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Characterisation of Pantograph Dynamic Behaviour at Different Operating Heights

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Abstract

The dynamic interaction between railway pantographs and overhead contact lines (OCL) is a key factor governing current collection quality, component wear and system reliability. Existing pantograph characterisation methodologies and numerical models are typically identified and validated at a single nominal operating height, despite pantographs routinely operating across a wide range of extensions imposed by infrastructure constraints. This paper experimentally investigates the influence of operating height on the dynamic behaviour of a Wabtec-Brecknell Willis High Speed Pantograph (HSP). A comprehensive test programme is conducted using a full-scale pantograph test bench, including quasi-static stiffness measurements, force hysteresis tests and harmonic frequency sweep excitations. The pantograph is assessed at five representative operating heights spanning its working range. The results show that the pantograph exhibits dynamic response variation with operating height due to its nonlinear behaviour associated with friction and hysteresis. In particular, differences in frequency response characteristics are observed, including changes in resonant behaviour and response magnitude at higher frequencies. The findings demonstrate that pantograph extension has influence on dynamic performance and indicate that height-dependent pantograph models may provide a more representative basis for pantograph-OCL simulations involving contact wire height variations.

Keywords: pantograph dynamics, railway electrification, current collection performance, experimental characterisation, frequency response, lumped mass model.

1 Introduction

Railway electrification is a key enabler for achieving decarbonisation objectives, while increasing the capacity and sustainability of rail transport networks. In the United Kingdom, current and future electrification programmes increasingly involve routes with significant geometric constraints, including tunnels, over-bridges, station canopies, and level crossings, which often require substantial variations in contact wire height. As a result, pantographs are required to operate reliably across a wide range of extensions and maintain suitable current collection performance.

Current collection quality is governed by the dynamic interaction between the pantograph and the overhead contact line (OCL). Excessive fluctuations in contact force may lead to contact loss, arcing, accelerated wear of contact strips and contact wire, and ultimately reduced system reliability. Consequently, numerical simulation of pantograph-OCL interaction has become a widely accepted tool for the design, assessment, and optimisation of electrified railway infrastructures.

The predictive capability of these numerical tools depends strongly on the accuracy of the models used to represent both the OCL and the pantograph. The latter is commonly represented by lumped mass models, whose parameters are typically derived from experimental characterisation procedures defined in standards such as EN 50318 and EN 50317 [1,2]. This model formulation provides a practical balance between computational efficiency and physical fidelity, making them particularly suitable for large-scale simulation studies. In the UK, RSSB project T1105 [3] established a set of experimentally validated lumped mass models for pantographs operating on the national rail network.

Despite their widespread use, existing pantograph models are generally developed and validated at a single nominal operating height. This simplification neglects the fact that a pantograph is a variable-geometry mechanical system whose kinematic configuration changes continuously with extension. Variations in operating height modify linkage geometry, spring leverage ratios, mass distribution, and suspension characteristics, potentially affecting key dynamic properties such as equivalent stiffness, damping and natural frequencies.

Since these parameters directly influence the pantograph-OCL interaction, variations in pantograph extension may affect current collection performance. However, most existing characterisation procedures represent the pantograph using a single set of parameters derived at a nominal operating position. Consequently, there is currently insufficient understanding on how pantograph dynamic behaviour evolves across its operational envelope and how these changes should be represented in numerical models.

This knowledge gap is particularly relevant to the UK railway network, where contact wire height variations are frequently used to accommodate infrastructure restrictions associated with the constrained loading gauge. Under such conditions, pantographs may operate for significant periods away from their nominal position and, in some cases, close to their extension limits.

Previous research has investigated the implications of variable wire heights, particularly from an aerodynamic perspective [4]. However, the influence of operating height on the dynamic behaviour of the pantograph has not yet been systematically characterised. As a result, the extent to which height-dependent behaviour should be incorporated into pantograph models remains unclear.

To address this gap, the present study experimentally investigates the dynamic performance of the Wabtec-Brecknell Willis HSP pantograph at five representative operating heights, comprising low-wire, nominal-wire and high-wire configurations together with two intermediate positions. The experimental campaign employs a full-scale pantograph test bench and includes quasi-static stiffness measurements, hysteresis testing and frequency sweep excitation procedures. The resulting datasets are used to quantify the influence of operating height on pantograph dynamic behaviour and will support the future development of representative models for each working position. By improving the understanding of pantograph dynamics throughout the operational range, this work aims to enhance the accuracy of pantograph-OCL simulations involving significant vertical wire gradients.

