Toward early detection of faults in the railway pantograph structure: the Trenitalia project

Giancarlo Santamato[1*], Domenico Chiaradia[1], Massimiliano Solazzi[1], Antonio Frisoli[1]

***Abstract*—In this work, we summarize the results of the Trenitalia project during which we developed an inspection robot for the dynamic interrogation of the railway pantograph structure. Deep damage detection and statistical confidence were achieved by including nonlinear behavior and uncertainties. An extensive experimental campaign demonstrates the suitability of a first prototype to achieve damage diagnosis for different damage scenarios at the 95% confidence.**

I. INTRODUCTION

ETENSIVE research tackled the dynamic interaction between the railway pantograph and the catenary line. Still, at the depots, visual and manual inspection is the most common approach for pantograph assessment, and no investigation of the dynamics is pursued.

Actually, the pantograph endorses some of the most relevant challenges for a vibration-based structural health monitoring, like inherent nonlinear behavior - due to the presence of dry-friction joints - and significant uncertainties, since pantograph samples may exhibit gross variability in the layout, the used components, and the dry-friction level.

This paper presents the results of the Trenitalia project during which we developed a dedicated inspection robot realized for excitation and periodic diagnosis. Through an extensive experimental campaign we demonstrate that our first prototype achieves damage diagnosis for several fault types, with 95% statistical confidence, and in agreement with the European standard EN 50318:2018 [1].

Dynamic characterization is pursued through the identification of the Frequency Response Function (FRF) in the undamaged and damaged condition [2], according to the schematic of Fig. 1(a). The input is the dynamic force Q applied by the robot and measured by a load cell, while the output is the consequent structural displacement x, acquired by the actuation encoder. The inherent nonlinear behavior is addressed by carrying out structural dynamic tests for multiple levels of the excitation ranging in the interval 2 - 14 N to ascertain whether nonlinearity can be exploited for augmenting the information about the health status [3], [4]. In this regard, the control of the excitation becomes a relevant issue. Fig. 1(b) shows the estimates G_o of the force transfer function in the *open loop* and in the *closed loop* configuration G_c when the level of the chirp excitation was set to 8 N. Thus closing the loop allows almost homogeneous excitation power at each frequency bin, and thus the detection algorithm relies on the best linear approximation of the pantograph behavior for each level of the excitation.

Moreover, the typical large variability was included by identifying the FRFs on different pantograph samples. Four pantographs were tested with different operational lives and aging conditions. Three damage conditions were simulated affecting the block of the pan head suspensions, the hydraulic damper, and the integrity of a bolted joint.

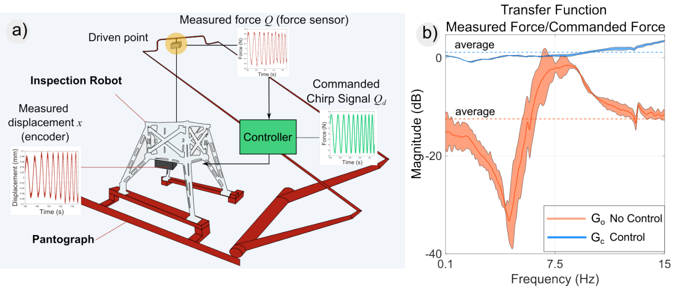

Fig. 1. (a) Input-output architecture for pantograph dynamic test. (b) Magnitude plot (decibel scale) of the force transfer function (measured force against the reference signal) in the open-loop (no control) and in the closed-loop configuration. The confidence bands have been evaluated at ± 2 σ.

II. DAMAGE DIAGNOSIS AT MULTI-EXCITATION LEVEL

The diagnosis strategy, illustrated in Fig. 2, consists of: i) vibration tests for multiple excitation levels, and estimation of the FRF; ii) statistical analysis; iii) synthesis of diagnosis based on the analysis of an aggregated damage index against the explored excitation levels.

In particular, the receptance FRF $H(\omega)$ (mm/N) is admitted as the characteristic feature computed through the p-Welch spectra. An hypothesis test is formulated under the assumption of Gaussian distribution comparing the FRF magnitude $|\hat{H}^U(\omega)|$ of a pantograph under test in the unknown condition to that of the safe structure $|\hat{H}^S(\omega)|$. The equality of the two FRFs is examined at a given α risk level through the statistical test:

$$z = \frac{||\hat{H}^S(\omega)| - |\hat{H}^U(\omega)||}{\sqrt{2\hat{\sigma}_S^2(\omega)}} \leq z_{1-\alpha/2} \tag{1}$$

where $z_{1-\alpha/2}$ stands for the standard normal distribution at the $1-\alpha/2$ confidence level limit, i.e. at the 95% of confidence, $z_{1-\alpha/2} = 2$. $\sigma^2(\omega) = \text{var}|\hat{H}^S(\omega)|$ stands for the variance of the undamaged structure.

When the null hypothesis cannot be accepted, we define an aggregated damage index I, corresponding to the average value of the statistical test over the frequency interval.

---

[1] Institute of Mechanical Intelligence and the Department of Excellence in Robotics & AI, Scuola Superiore Sant'Anna, Pisa, Italy.

