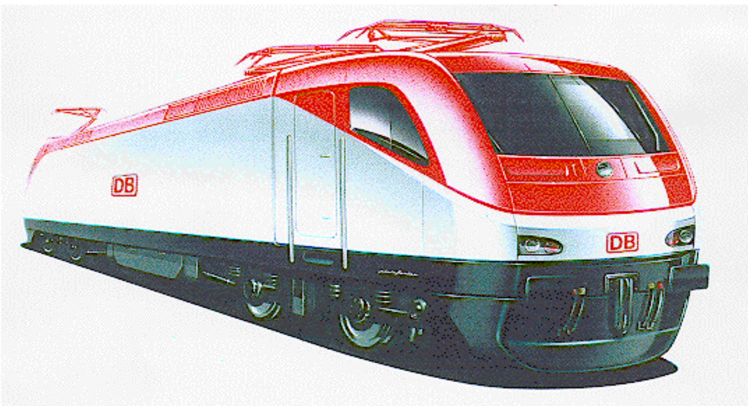
Improving the design of locomotive bogie and drive using ADAMS

by
Dr.-Ing. Peter Häse, Bombardier Transportation Ltd., Zurich (Switzerland)
and
Dipl.-Ing. ETH Christoph Decking, Advanced Information Solutions Ltd., Neuenhof (Switzerland)



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1 Introduction

International railway organisations have been in change throughout the last years. This is also a big challenge to all suppliers of rolling stock world-wide. One of the main topics is keeping the life-cycle-cost under control.
To work out high-quality and reasonable solutions it is necessary to better understand the loads acting on different subsystems of a bogie. This can be forces, torques or even accelerations.
Observations during several test-runs with different types of locomotives have shown that the loads caused by self-introduced vibrations can no longer be neglected.

2 Discrete Flexibilisation of the wheelset using ADAMS "discrete flexible link"

2.1 Goals of investigation

During commissioning an electrical locomotive with a so-called nose suspended drive a high acceleration level at the motor has been observed (figure 1). Especially the low-frequency content (< 100 Hz) of the spectra was an object of discussion due to the high vibration amplitude.

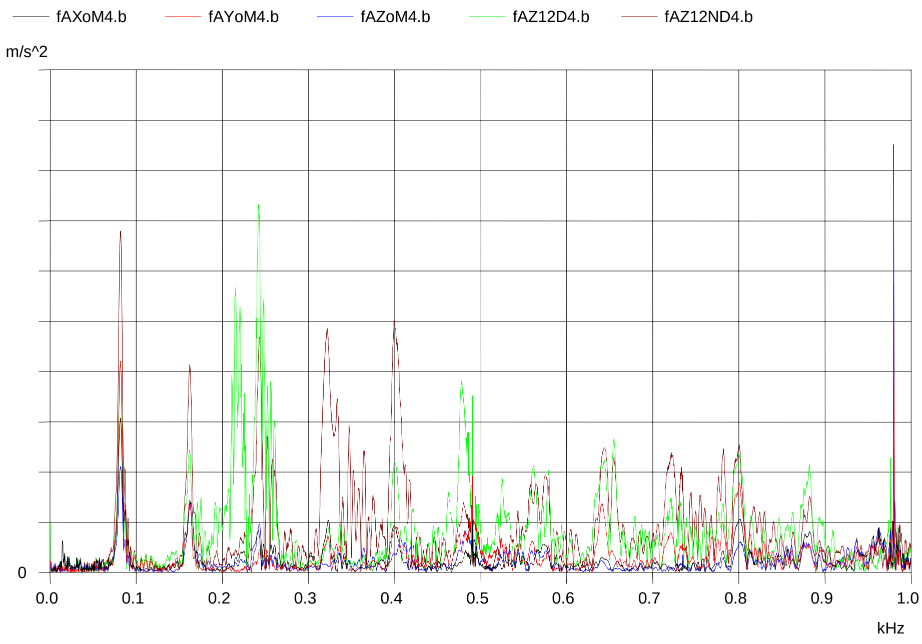

Figure 1 : Measured acceleration at the motor

In a first guess this oscillation was looked for torsional vibration of the wheels. But a closer look has shown that the frequency was to high for such kind of oscillation. Furtheron the observations showed that the vertical acceleration at the drive end (green line) of the motor was much lower than the acceleration at the non-drive end (brown line). Followed by that a more detailed investigation was started.