2 Methods

The experimental programme was designed to investigate the influence of operating height on the dynamic behaviour of the Wabtec-Brecknell Willis HSP pantograph. All testing was performed using the full-scale pantograph test bench at the Institute of Railway Research, University of Huddersfield (see Figure 1). The facility enables controlled excitation of the collector head under laboratory conditions, providing repeatable test inputs and comprehensive measurement of the pantograph response across its operational range.

Figure 1: Full-scale pantograph test bench at the University of Huddersfield.

To capture the variation in behaviour associated with pantograph extension, the HSP was tested at five representative working positions, ranging from 4.14 m to 5.94 m and encompassing its full operational range. Table 1 lists the designation of the pantograph heights tested and the associated contact wire height.

Denomination	Contact wire height [m]
High wire height	5.94
Intermediate high height	5.32
Nominal wire height	4.70
Intermediate low height	4.42
Low wire height	4.14

Table 1: Tested pantograph height and corresponding contact wire height.

2.1 Pantograph Instrumentation

The pantograph was comprehensively instrumented to capture both the applied excitation inputs and the resulting dynamic response at all operating heights considered. The instrumentation arrangement, illustrated in Figure 2, was designed to monitor the behaviour of the main pantograph assemblies and associated actuation systems in compliance with the relevant standards [1,2,5]. Measurements included accelerations at the collector strips, collector head cross-bar, and pantograph knuckle, together with inclination measurements of both the upper and lower arms. In addition, the pneumatic pressure and displacement of the pantograph raising actuator were recorded, alongside the head excitation displacement and acceleration imposed by the test bench. The contact force transmitted between the pantograph and the excitation actuators was also measured, providing a complete dataset for dynamic characterisation and model identification.

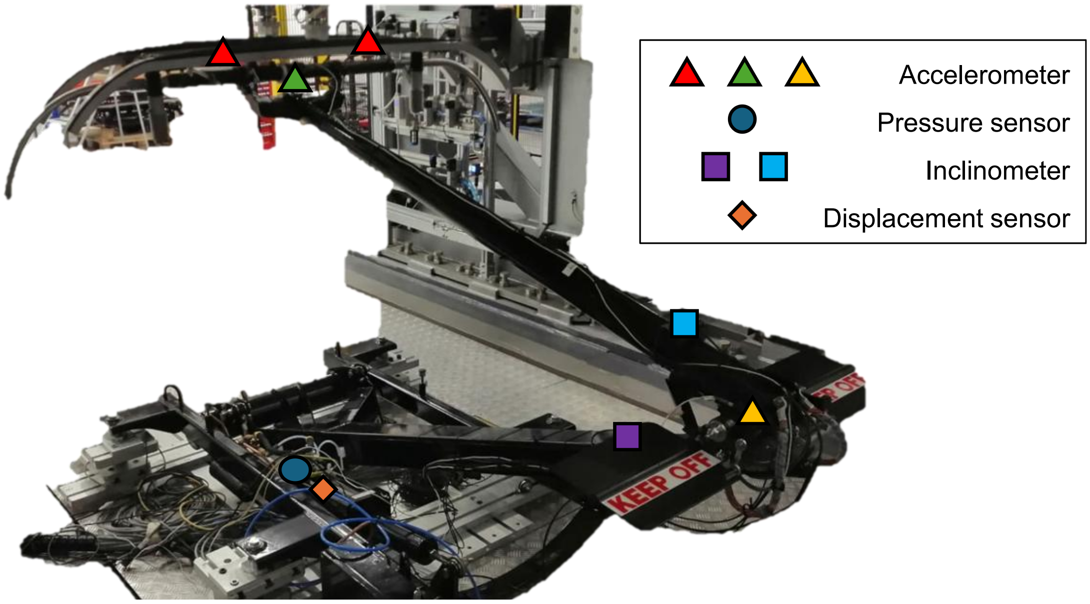

Figure 2: Pantograph instrumentation. Note: some sensors are hidden from this perspective.

