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On the use of experimental modal analysis for system identification of a railway pantograph

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ABSTRACT

This study investigates the use of experimental modal analysis to identify the modal properties of a railway pantograph system, including component behaviour within the system, for an extended frequency range in three main directions. A pantograph was mounted in a laboratory with multiple accelerometers attached and excited at the collector strip by an actuator with a sine sweep method ranging between 0 and 200 Hz. A major portion of the numerical investigations into pantograph-catenary interactions have a frequency focus below 20 Hz. The results show that this method is well suited for system identification of the pantograph, highlighting the wide range of system and component frequencies to be considered when building a numeric model. The test results for the particular pantograph used in the experiment revealed important frequencies higher than the 20 Hz limit, at 22 Hz, 39 Hz and 62 Hz.

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Pantograph; pantograph-catenary interaction; modal analysis; structural dynamics; laboratory; experimental

1. Introduction

The pantograph plays a significant role in the pantograph-catenary interaction. Numerical models are necessary to study different phenomena of the interaction more closely than field tests allow. It is thus important to describe each part, the catenary and the pantograph, as close to reality as possible. To date, most models are based on information given by the pantograph manufacturer or by modelling the parts of the pantograph as accurately as possible. Lumped mass models are the most commonly used, and some researchers use a more general multibody model [1]. The majority of numerical studies limit their investigations to 20 Hz due to the criteria in the EN50317 code [2], and a number of studies do not give their limit frequency. However, the benchmark many participated in used 200 Hz sampling, while the results were low-pass filtered at 20 Hz [3]. A modal analysis of different collector strips was performed by Collina et al. [4] to identify modes up to 400 Hz, and the results were used in numerical simulation up to 100 Hz. Bocciolone et al. [5] studied the aerodynamic effects on a pantograph at frequencies up to 40 Hz. Contact forces were investigated up to 80 Hz by Nåvik et al. [6] and up to 100 Hz by Song et al. [7] by studying irregularities. High-frequency

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disturbances due to contact wire irregularities has been studied by Song et al. [8]. The latest review paper on the pantograph-catenary interaction by Bruni et al. [1] states the following in the conclusions: '*The improvement of methods for measuring the pantograph–OCL contact force is one important challenge related with the testing and qualification of new pantographs and catenaries. Future research needs in this area are concerned with extending the frequency range of the measure beyond the present upper limit of 20 Hz*.' A criterion to establish a meaningful frequency value could be to choose a value that includes the fastest event of interest. Since EN50367 [9] states that the minimum length of an arc is 5 ms, a sample frequency of interest should at least be 200 Hz for all components of the pantograph-catenary interaction. This study is thus limited to 200 Hz.

To better understand the behaviour, a pantograph has been installed in a laboratory, instrumented with several accelerometers attached at carefully chosen positions, and excited using a stepped sine sweep procedure. The sine or stepped sine sweep method is a well-known experimental modal test in the literature and has been extensively used in a wide range of engineering features ranging from machine parts and space vehicles to civil engineering structures such as decks and entire buildings. The laboratory pantograph setup used in [10] also has the ability to produce sinusoidal loading and can thus be used for the same investigation but is limited to 20 Hz. Park et al. [11] used an experimental vibration analysis to validate their numerical model at 6.1 Hz, 9.8 Hz, and 14.3 Hz. Zhang et al. [12] used random excitation on a pantograph to establish the frequency response and found two main frequencies at 2.72 Hz and 8.0 Hz. Lee et al. [13] excited a pantograph on a range of frequencies between 0 and 20 Hz for verification of their numerical pantograph model, finding the first natural frequency to be 8 Hz. Xin et al. [14] used a frequency sweep in their investigations on the fault detection and diagnosis of high-speed pantograph dynamic behaviour. The stepped sine sweep procedure enables the possibility of identifying the natural frequencies of the pantograph. Thanks to the number of accelerometers used and the strategy of placement chosen, it is possible to determine which frequencies are important from which section and component of the pantograph. One of the essential outcomes of this study is to show how to identify frequencies that are important. The sensitivity to the different frequencies at the collector strips is the most important for the pantograph-catenary interaction. The study shows the importance of experimental modal analysis for investigating the behaviour of a railway pantograph to create the best possible basis for the frequencies the system response needs to reflect. This study also shows new frequencies of interest identified in the frequency band between 20 and 200 Hz. Previous studies have focused on measurements close to the collector strips and only in the vertical direction. This study extends this measurement by placing accelerometers on all structural components of the pantograph and investigating the vibrations in all three directions.

