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About airborne fatigue life predictions by means of full-field receptances. Part B: estimating the failure distribution with spectral methods.

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Abstract

Airborne pressure fields, with their variable spectral content in the acoustic and frequency domains, can become a threatening dynamic distributed loading for many surfaces in industrial applications, thus leading to airborne fatigue. Part A of this research path retrieves the structural force spectrum, as induced by the modelled airborne pressure fields on the real thin plate tested, which becomes the dynamic excitation for the structural dynamics in this Part B, leading to cumulative damage and fatigue life considerations. Reliable and advanced full-field receptance testing – as substitution of any other numerical model about the mounted realisation of the specific components – can nowadays be made by means of optical measurements. The quality achieved in the receptance maps helps in numerically derive the strain FRFs on the sensed surfaces. With proper constitutive models, the experiment-based mapping of the equivalent stresses can be achieved. Fatigue spectral methods turn this knowledge into component's life distributions with the unmatched mapping ability of contactless full-field techniques. Full-field optical receptance maps turn to be pivotal in accurately representing the structural dynamics when retrieving the induced force by airborne pressure fields in Part A, and when mapping the effective solicitations for the airborne fatigue life predictions of Part B.

Keywords: airborne structural forces; vibro-acoustics; full-field receptance FRFs; fatigue spectral methods; airborne fatigue failure mapping.

1. Introduction

Airborne pressure fields can be dangerous especially for lightweight parts with tight structural dynamics in the frequency range of interest, typical of aerospace and automotive engineering. The working life of these components can be severely shortened – also with catastrophic failures – due to unexpectedly high dynamic responses to the airborne pressure fields. Advanced design and manufacturing methodologies need therefore to consider carefully any generalised damping distribution and specific boundary conditions in the structural dynamics of the actual realisation of the mounted component, especially for mission critical ones. The key idea sketched in this brief article is to use a broad frequency band *experiment-based full-field FRF approach* to bring the complete & real structural dynamics into fatigue life expectations, which come as failure maps. The same *receptances* are exploited in Part A to retrieve the airborne structural force that is here the cause of airborne fatigue solicitations. In such a broad perspective, for

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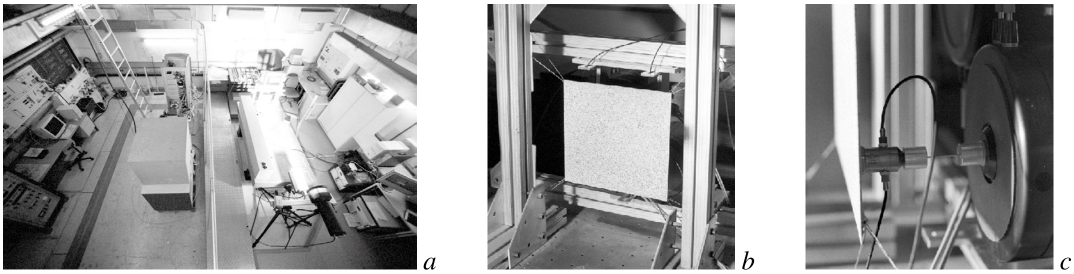

Figure 1. The lab in the TEFFMA project: aerial view in *a*, restrained plate sample in *b*, 2 shakers on the back of the plate in *c*.

the retained dynamics and for the high resolution mapping achievable, the location of potential defects might play an uttermost relevance in the crack & failure start. What follows is devoted to highlight the potentials of this smart approach with simple examples from Digital Image Correlation (DIC) optical (non-contact) full-field technique. The latter family of approaches can give: no structural dynamics distortions; a dense grid of sensing locations; a broad frequency band experimental vibration model, with accurate spatial description for complex patterns' identifications; an experimental dynamic model for strains (after accurate numerical derivation), stresses & failure criteria; accurate maps of cumulative damage distributions for fatigue life assessment, defect tolerance criteria and risk index maps, here dependable on the airborne induced excitation signature.

