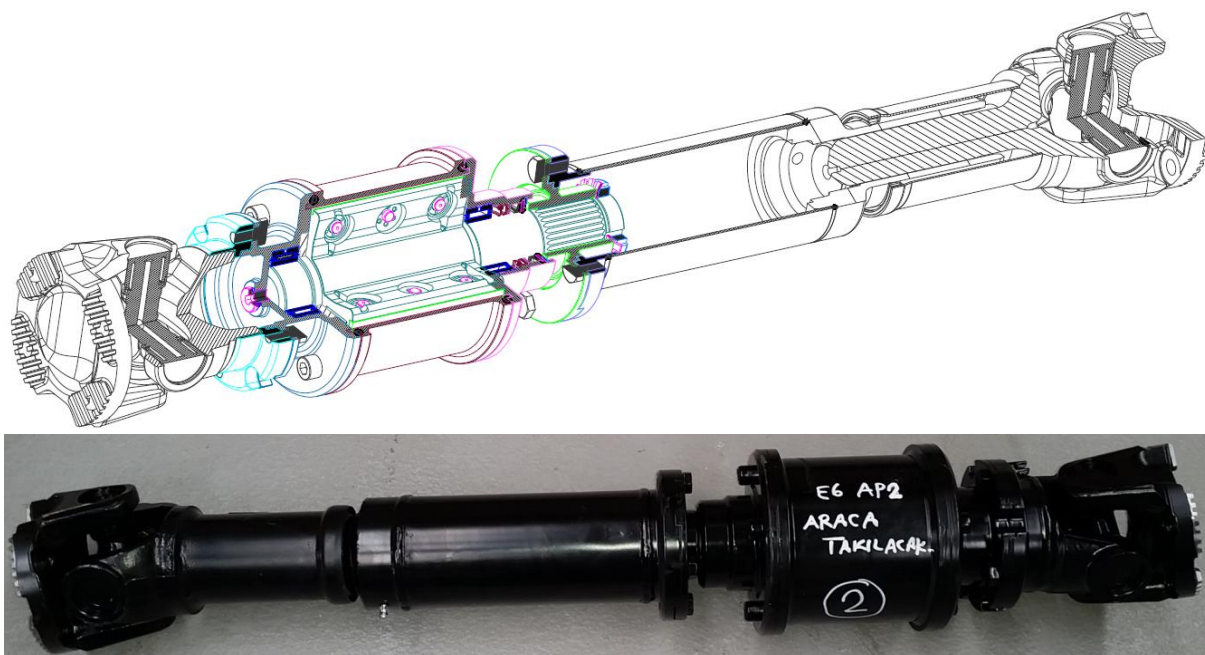


Figure 11: Production Drawing and Prototype of Long Drive Shaft with Viscous Coupling.

Table 2: Weight Status of Viscous Coupling.

	Weight (kg)
Long Drive Shaft without Viscous Coupling	22
Long Drive Shaft with Viscous Coupling – Primary	53
Long Drive Shaft with Viscous Coupling – Secondary	31

Prototypes are manufactured, as shown in Figure 11, for bench and on-vehicle tests. In order to correlate the natural mode analysis results, experimental modal analyses are performed as shown in Figure 12 and Figure 13. Frequency difference is less than 5 Hz in the first mode while the shape is the same. Durability bench test is also executed as shown Figure 14 and Figure 15.

The prototype of Long Drive Shaft with Viscous Coupling is also satisfied life expectations in durability test. Broken part in durability test and the point, in which highest stress is detected in FE analyses, are the same.



Figure 12: Production Drawing and Prototype of Long Drive Shaft with Viscous Coupling.