2. Laboratory setup

A Dozler pantograph was mounted in a laboratory with 14 triaxial accelerometers attached to it. The pantograph is a pantograph previously used on a diagnostic vehicle used for checking stagger; therefore, it has only one aluminium collector strip. An actuator is placed so that it excites the pantograph vertically at the top of the collector strip, slightly to the side of the middle. Two types of simulation methods use an actuator in the same position directly for their combined simulation method: the hybrid-in-loop method [12,15,16] and dynamically substructured (DSS) testing [17]. Several stepped sine sweep excitations are performed between 5 and 200 Hz.

The coordinate system for each accelerometer is that all the sensors are mounted with the cable plug towards the back of the pantograph so that the Z-axis is pointing upwards when the pantograph is flat on the roof, the X-axis is longitudinal to the pantograph and pointing forward, and the Y-axis is lateral and pointing left. The Y-axis will therefore be the same for all positions. However, the Z- and X-axes rotate and thus change from sensor to sensor, but sensors 1, 2 and 3 share the same axis. Not all directions are logged for each sensor due to acquisition limitations; the complete setup is shown in Table 1. The equipment used is listed below and can be seen mounted in Figure 1. The laboratory setup and the position of the accelerometers are shown in Figure 2.

- A Dozler pantograph
- 14 Dytran 3583BT triaxial accelerometers
- A National Instruments CompactRio, cRIO-9036
- A B&K 4808 Permanent Magnetic Vibration Exciter
- A B&K 2712 Power Amplifier
- A Labworks Inc. SC-121 Sine Servo Controller
- 3D printed brackets for accelerometer mounting on pantograph tube profiles

3. Methods

Experimental modal analysis is a large collection of methods that feature predefined registered input signals and the corresponding output signals of the process. In this study, a stepped sine sweep excitation method is chosen to evaluate the modal parameters of a railway pantograph. The stepped sine sweep method uses an excitation actuator technique where a sinusoidal pattern is generated that swipes from a start to an end frequency at regular intervals in time and frequency. In the current test setup, a frequency step change of 0.5 octaves per minute was used. The input force was sampled by an accelerometer placed at the connector point of the exciter. The time series has been evaluated using power spectral densities (PSD) by the Burg method with an order of 400 and uses the whole time series in the estimation. The accelerations are sampled at 2048 Hz.

4. Results

The acceleration time series from the sine sweeps has been analysed primarily by power spectral density analyses using Burg spectra. By peak picking, the peaks in the Burg spectra are used to estimate the system frequencies. The results in this study

Table 1. Sensors and channels; n/a means not recorded. Sensor 14 was mounted on the actuator.

Sensor		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Channel	X	n/a	n/a	n/a	6	8	10	12	14	16	19	21	24	27	n/a
	Y	0	2	4	n/a	n/a	n/a	n/a	n/a	17	n/a	22	25	28	n/a
	Z	1	3	5	7	9	11	13	15	18	20	23	26	29	31

Figure 1. Laboratory pantograph setup.

