Active Primary Spring for the Next Generation Train

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Abstract:
In this paper the design of an active primary spring for a single-wheel single running-gear railroad carriage is discussed. The setup is based on a leaf-spring design, which is implemented as fibre-composite part, combined with piezo-ceramic stack-actuators, enabling to dynamically influence the contact between wheel and rail. The motivation of the design as active component is discussed and the process of dimensioning of the leaf-spring is introduced. Final dimensions and active properties of the primary springs are given and discussed. An approach to a control scheme for first tests is presented as well as results from first dynamic tests with a downscaled prototype.
The paper closes with the outlook on tests and simulations which elucidate the integration into the concept of the mechatronic running gear.

Keywords: railway, lightweight construction, active spring, adaptive systems, piezo-ceramic actuator

Introduction
The design of fast and energy-efficient trains for personal transport is a topic of the research project "Next Generation Train" undertaken by the German Aerospace Center (DLR) [1,2]. For the fast long distance train designed in the project, goals are a low power-consumption per travelled distance compared to state of the art trains, while at the same time raising the operational design-speed to 400 km/h. In order to be energy-efficient, lightweight construction is central to the design process [3]. A concept of a carriage having a fibre-composite intensive frame and a mechatronic single wheel single running gear as shown in Fig. 1 is researched, thus reducing the mass of the running gear compared to a traditional double running gear.

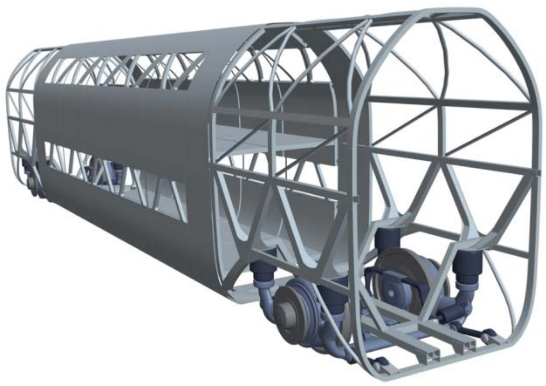

***Fig. 1:** Lightweight Carriage*

The single running gear is also designed with lightweight construction in mind [4] and is depicted in Fig. 2. As can be seen the single running gear has a single wheel configuration (i.e two single wheels instead of one axle with a pair of wheels) , due to the fact that the carriage is two-storied along the whole length in order to increase passenger density compared to state of the art trains. Mechatronic control of the single wheels drives is used to center the horizontal alignment of the wheels on the rail, thus enabling high speed travel with minimal wear and maximal stability [5]. Part of the single wheel single running gear setup is a two part suspension, where the function of the primary spring is mainly keeping the contact between the wheel and the rail, while the secondary spring is responsible for the passenger comfort.

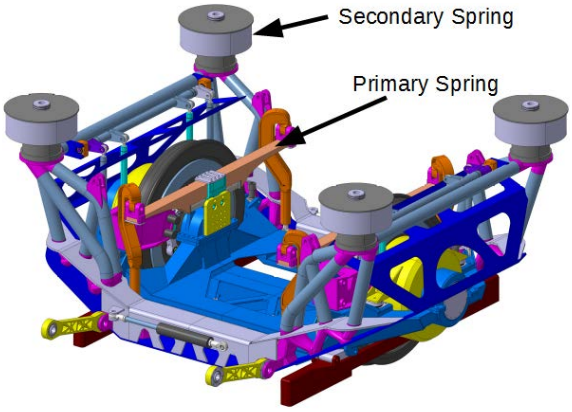

***Fig. 2:** Single Wheel Single Running Gear*

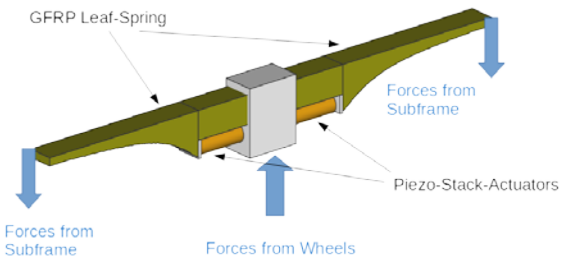

***Fig. 3:** Active Primary Spring*

Motivation
The design of the primary spring (see Fig. 3) has the following characteristics:

- Leaf-spring configuration
- Fibre-composite body
- Active degree of freedom

The leaf-spring configuration is result of packaging requirements of the running gear. Glass-fibre-composite materials enable high elastic deformation and fit the goal of lightweight construction. Finally the active degree of freedom of the primary spring enables influencing the rail-wheel contact, thus increasing security in high speed scenarios.
As can be seen in Fig. 3 piezo-ceramic actuators are placed at the root of the spring. When actuated the elongation of the actuators result in a bending of the spring and thus a relative vertical movement between the sub-frame of the running gear and the wheel carrier.
For first tests it is intended to implement a velocity feedback of the deformation resulting in adjustable damping in the setup, albeit other control schemes are possible to implement to further advance the performance of the running gear.