[*] corresponding author: `g.santamato@santannapisa.it`

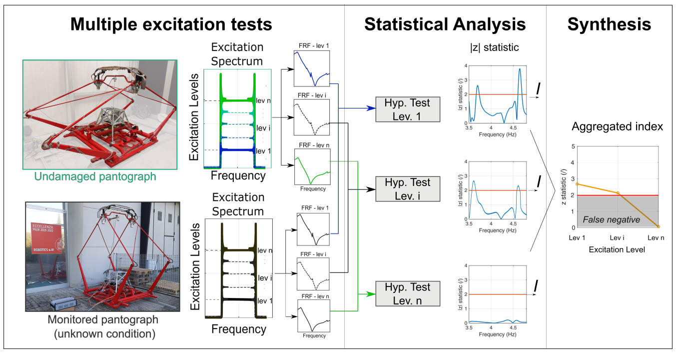

Fig. 2. Schematic of the statistical method proposed for the diagnosis of the railway pantograph, based on the FRFs estimated at multiple levels of the input excitation.

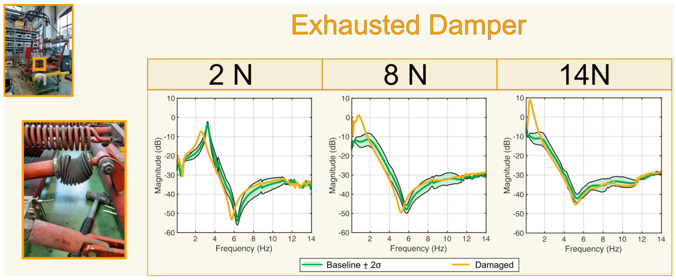

Fig. 3. Comparison of the Frequency Response Functions in the case of the exhausted damper with the baseline for three distinct levels of the input excitation.

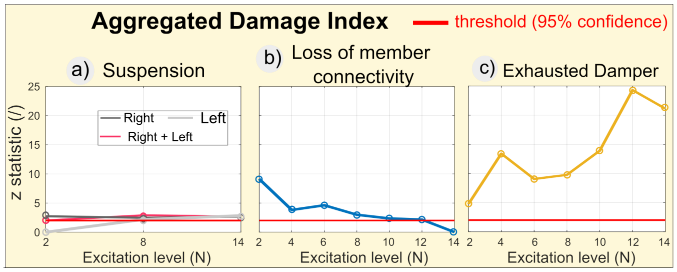

Fig. 4. Analysis of the aggregated damage index against the level of the excitation for three damage scenarios.

Characterization of the pantograph in the undamaged state was pursued from a population of pantographs of the same type, including: i) *new pantograph*; ii) *laboratory pantograph*: revised at the overhaul and subjected only to natural aging; iii) *overhaul pantograph* - subjected to 4 years of operation; iv) *damage simulations pantograph* - the laboratory pantograph subjected to simulated damages. The baseline at a given excitation level is obtained by averaging data from the corresponding three undamaged pantographs.

Three damage scenarios have been considered. The first is the block of the pan head suspension, to mimic the crucial oxidation of the springs. Three sub-conditions were investigated, namely the block of the right suspension, the left suspension, and then both suspensions. The second damage scenario is the exhausted damper, subjected to complete leakage of the oil. The last damage scenario is the loss of member connectivity in the bolted connections. Such a damage scenario represents a local and subtle alteration to the structural integrity of the pantograph.

III. RESULTS AND CONCLUSIONS

Fig. 3 shows the FRFs for the damage scenario concerned with the exhausted damper, showing the dependence on the excitation level. A softening behavior is observed in the frequency range of 0.1 - 3 Hz since the dominant peak is shifted towards a lower frequency. Moreover, for the excitation levels of 8 N and 14 N, the magnitude of the peak is increased by 11 dB and 18 dB, respectively. A synthesis of the damage detection is represented in Fig. 4, where we plot the aggregated index against the threshold.

In Fig. 4(a) we observe that the statistical error for the block of the pan head suspension is not dependent on the excitation level since the block of the right suspension is detected for all three levels of the excitation. Contrariwise, the block of the left suspension is not detected (false negative) at the low level of the excitation. Close values of the statistic are found for the block of both suspensions. In Fig. 4(b) we observe that the exhausted damper is always detected since the value of the statistic is sensibly above the threshold for all the values of the excitation level. Besides, the statistical error increases with the excitation level by a factor of around 4. In Fig. 4(c), the error concerned with the loss of member connectivity decreases with the excitation level. In particular, for the high values of the excitation of 14 N, damage is not detected (false negatives).

Indicative damage identification was achieved showing the potentiality of the proposed device and methodology for pantographs diagnosis. Still, some false positives were found at the low levels of the input excitation where the pantograph response is more sensitive to boundary conditions due to higher frictional nonlinearity.

In the future, we aim to develop a mature version of our prototype that allows further sensor channels and faster setup with the aim to test a broader population of pantographs subjected to a multitude of damage conditions.

ACKNOWLEDGEMENTS

The present publication was created with the financing of the Trenitalia Project.

REFERENCES

[1] CENELEC, "Railway applications - current collection systems - validation of simulation of the dynamic interaction between pantograph and overhead contact line," 2018.

[2] F. P. Kopsaftopoulos and S. D. Fassois, "Vibration based health monitoring for a lightweight truss structure: experimental assessment of several statistical time series methods," *Mechanical Systems and Signal Processing*, vol. 24, no. 7, pp. 1977–1997, 2010.

[3] G. Santamato, M. Solazzi, and A. Frisoli, "Investigating the effect of dry-friction on damage detection tests," *Journal of Sound and Vibration*, vol. 568, p. 117949, 2024.

[4] G. Santamato, D. Chiaradia, M. Solazzi, and A. Frisoli, "Detecting early damages in the railway pantograph mechanism: a multiple excitation approach for the frequency domain," *Vehicle System Dynamics*, pp. 1–22, 2023.