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FROM ACOUSTIC TESTING AND MODELING TOWARDS MULTI-PHYSICAL DIGITAL TWINS: USE CASES AND DEMONSTRATORS

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ABSTRACT

In the past decades, noise has gained growing significance. Also in mechanical engineering, increasingly complex mecha(tro)nic systems are emerging which have to perform optimally while satisfying ever more stringent noise regulations and customer expectations. Nowadays, electrification and transition to greener technologies and materials leads to novel noise sources and problems, posing significant engineering challenges.

With increasing computation power over the past decades, also rapid technological evolutions have unfolded in acoustics: from testing to numerical modeling and simulation, from mono- to multi-physical simulation, from offline to real-time online simulations, … Thanks to these evolutions, noise is evolving from an attribute to quantify and control towards an integrated design parameter for the entire lifetime of systems, enabled by reduced order modeling, innovative signal processing techniques, novel emerging vibro-acoustic solutions and optimization. Moreover, combining fast multi-physical models with acoustic measurements has opened the door to a variety of novel developments including auralization, virtual sensing, real-time state/parameter estimation and prognostics.

This paper gives an overview of the dynamics (noise, vibration & motion) research at the KU Leuven Mechanical Engineering Department, in the LMSD research group.

Keywords: *testing, modeling, multi-physics, digital twins*

1. INTRODUCTION

In the past decades, the field of noise, vibration and harshness (NVH) engineering has expanded and evolved. With the growing awareness of the negative impact of noise on human health, the increasingly stringent noise legislation and ever more demanding customer expectations, noise has not only changed from an (unwanted) byproduct to a key product differentiator, but also to a key quantity which is accounted for and exploited at every life phase of a product. At the same time, mechanical engineering systems have evolved to mechatronic systems. These are not only more complex to design, model and analyze, but also create the opportunity for built-in sensorization and continuous data streams between products and virtual counterparts.

Together with this evolution, the LMSD System Dynamics research group at KU Leuven grew from the Noise & Vibrations research group which in its turn started over 5 decades ago as the MOD – Modal analysis research group. The research at LMSD spans a broad spectrum from methodologies, over theoretical foundations, to various application domains: by understanding, monitoring and controlling the dynamics (motion-vibration-acoustics) of mecha(tro)nic systems, LMSD aims at creating added value

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during every phase (design, manufacturing, and operations) in their lifetime. Having built out dedicated in-house testing and validation platforms, as well as software toolchains, the research group closely co-innovates together with world-wide research and industry partners and, in doing so, actively cross-fertilizes between applied and industrial research[1][2] [1]. Furthermore, to create scientific as well as societal impact, LMSD regularly brings its latest developments closer to the wide public[3,4].

The rest of this paper presents several recent developments and (industrial) use cases in acoustics research at LMSD. After describing progress in acoustic testing and modeling in Sections 2 and 3, Section 4 discusses advanced techniques for (vibro-)acoustic measurement and analysis. Novel (vibro-)acoustic solutions are the topic of Section 5. Section 6 discusses how models and measurements come together in Digital Twins and add value, and Section 7 provides an outlook on how this digitally connected concept can be elevated to close the loop across all life phases of products. Section 8 summarizes the main conclusions.

2. ACOUSTIC TESTING

With the change from analog to digital, the increase in computing power, and the downscaling of circuits, acoustic measurement devices have become more portable, precise and versatile in the past decades (Fig. 1). Along with that digital (r)evolution, acoustic testing nowadays comprises far more than sound pressure recording, covering a broad spectrum ranging from characterization and (model) updating/validation (Section 3) to condition monitoring (Section 4), sensing and digital twinning (Section 6).

Figure 1. Historical collection of LMSD's vibro-acoustic measurement systems.

[1] https://www.mech.kuleuven.be/en/mod/Projects
[2] https://www.youtube.com/watch?v=gQBgfSLdwJg
[3] https://www.linkedin.com/showcase/lmsd-kuleuven
[4] https://www.youtube.com/@lmsd-kuleuven

Standard (vibro-)acoustic measurement techniques rely on controlled environments, for which simple analytical models can relate sound pressure measurements to the quantities of interest. However, these idealized environments are often not representative for the final application. Over the years, various non-standard test rigs have been developed to enable the characterization of (vibro-)acoustic properties in more representative environments (Fig. 2), often relying on virtual counterparts (Section 6).