2.2 Testing Program

An experimental programme was developed to characterise the dynamic behaviour of the pantograph across its operational range. The testing campaign comprised three test methodologies designed to evaluate the mechanical properties, nonlinear behaviour, and dynamic response of the pantograph.

The first test series examined the collector head suspension characteristics. Quasi-static stiffness measurements were obtained by applying controlled vertical displacements to the collector strips while the head cross-bar remained locked. The resulting reaction forces were recorded and used to derive force–displacement relationships, from which equivalent stiffness parameters of the head suspension were determined. These tests were conducted at the centre of the collector strip and at the stagger edge, 230 mm from the centre.

The second test series involved force hysteresis measurements to assess frictional effects and nonlinear behaviour within the pantograph mechanism. In these tests, the pantograph was raised and lowered through its operating range at different speeds. A similar procedure is described in Section 4.4 of EN 50206-1 [5]; however, whereas the standard measures the force below the head suspension, the present method measures the force above the suspension. This provides a direct assessment of the interaction between the collector head and the contact wire.

Finally, dynamic characterisation was conducted through harmonic frequency sweep excitation tests. The collector head was excited over a frequency range of 0.5 Hz to 20 Hz, using 0.5 Hz increments, with smaller 0.25 Hz steps in regions where the dynamic response changed more rapidly. At each excitation frequency, all instrumentation channels were recorded to capture the corresponding pantograph response. The test was repeated for each operating height configuration to assess the effect of pantograph extension on dynamic behaviour.

To highlight the pantograph's nonlinear response, different excitation amplitudes were applied at each frequency using one of two approaches:

- a fixed displacement amplitude, with frequency increased until contact loss was detected; or
- a variable displacement amplitude selected to produce a contact force amplitude in the range of 20-25 N, as recommended in EN 50318 [1].

2.3 Data Processing and Pantograph Model Identification

The experimental datasets obtained during the test campaign were processed to quantify the influence of operating height on the dynamic behaviour of the pantograph. The analysis focuses on identifying variations in the main mechanical and dynamic properties of the system, including stiffness, damping, resonant frequencies, and response amplitudes across the range of operating heights investigated.

For the dynamic tests, the recorded excitation and response signals were post-processed to derive frequency response functions (FRF), describing the relationship between the imposed collector head excitation and the resulting pantograph response. Both amplitude and phase information were considered, enabling direct comparison between the different operating height configurations.

The resulting datasets will be used in future work to develop and validate lumped-mass (LM) models for each operating height.

3 Results

The experimental results for the HSP pantograph are presented below, grouped by test methodology.

3.1 Head Suspension Stiffness Test

Figure 3 shows the force-deflection relationship for the collector strips of the HSP pantograph. The left-hand plot corresponds to the test performed at the centre of the collector strip, while the right-hand plot shows the test carried out 230 mm from the strip centre. Linear fits were obtained for each dataset and are also included in the figure.

