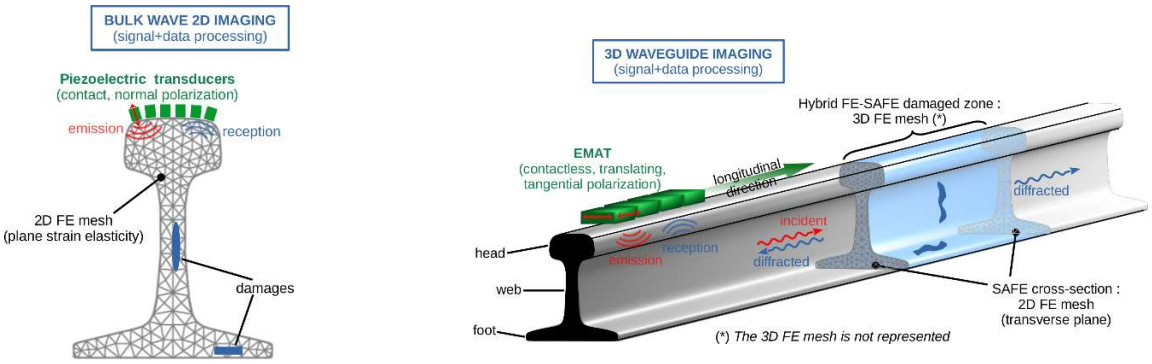
AAPG2024	ULTRATRAIL	PRCE
Coordinated by :	Laurent LAGUERRE	48 months
CE22 Transport and mobility, constructions in urban and peri-urban areas		

ULTRATRAIL (ULTRAsonic Testing of RAIL foot)



(a) (b)

ULTRATRAIL at a glance: **Digital twins and real-life experiments.** *Deep buried rail defects (WP1) imaging from top-of-the-rail single-sided inspection: (a) using a bulk wave in-section approach (WP2) and (b) using a guided-wave approach (WP4) illustrated with EMATs probing (WP3).*

I. Pre-proposal's context, positioning and objective(s)

The recent safety incidents on the French railway network (the TGV derailment at Marseille St Charles) underline the fact that the condition of rail infrastructure is of major concern in transportation and users' safety. The failure of key components as rail and/or crossing has been identified as the major cause. These are due to internal defects localized in the rail foot (corrosion, damage) as confirmed by the destructive analyses performed at the Metallurgical Expertise laboratory of SNCF Réseau. Safety is an absolute priority for SNCF Reseau as attested by its own strategic project "Tous SNCF Ambition Réseau" [1a]. Improving rail maintenance and knowledge on this asset is thus part of it. Furthermore, the "doubling rail freight" target plan at 2050 horizon by SNCF's CEO for French transportation, in a sustainable future perspective [1b], will reflect on the network maintenance demand.

Non-destructive evaluation (NDE) of railway tracks is a key link of network maintenance. Inspections with conventional devices operating from the top of rail have proved their ability to control the condition of the rail head (the upper part of the rail) with accuracy. These devices fail to keep the same reliability for the lower parts of the rail, *i.e.* the web and foot regions, where deep buried defects possibly leading to severe damage (as sudden rail breakage), still remain non-detectable. 50% of sudden rail breakage represents only 10% of the referenced defects. Novel dedicated-NDE-solutions are though needed to inspect these regions. Integrated in the SNCF maintenance strategy, they will contribute to both reducing the risk of rail breakage and the costs of cumbersome, time-consuming, limited visual inspections campaigns.

Answering the challenging question of the inspection of such deep zones with NDE systems located along the running surface from the top of the rail needs a breakthrough. This one-sided access limits the field of candidates and indeed excludes inspection-device-based methodologies operating directly on the web rail or the foot rail as proposed recently [2-4]. But, it insures in turn that inaccessible parts of the rail (because of construction layouts), for example, at the level-crossing rail, could be inspected. A literature overview of the inspection devices operating along the rail running surface, shows these are mainly focused on "rail head inspection" [5]. These low penetration depth devices [6] (surface wave, eddy current, or magnetic flux leakage -based) are inefficient for the detection of deep buried damage. So far, as discussed in [7], *"no commercial solution has been reported for foot flaw detection"*.

The objectives of our project are to overcome the limitations of the conventional practice in the domain by proposing a feasibility analysis based on novel methodologies relying on ultrasonic wave propagation prone to answer the major issue of the detection/localisation of deep buried defects under one-sided access illumination/observation conditions along the rail running surface. The aims of the proposal are to (a) stretch the classical frame of methodologies based on travel time to explore

volume and/or guided wave diffraction "topological" imaging (b) design, build experimental piezoelectric and EMATs (*Electro-Magneto-Acoustic Transducers*) devices for its implementation, (c) contribute to their validation on realistic dedicated rail specimens at scale 1.