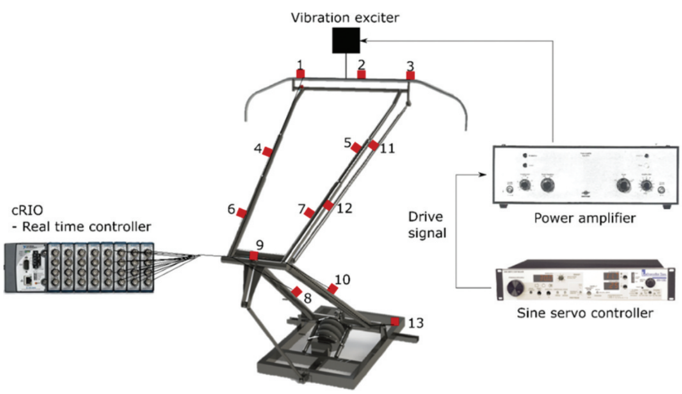

Figure 2. Laboratory pantograph experimental setup and position of accelerometers. Sensor 14 was mounted on the actuator.

are based on the analyses of four sine sweeps between 5 and 200 Hz. The Burg spectra from all four sine sweeps in a frequency range of 0–50 Hz are plotted on top of each other in Figure 3 with the Y-axis in logarithmic scale. For completeness, Figures 5 and 6 show the same results from 50 to 100 Hz and 100 to 200 Hz,