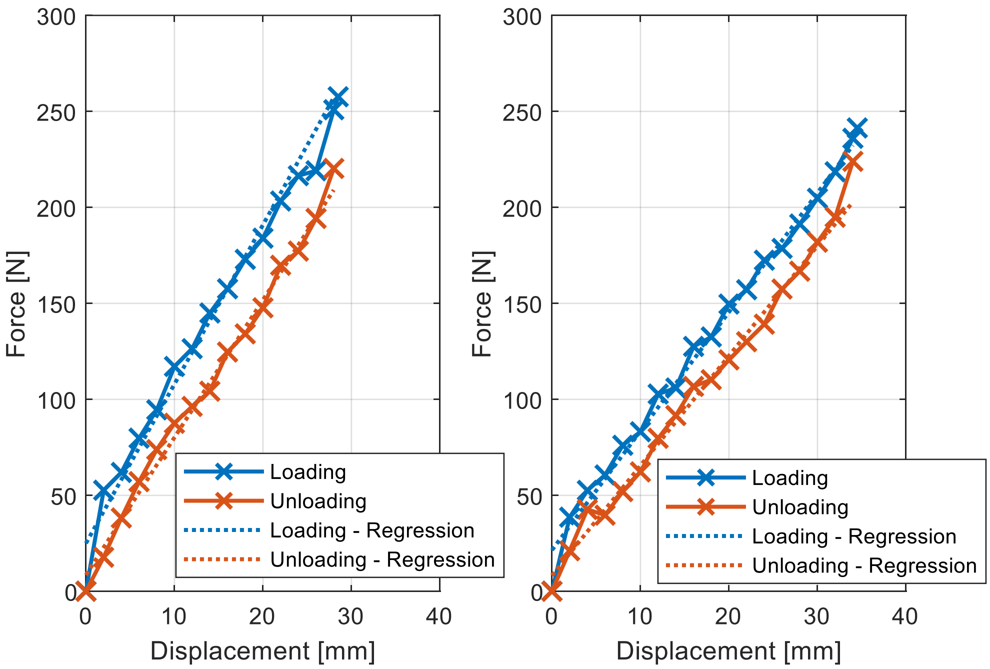

Figure 3: Force-displacement graphs for the HSP head suspension. Left: Centre test, Right: 230 mm offset test.

As shown in Figure 3, the loading and unloading paths do not coincide, indicating hysteretic behaviour in the suspension. For a given deflection, the unloading force is consistently lower than the loading force. In addition, the force measured at the centre of the collector strip is higher than that recorded at the offset location. The linear regression results were used to determine an equivalent stiffness for each dataset, as summarised in Table 2.

Centre	Side (230 mm)
Loading [mm]	Loading [mm]
Force = **8.293**x + 25.038 [N]	Force = **6.202**x + 21.492 [N]
Unloading [mm]	Unloading [mm]
Force = **7.162**x + 8.555 [N]	Force = **5.722**x + 8.277 [N]
Mean Stiffness	Mean Stiffness
7727 N/m	5962 N/m

Table 2: Linear regression analysis for the HSP head suspension test.

The results indicate a mean head suspension stiffness of 7727 N/m at the centre of the strip, decreasing to 5962 N/m at the edge of the stagger.

3.2 Force Hysteresis Test

In this test, the pantograph was driven from its lowest position to its highest position and back down at a constant speed. Figure 4 shows the opening height-force relationship for the HSP pantograph at different travel speeds of 25, 50, 75, 100, 150 and 175 mm/s.

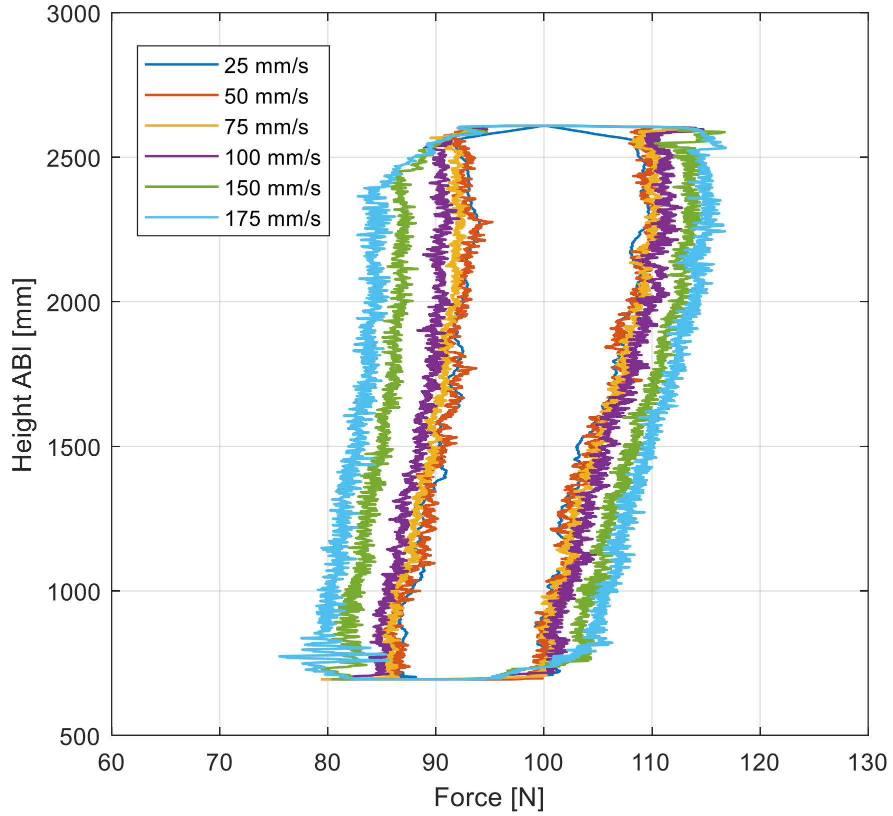

Figure 4: Force hysteresis behaviour for tests at different movement speeds.