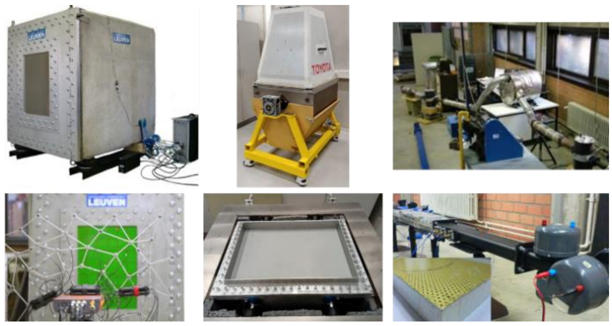

Figure 2. (left, center) Non-standard test-rigs for (vibro-)acoustic transmission, absorption & radiation, (right) modular infrastructure for characterization of (flow-)acoustic properties of duct systems.

These test rigs are augmented with various measurement systems, including sound intensity probes, acoustic arrays, acoustic camera, (scanning) laser doppler vibrometers (SLDV), ... Furthermore, digital counterparts of these test rigs have been created using different modeling strategies (Section 3), which not only enables updating models of tested components, but also allows gaining additional insights via model-measurement combinations (Section 6).

SLDVs have especially gained interest as they enable full-field characterization, not only useful for (source) localization (Fig. 3), but also for analyzing structural wave phenomena in novel materials (Section 5). Recently, also camera-based measurements have gained interest in vibro-acoustics. In contrast to conventional acoustic sensors, cameras allow directly observing the structure-borne noise source. Methods were developed to predict full-field acoustic radiation of vibrating surfaces independently of the acoustic environment (Fig. 4) by leveraging camera measurements with acoustic models (see also Section 6). These techniques especially also hold promise for vibro-acoustic problems involving transient behavior and moving systems.

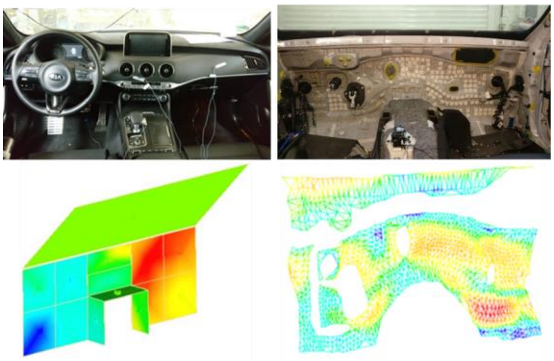

Figure 3. (left) Sound intensity, (right) SLDV-based vibration field measurements of a car firewall [2].

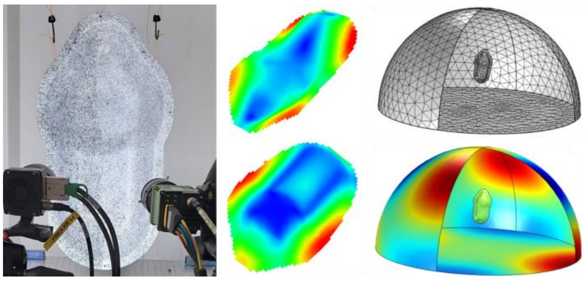

Figure 4. (left & center) Camera-based vibration field measurement, (right) combined measurement-model based acoustic radiation estimation [3].

In particular with the rise of novel emerging materials and structures such as metamaterials (Section 5), which exhibit non-conventional acoustic wave propagation behavior, dedicated acoustic test setups and routines have been developed (Fig. 5) that enable characterizing their performance already early in design process, without need for full 3D simulation, design, manufacturing and testing.

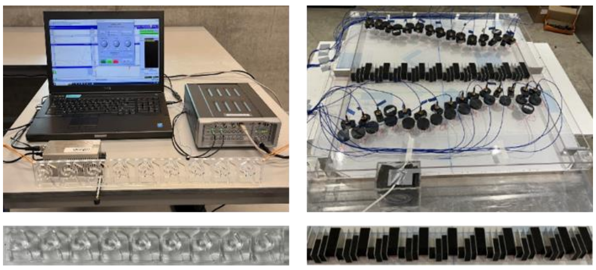

Figure 5. (left) Hammer impact-based method to validate the Sound Transmission Loss (STL) of 2D structures [4], (right) 2D rectangular waveguide for angle-dependent transmission, reflection and absorption coefficient characterization [5].