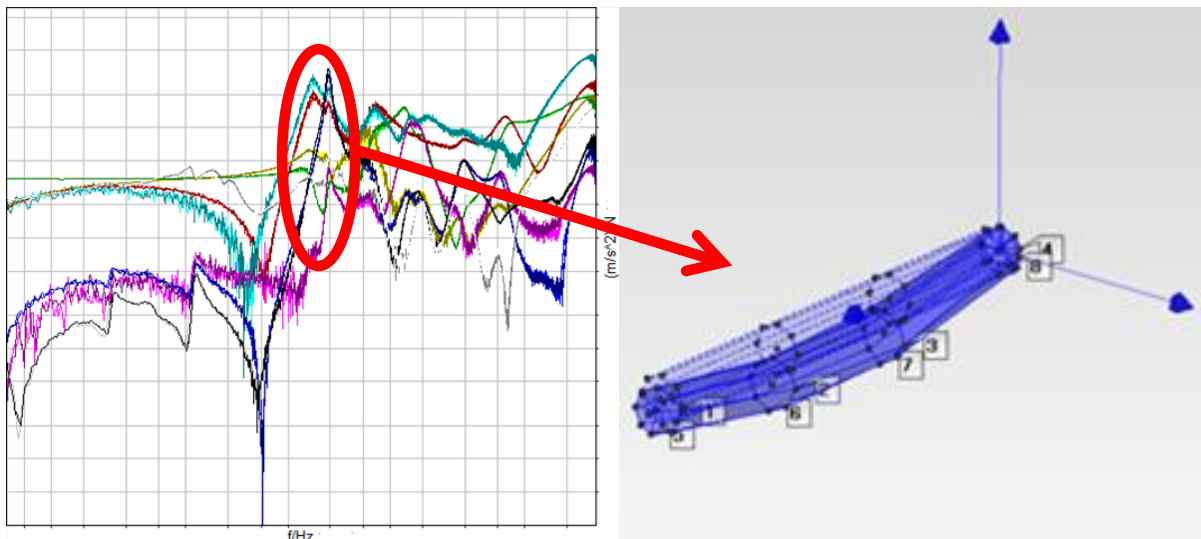


Figure 13: Results of Experimental Modal Analyses.

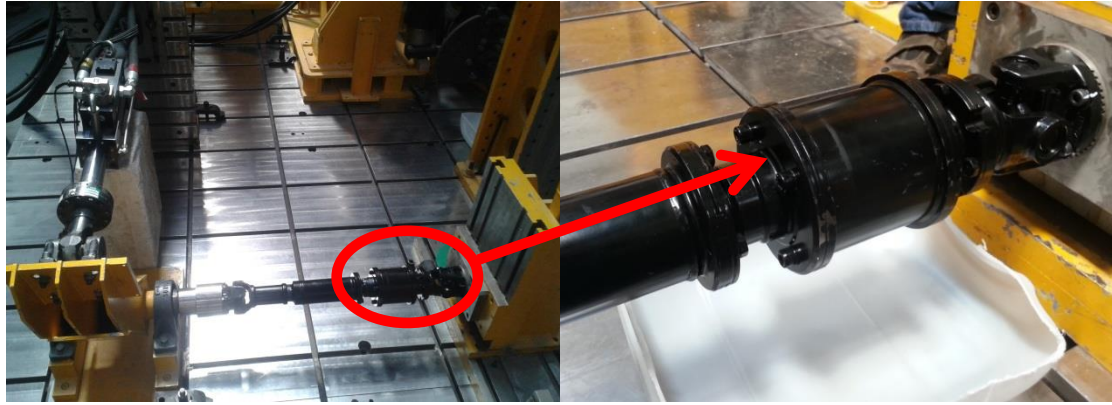


Figure 14: Durability Test Bench.



Figure 15: Broken Part and Viscous Coupling Parts after Durability Test.



Figure 16: Vehicle Assembled Long Drive Shaft with Optimized Viscous Coupling.

6 CONCLUDING REMARKS

This paper summarizes process steps of a case study about reducing driveline oscillations in a laterally placed powertrain with an automated transmission and angle drive gearbox in an eight-meter length low-floor bus. After clunk problem arouses, possible causes, factors and solution methods have been investigated. Following failed trials of torsional couplings, an optimized viscous coupling is seen to satisfy physical expectations as well as customer perception of vehicle quality, in terms of vehicle fore-aft and clunk noise during launch and parking manoeuvres.

Viscous coupling design optimization, to reduce its weight, will be continued. Due to fact that it fulfils three times longer life according to expectations, there are potentially weight

reduction items. In order to increase the critic shaft revaluation speed, the design of shaft and viscous coupling might be more entwined together.

ACKNOWLEDGEMENTS

The authors would like to thank their colleagues at Hexagon Studio, for their comments and helpful suggestions. We are also immensely grateful to Selçuk Alagöz, Sercan Sunar, Soner Zıvalı, and Cüneyt Üzüm.

The authors also wish to apologize for the unintentional exclusions of missing references and would appreciate receiving comments and pointers to other relevant literature for a future update.

The presented study was carried out in the context of the research project “Yolcu Taşıtlarının Motor Hareket Aktarma Organlarında Oluşan Titreşim – Gürültü Problemleri için Sistem Geliştirilmesi Projesi (Project #: 3160793)” and funded by National Support Programs (1501 - Tübitak Sanayi Ar-Ge Projeleri Destekleme Programı).

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