The height values in the graph are expressed as Height ABI, i.e. above the base of the insulator. The force hysteresis is clearly visible, with the upward stroke producing lower forces than the downward stroke. For speeds below 50 mm/s, the results largely overlap; however, at higher speeds, the hysteresis loop becomes progressively wider, indicating an increase in force hysteresis with speed.

In addition, the force response appears slightly asymmetric, with lower average force values at smaller opening heights than at larger ones.

3.3 Frequency Sweep Test

In this test, a predefined sinusoidal displacement was imposed on the collector strips at a specified frequency and amplitude. Repeated tests at the same frequency were carried out using different amplitudes, following the procedures described in Section 2.2. Figure 5 shows the tested frequency-amplitude pairs obtained using the constant-amplitude, increasing-frequency approach for each pantograph opening height.

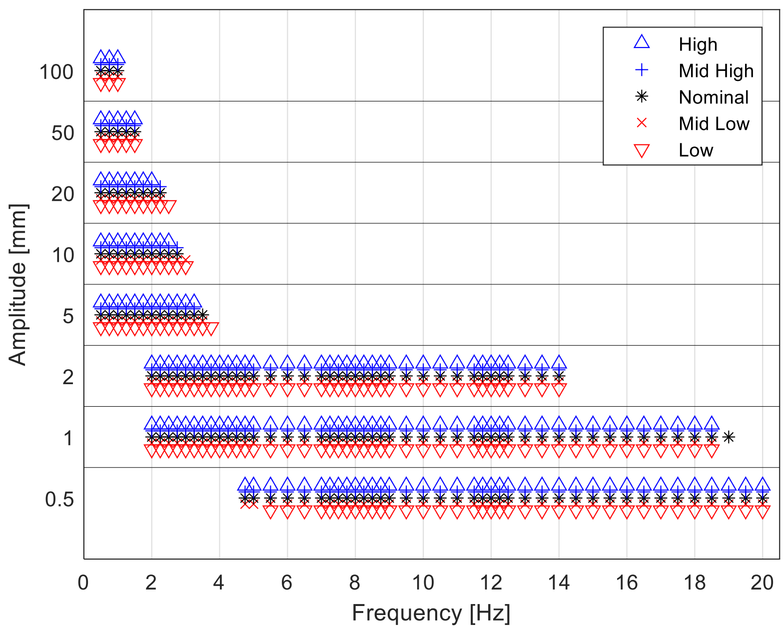

Figure 5: Constant excitation amplitude sweep approach frequency-amplitude pairs.

From Figure 5, it can be observed that for excitation amplitudes between 5 mm and 20 mm, lower pantograph heights allow higher frequencies to be reached for the same excitation amplitude. By contrast, for amplitudes of 2 mm and below, and 50 mm and above, the influence of opening height on the achievable frequency is negligible. Figure 5 also shows that some low-amplitude, low-frequency cases are missing: frequency-amplitude combinations that produced a force amplitude of 5 N or less did not generate meaningful responses, as the pantograph remained almost static. These cases were therefore excluded from the analysis.

Figure 6 presents the frequency-amplitude pairs, for each opening height, that produced a contact force amplitude within the 20-25 N range.