3. ACOUSTIC MODELING

In the past decades, element-based numerical techniques such as the Finite Element Method (FEM) and Boundary Element Method (BEM) have become industry standard for solving large and complex (vibro)-acoustic problems (Fig. 6a). With increasing frequency, element sizes must decrease, which drives up computation cost of element-based techniques, limiting their application mostly to lower frequencies. Although high-frequency techniques such as Statistical Energy Analysis (SEA) exist, a mid-frequency gap persisted and drove the search for mid-frequency methods[5]. In particular, at LMSD, the Wave Based Method (WBM) for (vibro)acoustics was developed, which is an indirect Trefftz approach. It partitions the (interior/exterior) problem in large convex subdomains, approximating the solution with wave functions, being exact solutions of the governing equation [6]. Although mainly suitable for problems with limited geometrical complexity, WBM was shown to be more efficient than FEM and BEM for said problems. Hybrids with FEM (Fig. 6b), BEM and SEA were developed to combine the best of several worlds. Later, to allow ensuring geometrical exactness - which element based techniques typically lose - isogeometric analysis (IGA)-based FEM and BEM have been proposed [7,8], using Non-Uniform Rational B-splines (NURBS) to represent the geometry and discretize the wave equation (Fig. 6c) instead of polynomials in classical FEM or BEM.

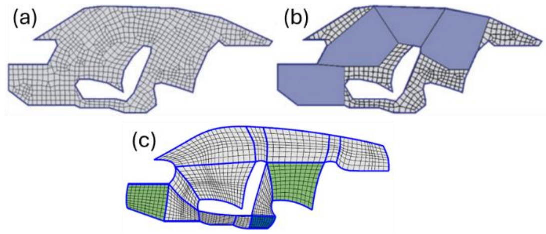

Figure 6. Numerical modeling methods in acoustics: (a) FEM, (b) WBM and hybrid WB-FEM for mid-frequency analysis [6], (c) IGA FEM [7].

Performing a frequency sweep either with FEM or BEM can induce high computation costs (solution time, memory). Such costs can be alleviated, by so-called Model Order Reduction (MOR) techniques, where the structure of the system and the repetitiveness of the procedure are exploited to provide a fast yet accurate solution. Specifically, in case of affine systems (e.g. regular vibro-acoustic FE models), it is possible to split the calculation in an expensive offline part and a cheap online part. In the offline part a reduction

[5] https://www.youtube.com/watch?v=m9OHmurazTA

basis is computed and the system matrices are projected on this basis. The different MOR strategies typically differ in the way the reduction bases are computed. Common techniques are POD, reduced basis method, rational Krylov approximation, … When combined with exterior acoustics, boundary treatments, and time-domain solution procedures, particular attention has gone to preserve stability (Fig. 7) [9]. Compared to FEM, MOR for BEM is more challenging as the frequency is non-affinely involved in the system matrices. To enable the application of MOR, the system needs to be approximated through an affine expression [10].

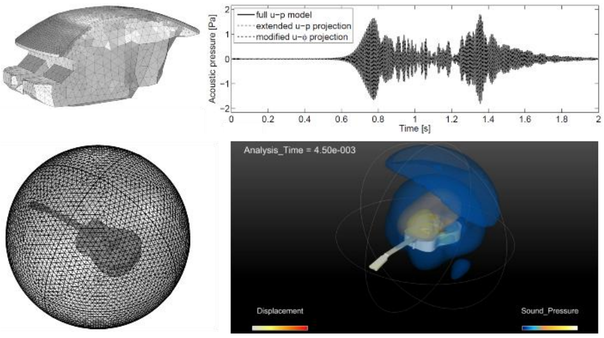

Figure 7. MOR for time stable, efficient FE time-domain simulations for interior/exterior acoustics [9].

