Next Generation Train (NGT): Cooperation between DLR and Lucchini RS Group for innovative railway vehicles

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Abstract

At the German Aerospace Center (DLR) there is a project for railway applications with a focus on, among other things, lightweight design and the introduction of innovative architectures and solutions at the bogie level. In particular, from the viewpoint of the bogie design and the bogie configuration, a highly innovative concept was adopted, pursuing a lightweight solution by implementing topology-optimization-derived steel structures with a low-floor bridged axle configuration and independently rotating wheels (IRW), sprung direct-drive high frequency AC-synchronous motors and a mechatronic control system to govern the steering angle of the bogie using differential motor torques. The DLR and Lucchini RS Group cooperated in order to co-design the bogie's wheels and shafts, the latter having a special layout due to the IRW configuration. The activities included the geometrical and dimensional definition, the structural verification of the components' static and fatigue behavior and the proper technological practices at the manufacturing stage. In particular the interface between the wheel and the traction motor required special local machining. The outcome of the partnership between the DLR and Lucchini RS was presented at the InnoTrans 2022, held in Berlin in September 2022, in the form of the NGT FuN bogie prototype and research facility.

Keywords: High-speed, IRW, wheelset, research, NGT

1. INTRODUCTION

1.1. Next Generation Train (NGT) Project

For several years, the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, German acronym DLR) has been working on advanced railway applications within a project called Next Generation Train (NGT). The aim of this project is to develop innovative solutions and vehicles for various applications, as exemplified by the technology demonstrators NGT High Speed Train (NGT HST) for very-high-speed passenger service, NGT LINK for hybrid high-speed intercity service and NGT CARGO for very-high-speed autonomous freight transportation. Among the main drivers and targets of the project on the structural side are lightweight design, optimization of crash behavior and the introduction of innovative architectures and solutions at the bogie level.

NGT HST is a high-speed passenger train designed to run at speeds up to 400 km/h while also substantially reducing specific energy requirements relative to existing high-speed trains. One of the ways that this is achieved is through a comprehensive lightweight design approach in the train's development [12]. For the bogie design, this means for example reducing the masses, in particular unsprung masses, as much as possible. A potentially conflicting design constraint but at the same time a very important aspect of the train's concept is its full double-deck design with both decks extending over the entire length of the train, which in turn necessitates a low-floor bogie design. This low-floor bogie design is achieved through the use of a single pair of independently rotating wheels (IRW) connected through an axle bridge forming an inverted portal axle. The wheel/shaft assemblies used in this IRW design (Figure 1) will hereafter be referred to as a "wheel units", since the term "wheelset" implies a conventional assembly with two wheels on a full-length shaft. The wheel units described here were developed in cooperation with Lucchini RS Group.

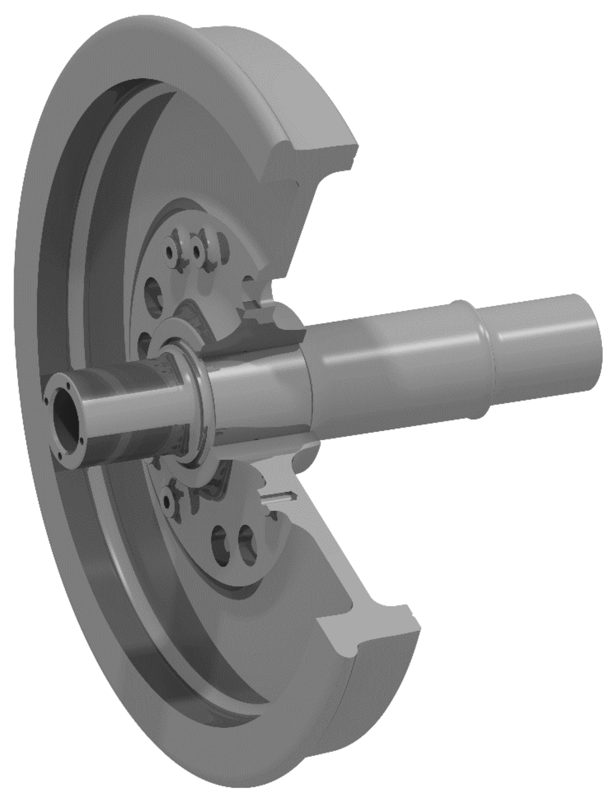

Figure 1: Layout of the "wheel unit" (wheel/shaft assembly)

1.2. NGT FuN

Building upon the virtual bogie design developed in the course of the NGT project, extensive finite element and multi-body simulations as well as successful experiments with a 1:5 scale test bench bogie model, a functional prototype of the NGT bogie has been realized as part of the NGT bogie research infrastructure project (Forschungsinfrastruktur NGT-Fahrwerk, German acronym FuN, Figure 3). FuN will be used to test the behaviour and functions of the bogie on rolling test rigs for an initial three years. Further testing in a rail vehicle on a test track facility is planned.