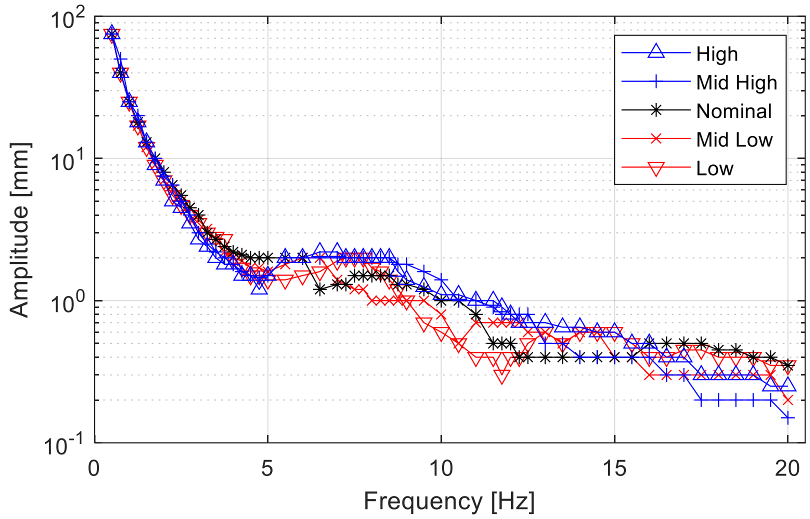

Figure 6: Banded force amplitude sweep approach frequency-amplitude pairs.

As shown in Figure 6, for frequencies up to approximately 2 Hz, the selected frequency-amplitude pairs are largely unaffected by pantograph opening height. At higher frequencies, the results begin to diverge, although the underlying trend is not straightforward to interpret.

To analyse the frequency response of the pantograph, different transfer functions, or frequency response functions (FRF), may be used. The results are therefore presented here in terms of accelerance, which relates force to acceleration. Figures Figure 7, Figure 8, and Figure 9 show the accelerance magnitude and phase for the different excitation profiles. Figures Figure 7 and Figure 8 correspond to constant excitation amplitudes of 5 mm and 1 mm, respectively, while Figure 9 presents the response obtained using the banded contact-force excitation.

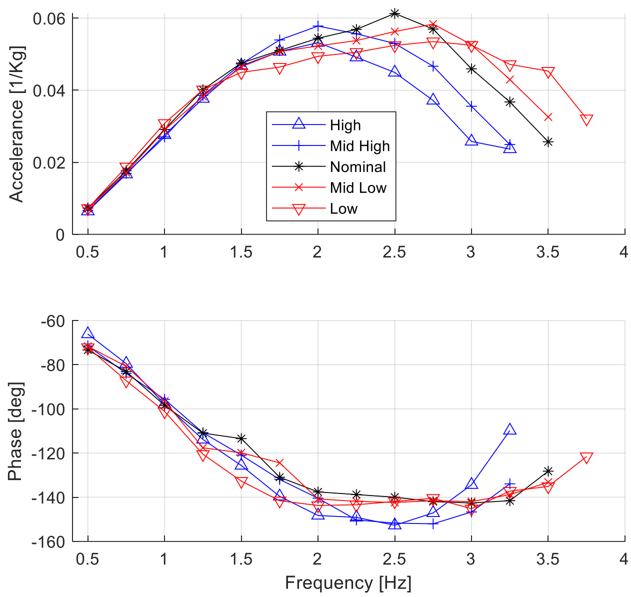

Figure 7: Accelerance magnitude and phase diagrams for 5-mm constant excitation.

In Figure 7, the responses for the five opening heights overlap up to approximately 1.25 Hz. A clear peak in magnitude is visible for all curves between 2 and 3 Hz, accompanied by a corresponding phase dip in the same region, indicating a resonant frequency. This first resonance shifts with increasing opening height, from around 2 Hz at the lowest position to approximately 3 Hz at the highest, representing a 50% increase.