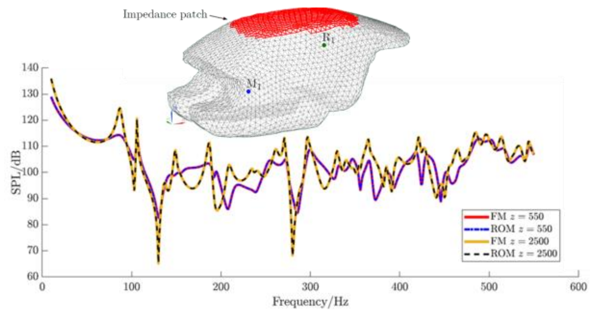

Figure 8. pMOR for acoustic BEM. Interior acoustic treatment modeled with impedance patch [10].

Following the same logic as in conventional MOR for FEM and BEM, it is possible to increase the number of parameters to include e.g. material, source position, shape … which has led to parametric MOR (pMOR) techniques, for instance by sampling information from the parameter space beforehand (Fig. 8) [10]. Doing so, pMOR allows fast transitions among different design configurations, either for design or fast inverse parameter estimation (Section 6). Recently, time-stable MOR routines for vibro-acoustic models including frequency-dependent admittance relations, porous and poro-elastic layers, and PMLs have also been developed [11].

Another avenue on the rise is the use of Machine Learning (ML), not only for MOR, but also to accelerate and improve acoustic model generation. E.g. in absence of CAD data, techniques have been developed to enable creating geometrically accurate acoustic meshes using photo-grammetry (Fig. 9). The latter allows for a high degree of customization of acoustic predictions, but also for improved immersion when considering also the receiver and sound perception in the acoustic problem for e.g. auralization [12].

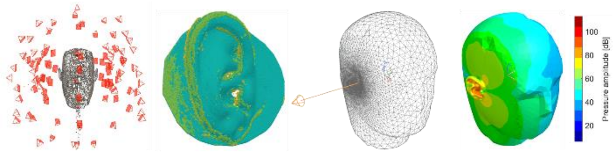

Figure 9. Dummy head ear scans are fed to DNNs trained on point cloud denoising for numerical Head-Related Transfer Function (HRTF) prediction [12].

4. (VIBRO)ACOUSTIC MONITORING AND DETECTION

In many industrial applications including manufacturing, power generation and transportation, rotating machinery plays a pivotal role. As continuously operating drivetrains predisposes their rotating components (e.g. gears, bearings …) to a risk of failure, condition monitoring for accurate and on-time fault detection has grown indispensable.

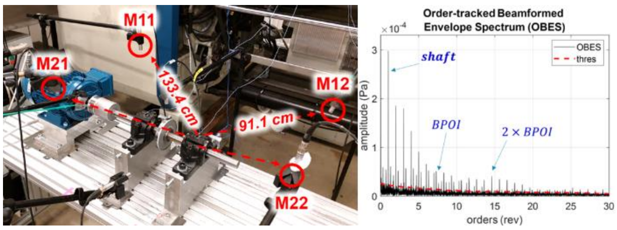

Figure 10. (left) In-house modular drivetrain test setup for bearings & gears diagnostics instrumented with accelerometers and microphones, (right) tracked spectrum of a damaged bearing [13].

While vibration sensors have been historically used for fault detection, recent work has focused on also harnessing the integratory capability of microphones to capture the global, overall acoustic signature of the entire drivetrain with limited and non-contact sensors. Several dedicated setups for drivetrain components have been built and instrumented at LMSD to develop and validate novel advanced signal processing techniques for vibro-acoustics based condition monitoring (Fig. 10) [13].

On the other hand, also nondestructive testing (NDT) has been a topic of extensive research lately with the goal of detecting defects in complex composite parts and assemblies in a limited inspection time. Classical NDT often relies on thermal imaging techniques and ultrasound. At LMSD, the use of vibro-acoustic signals to detect and identify damage is researched (e.g. loose bolt detection with MUSIC[6], Fig. 11). Combining vibro-acoustic information originating from defects with accurate numerical models enables enhancing the detection of such defects (Section 6), while lowering the required number of sensors [14].

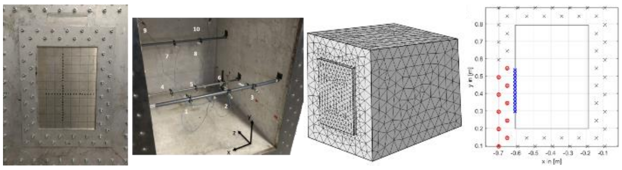

Figure 11. Structural damage (loose bolt) detection of assembly using acoustic measurements (with/ without combination with numerical model) [14].