The works in both Part A & B are the latest spin-off activities, rooting to the *Towards Experimental Full-Field Modal Analysis* (TEFFMA) project at TU-Wien, after the grown seeds put in the HPMI-CT-1999-00029 *Speckle Interferometry for Industrial Needs* Post-doctoral Marie Curie Industry Host Fellowship project at Dantec Ettemeyer GmbH. Since that testing (see Zanarini (2005a,b)) it became self-evident how full-field measurements could give relevant mapping about the local behaviour for enhanced structural dynamics assessments (see Zanarini (2007)) and fatigue spectral methods (see Zanarini (2008a,b)). The results in the former were the basis for the TEFFMA birth, whose works on SLDV, DIC & ESPI techniques saw earlier presentations in Zanarini (2014a,b). In Zanarini (2018) a gathering of the works of TEFFMA was firstly attempted, while in Zanarini (2019a) an extensive description of the whole receptance testing was faced and in Zanarini (2019b) the Experimental Full Field Modal Analysis was detailed together with model updating attempts. The works in Zanarini (2020) underlined the quality of the datasets in full-field dynamic testing. The same quality inspired in Zanarini (2022d, 2023a,b, 2025a) the sound propagation simulation by means of the Rayleigh integral approximation, as well as the pseudo-inverse vibro-acoustics of Zanarini (2024a,d, 2025b,c). In Zanarini (2022b) a precise comparison was made about new achievements for rotational and strain FRF high resolution maps. In Zanarini (2022a,c, 2023c) the risk grading concept was first introduced by the exploitation of ESPI datasets, which are, contrary to DIC here used (or in Zanarini (2024b,c)) or SLDV as in Zanarini (2025d), difficult to be deployed outside a laboratory.

A brief description of the testing is outlined in Section 2, with attention on the set-up, on the used gears and on the obtained raw results. Section 3 deals with the numerical derivation of strain and stress fields from receptance maps, which are relevant to the cumulative damage spectral methods in Section 4, exploiting the airborne structural force retrieved in Part A, before the final conclusions in Section 5.

2. The testing for the TEFFMA project in brief

As underlined in Part A, the most detailed notes on the test campaign appeared in Zanarini (2019a), with further suggestions in Zanarini (2019b, 2020, 2022b, 2024a, 2025a), but here is a brief summary of what was available at TU-Wien as in Fig.1: a dedicated seismic floor room; traditional tools for vibration & modal analysis; but, in particular, there were SLDV, Hi-Speed DIC and ESPI as non-contacting optical full-field measurement instruments.

2.1. Setting-up the rig for concurrent measurements

Accurate studies were needed to understand each technological limit and if a common test for concurrent usage might have been really possible. All this brought to a unique set-up for the comparison of the 3 optical technologies in full-field FRF measurements; great attention was paid on the design of experiments for further research in modal

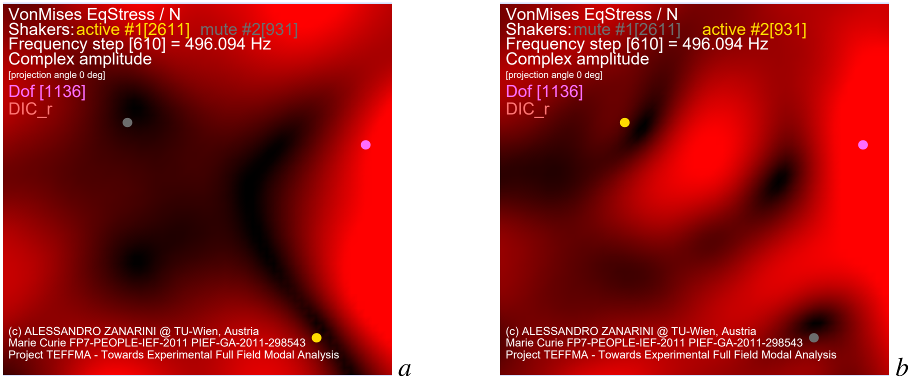

Figure 2. Examples of *von Mises equivalent stress FRF maps* from optical techniques, direct experimental FRF models at 496 Hz, DIC examples: from shaker 1 in *a*, from shaker 2 in *b*.

analysis. After an accurate tuning, a feasible performance overlapping was sought directly out of each instrument, reminding that the same structural dynamics can be sensed in complementary domains, which means frequency for SLDV & ESPI, time for DIC. The comparisons of the Operative Deflection Shapes, directly out of each instrument proprietary software, seem really promising, but only qualitative, as nothing is precisely super-imposable. A topology transform methodology might be used for quantitative comparisons in the same physical locations of the specimen.

2.2. *Estimated full-field FRFs & Coherence from optical measurements*

Receptance FRF ($\in \mathbb{C}$) & *Coherence function's* ($\in \mathbb{R}[0, 1]$) maps at specific frequencies and excitation sources can be obtained as in Zanarini (2019a), to appreciate the spatial consistency & continuity of the data, with clean shapes, sharp nodal lines and excellent *Coherences*, especially from ESPI.

3. Deriving Strain & Stress FRFs from full-field receptances

The high quality of these *receptance FRF maps*, also obtainable from DIC, deserves further investigations for spatially derived quantities, starting from highly detailed strain FRF maps, towards combinations of stress FRF maps.