Figure 2: Rendering of the FuN research facility, with the NGT bogie installed in an integration test stand featuring a small roller rig

1.3. Development participants

The German Aerospace Center DLR (Deutsches Zentrum für Luft- und Raumfahrt) is active in several research areas including aeronautics, space research and technology, transport, energy, defense and security, space administration and project management. It has approximately 10 000 employees across 55 institutes at 30 sites spread throughout Germany, with offices in Brussels, Paris, Tokyo and Washington.

Lucchini RS Group is an Italy-based and worldwide known designer and manufacturer of wheelsets, wheels and axles for every railway application, ranging from freight wagons to locomotives, passenger vehicles and High Speed.

2. Bogie Design Principles and Features

2.1. Mechanical layout

Figure 3 shows the conceptual design of the NGT bogie. The axle bridge carries the wheels and the electric drives and is capable of rotating around a virtual pivot constituted by the arrangement of two axle bridge links. These axle bridge links and the primary suspension connect the axle bridge to the secondary frame which in turn is linked to the car body by the secondary suspension and traction rods.

The design of the axle bridge is tailored to have low floors even in double-deck trains. Even in single-deck vehicles, low floors are of advantage since they allow for stairless access to the train and make it easily accessible for persons with reduced mobility. Figure 4 presents a front view of the bogie in order demonstrate the gain with respect to the design space of a low floor aisle between the wheels.

2.2. Functional Design and Considerations

As the IRW-design lacks the passive self-centering tendency of a classical wheelset, the NGT bogie is mechatronically controlled to active guide the wheels along the track. The guidance function is accomplished by applying differential torques to the wheel drives that initiate a yaw motion of the axle bridge. This way, the bogie is capable of steering into curves and counteracting disturbances, e.g. those introduced by rail irregularities. Wear and noise reduction are additional benefits that are targeted.

The electric motors are of a permanent magnet synchronous design and directly drive the wheels without gears. They provide 180 kW and 2050 Nm, each. They are spring-mounted to the axle bridge and flexibly coupled directly to the wheel webs in order to reduce the unsprung mass, improve the track-friendliness and protect the motors from highly dynamic track excitations.

In initial considerations, large wheel diameters of 1250 mm were considered in order to increase the effective electromechanical diameter and thus the available torque

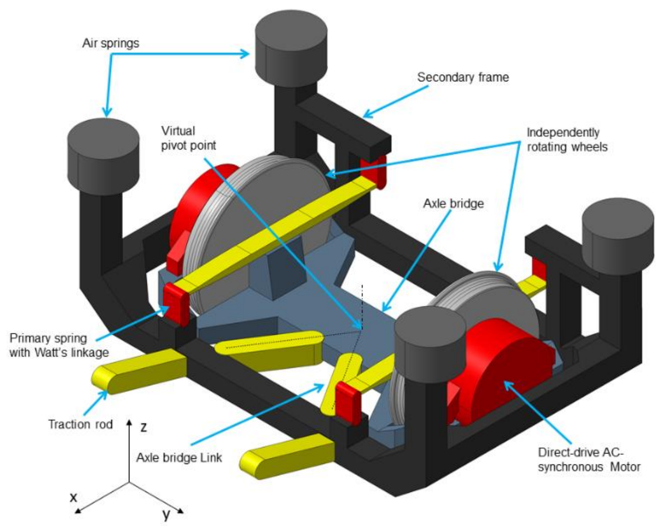

Figure 3: Sketch of the conceptual design of the NGT bogie [1]

as much as possible. However, large wheel diameters are associated with large moments of inertia that in turn require large guiding torques in particular in curves with superelevations in order to steer the axle bridge. These undesirable gyroscopic effects, as well as the overall weight of the bogie, could be significantly reduced by choosing a wheel diameter of 980 mm, see [2] for details.

The overall weight of the complete bogie (Figure 4) amounts to approximately 3000 kg, which is the result of a comprehensive optimization in order to reduce the weight and preserve as much payload capacity as possible [3].