5. INNOVATIVE VIBRO-ACOUSTIC SOLUTIONS

As classical passive solutions to increase sound insulation and/or absorption rely on adding mass and/or volume, they are less suitable for low frequencies. With the advent of more powerful controllers, active noise control gained a lot of interest in the 90s for low-frequency noise abatement [15]. Two decades later, (vibro-)acoustic metamaterials emerged and have meanwhile shown great potential as lightweight and compact solutions for high noise and vibration attenuation in targeted frequency ranges called “stop bands” [16], enabled by sub-wavelength added resonant inclusions on or in a (flexible)host structure.

To characterize, design and optimize the performance of (vibro-)acoustic metamaterials, a complete toolchain has been developed at LMSD[7] which enables covering all relevant physics, as well as translation from idealized infinite periodic structure theory to more complex, practically realizable solutions (Fig. 12) [17]. Their versatility and effectiveness in treating vibration, acoustic radiation and transmission problems has been proven through a variety of demonstrators, ranging from academic to industrial application (Fig. 13) [16, 18, 19].

Nowadays, metamaterials research at LMSD is expanding towards (mass-)manufacturability (e.g. injection molding) and variability, (topology-optimized [4]) multi-functional metastructures[8] and phase gradient acoustic metamaterials (Fig. 5) [5], as well as active (piezoelectric) metamaterials.

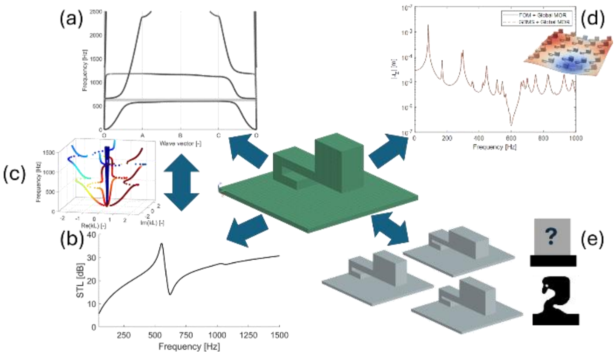

Figure 12. Unit cell modeling developments: (a) fast dispersion curve predictions, (b) periodic structure STL computations, (c) wave mode contributions to STL, (d) finite structure forced response computations, (e) design/topology optimization.

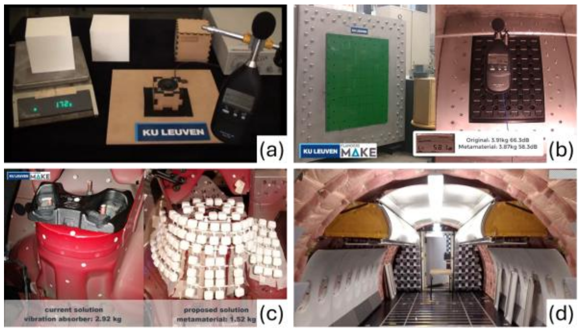

Figure 13. (a) 3D printed metamaterial enclosure[9], (b) lightweight thermoformed metamaterial panel[10], (c) 3D printed metamaterial patches on the rear shock tower of a vehicle[11], (d) laser cut add-on to aircraft fuselage panels [19].

6. VIBRO-ACOUSTIC DIGITAL TWINNING

Leveraging increasingly fast yet accurate (vibro-)acoustic models together with measurement data, enables creating digital twins[12], which are not only continuously updated

[6] https://www.youtube.com/watch?v=H0nFtsJ4HYM
[7] https://www.youtube.com/watch?v=DPbPjo3du5Q
[8] https://www.youtube.com/watch?v=jFNa8gOn-eo
[9] https://www.youtube.com/watch?v=JUi3qK32mf0
[10] https://www.youtube.com/watch?v=GWHeiEnx4ks
[11] https://www.youtube.com/watch?v=MdHVCnvj9x0
[12] https://www.youtube.com/watch?v=_d1oMRVlvMA

with reality, but provide insight in difficult to measure or unmeasurable quantities. Deploying the developed modeling strategies and in-house available test rigs and physical assets at LMSD, in the past years, a Digital Twin Experience Center has been established (Fig. 14).