The relevant work program will be structured around the following work packages:
WP0 - Steering and project management (Gustave Eiffel Univ.[UGE] lead): This multidisciplinary action plan aims to supervise project coordination and management by guiding the actions of involved partner teams and reporting to the committees (the steering committee, the scientific committee).

WP1 - State-of the-art and specifications (SNCF Réseau [SncfR] lead): WP1 is intended to give an overview of the rail damage typologies and SncfR feedback about the deployment of their own NDE methods in relation with the proposal. SncfR will supervise the specifications and machining of the damaged rail mockup specimens at scale 1 used for in-lab experiments conducted with the specific NDE tools developed during the ULTRATRAIL project. SncfR will plan and provide access to railway tracks. SncfR will also been involved in the experimental campaigns. WP1 impacts all the WPs.

WP2 – Piezoelectric demonstrator for 2D contact topological imaging (Bordeaux Univ.[UBo] lead): The WP2 objectives are to design, build and evaluate an experimental buried defect topological-imaging (as TI) demonstrator for rail monitoring based on an optimized piezoelectric transducer network located on the head of the rail. The present approach allows in-section imaging and is based on a 2D wave propagation assumption. It is experimentally demonstrated that the TI framework [8-9] allows processing of a reverberated field information in an academic case **[10]**. Thus, no direct wave path between the transducers and the region of interest is required. In other words, the regions that are masked from the transducers by the structure geometry can be monitored. This is a major breakthrough in comparison to classical delay and sum imaging techniques. The difficult access to the lower parts of the rails makes TI a good candidate for monitoring them from the easily accessible upper part of the rail. Still, the application of its framework to such an industrial case is not straightforward as the wave propagation in the undamaged rail has to be known. The specific shape of the rail section and the necessary distinction between a non-critical wear and actual defects require the design of an optimized measurement apparatus, an adaptation of the imaging method and an optimized signal processing for increased signal-to-noise ratio. The apparatus virtual design and the adaptation of the TI framework to truncated reverberated fields has been successfully performed at I2M (UBo) in collaboration with SncfR based on numerical experiments **[11]**. To perform the experimental defect imaging and achieve its required robustness, we face several challenges: the *in-situ* defect signature extraction (the so-called residue), the optimal insonification for improving the signal-to-noise ratio, the conformal array to the curved rail shape.

WP3 – EMATs development towards non-contact imaging (UGE lead)**:** Piezoelectric transducers as used in WP2 has great potential in terms of imaging capacities thanks to the various compact geometrical arrangements they allow (array) and their great sensitivity too. The need of a coupling (liquid or dry, depending on the waves involved) hinders the high-speed capability, if required, of any piezoelectric-based rail inspection device. EMATs are attractive because of their contactless nature. UGE is experienced in the development of EMATs- devoted to cable inspection (**[12-13]**). EMATs, in the NDE rail community, are mainly developed for the inspection of the rail head, with surface waves ([14-15]). Deep buried defects as those concerned in the proposal, have to gain from the ability of EMATs to also deal with shear waves (volume waves or guided wave) by contrast to other contactless device candidates (air coupled or laser-based). More specifically, shear horizontal waves could be promising for the detection of transverse vertical cracks in the lower region of the rail (web, foot). If EMATs lend to various designs to meet the expected wave polarization requirement at moderate costs, they often lead to bulky devices whose integration into any imaging strategy has to be considered carefully. The objectives of this WP3 are twofold: (1) contributing to the reduction of the bulky/power nature of these EMATs, an open question in the community [16], in order to consider their possible integration, in relation with the results of WP2 and WP4, as elements along the transverse dimension

of the running surface (2) designing/building single EMATs devoted to deep buried defects (as selected in WP1) and test their performance according to the wave diffraction imaging methodology emerging from point 3 of WP4. This methodology will exploit the information of wave propagation (volume wave or/and guided wave) along the rail longitudinal direction with EMAT elements distributed at the running surface as proposed in WP4. These aspects will be investigated with the TI algorithm in collaboration with WP2 andWP4.

