The TRChallenge – Experimental quantification of nonlinear modal parameters and confrontation with the predictions

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ABSTRACT
In recent years, the prediction of the behavior of structures with high-level nonlinearities has been a challenging area of research. In 2021, the Tribomechadynamics Research Challenge was proposed to evaluate the current state of the art in modelling in the community of jointed structures: the task was a blind prediction of the nonlinear dynamic response of a system including a frictional and a geometric nonlinearity. Participants of the challenge were given only the technical drawings, including material and surface specifications required to manufacture and assemble the system and were asked to predict the frequency and damping ratio of the lowest-frequency elastic mode as function of the amplitude. The behavior of the real system was experimentally characterized during the Tribomechadynamics Research Camp 2022. This contribution presents the experimental work performed during the research camp. As the nature of the structure requires a base excitation, two recently developed nonlinear testing techniques have been explored to extract the modal parameters: the response-controlled testing method and the phase-resonant testing method. The results obtained with the different methods are compared and the blind predictions are confronted with the experimental results in order to assess their accuracy.

Keywords: Frictional and geometric non-linearity, backbone curve, Phased-Locked-Loop, Tribomechadynamics.

INTRODUCTION

The benchmark structure of the Tribomechadynamics Research Challenge 2021 [1] consists of a thin plate, called panel, which is mounted between two pillars of a support structure and two blades via six M5 bolts and washers on each side. The contact between panel, blade and support is expected to introduce contact nonlinearity and friction damping. The panel has a thickness of 1.5 mm and is arched by an angle of 2° since the contact surfaces of the pillars are misaligned. The preload is expected to introduce geometric nonlinearity in the form of bending-stretching coupling. Thin curved panels are widely used in aircraft, space, and wind turbine industries to achieve high strength-to-weight ratios. However, these slender structures are subjected to geometric and frictional nonlinearities because of large deformation and mechanical fasteners. The participants of the research challenge (Tab. 1) were provided with a CAD model and technical drawings of the system, including material and surface specifications. The participants had the total freedom to chose between different approaches and analysis to model the given system. This led to a wide variation of assumptions and methods used in the different models performed. A significant discrepancy is found in the predictions of the modal properties on the center point of the panel. The linear natural frequency predictions varies from 65 Hz to 120 Hz. The variation of the natural frequency of the lowest-frequency elastic mode does not follow the same trend for the different predictions: some groups predict no evolution, other results show a significant frequency decrease (−20 %, softening of the structure) followed by a frequency increase (hardening, up to 20 %) and a purely hardening behavior of the structure of approximately 75 % was also obtained. The amplitude-dependent damping ratios shows a variation of several orders of magnitude between the different predictions ranging from 0.003 % up to approximately 1 %.

The aim of this work is to identify the actual behavior of the manufactured structure, so that the modeling results can be put into context and potential model updating can take place in the future. The nature of the structure makes it necessary to provide the dynamic loading in the form of base excitation via a large shaker. Thus, the excitation forces cannot be directly measured, which makes it impossible to quantify the damping directly from backbone curves. Therefore, two recently developed nonlinear testing techniques are used to extract the amplitude-dependent modal properties of the system: the Response-Controlled Testing (RCT) method and the phase-resonant testing method. A validation of the linearized modal basis is performed by comparing the results of low-amplitude tests with the results of random vibration tests. The amplitude-dependent modal parameters obtained by both test methods are compared to each other and to the blind predictions.

Table 1: Research groups that participated in the Tribomechadynamics Research Challenge in 2021.

Research group	Abreviation	References
Brigham Young University/the University of Wisconsin-Madison	(BYU/ UW)	[2]
University of Erlangen-Nuremberg Germany	(FAU)	
Imperial College London	(ICL)	[3]
Northwestern Polytechnical University China	(NWPU)	
Sandia National Laboratories USASU	(SNL)	
Swansea University UK	(SU)	
University of Stuttgart	(USTUTT)	

EXPERIMENTAL SETUP AND TEST STRATEGIES

The support structure is connected to a shaker table and the system is tested under base excitation. A differential Laser Doppler Vibrometer (LDV) is considered to measure the relative velocity at the center of the panel with respect to the left blade. The base velocity is measured using an additional LDV pointed to the right blade. These sensors are specifically used for controlling excitation and response signals.In addition a Multi-Point Vibrometer (MPV) is used to acquire velocity measurements from different locations along the support and the panel. A set of 15 points positioned in a 5×3 grid on the surface of the plate is considered as shown in Fig. 1. The dynamic behavior of the structure is evaluated based on the MPV measurement data.