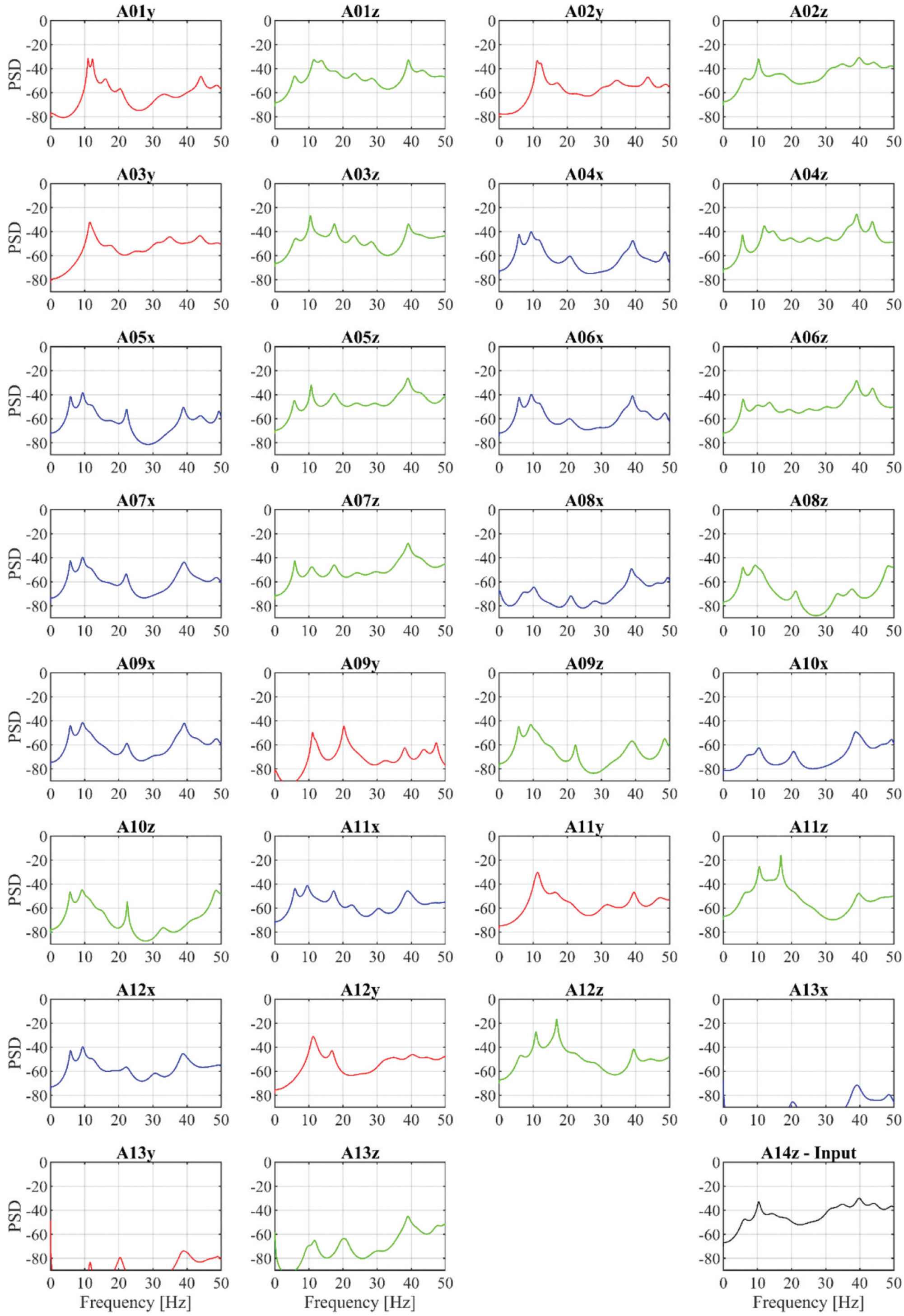

Figure 3. Logarithmic PSD of acceleration time series from four sine sweeps, 0–50 Hz.

respectively. From the diagram, it is easy to see any variations in estimates from the individual tests. In general, the tests show only small variations, which indicates stable poles in the spectral analysis and good estimates of system frequencies for global as well as individual components. In fact, the small deviations are such that the representations in the diagrams easily can be misinterpreted as a thicker line font.

As expected, this technique works well to identify important system frequencies with good accuracy. The first important frequencies in the different axes for this pantograph are as follows: X-axis, 5.9 Hz, 10 Hz, and 21 Hz; Y-axis, 11 Hz, 12 Hz, and 16.7 Hz; Z-axis, 5.6 Hz, 11 Hz, 16.8 Hz, and 22 Hz. Some of these frequencies are closely spaced frequencies and thus are expected to influence each other. An interesting result is that all three directions have a significant peak in the ranges of 10–11 Hz, 21–22 Hz and approximately 39 Hz. Picking all the peaks from the logarithmic PSD of all time series, 4 tests and 32 channels giving approx. 3200 peaks between 0 and 200 Hz, and plotting them in a histogram gives an indication of which frequencies that are found in most PSDs and therefore considered system frequencies. Figure 4 shows that for the current pantograph used in the test, there are several system frequencies in the area of 5–200 Hz, in addition to the frequencies mentioned already.

In the estimated PSDs, many peaks can be seen above 20 Hz. Some of these peaks look more distinct and more important than others. There is one frequency at 39 Hz and one at 62 Hz in the vertical direction that are system frequencies that are present in all sensors except for the ones mounted from the knee and down. The frequency at 62 Hz is not present in sensor 2, see Figure 6, making it possible to interpret it as a torsional movement of the upper arm, while the 39 Hz frequency is a vertical movement of the upper arm. These are expected to be of great importance for the pan head.

The lateral vibrations are also interesting to investigate. Above 20 Hz, the frequencies at 56, 62 and 69 Hz are of particular interest. The one at 62 Hz is expected since it was previously identified in the vertical direction and thus further supports the notion of a torsional mode.

Higher frequency content can also be seen in Figure 6. Here, a set of frequencies between 110 and 130 Hz is observed as well as a frequency at approximately 170 Hz. For some accelerometer positions, these modes experience the same level of energy content as the previously identified frequencies between 5 and 100 Hz.

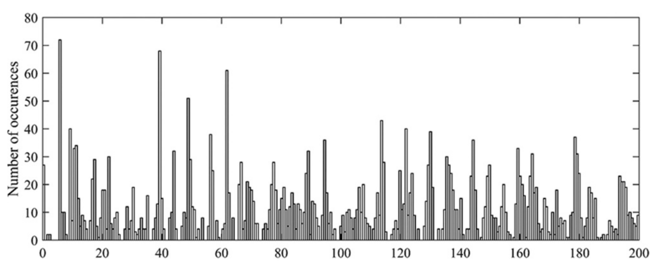

Figure 4. Histogram of all the peaks from the logarithmic PSD of all time series; 4 tests, 32 channels, approx. 3200 peaks from 0 to 200 Hz.

4.1. Component analysis

4.1.1. Pan head

The frequency with the largest response at the pan head is approximately 10–11 Hz, both vertical and lateral. The response in this frequency range can also be seen in all other locations and directions. A response similar in energy can be seen at 62.2 Hz and slightly less at 56.6 Hz. Considerable peaks can also be seen at 150 Hz and 162 Hz.