2.2 Build the drive model

The bogie was modelled by using ADAMS/View and the “Bogie and Drive Library” presented at the ADAMS/Rail User’s Conference 2000 [1]. As an extension of that model the axle shaft was ‘sliced’ into six parts using ADAMS/View “discrete flexible link”. The same procedure was used for modelling the rotor shaft. The plan view of the result is shown in figure 2.

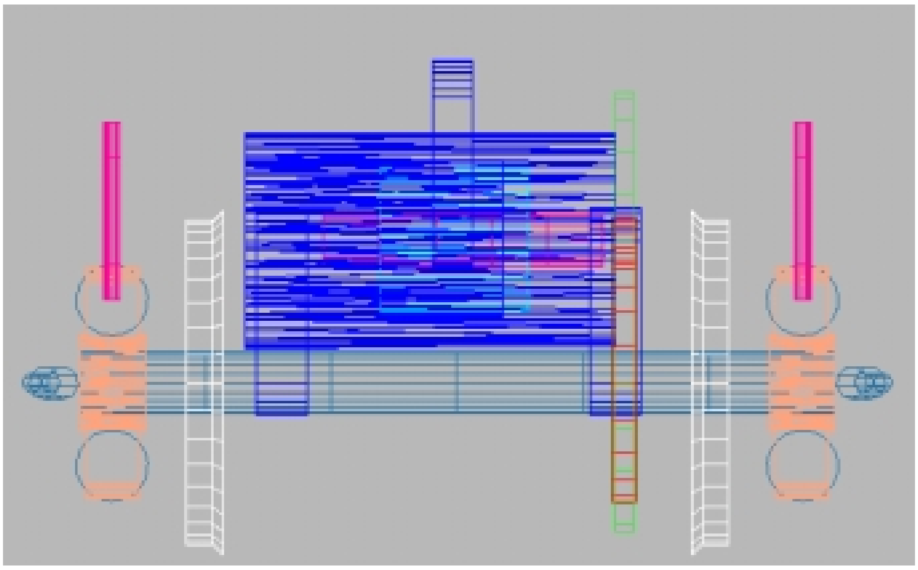

Figure 2: Model of drive

2.3 *Example of results*

The investigation of the eigen modes using ADAMS/Linear showed a lot of additional eigen frequencies and one frequency of approximately 80 Hz was found very quickly. The animation in figure 3 demonstrates that this mode (right) fits much better the measuring results than the “pure” torsional mode (left).