3.1. *Dynamic Strain FRFs*

By means of a robust differential operator (see in particular Zanarini (2022b)) on the *receptance map* $\mathbf{d}(x, y, j\omega)$ along *x & y* directions, the *full-field generalised strain FRFs* can be obtained in each map location and frequency line:

$$\varepsilon(x, y, j\omega)_{ik} = \frac{1}{2}\left(\frac{\partial \mathbf{d}(x, y, j\omega)_i}{\partial q_k} + \frac{\partial \mathbf{d}(x, y, j\omega)_k}{\partial q_i}\right), \tag{1}$$

as well as the *strain tensor* components due to out-of-plane bending-related displacements of the plate of thickness s:

$$\varepsilon(x, y, j\omega)_{xx_b} = -\frac{s}{2}\frac{\partial^2 \mathbf{d}(x, y, j\omega)_z}{\partial x^2},\ \varepsilon(x, y, j\omega)_{yy_b} = -\frac{s}{2}\frac{\partial^2 \mathbf{d}(x, y, j\omega)_z}{\partial y^2}, \gamma(x, y, j\omega)_{xy_b} = \gamma(x, y, j\omega)_{yx_b} = -s\frac{\partial^2 \mathbf{d}(x, y, j\omega)_z}{\partial x \partial y}. \tag{2}$$

Also the *Principal Strain FRF maps*, from both shakers, can be obtained at each frequency line of the domain, with a *complex-valued* data representation, to retain any phase relation: it becomes an impressively adherent characterisation of the experiment-based strain distribution over the sensed surface in spatial and frequency domains.

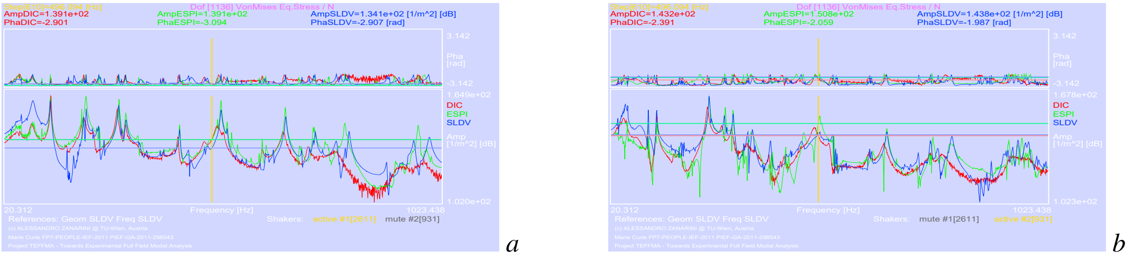

Figure 3. Examples of *von Mises equivalent stress FRF graphs* from optical techniques, direct experimental FRF models in the 20-1024 Hz range, DIC-ESPI-SLDV examples: from shaker 1 in *a*, from shaker 2 in *b*.

Figure 4. Examples of *white noise von Mises equivalent stress PSD* graphs from optical techniques, direct experimental FRF models in the 20-1024 Hz range, DIC-ESPI-SLDV examples: from shaker 1 in *a*, from shaker 2 in *b*.

3.2. Dynamic Stress FRFs

With the introduction of a constitutive model (linear isotropic here, for the aluminium sample in Fig.1*b*, with the following material parameters: E elastic modulus, ν Poisson ratio, G shear modulus, Λ Lamé constant), the *Stress FRF tensor* components can be evaluated from *Strain FRFs* in Eqs.1-2:

$$\begin{aligned}\sigma_\omega(x,y)_{ii} &= 2G\varepsilon_\omega(x,y)_{ii} + \Lambda\left(\varepsilon_\omega(x,y)_{xx} + \varepsilon_\omega(x,y)_{yy}\right);\\ \sigma_\omega(x,y)_{ij} &= 2G\varepsilon_\omega(x,y)_{ij}; G = E/2\,(1+\nu); \Lambda = E\nu/((1+\nu)\,(1-2\nu)).\end{aligned} \tag{3}$$

Therefore, with the constitutive model of any specific material (anisotropic and locally linearised included), also the *experiment-based Principal Stress FRF maps* can be evaluated from the *full-field receptance* $\mathbf{d}(x, y, j\omega)$.