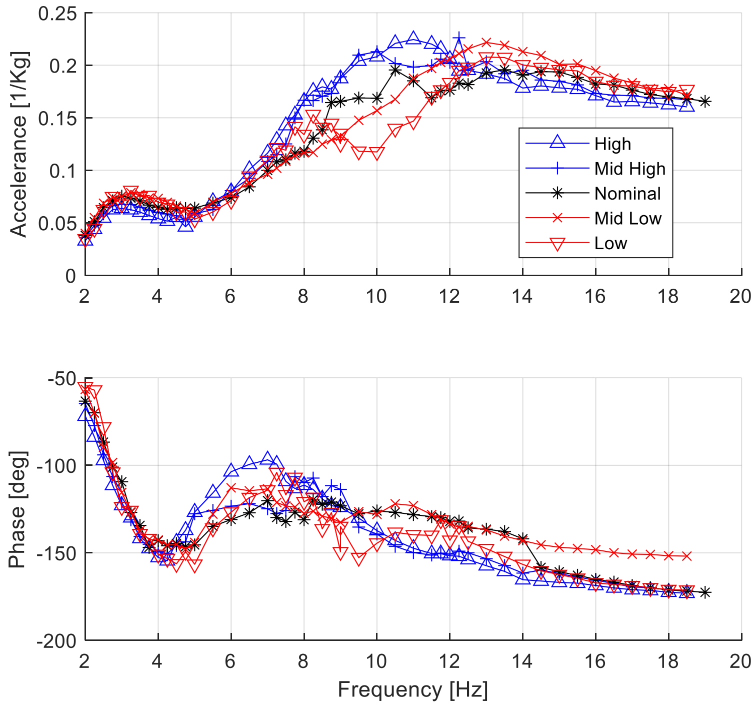

Figure 8: Accelerance magnitude and phase diagrams for 1-mm constant excitation.

In Figure 8, the responses for all five opening heights overlap up to approximately 4.0 Hz in both magnitude and phase. All cases show a phase dip around 4.25 Hz and tend towards similar values as the frequency approaches 20 Hz. However, between 5 and 14 Hz, the curves exhibit distinct behaviour that depends on opening height. For example, the mid-low height case shows an increase in magnitude between 5 and 13 Hz, whereas the highest wire heights exhibit a magnitude peak at around 11 Hz before decreasing towards 20 Hz. In the phase plot, the highest wire position shows a pronounced peak at around 7 Hz, while the other opening heights display more varied behaviour.

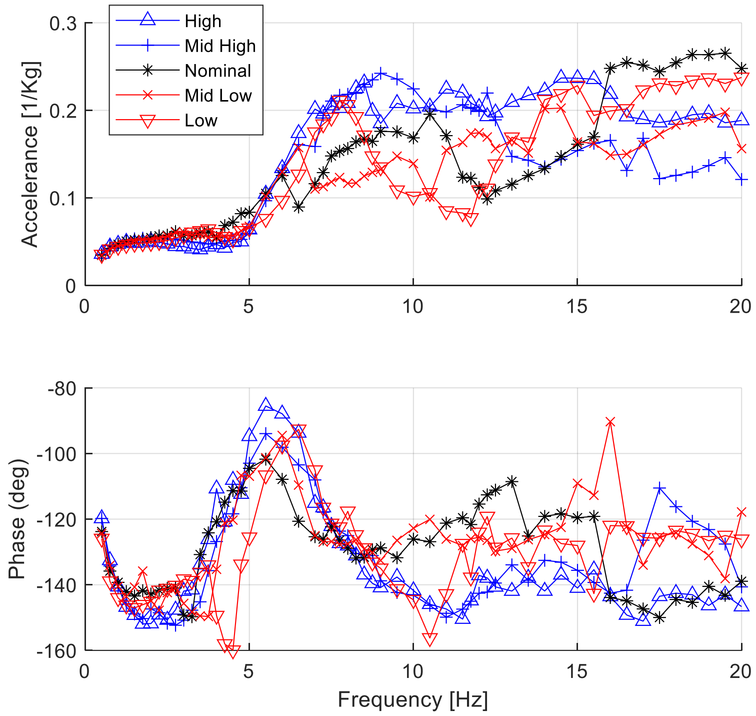

Figure 9: Accelerance magnitude and phase diagrams for banded contact force excitation.

In Figure 9, the results for the different opening heights are similar up to approximately 4 Hz. Above this frequency, the responses gradually diverge.

4 Conclusions and Contributions

This work investigates the influence of operating height on the dynamic behaviour of a Wabtec-Brecknell Willis HSP pantograph through head suspension, hysteresis and frequency sweep testing at five representative opening positions.

The results show that the pantograph exhibits significant nonlinear behaviour, with its response being affected by friction and hysteresis. The hysteresis tests demonstrate increasing force differences between raising and lowering motions as speed increased.

Dynamic testing reveals that the pantograph operating height influences the frequency response of the system. While the responses are similar at low frequencies, noticeable differences emerged above approximately 4 Hz, including shifts in resonant behaviour and changes in FRF magnitude and phase.

Overall, the findings of this work indicate that operating height has a noticeable effect on pantograph dynamics, which should be considered when developing pantograph-OCL simulation models. Height-dependent pantograph numerical models can, therefore, provide a more representative description of pantograph behaviour across its operational range.

Acknowledgements

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