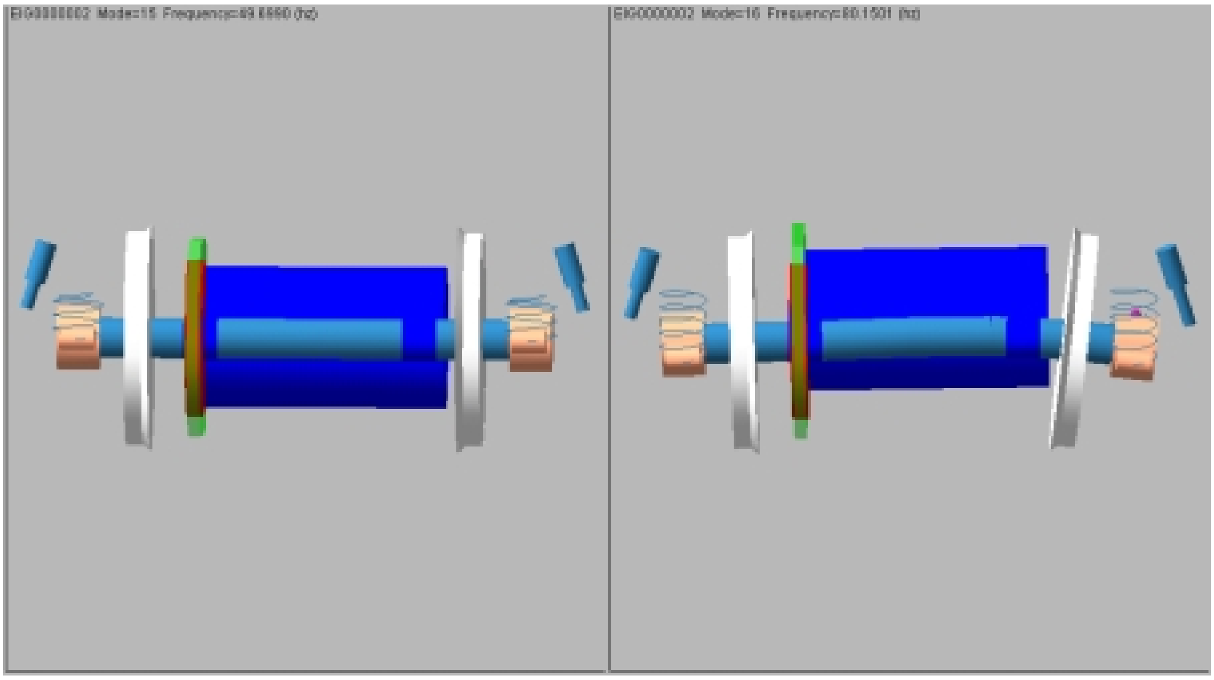

Figure 3: Torsional mode (left) and bending mode (right) of the axle shaft

A more honest investigation calculating the nominal displacements of all parts confirmed this result.

Mode Number	15	16
Description	Torsion of wheelset	Bending of wheelset
Frequency	~50 Hz	~80 Hz
Damping	very low	very low
Kinetic Energy	1	2
Bouncing of drive	yes	yes
Rolling of drive	no	yes

However, it is of interest that this new mode was found under the same conditions which normally cause the pure torsion mode.

3 Including the bogie frame as flexible structure derived from FE-Model

3.1 Goals of investigation

During the last years the so-called "Flexifloat" bogie came out as the standard for locomotives built by the Adtranz-company. Together with the fully suspended drive "IGA" it is used within different high-speed locomotives, running for example in Germany, Italy, Poland and will be introduced soon in the US. So we can state that this design performs well and reliable under different operating conditions. However, potential improvements in some detail could be seen especially in the field mentioned above.
On the other hand the improved capabilities of simulation tools should be tested. For this very special kind of investigation a coupling of the latest version of ADAMS/Rail and ADAMS/Flex seemed to be helpful.

3.2 Build the bogie model

3.2.1 Using the advantages of ADAMS/Rail's „template" structure

The most common way to use ADAMS/Rail is to investigate the dynamics of a running vehicle. Thus a bogie is modelled by a number of rigid bodies like wheels or wheelset and the bogie frame. This parts are connected by primary and secondary springs and dampers.
Thereby the drive is usually simplified and reduced to one body which is elastically mounted to the other parts. Another field of investigation uses the Finite Element Method to model the bogie frame and calculate loads and stresses within this part itself.
So the following improvements in modelling had to be made:

- Detailed modelling of the drive, consisting of motor (rotor and stator), gearbox, different gearwheels and hollow shaft as separate parts (see also [1])
- Integrating the FE-model of the bogie frame.

Here the structured modelling technology based on subsystems supported by the current ADAMS/Rail version was very useful. The whole model is split into the following substructures ("templates"):

- Wheelset
  (consists of two wheels connected by a revolute joint and a torsional spring)
- Primary suspension
- Drive
  (consists of rotor, stator, gearbox, gearwheels and hollow shaft)
- Push-pull-rod
- Rigid bogie frame, including secondary suspension
- Flexible bogie frame, including secondary suspension

At this "Subsystem level" all required action forces and/or torque have been added. This structure is shown in the figure below. It should be clear that it was essential to have the same "mount parts" and "connectors" at the rigid bogie frame and as well at the flexible bogie frame.