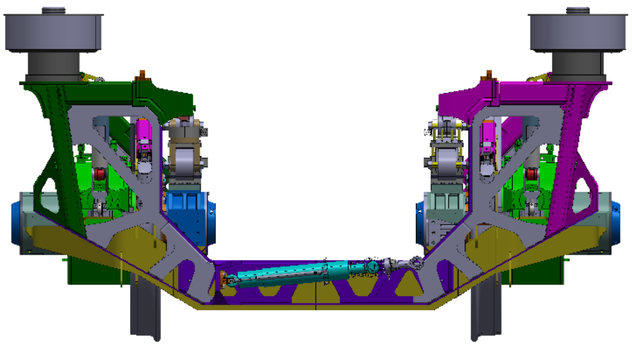

Figure 4: Front view on the bogie CAD design

3. Wheel and Shaft Design

In order to comply with the design and interface constraints applicable for the NGT bogie, dedicated non-standard solutions were developed by the DLR and Lucchini RS Group for the wheel and the shaft.

In particular, the adopted design solutions feature the following main characteristics:

- independently rotating wheels, each mounted on a shaft assembled onto the axle bridge. As a consequence, there is no torsional connection between the two wheels sharing the same rotation axis and this has a relevant influence on the design configuration, on the dimensions and on the structural verification strategy to be adopted for the shaft;
- special interfaces for coupling the driving unit directly onto the wheel, which imply some design and technological challenges at the structural verification and production stages;
- highly optimized unsprung masses, with the necessity of ensuring sufficient safety and reliability levels while adopting a lightweight design approach.

In the following, a more detailed description of the applicable design scenario and of the approach adopted for the wheel and the shaft definition is given, along with some insights into the technological challenges faced at the production stage and some considerations related to the Total Life Cycle Cost (TLCC) of the application.

3.1. The design scenario

The main input data agreed to between the parties and considered for the wheel and shaft design definition are summarized in the following table.

TABLE I. MAIN INPUT DATA FOR WHEEL AND SHAFT DESIGN

Component	**Main input for the wheel and shaft design**		
	Parameter	***Value***	***Unit***
Wheel unit and axle bridge	Maximum load per axle bridge	16 000	kg
	Design speed	430	km/h
	Distance between the rolling circles of the two wheels mounted o the same axle bridge	1500	mm
	Wheels back-to-back distance	1360	mm
Shaft	Hollow bore diameter	85	mm
	Distance between the centres of bearings assembled onto one shaft	623.5	mm
	Bearings seats diameter	130	mm
Wheel	Rolling diameter, new	980	mm
	Rolling diameter, fully worn	920	mm

For the wheel, the adoption of the tread profile S1002/h28/e32.5/6.7% according to the European standard EN 13715 [4] was agreed upon; it corresponds to a solution widely used for several different applications in Europe, including many high-speed vehicles.

3.2. Shaft design definition and verification

For the design definition and verification of the shaft, the provisions of the European standard EN 13103-1 [5] were applied as far as possible, though some adaptions were necessary since such documents generally consider conventional configuration, for instance a wheelset with outboard bearings, and cannot be directly applied in all aspects to the NGT axle bridge layout.

However, Lucchini RS managed to adapt the prescriptions of [5] for the definition of the type and magnitude of the design loads to be considered for the structural verification of the shaft. The component sections selected for the infinite life fatigue assessment required by [5] are shown in Figure 5.

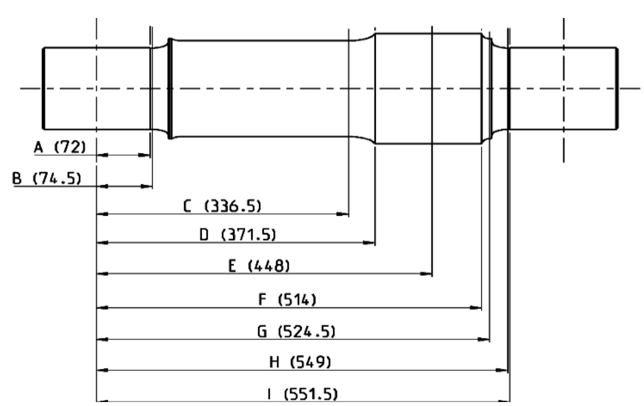

Figure 5: Sections considered for the design verification of the shaft

In terms of metallurgical solution, the stress results obtained from the structural calculations led to the selection of the steel grade EA1N according to the European standard EN 13261

[6], which grants sufficient reliability even in the presence of the relatively large hollow bore diameter (85 mm) which was included in order to achieve a lightweight configuration.