4. Cumulative damage & fatigue life assessment by means of spectral methods

With such a broad set of detailed *experiment-based Stress FRF maps*, we can evaluate cumulative damage with the *spectral methods* for high cycles fatigue in every dof of the sensed surface, with *unprecedented mapping abilities*. A spectral method targets the evaluation of an *equivalent range of stress cycles* $S_{eq}(x, y)$, in each location (x, y) of the *experiment-based Stress FRF maps*, representative of the damage inferred by the whole spectrum of the airborne retrieved structural force on all the locations of the sensed surface. The notation (x, y) is used for the spatial extension to maps.

Many *spectral methods* are based on $m_k = \int_0^\infty f^k PSD_{VM}(\omega)d\omega$, the *k-th order moments* of the frequency by the *power spectral density (PSD)* of *von Mises equivalent stress* $PSD_{VM}(\omega)$, from which other parameters can be obtained, such as the *effective frequency* $F_{zerocrossing} = F_{zc} = \sqrt{m_2/m_0}$, the *expected number of peaks per unit time* $F_{peaks} = F_p = \sqrt{m_4/m_2}$, and the *irregularity factor* $\gamma = \gamma_2 = F_{zc}/F_p = m_2/\sqrt{m_0 m_4}$.

4.1. The role of von Mises equivalent stress FRFs from optical techniques

The *PSD of von Mises equivalent stress* is crucial and evaluated from the *von Mises equivalent stress FRFs* and respective excitations, here rendered in the maps at a single frequency in Fig.2 and in single dof graphs of Fig.3, from both shakers (here white noise excitation). Instead, the retrieved (in Part A) airborne structural force of Fig.5 has quite

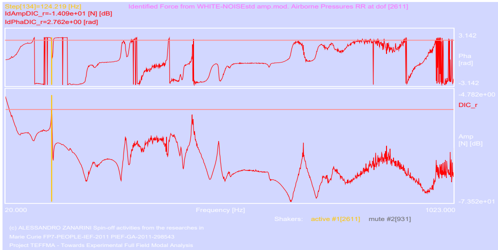

Figure 5. The *identified force* graph in the frequency domain, evaluated as force in shaker 1 from the whole airborne acoustic pressure field.

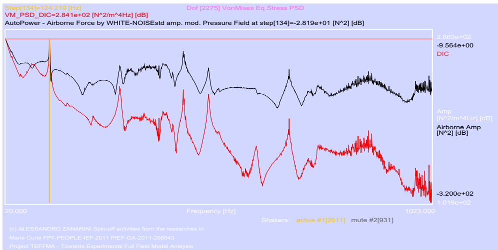

Figure 6. Example of a *von Mises equivalent stress PSD* and of the airborne excitation auto-power from the *identified force* graph in the frequency domain, evaluated as force in shaker 1 from the whole airborne acoustic pressure field.

a diversified spectrum, with the specific output as in Fig.6. Note that the *experiment-based full-field stress FRFs*, with their *principal components*, are usable with any fatigue spectral method (see e.g. Dirlik and Benasciutti (2021)), in particular those that retain the phase relations in the frequency domain, for further comparative works.

4.2. *Dirlik semi-empirical spectral method parameters*

Among the many available (see Dirlik and Benasciutti (2021); Zorman et al. (2023)), the *Dirlik semi-empirical spectral method* in Dirlik (1985) was here implemented, as it gives a sound prediction of the fatigue life for wide-frequency-band spectra of stress responses, combining the factors in Eq.4:

$$\begin{aligned} &\chi_m = (m_1/m_0)\,(m_2/m_4)^{1/2}\,; D_1 = 2\left(\chi_m - \gamma^2\right)/\left(1+\gamma^2\right); R = \left(\gamma - \chi_m - D_1^2\right)/\left(1-\gamma - D_1 + D_1^2\right) \\ &D_2 = \left(1-\gamma-D_1+D_1^2\right)/\left(1-R\right); D_3 = 1 - D_1 - D_2; Q = 1.25\left(\gamma - D_3 - D_2 R\right)/D_1; \end{aligned} \tag{4}$$

to finally obtain, in each location (x, y), the *Equivalent Range of Stress Cycles* S_{eq} raised to b exponent

$$S_{eq}^b = D_1(2\sqrt{m_0}Q)^b\Gamma(b+1) + (2^{3/2}\sqrt{m_0})^b\Gamma(1+b/2)[D_2R^b + D_3], \tag{5}$$

the *Time-to-Failure spatial distribution* $T_{failure}(x, y)$, and the *Frequency-to-failure distribution* $F_{failure}(x, y)$, respectively evaluated across all the dofs (x, y) of the maps, function of $S_{eq}(x, y)$, of $F_p(x, y)$ and of the K_r fatigue strength coefficient and b exponent, as:

$$T_{failure}(x,y) = K_r/\left[F_p(x,y)S_{eq}^b(x,y)\right], \qquad F_{failure}(x,y) = \left[F_p(x,y)S_{eq}^b(x,y)\right]/K_r. \tag{6}$$