4.1.2. Anti-roll bar

The largest values among all the PSDs can be found at the anti-roll bar at 16.8 Hz and 62 Hz. Both are in the Z-direction, indicating bending modes of the anti-roll bar. The main component frequency of the roll bar is 16.8 Hz, giving a major response in the anti-roll bar but barely influencing other parts. It is clearly visible in the collector strip and the upper arm's right bar; however, it is not present in the rest of the pantograph. On the other side, 62 Hz is prominent in several other locations, making it an important frequency.

4.1.3. The upper arm

The upper arm has two identical components, two circular tubes with three different outer cross-sections: 30 mm, 40 mm, and 50 mm. Both 39 Hz and 62 Hz were identified previously to be two important frequencies for the upper arm. In addition, these two tubes are the only components showing a response at 48.7 Hz. The upper arm left bar is the only component with a prominent response at 44 Hz in the Z-direction. The right bar has a clear response at 17.6 Hz, which can only be seen in the closest point on the panhead and in the longitudinal direction in the upper part of the anti-roll bar. It is quite close to the bending frequency of the anti-roll bar at 16.8 Hz and might have some interaction.

4.1.4. The lower arm

The response in the Z-direction of sensors A8 and A10 at 66 Hz indicates a bending mode of the lower arm. Responses at the same frequency can slightly be seen in the longitudinal direction of the upper arms (A4 – A7) and in the knee.

4.1.5. Ending remarks: component analysis

The results of the component analysis show that several, but not all, of the component frequencies can clearly be seen in the pan head. This shows that it is important to be aware that all components can influence the pantograph-catenary interaction.

5. Conclusions

This paper shows the importance of detailed experimental modal analysis for a pantograph when creating a numerical model to investigate the pantograph-catenary interaction. The study shows that it is as important to identify more local frequencies of important components as it is to identify global frequencies for the system, both for the interaction as well as the service life and strain on the