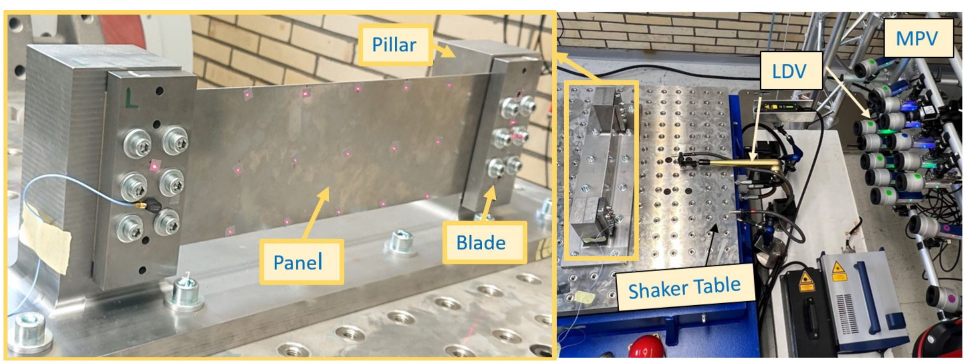
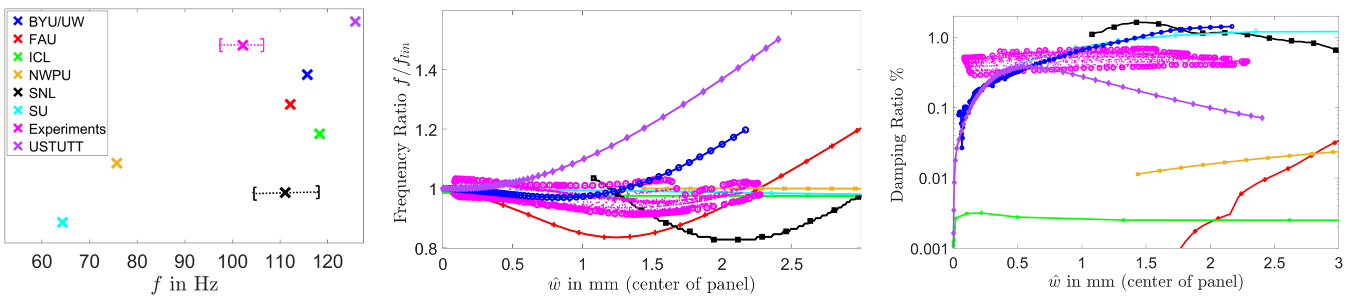


Figure 1: Experimental setup: (a) different parts of the dynamic system, (b) components of the setup.

Different experimental techniques are applied to the test structure to quantify the impact of the frictional and geometric nonlinearity. Initially, a validation of the linearized modal basis is performed. Therefore, the linear responses of the structure for small vibration levels obtained by random tests and by the different testing strategies are compared. Afterwards, the nonlinear behavior around the first resonance mode at higher vibration levels is investigated. The Response-Controlled Testing (RCT) method [4] is used to obtain quasi-linear responses of the structure for a controlled displacement of the panel center with respect to the support structure. The phase lag between excitation and response is stepped from 75° to 105°, maintaining constant response amplitude. The quasi-linear frequency response curves generated from steady state solution are used to find frequency and damping using Circle Fit Method. These results are compared to the phase-resonant testing method. The backbone curve is tracked using a Phased-Locked-Loop (PLL) controller in order to extract the amplitude-dependent frequency and damping. During PLL tests, the shaker voltage is stepped, maintaining constant phase lag of 90° to generate the backbone curve. The damping ratio is determined by a model-free approach from the balance of supplied and dissipated power in the system [5]. Repeatability tests are carried out to ensure the robustness of the measurements. Finally, the experimentally extracted amplitude-dependent natural frequencies and damping are compared to each other, and the results are compared to the model predictions, carried out by the different research groups in the context of the 2021 Tribomechadynamics Research Challenge.

RESULTS

The linear response obtained from a random vibration tests with small vibration amplitudes showed a good agreement with results obtained from RCT and PLL testing at lower vibration amplitudes. Furthermore, the RCT results are comprised in the uncertainty interval of the PLL results for most of the tested cases up to a displacement amplitude of 2.1 mm. Fig. 2 shows a comparison between the experimental results obtained by PLL (pink) and the predictions.The SNL predictions show a good agreement with the experimental linear natural frequency (f_{lin}) results as shown in Fig. 2a. Figure 2b shows the evolution of the normalized natural frequency of the first resonance mode (f/f_{lin}) with the relative displacement at the center of the panel ($\hat{\omega}$). The experimental results identified a softening then a hardening behavior of the structure. A similar trend was obtained by the predictions from SNL, BYU/ UW and FAU teams. However, the variation of the frequency is higher in the predictions (0.8 to 1.2) than in the experiments (0.95 to 1.05). The experimentally obtained damping ratios, shown in Fig. 2c, is comprised between 0.2 % and 0.7 % and increases with $\hat{w}$. Concerning the predicted outcomes, the results of four groups are in the same order of magnitude (SNL) and within the uncertainty interval of the measurement results (SU, USTUTT, BYU/UW). The different nonlinear testing approaches work well for small to medium displacement amplitudes. Amplitudes higher than 2.1 mm were not tested because of difficulty to control, stresses exceeding elastic regime, temperature sensitivity and limitation of the MPV measurement range.



(a) Linear Frequency

(b) Amplitude Dependent Frequency

(c) Amplitude Dependent Damping

Figure 2: Modal properties of first resonance mode: (a) linear natural frequency f_{lin}, (b) normalized natural frequency f/f_{lin} vs. displacement amplitude $\hat{\omega}$, (c) damping ratio vs. displacement amplitude $\hat{\omega}$

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CONCLUSION

The results of the work show that the two different nonlinear testing approaches, RCT and PLL, allow to extract the modal parameters of a structure under base excitation. The experimental results allow to confront the different predictions to the behavior of the real structure as a follow-up to the 2021 Tribomechadynamics Research Challenge.

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