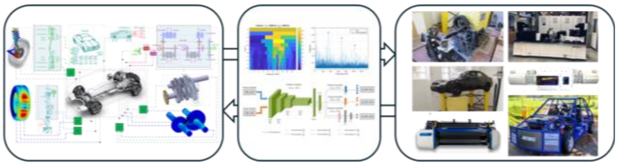

Figure 14. digital twins at LMSD: (left) modeling & simulation platforms for component and system dynamics, (center) estimation, signal processing & ML, (right) full-scale mechatronic systems.

Setting up digital twins for NVH requires digitizing the full chain from source/inputs, over path to receiver. Hence, multi-physical and multi-domain simulation frameworks have been set up, combining e.g. multibody simulation, 1D and 3D simulations, electromagnetic simulations and vibro-acoustic simulations (Fig. 15) [20].

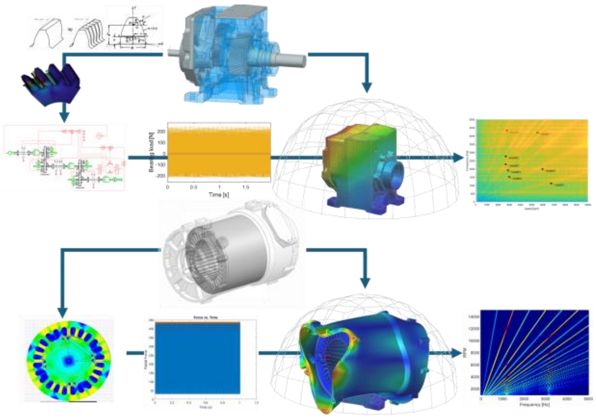

Figure 15. Multi-physical simulation workflow for (top) gearbox and (bottom) e-motor noise [20].

Through combining dedicated test-setups & physics-based (digital) counterparts, these digital twins enable amongst others experimental model-based input and parameter estimation of vibro-acoustic systems[13] as well as optimizing sensor selection and placement: e.g. for operational load estimation (Fig. 16), for source localization in complex environments, for acoustic material identification in reverberant environments [22], for acoustic material characterization under various flow conditions, … In particular acoustic virtual sensing[14], model-based augmented sensing of input forces, acoustic pressure and intensity with numerical models (Fig. 17), but also experimental modal models for e.g. virtual acoustic measurements in exterior vibro-acoustic problems (Fig. 18) have been developed and demonstrated.

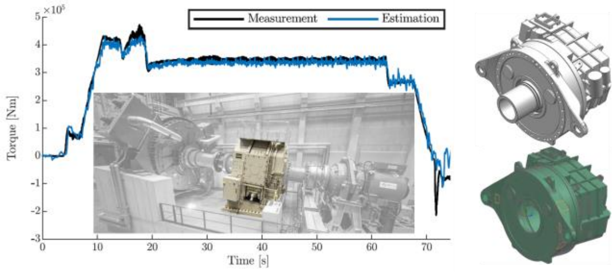

Figure 16. Virtual torque sensing of ZF wind turbine gearbox tested on the 4MW drivetrain testing infrastructure at Center for Wind Power Drives [21].

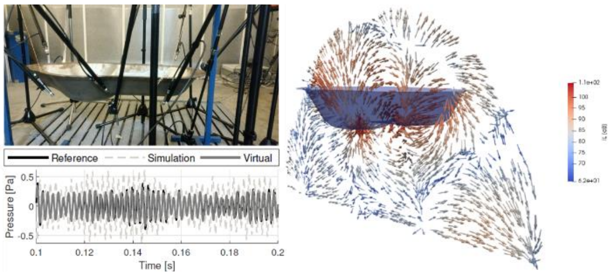

Figure 17. (top left) Measurement setup in in-house semi-anechoic room, (bottom left) measured, simulated and estimated sound pressure, (right) sound intensity field estimation [23].

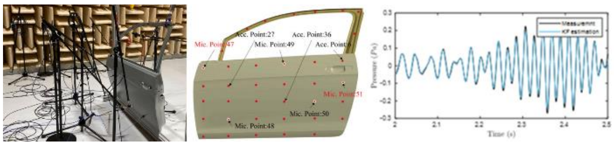

Figure 18. (left) Operational vibro-acoustic measurements, (center) experimental model, (right) measured and estimated sound pressure [24].