As for technological aspects, the special layout of the shaft and, in particular its length (much shorter than for conventional railway axles), implied some specific adaptions of the machining practices at the production stage.

3.3. Wheel design definition and verification

Similarly to the shaft, some adaptions were also needed for the solid wheel design with respect to the usual practices adopted for conventional solutions.

In fact, while the design loads can be computed directly from the provisions of the European standard EN 13979-1 [7], the fatigue verification criteria defined in that normative reference required some adaptions for the verification of the special interfaces for the coupling of the traction motors with the wheel, e.g. by considering the potential presence of a multiaxial stress state. Additionally, the effects of the tractive actions transmitted to the wheel by the driving systems were included in the analyses, so the overall loading scheme was more complicated than in conventional cases.

The 3D FEM model used for the structural verification of the wheel is shown in Figure 6.

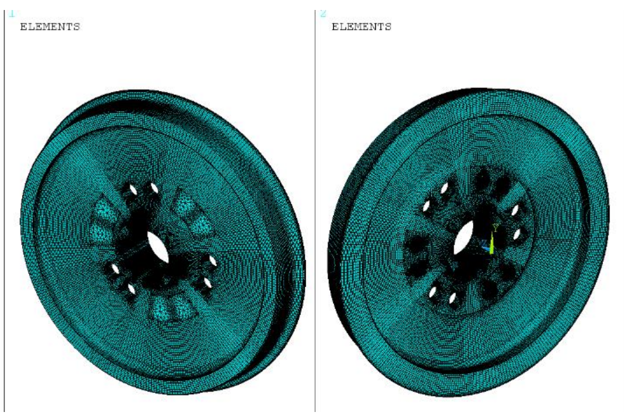

Figure 6: 3D FEM model used for the wheel structural verification.

The computed safety factors granted a satisfactory reliability level for the wheel and met the lightweight design criteria agreed to between the parties.

As for the material, the steel grade ER8 according to the European standard EN 13262 [8] was selected: it is a worldwide service-proven metallurgical solution for several different railway applications, including High Speed, and, also according to Lucchini RS experience [9], it is expected to exhibit suitable behaviour. However, this does not exclude any potential future improvement once a reliable service feedback for NGT is available, e.g. fine tuning of the steel grade selection and/or optimization of the tread profile geometry, with the aim of maximizing the application performance in terms of TLCC.

As for the shaft, also the wheel design implied some technological challenges, specifically, the adoption of special practices at the production stage for the machining of the interfaces between the wheel and the driving unit.

3.4. Wheel unit assembly

For the assembly of the wheel into the shaft, the provisions of the European standard EN 13260 [10] were adopted, once again as far as possible, since the standard mainly applies to conventional outboard bearings wheelsets.

The connection between the components, checked theoretically by dedicated FEM calculations, was obtained by applying the shrink-fitting process (selected for technological easiness) and properly verified by a counter-pressure test according to the provisions of [10].

4. OUTLOOK AND CONCLUSION

The development of the NGT running gear and its realization in the form of the FuN research facility is part of a continuous process of experimentation, analysis and improvement being carried out by the DLR and in cooperation with partners like Lucchini RS Group. The wheel units described in this paper represent the embodiment of the current state of bogie development at the DLR and are due to be tested, along with all other systems and components incorporated into the NGT bogie, in a test campaign expected to span the next several years.

FuN is a research facility that can be used to test new technologies and designs, but this process can of course only be of maximum utility through the careful testing of successive iterations. The wheel units described here are the result of years of research and development and are already highly optimized in their current state, but even before testing of the complete NGT bogie has begun, the nature of scientific and engineering research means that the parties involved are already considering future developments and their potential to improve various characteristics of the current design. One area of the wheel unit design particularly inviting to future research is tread profile optimization. The tread profile currently used is the result of decades of empirical research and development of classical wheelsets in European railways. With the mechatronically controlled IRW concept used in the NGT bogie, the opportunity presents itself to implement completely new wheel geometries with the potential to significantly improve upon many of the weaknesses of the current state of the art.

For the NGT project and the developments described here to be truly successful, it is important that they serve to improve the rail transport in the future. The new technologies and concepts demonstrated in the NGT bogie are being developed with specific goals of reducing emissions, wear and TLCC associated with rail transport. Achieving these goals stands to make an already efficient sector more attractive for all stakeholders and contribute to the decarbonization of the transportation sector by encouraging a modal shift away from other more polluting modes.

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