WP4 - 3D modeling of damaged rails and digital twin for waveguide imaging (UGE lead): A limitation of WP2 is in the 2D plane strain assumption of the forward problem, thus weakening the imaging identifying process for 3D damages. In reality, wave propagation in rails is guided in the out-of-plane direction, leading to a 3D problem: rails are waveguides. This high-frequency (HF) modeling problem, unbounded in the longitudinal direction, leads to high computational costs with classical fully 3D modeling commercial tools. Progress has been recently made with methods dedicated to waveguides ([17-18] for rails) with (a) the Semi-Analytical Finite Element method (SAFE), to compute waves in homogeneous waveguides of arbitrary 2D cross-section, and (b) the hybrid FE-SAFE method, based on transparent boundary conditions on a small 3D-FE box around the vicinity of a local damage, to compute wave-defect interaction in locally inhomogeneous waveguides, (c) nonmodal Fourier-Laplace semi-analytical approach. Some of these tools also developed at UGE (a, b) and I2M (c) are now mature for the large-scale HF modeling of rails ([**19-20**,**21**]). The goal of WP4 is threefold: (1) generating 3D synthetic data for damaged rails (see WP1) to assess the limits of the 2D assumption of WP2, (2) determining the modal features of waves in healthy rails as a function of frequency (wavenumbers, velocities, cross-section distributions), (3) developing a digital twin for 3D imaging exploiting the full waveforms and considering the challenging one-sided rail access.
Point 3 is the central and most innovative one of the WP4. New ways of imaging rails and identifying 3D defects are likely to emerge and will be explored (one can imagine the gain of a non-contact device for a distributed longitudinal measure, with few sensors along the rail). Besides, the sensitivity-based TI algorithm will remain very fast, even in 3D: only two pure propagation problems are concerned (the forward and adjoint problems without damage), that are quickly solved, thanks to the guided wave modal formalism or nonmodal Fourier-Laplace semi-analytical approach. Point 3 involves parametric studies as: number, location and polarization of transducers, frequency range, imaging functions, noise sensitivity. WP4 paves the way for ultrafast, real-time, automated and onsite imaging of rails.

II. Partnership (consortium or team)

Our consortium is made up of two public-sector academic institutions and one public limited company, each with particular expertise relevant to the project, but who cannot undertake alone the whole work program. All the WPs are interleaved, with partners involved in each WPs and leads identified. The consortium complementarity is very strong. SncfR and I2M have literally laid the project foundation thanks to their prior works **[11]**. This initial partnership will be consolidated and powered up with the ULTRATRAIL project through the complementary approaches brought by UGE with guided wave and EMATs, and through test-sites facilities offer brought by SncfR for the experimental implementations phase. Let us also mention, UGE and I2M have been collaborating over years in the elastic wave-based NDE (shared PhD supervisions, research cooperation, national programs as MecaWave, …).

Dr L. Laguerre, research director at UGE, is the ULTRATRAIL project coordinator. Its planned contribution is about 20% of full-time. He is a 25-year-experienced researcher in wave- propagation-based-NDE of subsurface and civil engineering structures, with special skills on elastic-guided-wave-NDE of civil engineering cables. He has been involved in several research and industrial projects. He served as a committee member of the Acoustics and IWAGPR conferences and European Research Group «Wave propagation in complex media for quantitative NDE». He is active in technology transfer to bridge cable NDE (patented with Solétanche-Freyssinet, www.sixense-group.com/en/newsroom/ile-de-re-viaduct).

Gustave Eiffel University laboratory GeoEND develops NDE and geophysical methods and systems for civil engineering structures and subsurface monitoring. Dr F. Treyssède and Dr L. Laguerre have a strong know-how in guided-wave propagation modelling in complex media (embedded tendons, umbilical cables, ...) with dedicated numerical tools (**[19-20]**), as well experimental devices (in-lab and onsite) focused on high/low ultrasonic piezoelectric or magnetostriction-based-EMATs systems for guided-wave NDE of structural members (**[12-13]**). UGE will be involved respectively as leader in WP4 and WP3 [Resources: 1.5 year postdoctoral (WP3) and 1 PhD (WP4)] and cooperates to all other WPs.

I2M, UMR 5295 (Bordeaux University), the Physical Acoustics Dept of I2M is an established research team interested, among others, in linear/non-linear NDE of a large range of materials and components. Dr S. Rodriguez is a specialist of TI methods and he has skills in both numerical modelling and experimental setup implementation. He conducted the partnership project with I2M and SncfR for in-foot rail defect imaging **[11]**. Dr E. Ducasse is an expert in inverse problems and develops innovative approaches for waveguide numerical modelling **[21]** that are complementary to Dr Treyssède ones. The project will also benefit from various experimental facilities, such as multichannel ultrasound electronics and 3D laser velocimetry. UBo will be involved respectively as leader in WP2 and co-leader in WP4 [Resources: 1 PhD (WP2) and 1 Master Internship (WP2)] and cooperates to all other WPs.