7. THE FUTURE

Building models and validating products requires accurate data. In the current Industry4.0 era, data is becoming increasingly abundant: during every life phase of a product,

[13] https://www.youtube.com/watch?v=1dW2g6tYsgI

[14] https://www.youtube.com/watch?v=fx6-yIMkN6s

digital information (digitized knowledge, simulation models, test data, production data, etc.) is generated, from early concept design, over detailed design and analysis, virtual and physical prototyping, product validation, commissioning, production and assembly, quality control, to the operational product in-use phase, and even the end-of-life (re-use, re-cycling, re-manufacturing) phases. Digital twins allow collecting and comprehensively managing all digital information linked to a unique product in all its different life phases, and to generate unprecedented added value by digitally connecting these phases in a closed loop, coined by KU Leuven as the "infinity loop" (Fig. 19). As such, the amount of available information and knowledge per product substantially increases, and more optimized and effective decisions can be taken.

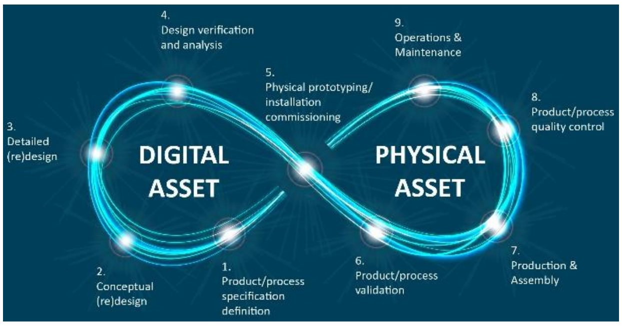

Figure 19. Enabled by digital twins, the infinity loop digitally connects all life phases in a closed loop.

From a vibro-acoustic point of view, this opens the door to various scenarios, such as for example (i) improved product validation since individual variations in part geometry or (mis-)alignment can be propagated to update nominal design models and hence take the effect of off-design into account, (ii) more accurate operational estimation, as these updated vibro-acoustic models allow for better estimates of transfer functions and thus better estimation of loads or states of the mecha(tro)nic system, and (iii) better next-generation designs as operational and end-of-life information can be fed-back to the designers, and many more scenarios.

8. CONCLUSIONS

In line with the increasing importance of quieter living and working environments, acoustic modeling and testing procedures keep improving, and innovative NVH solutions keep getting closer to widespread application. Noise and vibrations are omnipresent, and with the advent of (vibro-acoustic) digital twins, capabilities to both control NVH as well as harness its value at every life phase of the product lifecycle are ever expanding, thereby enabling the development of high-tech products, processes and systems, while at the same time accounting for the health of people and the well-being of society, for a sustainable environment and energy supply, and for safe and comfortable mobility.

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10. REFERENCES

[1] C. Claeys, B. Pluymers, H. Van Der Auweraer & W. Desmet (2018). Dual-Desk PhD researchers. *Proc. of the UIIN Conference 2018.*

[2] K. J. Chang, N. G. R. de Melo Filho, L. Van Belle, C. Claeys & W. Desmet (2019). A study on the application of locally resonant acoustic metamaterial for reducing a vehicle's engine noise. *Proc. of INTERNOISE 2019*, Vol. 259, No. 9, pp. 102-113.

[3] F. S. Egner, W. Desmet & E. Deckers (2023). Full-field Camera Measurements for Structural and Vibro-acoustic System Analysis.

[4] V. Cool, C. Claeys, H. Denayer, F. Naets & E. Deckers (2024). Experimental validation of a topology optimized 2D sandwich panel for sound transmission minimization. *Mech. Syst. Signal Process.*, 211, 111197.

[5] Z. Zhang, H. Denayer, C. Claeys, W. Desmet & E. Deckers (2021). Angle-dependent reflection, transmission and absorption coefficients measurement using a 2D waveguide. *Appl. Acoust.*, 177, 107946.

[6] E. Deckers, O. Atak, L. Coox, R. D'Amico, H. Devriendt, S. Jonckheere, ... & W. Desmet (2014). The wave based method: An overview of 15 years of research. *Wave Motion*, 51(4), 550-565.

[7] L. Coox, E. Deckers, D. Vandepitte & W. Desmet (2016). A performance study of NURBS-based isogeometric analysis for interior two-dimensional time-harmonic acoustics. *Comput. Methods Appl. Mech. Eng.*, 305, 441-467.