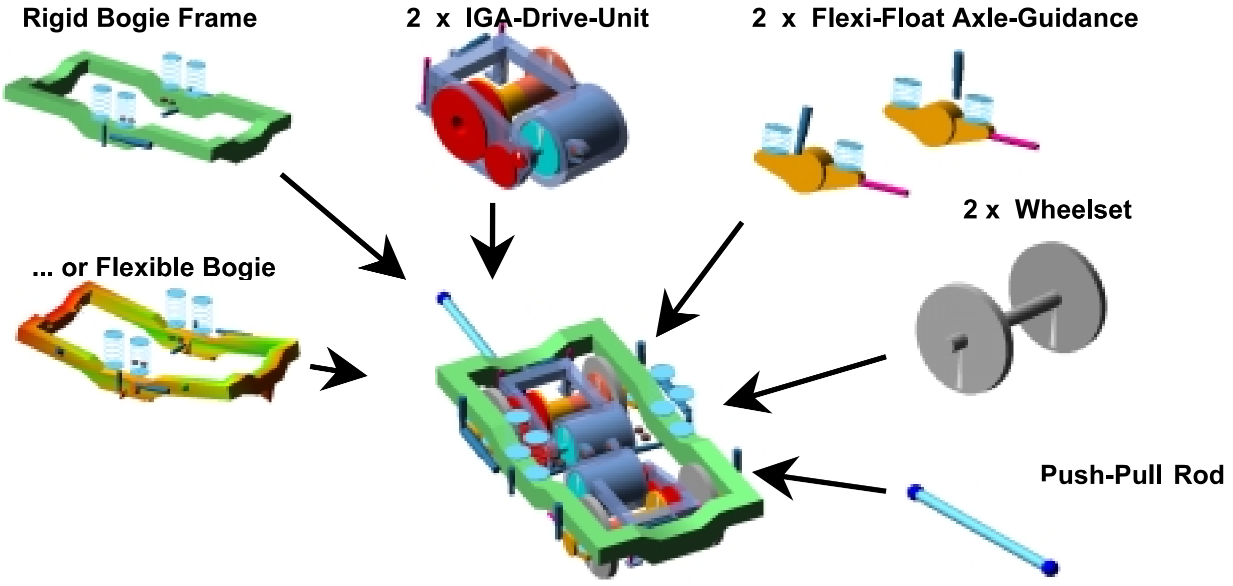

Figure 4: “Template” structure of bogie and drive

At the “system level” the first three substructures mentioned above were doubled and repositioned. By that all inputs and outputs defined before were doubled automatically. Finally at the “assembly level” the required subsystems were put together. That means that at least two different assemblies “rigid_bogie_model.asy” and “flexible_bogie_model.asy” had to be created.

3.2.2 Integrating the Flexible Bogie Frame

Comparisons between measurements and simulation results of rigid-bogie-frame-models have shown that some measured movements of the whole bogie-system did not appear in the simulation or the measured figures could not be fully explained by the models used. More detailed investigations pointed out that the bogie-frame which has been considered so far as rigid, brings in its own dynamic behaviour into the system resulting in torsional and bending deformations of the bogie-frame.

Figure 5: Modal Neutral File (*.mnf) exported from NASTRAN

This additional demand for simulating torsional and bending movements of the whole bogie frame requires a flexible bogie frame structure instead of the rigid one. Such a flexibility in the bogie frame can be received by including a flexible structure derived from FEM-Software (Finite Element Method) as NASTRAN into the model.
The specialised department of Adtranz/Germany created this structure-file (.mnf) which was referenced in the ADAMS/Rail Subsystem. Now there are two subsystems for the bogie frame available (one rigid and one flexible) and with the modular structure of ADAMS/Rail the user can now assemble the drive with rigid or with flexible bogie frame as he likes.

3.3 Performing the Analysis

There was a need to perform the analysis mainly within the frequency domain. Because ADAMS/Rail itself does not have the capability to perform such analysis in general the whole model had to be transferred from the ADAMS/Rail Standard-User- to the ADAMS/View-environment. And – as a small disadvantage – vice-versa in order to change parameters of special ADAMS/Rail elements like ar_bushing. To support this task and especially to make it fail-save a number of *.cmd-files have been created.

As a first result a linear analysis of the eigen modes was performed as known from ADAMS/View. In comparison to the rigid bogie model three weekly damped modes were found in the critical range between 50Hz and 70 Hz (see table 1 and 2).

Already in the animation of the eigen modes it becomes clear that the bogie frame is twisting if a torsional vibration occurres in the wheelset. This may be shown in the following picture:

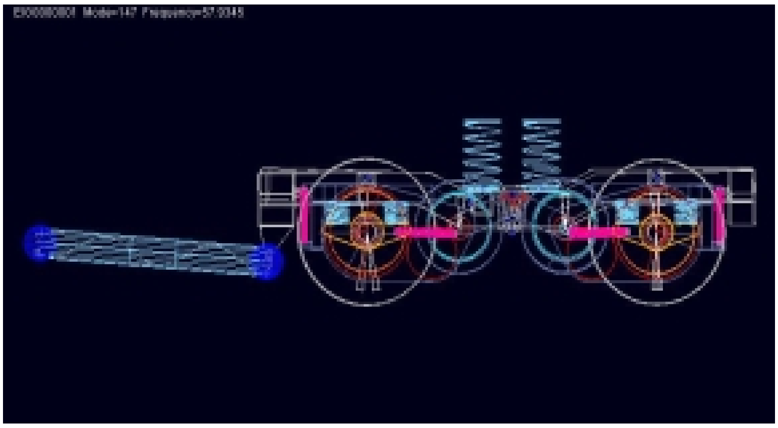

Figure 6 : Animation of eigen mode No. 144

MODE	UNDAMPED NATURAL	DAMPING	REAL	IMAGINARY	DESCRIPTION
NUMBER	FREQUENCY	RATIO			
45	4.20E+01	5.65E-02	-2.38E+00	+/- 4.197908E+001	
46	**5.25E+01**	**1.14E-01**	**-5.99E+00**	**+/- 5.220262E+001**	Longitudinal oscillation of axle and bogie frame
47	**5.79E+01**	**1.15E-02**	**-6.63E-01**	**+/- 5.789937E+001**	Torsional vibration of axle
48	**5.79E+01**	**1.15E-02**	**-6.64E-01**	**+/- 5.790744E+001**	Torsional vibration of axle
49	**6.18E+01**	**9.97E-02**	**-6.16E+00**	**+/- 6.146334E+001**	Bouncing of hollow shaft, out of phase
50	**6.17E+01**	**8.56E-02**	**-5.29E+00**	**+/- 6.151972E+001**	Bouncing of hollow shaft, in phase
51	**6.22E+01**	**2.86E-02**	**-1.78E+00**	**+/- 6.221153E+001**	Bouncing of bogie frame rolling of drive
52	**6.49E+01**	**1.08E-01**	**-6.99E+00**	**+/- 6.454052E+001**	Longitudinal oscillation of hollow shaft, out of phase
53	**6.54E+01**	**1.10E-01**	**-7.19E+00**	**+/- 6.496179E+001**	Longitudinal oscillation of hollow shaft, in phase
54	7.38E+01	1.45E-02	-1.07E+00	+/- 7.383477E+001	
55	7.39E+01	1.37E-02	-1.01E+00	+/- 7.393978E+001	

Table 1: **Eigen modes (50 ... 70 Hz), “rigid”-model**

MODE	UNDAMPED NATURAL	DAMPING	REAL	IMAGINARY	DESCRIPTION
NUMBER	FREQUENCY	RATIO			
127	4.54E+01	3.59E-02	-1.63E+00	+/- 4.540648E+001	
137	**5.17E+01**	**1.26E-01**	**-6.50E+00**	**+/- 5.127071E+001**	Bending of bogie frame a& longitudinal oscillation
143	**5.49E+01**	**1.76E-02**	**-9.66E-01**	**+/- 5.485451E+001**	Pitching of motor suspension
144	**5.65E+01**	**3.34E-02**	**-1.89E+00**	**+/- 5.651293E+001**	„Twist“ of bogie frame
146	**5.79E+01**	**1.16E-02**	**-6.73E-01**	**+/- 5.791711E+001**	Torsional vibration of axle
147	**5.79E+01**	**1.30E-02**	**-7.51E-01**	**+/- 5.793451E+001**	Torsional vibration of axle
151	**6.07E+01**	**9.63E-02**	**-5.84E+00**	**+/- 6.041434E+001**	Bouncing of the hollow shaft 2
157	**6.25E+01**	**1.02E-01**	**-6.35E+00**	**+/- 6.214086E+001**	Bouncing of the hollow shaft 1
158	**6.24E+01**	**1.71E-02**	**-1.07E+00**	**+/- 6.242612E+001**	Twist of bogie frame
161	**6.52E+01**	**1.10E-01**	**-7.16E+00**	**+/- 6.480572E+001**	Oscillation of hollow shaft
162	**6.51E+01**	**9.32E-02**	**-6.07E+00**	**+/- 6.485144E+001**	Oscillation of hollow shaft
164	**6.54E+01**	**7.18E-02**	**-4.70E+00**	**+/- 6.527774E+001**	Oscillation of hollow shaft
170	7.13E+01	2.46E-02	-1.75E+00	+/- 7.129933E+001	