Design

Design of the primary spring is driven by the stiffness of the spring, given by dynamic requirements of the design of the whole carriage. Nonetheless it is mandatory to have enough strength to carry all loads which result from different use scenarios.
The design parameters used to design the primary spring are given (relative to a half-model of the spring) as:

- Stiffness c: 1000 N/mm
- Force from empty carriage F_{empty}: 30750 N
- Force from full carriage F_{full}: 41250 N
- Deformation from dynamic loads: +/- 20 mm
- Length: 76,5 cm
- Maximum Width: 8 cm

The design process is iterative and starts with a surface on which the fibre-composite laminate is stacked. In Fig. 4 this surface and the connection to the wheel-carrier and the sub-frame as well as the connection to the piezo-stack actuator are depicted. Next a laminate setup is chosen resulting in an FE-model as given in Fig. 5. The spring shown in this model represents the piezo-stack actuator, the parameters of which were chosen from a big commercially available standard actuator.
The stiffness is calculated and the laminate is variated until the result meets the design parameter.
In a next step the model is loaded with the equivalent loads of F_{empty}–c·20 mm and F_{full}+c·20 mm.
The strength of the actuator and the fibre-composite body are checked. Using ANSYS Composite PrepPost module (ACP), failure criteria for the fibre-composite body are defined, in this vase maximum strain criteria were used. An example of this is given in Fig. 6, where the criterion of matrix failure in the most loaded layer is shown as inverse reserve factor (value below 1 equals a sufficient strength, a value above 1 equals a failure). If any of the failure criteria denote an insufficient strength, the laminate is again variated until stiffness as well as strength is in the limits of the design parameters.
More details on the design process itself can be found in [6].
The resulting laminate is built from layers of unidirectional S-Glass with some layers of carbon fibre near the elastic neutral axis of the leaf-spring.
The resulting active degree of freedom Δl is calculated to be 0.78 mm

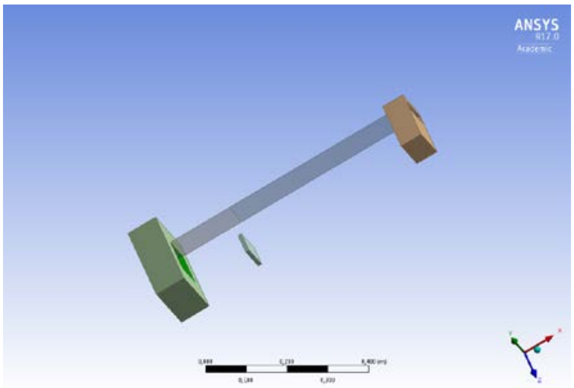

Fig. 4: *Starting Geometry for Design of Fibre-Composite Leaf-Spring*

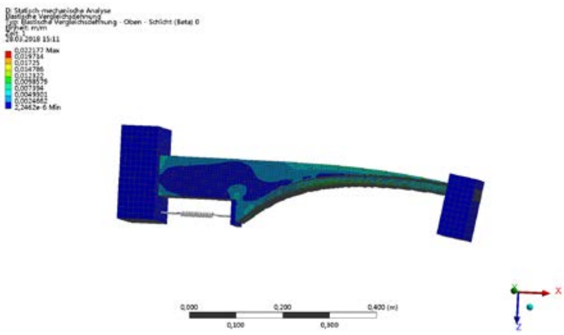

Fig. 5: *FE Model of Primary Spring*

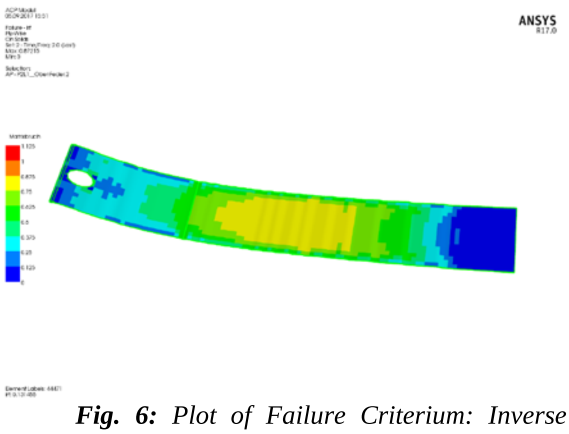

Fig. 6: *Plot of Failure Criterium: Inverse Reserve Factor against Matrix Failure*

Downscaled Model

As the manufacturing and testing of a full-scale primary spring is not feasible due to costs, an 1:5 downscaled model of a half-spring was built. A picture of the downscaled spring mounted in clamping device is given in Fig. 7.