[8] E. O. Inci, L. Coox, O. Atak, E. Deckers & W. Desmet (2020). Applications of an isogeometric indirect boundary element method and the importance of accurate geometrical representation in acoustic problems. *Eng. Anal. Boundary Elem.*, 110, 124-136.

[9] A. van de Walle, F. Naets, E. Deckers & W. Desmet (2017). Stability-preserving model order reduction for time-domain simulation of vibro-acoustic FE models. *Int. J. Numer. Methods Eng.*, 109(6), 889-912.

[10] D. Panagiotopoulos, W. Desmet & E. Deckers (2022). Parametric model order reduction for acoustic boundary element method systems through a multiparameter Krylov subspaces recycling strategy. *Int. J. Numer. Methods Eng.*, 123(22), 5546-5569.

[11] Y. Cai, S. van Ophem, W. Desmet & E. Deckers (2024). Model order reduction of time-domain vibro-acoustic finite element simulations with poroelastic materials. *Comput. Methods Appl. Mech. Eng.*, 426, 116980.

[12] F. Di Giusto, S. van Ophem, W. Desmet & E. Deckers (2023). Analysis of laser scanning and photogrammetric scanning accuracy on the numerical determination of Head-Related Transfer Functions of a dummy head. *Acta Acust.*, 7, 53.

[13] A.M. Mauricio, H. Denayer, & K. Gryllias. (2023). Beamformed Envelope Spectrum Of Acoustic Signals For Bearing Diagnostics Under Varying Speed Conditions. *Proc. of NOVEM 2023*, paper 7B-4-036.

[14] P. Becht, E. Deckers, C. Claeys, B. Pluymers & W. Desmet (2019). Loose bolt detection in a complex assembly using a vibro-acoustic sensor array. *Mech. Syst. Signal Process.*, 130, 433-451.

[15] L. de Oliveira, K. Janssens, P. Gajdatsy, H. Van der Auweraer, P. Varoto, P. Sas, W. Desmet (2009). Active sound quality control of engine induced cavity noise. *Mech. Syst. Signal Process.*, 23 (2), 476-488.

[16] C. Claeys, E. Deckers, B. Pluymers & W. Desmet (2016). A lightweight vibro-acoustic metamaterial demonstrator: Numerical and experimental investigation. *Mech. Syst. Signal Process*, 70, 853-880.

[17] V. Cool, E. Deckers, L. Van Belle & C. Claeys (2024). A guide to numerical dispersion curve calculations: Explanation, interpretation and basic Matlab code. *Mech. Syst. Signal Process.*, 215, 111393.

[18] L. Van Belle, L. Sangiuliano, N. G. R. de Melo Filho, M. Clasing Villanueva, R. F. Boukadia, S. Ahsani ... & W. Desmet (2021). Vibro-acoustic metamaterials for improved interior NVH performance in vehicles. *Future Interior Concepts*, 31-51.

[19] F. A. Pires, R. F. Boukadia, M. Wandel, C. Thomas, E. Deckers, W. Desmet & C. Claeys (2025). Novel resonator concept for improved performance of locally resonant based metamaterials. *Thin-Walled Struct.*, 209, 112866.

[20] H. Wang, L. Van Belle & F Naets (2024) Model based noise and vibration analysis framework of electric vehicle e-motor and gearbox. *Proc. of ISMA2024.*

[21] J. Bosmans, S. Gallas, V. Smeets, M. Kirchner, L. Geens, J. Croes & W. Desmet (2025). Experimental validation of virtual torque sensing for wind turbine gearboxes based on strain measurements. *Wind Energy*, 28(2), e2955.

[22] D. Panagiotopoulos & E. Deckers (2023). Inverse impedance identification using an efficient BEM strategy. *In Proc. of Forum Acusticum 2023*.

[23] S. van Ophem, E. Deckers & W. Desmet (2019). Model based virtual intensity measurements for exterior vibro-acoustic radiation. *Mech. Syst. Signal Process.*, 134, 106315.

[24] J. Staiger, S. van Ophem, J. Troge, & F. Naets (2024). Virtual measurements for exterior vibro-acoustic problems using experimental modal models. *Mech. Syst. Signal Process.*, 209, 111110.