Table 2 : Eigen modes (50 ... 70 Hz), “flex”-model

3.4 Example of results

3.4.1 Frequency Domain

As mentioned above the main investigation was made in the frequency domain. Basically the transfer function ("bode-plots" in ADAMS) were calculated. The system is excited by a force acting at the contact point between rail and wheel. As outputs the following values have been selected:

- Vertical acceleration of the stator at both bearings
- Vertical Force in the motor suspension

Although this transfer functions may be calculated with ADAMS/Postprocessor directly a different way was chosen for better handling and presentation. After finding the static equilibrium the system was linearised and exported to MATLAB's state-space-representation. The calculation of the transfer function itself was performed by using MATLAB's Control System Toolbox.
In order to show the influence of the different boundary conditions three cases were taken into account:

- Drive/bogie mounted to ground (blue)
- Drive with rigid bogie frame (green)
- Drive with flexible bogie frame (red)

As an example of the results the vertical acceleration at the motor bearings is shown in the following figure:

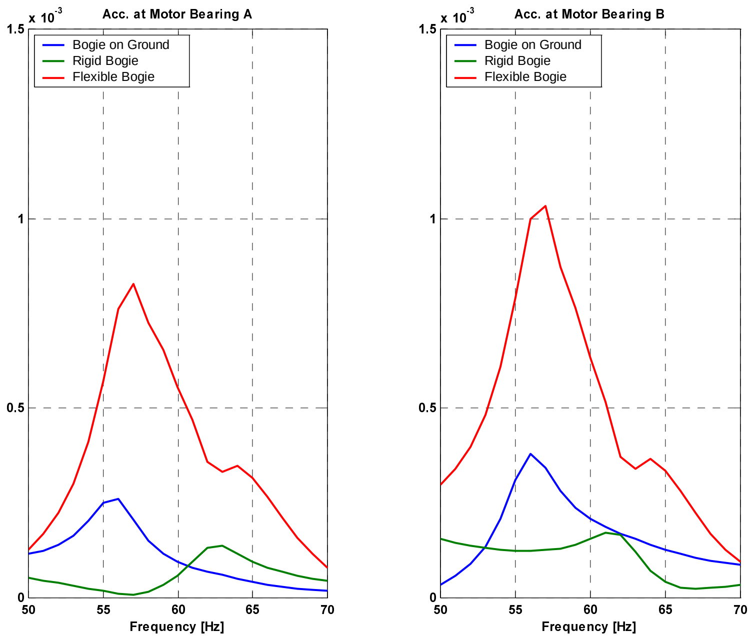

Figure 7 : Transfer function, acceleration at motor bearings

In the next step the influence of wheel wear was investigated. Due to the wear the moment of inertia of the wheels decreases and the frequency of the self-introduced oscillation increases. To perform this investigation the force was acting on both wheels with the same magnitude but with a phase shift of 180 degree (out of phase).

The influence of the wheel wear is shown in the following figure:

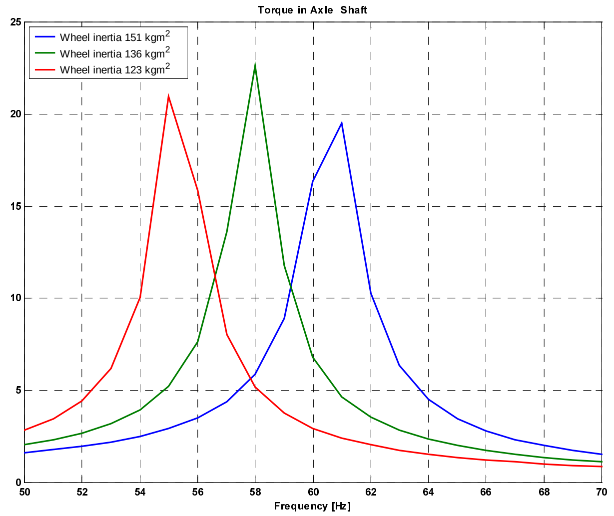

Figure 8 : Transfer function, torque within wheel shaft

With these modifications the measures mentioned above were calculated again. The corresponding accelerations at the motor bearings are shown in the figures 9 and 10.