SNCF Réseau (53,000 employees) develops railway services and ensures train traffic over the 28,000 km of lines, as well as their maintenance, modernisation and safety. As a public authorities and regions partner and guarantor of neutral, equitable access to the infrastructure, SncfR's priority is to satisfy its customers, mainly the rail transport companies and the organising authorities. Its Engineering Dept (ED) designs the network's development. It is involved in many expertise areas (rail maintenance, urban integration, noise reduction, waste treatment, …). Its objective is a safer, more efficient and environment friendly network. Mr N. Patteeuw was the SncfR leader of the project with I2M **[11]**. He is a technical expert focused in railway products, rail metallurgy, and damage. SNCFR will be involved respectively as leader in WP1 [Resources: 1-year engineer (WP1)] and cooperates to all other WPs.

III. References related to the project

[1a,b] www.sncf-reseau.com/fr/entreprise/newsroom/actualite/tous-sncf-ambition-reseau-projet-strategique-entreprise-met-cap-sur-2030, et medias.sncf.com/sncfcom/pdf/strategie/fer-carbone.pdf [2] Hu S, Shi W, Lu C, Chen Y, Chen G, Shen G (2021) Rapid detection of cracks in the rail foot by US b-scan imaging using a shear horizontal guided wave EMAT, NDT&E Int, 120, 102437. [3] Li Y, Liu Z, Miao Y, Yuan W, Liu Z (2020) Study of spiral-coil EMAT for rail subsurface inspection, Ultrasonics, 108. [4] Evans M, Lucas A, Ingram I (2018). The inspection of level crossing rails using guided waves, Constr. and Build. Mat., 179. [5] Mićić M, Brajović L, Lazarević L, Popović Z (2023) Inspection of RCF rail defects–Review of NDT methods. Mech. Syst. and Signal Proc., 182, 109568. [6] Papaelias M Ph, Roberts C, Davis CL (2008) A review on NDE of rails: state-of-the-art and future development, Proc. Inst. Mech. Eng.: J Rail and Rapid Transit, 222(4). [7] Alahakoon S, Sun YQ, Spiryagin M, Cole C (2018) Rail flaw detection technologies for safer, reliable transportation: a review. J Dyn. Syst, Meas. and Control, 140(2). [8] Guzina BB, Bonnet M (2004). Topological derivative for the inverse scattering of elastic waves, Quart. J Mech. and Appl. Maths, 57(2). [9] Dominguez N, Gibiat V, Esquerre Y (2005) Time domain topological gradient and time reversal analogy: an inverse method for ultrasonic target detection, Wave motion, 42(1). **[10]** Rodriguez S, Veidt M, Castaings M, Ducasse E, Deschamps M (2014) One channel defect imaging in a reverberating medium, Appl. Physics Lett., 105(24), 244107. **[11]** Rodriguez S, Gayoux V, Ducasse E, Castaings M, Patteeuw N (2022) Ultrasonic imaging of buried defects in rails. NDT&E Int, 102737. **[12]** Laguerre L, Aime JC, Brissaud M (2002) Magnetostrictive pulse-echo device for non-destructive evaluation of cylindrical steel materials using longitudinal guided waves, Ultrasonics, 39(7). **[13]** Kurz JH, Laguerre L, Niese F, Gaillet L, Szielasko K, Tschuncky R, Treyssede F (2013) NDT for need based maintenance of bridge cables, ropes and prestressed elements. J Civil Struct. Health Monit., 3(4). [14] Edwards RS, Dixon S, Jian X (2006) Characterisation of defects in the railhead using ultrasonic surface waves, NDT&E Int, 39(6). [15] RIFLEX: Rail Inspection by Flexible EMATs (2016) www.youtube.com/watch?v=Vleu2SNJEWw [16] Isla J, Cegla F (2017) EMAT phased array: A feasibility study of surface crack detection, Ultrasonics, 78. [17] Spada A, Capriotti M, Lanza di Scalea F (2022) Global-local model for 3D guided wave scattering with application to rail flaw detection, Struct. Health Monit. 21. [18] Ramatlo D, Long C, Loveday P, Wilke D (2020) A modelling framework for simulation of US guided wave-based inspection of welded rail tracks, Ultrasonics 108, 106215. **[19]** Benmeddour F, Treyssède F, Laguerre L, Numerical modeling of guided wave interaction with non-axisymmetric cracks in elastic cylinders (2011) Int J Solids and Struct. 48. **[20]** Gallezot M, Treyssède F, Laguerre L, Numerical modelling of wave scattering by local inhomogeneities in elastic waveguides embedded into infinite media (2019), J Sound and Vib. 443. **[21]** Mora P, E Ducasse, M Deschamps (2016), Transient 3D elastodynamic field in an embedded multilayered anisotropic plate, Ultrasonics, 69.