4.3. *Airborne frequency-to-failure mapping*

As already shown in Zanarini (2018, 2022c,a, 2023c, 2024b,c, 2025d), the *von Mises equivalent stress PSDs* are linked, through the *stress FRFs*, to the specific *excitation signature* and *energy injection point* (or shaker). This time the structural excitation is retrieved from the specific airborne pressure fields, as obtained in Part A and reported in Fig.5. Therefore, changing the airborne pressure fields brings different *von Mises equivalent stress PSDs*, thus *Time-to-Failure* or *Frequency-to-failure spatial distributions* in Eq.6.

In the examples of Fig.7 it is displayed the right part of Eq.6, to obtain the *Frequency-to-failure distribution*, showing where the component will be more prone to failure, given such an airborne induced structural force. By moving the location of the magenta dof, the information about the relative position in the *Frequency-to-failure map* can be obtained, and eventually linked, by a *Risk Index*, to a map of defects found by NDTs or other approaches (see Oliveira et al. (2022); Araújo dos Santos and Lopes (2024), therefore stating if a potential defect is tolerable or not, with clear safety repercussions in production or exercise. Note that by changing the airborne pressure field patterns leads to completely different *Frequency-to-failure maps*, due to the changed emphasis on the broad frequency band airborne induced contributions. This to underline the effectiveness of *full-field FRF based frequency-to-failure mapping*: it is sufficient to change the *dynamic signature* of the airborne excitation, and its location, to understand how the problematic areas on the sample can change.

The *damage location assessment* on real components may play a relevant role under the *defect tolerance strategies*. The chosen dof in Fig.7 below was just a virtual example for considerations, but the same ESPI-based *NDT* shown in Zanarini (2022f) may give a *real defect distribution map*, which can be the input in *Frequency-to-failure maps*, here obtained by DIC full-field dynamic testing (ESPI in Zanarini (2022e)), both for production & exercise of the parts. In this coupled strategy, the real location of the defect on the map can tell if it can be accepted or not, in manufacturing or exercise, once the real structural dynamics and airborne excitation signature are fully known without simplifications.

5. Conclusions

This brief paper has shown how a methodologically sound *airborne fatigue life assessment* can be run also on *DIC-based full-field FRFs*, which have less restraints than those from the ESPI approach. It was therefore possible to run the accurate evaluation of *Strain FRF maps*, of *Stress & von Mises equivalent stress FRF maps* with proper constitutive models, of *von Mises PSDs* directly from *experimental DIC-based full-field FRFs* and the retrieved airborne induced structural force, of the *fatigue life predictions* by means of *spectral methods*, to grade the dangerous location of starting fatigue cracks due to airborne pressure fields, once the real dynamic behaviour is fully retained and not simplified.

Experimental optical full-field measurement techniques, also in the DIC variant, are becoming mature & reliable for an *airborne fatigue life assessment* in production and working conditions, because of their ability to retain a refined and dense structural dynamics in both the frequency and spatial domain, directly from real samples and without any FE model to be carefully updated in the whole frequency domain.

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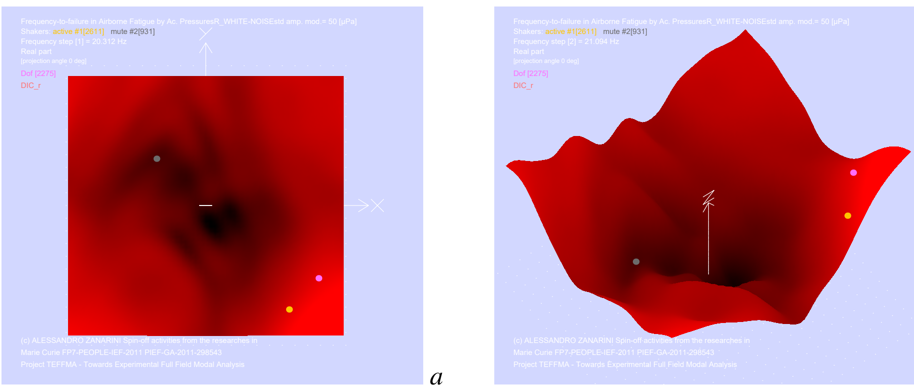

a *b*

Figure 7. The *Frequency-to-failure distribution* of the sample, due to *airborne pressure fields* in shaker 1: top view in *a*, 3D view in *b*.

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