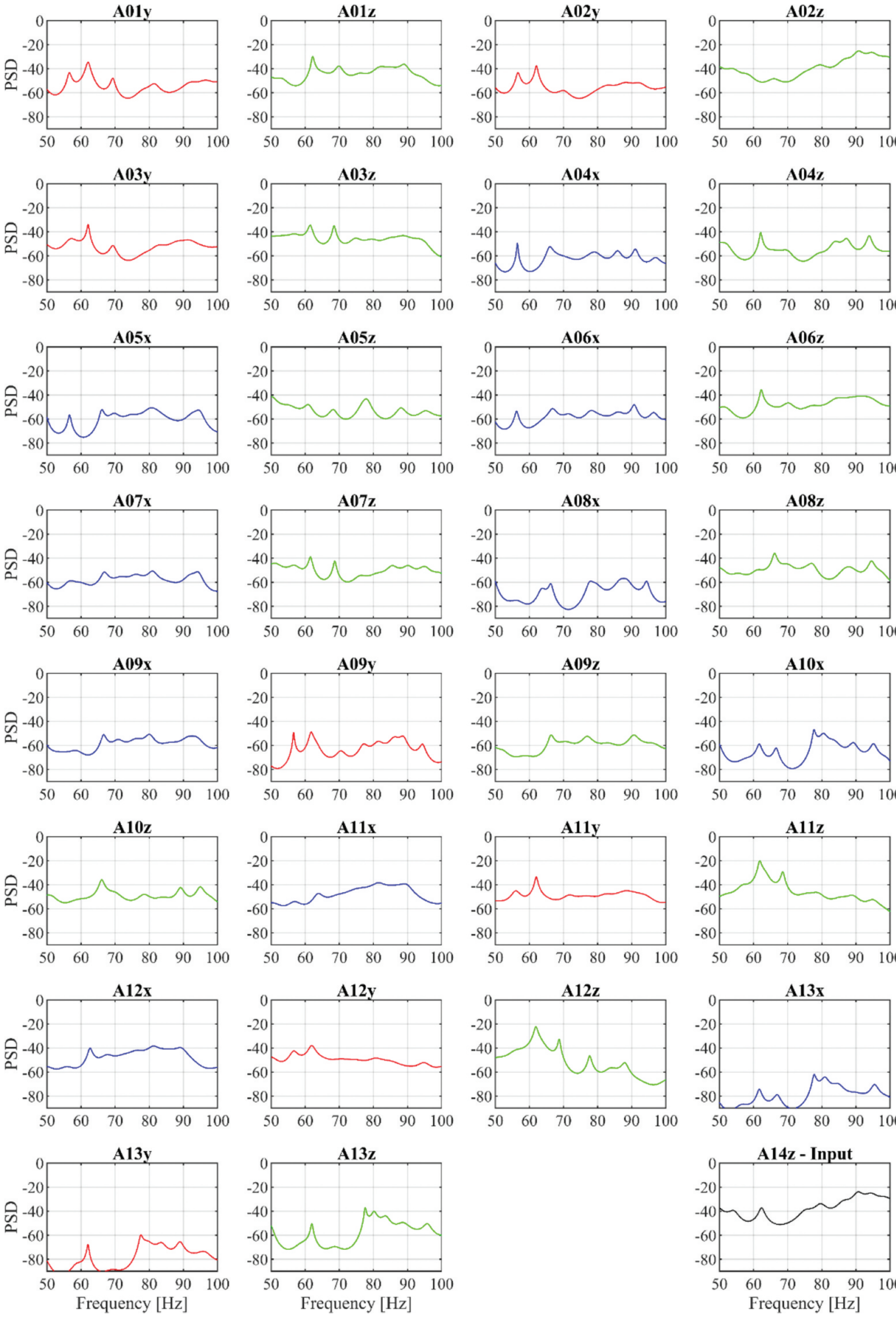

Figure 5. Logarithmic PSD of acceleration time series from four sine sweeps, 50–100 Hz.