At the first look the results are completely different between taking into account the bogie frame as rigid part and modelling it as a flexible object. But after comparing the eigen modes presented in table 1 and 2 the results are easier to understand. In case of the rigid bogie frame the mode number 51 plays the major role. Modelling the bogie frame as flexible part this mode has moved to higher frequencies out of the focused range. Due to the fact that such frequencies have not been measured at any test runs the advantage of the improved modelling is confirmed.

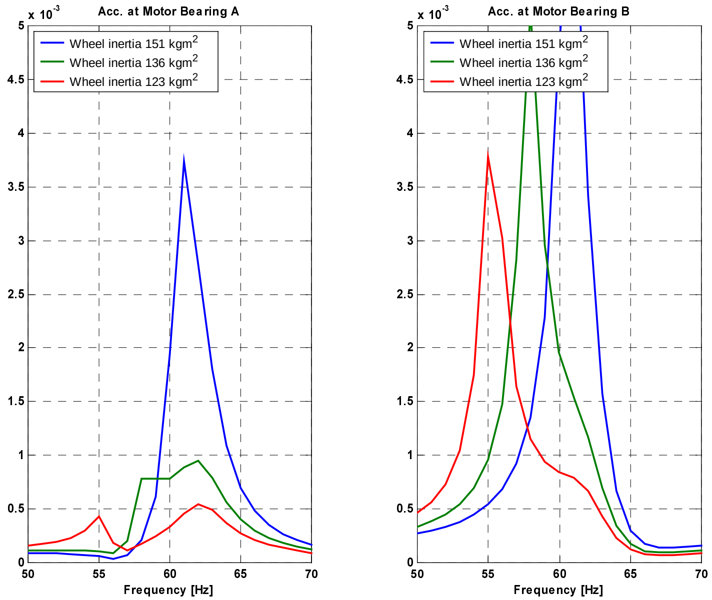

Figure 9: Acceleration at motor bearings, “rigid” bogie frame

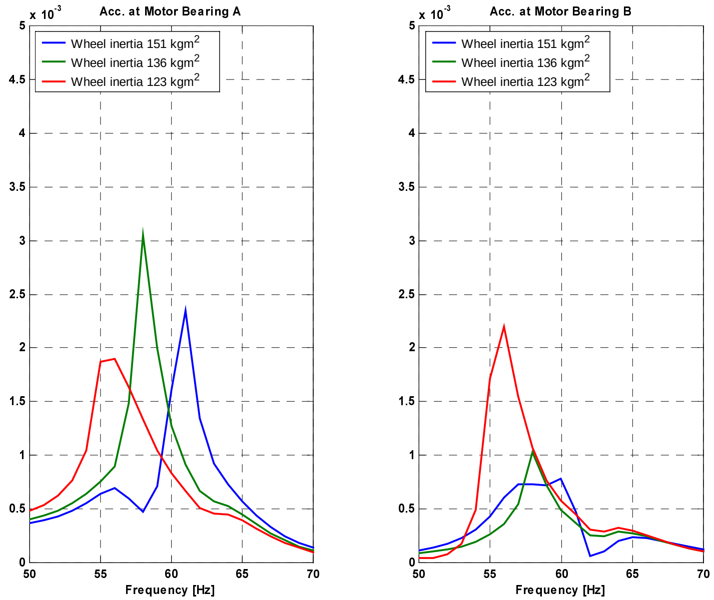

Figure 10: Acceleration at motor bearings, “flexible” bogie frame

3.4.2 Time Domain

Although the investigation within the frequency domain is preferred for such kind of investigation, the time domain is also useful and can give us a closer look into the dynamics of these oscillation. For example the forces acting at the motor suspensions are shown here:

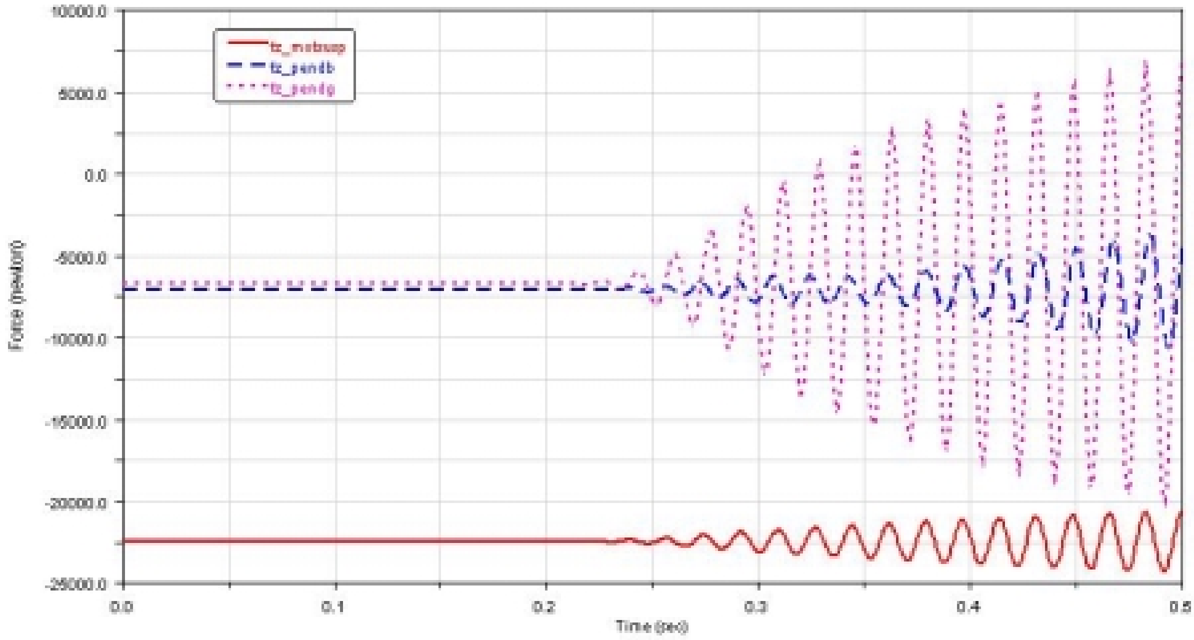

Figure 11 : Forces within motor suspension

Certainly, the absolute values of forces are depending from the magnitude and frequency of excitation which is rather unknown. So the figures may only give a first impression of the behaviour of the bogie and drive under such special conditions.

Investigation of self-introduced oscillations often requires taking into account the behaviour of the electrical and control part of the drive chain. Because the behaviour of the asynchronous motor, the power converter and especially the control subsystem are non-linear and time-discrete, the use of co-simulation is recommended. For this goal the electrical and control systems can be modelled using MATLAB and SIMULINK. The coupling with ADAMS requires only a small number of additional steps. Such investigation may only be done in the time domain.

3.4.3 Comparison with measurements

The results point out important differences caused by the different boundary conditions. Even if it's very difficult to verify these results by measurements we expected that the calculation taking into account the flexibility of the bogie frame are much closer to the reality. This assumption might be supported by the following values:

Measure	Position	Unit	Test	Simulation	Remark
Acc. z-direction	Gear box, front	ms^{-2}	13.3	18.9	
Acc. z-direction	Motor support, front	ms^{-2}	13.3		
Acc. z-direction	Motor support, middle	ms^{-2}	13.3	(10.9)	Calculation: at centre mass
Acc. z-direction	Bogie frame, right	ms^{-2}	> 13.3	30	Calculation : at pendulum
Acc. z-direction	Bogie frame, middle	ms^{-2}	> 13.3		
Acc. z-direction	Bogie frame, left	ms^{-2}	> 13.3	42	Calculation : at pendulum
Acc. x-direction	Axle box, left	ms^{-2}	13.3	(10.4)	Calculation : Defined by excitation
Torque	Hollow shaft	kNm	30	37.4	

Table 3: Comparison between measured and calculated data

Please note, that a number of measured results was saturated due to the measuring equipment.

So we can state that the implementation of the flexible bogie frame is able to increase the accuracy of the simulation results enormously. An additional dominant eigenmode (bending- an torsion-mode of the whole bogie) could be reproduced. Based on these calculations countermeasures may be worked out and investigated later [2].

4 References

[1] Häse, P. and Decking, Ch.
Investigation of Drive Systems Using ADAMS and MATLAB/SIMULINK
ADAMS/Rail User's Conference 2000, Haarlem/NL

[2] Contreras Carranza, L. A.
Torsionsschwingungen in Radsatzantrieben von Schienenfahrzeugen – ihre Unterdrückung mittels angekoppelter Gummidrehschwingungstilger
VDI-Tagung Schwingungen in Antrieben , Würzburg, 2001