While the shape of the 1:5 spring is the same as of the original, it differs from the 1:1 spring in some respects:

- The material is purely E-Glass
- The layup of the laminate is in the direction of thickness, the shape is result of milling instead of scarfing of layers.
- The used actuators have another shape, due to availability.
- Strength is not of concern for the scaled model

The following table gives a comparison of some parameters of the 1:1 spring, the parameters of the downscaled version of identical built and the parameters of the downscaled version as built:

	1:1	1:5 nominal	1:5 real
c	1000 N/mm	200 N/mm	114 N/mm
Δl_{active}	0.78 mm	0.156 mm	0.145 mm
F_{empty}	30750 N	1230 N	700 N
Δl_{Fempty}	30.75 mm	6.15 mm	6.15 mm

As the dynamic behaviour (i.e, frequency response) even of the nominal scaled model would differ from the 1:1 model the difference in stiffness c is negligible.

The main goal for the tests is to have congruity of the geometrical scaling of the model. Thus the deformation Δl_{Fempty} of 6.15 mm for the unloaded carriage is simulated by adjusting the load of F_{empty} to 700 N.

As can be seen the measured active degree of freedom Δl_{active} is already within 7% of the desired value.

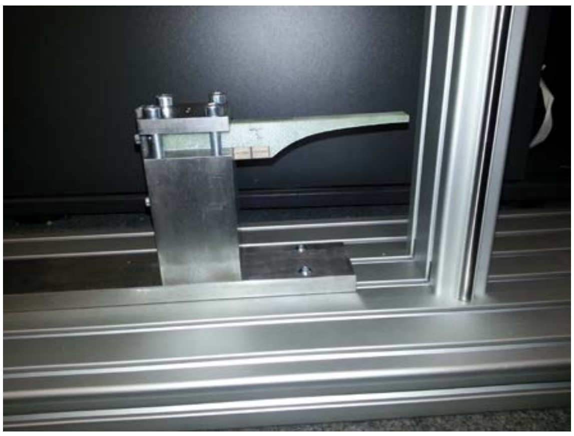

Fig. 7: *Downscaled Model of Primary Spring*

Dynamic Tests

The downscaled model will be used to test control algorithms to be used in the running gear. A test-stand as shown in Fig. 8 is built. The following parts are part of the test-stand:

- The 1:5 spring mounted in a clamping device.
- A base plate where the clamping device and a perpendicular rail is mounted. This plate can be attached to a dynamic shaker or testing machine to simulate excitation by the wheels.
- A platform connected to the perpendicular rails with linear bearings on the one hand and on the other hand to the free end of the spring. The rail and linear bearings ensure that loads are introduced to the spring purely in vertical direction.
- Weights put to the platform to simulate the load of the carriage.

First dynamic test in the test-stand were done to identify the first eigenfrequencies of the spring combined with different weights and corresponding damping factors. This is done to have a baseline for determining the active damping capabilities of the planned feedback controller, which are to be tested first.

The first tests showed that the test-stand unfortunately has very high damping, which is increasing with applied weight. A measurement of the eigenfrequency with the intended load of 700 N was not possible, as the damping was to high to get a full vibration amplitude after an impuls-excitation.

At a lower load of 315 N a resonant frequency of 9.1 Hz was detected, which correspond well to the theoretical value of 9.0 Hz. At this frequency the active degree of freedom was 0.96 mm.

Further adjustments on the test –stand have to be done in order to test the active damping. The main goal must be to reduce the damping of the test stand itself.

Fig. 8: *Modell under Load in Test-Stand*

Conclusions and Outlook

For the design of an active primary spring for the Next Generation Train a concept and a design rule were proposed and tested. Within the given parameters of the research project a solution could be found which should satisfy the stiffness and strength requisites.

In order to test control algorithms a downscaled model was build and integrated into a test-stand. The downscaled model was characterized and parameters for the test-stand identified.

In order to proceed with tests of active vibration control the test-stand has to be modified to reduce inherent damping.

In the near future further test will be done, eventually mounting the test-stand to a Shaker to simulate excitation from the rail.

In the course of the next years it is planned to test a full scale running gear including the active primary spring.

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