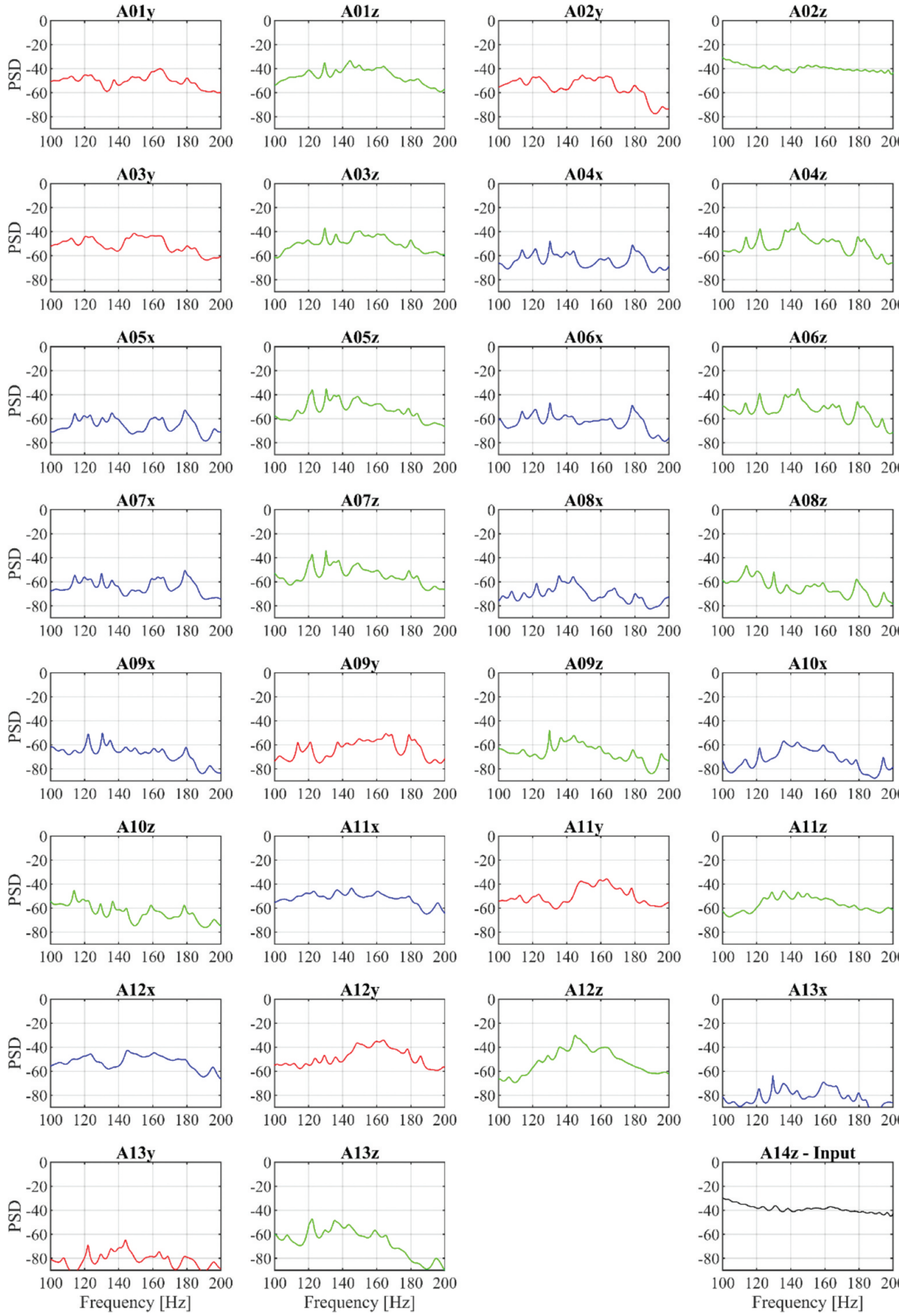

Figure 6. Logarithmic PSD of acceleration time series from four sine sweeps, 100–200 Hz.

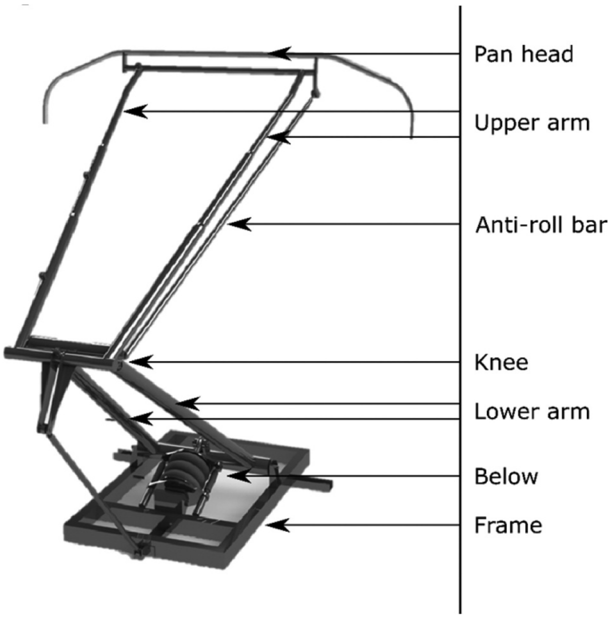

Figure 7. Overview of pantograph parts and the naming used in the component study.

components. The use of a step sine sweep is shown to accurately predict the system frequencies, and if enough measuring points can also be investigated, the individual structural components and important frequencies can be identified. It is shown that there may be frequencies of importance that are not included in the commonly used simplified multibody dynamic models. When railways use stiffer catenaries in high-speed rail applications, there may be higher frequencies that play an important role and should be considered. For softer catenary systems, there may not be many important system frequencies over 100 Hz, but this needs to be experimentally shown. The paper investigates these frequencies in a range wider than previously done in the literature and extends knowledge from only looking at vibrations in the vertical direction to three-directional analyses. The most important frequencies below 20 Hz for the studied pantograph are at 10–11 Hz and 20–22 Hz, which can be found in all three directions and for most positions. Above 20 Hz, the vertical components at 39 Hz and 62 Hz and the lateral components at 39 Hz, 56 Hz, 62 Hz and 69 Hz are the most important and require more thorough investigation. The frequencies at 39 and 62 Hz are of particular interest because they show a vertical motion and a torsional motion at the upper part, respectively. The paper clearly shows the benefits of performing an experimental modal analysis by identifying frequencies not studied previously and in a range that is needed for future research.

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Disclosure statement

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References

[1] Bruni S, Bucca G, Carnevale M, et al. Pantograph–catenary interaction: recent achievements and future research challenges. Int J Rail Transp. 2018;6:57–82.
[2] European Committee for Electrotechnical Standardization (CENELEC). EN 50317:2012 Railway applications - Current collection systems - Requirements for and validation of measurements of the dynamic interaction between pantograph and overhead contact line. Brussels: CENELEC; 2012. p. 20.
[3] Bruni S, Ambrosio J, Carnicero A, et al. The results of the pantograph–catenary interaction benchmark. Veh Syst Dyn. 2015;53:412–435.
[4] Collina A, Lo CA, Carnevale M. Effect of collector deformable modes in pantograph—catenary dynamic interaction. Proc Inst Mech Eng Part F J Rail Rapid Transit. 2009;223:1–14.
[5] Bocciolone M, Resta F, Rocchi D, et al. Pantograph aerodynamic effects on the pantograph–catenary interaction. Veh Syst Dyn. 2006;44:560–570.
[6] Nåvik P, Rønnquist A, Stichel S. Variation in predicting pantograph–catenary interaction contact forces, numerical simulations and field measurements. Veh Syst Dyn. 2017;55:1265–1282.
[7] Song D, Jiang Y, Zhang W. Dynamic performance of a pantograph–catenary system with consideration of the contact surface. Proc Inst Mech Eng Part F J Rail Rapid Transit. 2018;232:262–274.
[8] Song Y, Liu Z, Rønnquist A, et al. Contact wire irregularity stochastics and effect on high-speed railway pantograph-catenary interactions. IEEE Trans Instrum Meas. 2020;1:1–11.
[9] European Committee for Electrotechnical Standardization (CENELEC). EN50367:2012 Railway applications - current collection systems -Technical criteria for the interaction between pantograph and overhead line. Brussels: CENELEC; 2012.
[10] Bucca G, Carnevale M, Comolli L, et al. Assessment of current collection quality of ETR1000-V300 Zefiro pantograph: an innovative measurement set-up and test results. Research 11th World Congress Railway Research. (WCRR 2016). Milan; 2016. p. 6.
[11] Park T-J, Han C-S, Jang J-H. Dynamic sensitivity analysis for the pantograph of a high-speed rail vehicle. J Sound Vib. 2003;266:235–260.
[12] Zhang W, Mei G, Wu X, et al. Hybrid simulation of dynamics for the pantograph-catenary system. Veh Syst Dyn. 2002;38:393–414.

[13] Lee JH, Park TW, Oh HK, et al. Analysis of dynamic interaction between catenary and pantograph with experimental verification and performance evaluation in new high-speed line. Veh Syst Dyn. 2015;53:1117–1134.
[14] Xin T, Roberts C, Weston P, et al. Condition monitoring of railway pantographs to achieve fault detection and fault diagnosis. Proc Inst Mech Eng Part F J Rail Rapid Transit. 2020;234:289–300.
[15] Facchinetti A, Gasparetto L, Bruni S. Real-time catenary models for the hardware-in-the-loop simulation of the pantograph–catenary interaction. Veh Syst Dyn. 2013;51:499–516.
[16] Schirrer A, Aschauer G, Talic E, et al. Catenary emulation for hardware-in-the-loop pantograph testing with a model predictive energy-conserving control algorithm. Mechatronics. 2017;41:17–28.
[17] Kobayashi S, Stoten DP, Yamashita Y, et al. Dynamically substructured testing of railway pantograph/catenary systems. Proc Inst Mech Eng Part F J Rail Rapid Transit. 2018;0954409718799900. DOI:10.1177/0954409718799900