WP3: *Dynamic load and response analysis of nonlinear assemblies*. Lead: Schwingshackl at Imperial College

Overview.

This theme will provide the fundamental understanding of the nonlinear vibration transmission in fully assembled aero-engines. Current research is strongly focused on individual components and localised nonlinear sub-assemblies, but for engine design optimisation, realistic life predictions, effective vibration control, and structural health monitoring applications a detailed understanding of the global nonlinear dynamic response is required.

The background and motivation. The dynamic behaviour of a structure can strongly influence the functional performance, potentially leading to reduced efficiency, disruption in operation, discomfort, reduced accuracy, or even temporary or permanent malfunction of the system. This has led to decades of research in structural dynamics, leading to reliable experimental and analytical techniques at component level. The application of these linear techniques to fully assembled structures led to the realisation that the assembly was more than its individual linear components, and that the nonlinear behaviour at the interfaces had to be considered as well. This led to a strong interest in the nonlinear dynamic behaviour with a particular focus on small subassemblies (eg. blade root damping, under platform dampers, bolted joints) due to the complexity of the problem. The restriction of the dynamic analysis to linear or small scale nonlinear vibration problems presents a significant limitation for the current design of aero engine leading to the requirement of lengthy and expensive engine certification tests. New materials (composites, CMC), different transmission systems (gear box), and future electric and distributed propulsion concepts will increase the nonlinear coupling between the individual structural components, requiring a strongly improved understanding of the nonlinear dynamic behaviour of the entire assembly.

The dynamic response of the full assembly is dependent on a large range of factors, such as different types of excitation (aero, out of balance, gear box, electrical), a multitude of linear structural components, and a variety of interfaces (bearings, squeeze film dampers, frictional joints, electromagnetic interaction), which together lead to a coupled nonlinear vibration behaviour. The strong nonlinear interaction of a large numbers of individual components and the resulting vibration energy distribution in the system is currently not well understood, and the main objective of this research theme is the **fundamental understanding of the nonlinear vibration energy transmission and its active and passive exploitation in large assembled structures** to ensure reliable future aero-engine development.

Distributed vibration monitoring. The linear vibration behaviour of aero engines has been investigated over decades leading to the development of advanced excitation systems [CWS#22] (electromagnetic shakers, air jets), full filed measurement techniques [CWS#2] (Scanning LDV, high speed camera, blade tip timing) and efficient analysis approaches [CWS#15] (multi-input multi-output modal analysis (MIMO)). These techniques are regularly used to identify the dynamics of individual components and large linear assemblies (eg. MIMO testing of aircraft fuselage), and are now increasingly expanded to nonlinear dynamic experimentation [1, CWS#8] to provide additional insight and understanding. Nonlinear dynamic analysis is currently being developed [2], but is still very much focused on individual sub-assemblies, such as under platform dampers [CWS#20] (see Fig. 1), blade roots, or a bolted joint [3, CWS#22], to provide the understanding of the individual interface. Recent research efforts at the Vibration UTC in cross-shaft coupling and bladed-disk shaft interaction (see Fig.2) is considering slightly larger subassembly levels but it still leaves a large gap between current understanding and operational vibration from an engine certification test. The latter provides realistic engine data, but a limited amount of sensors, a hostile measurement environment, an often unknown excitation source, and shortcomings in the data analysis lead to rather limited dynamic

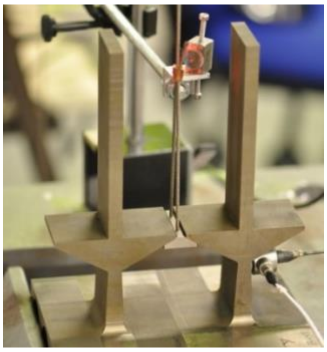

Figure 1 Under Platform Damper test rig at Imperial College

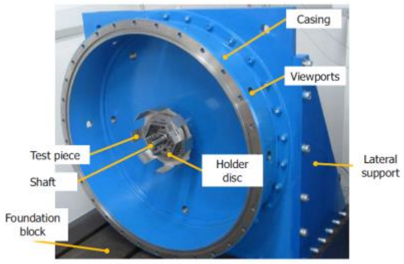

Figure 2 Rotating test rig with MIMO strain modal analysis

information of the whole system. Recent attempts to identify nonlinear dynamic behaviour from large assembled structures [4, CWS#12] has further highlighted the necessity for a better fundamental understanding of the vibration energy distribution inside the engine. To obtain this information a targeted and accurate excitation of the full assembly, simultaneous capture of the vibration response across the engine and efficient analysis of large amounts of data will be required.

Main elements of work.

Task 1 (month 1-3) will focus on a state of the art review on experimental nonlinear vibration measurements, with a special focus on full assembly testing. In parallel, **Task 2** (month 1-8) will install an appropriate fully assembled test structure in the vibration laboratory at Imperial, to provide a realistic vibration environment. **Task 3** (month 8-18) will develop a new test methodology for a distributed excitation to mimic an operational vibration environment. A mixture of high voltage piezoelectric patches, electromagnets, electromagnetic shakers and magnetic bearings (Nottingham) will be used to create a unique distributed excitation network for large scale multi input excitation. Analytic models of the different exciter systems will be developed and included in a control system allow the generation of a multitude of localised and distributed excitation patterns. **Task 4** (month 18-30) will introduce a detailed sensor network to map the nonlinear vibration energy in the rotating and stationary frame. Nonlinear test planning will be used to identify the best combination and location of strain gauge arrays, blade tip timing, 3D Scanning LDV technology, high speed cameras, ultrasonic sensors, proximity probes, ..., to capture the vibration environment throughout the engine simultaneously. Processing this unprecedented amount of nonlinear dynamic information poses a significant challenge which will be addressed in the central **Task 5** (month 3-26). A new data processing frame work will be developed, that combines dynamic analysis methodology such as multi-input multi-output, sub-structuring, model reduction, complex nonlinear modes and nonlinear identification with modern data analysis approaches based on neural networks, statistic data analysis and data compression. The system will decide which data is required at full sampling rate, which can be compressed and to what level, and what data is redundant to reduce the data to less than 10% of the original volume. **Task 6** (month 26-36) will use the developed technology for a highly detailed multi-input multi-output test of the assembled structure to generate a nonlinear vibration energy map of the entire system. This data will provide the required fundamental understanding of the vibration energy distribution in a complex system and help identifying the crucial components in the vibration path. It will form the basis for the envisioned second stages of the program, which will focus on the development of nonlinear dynamic modelling techniques for the full assembly and strategies to optimise the vibration response via passive and active vibration control (nonlinear damping, piezo control).

Overlaps with other parts of the programme.

There will be strong interaction of Task 3 with Nottingham on rotor dynamic excitation and control. Oxford's (WP2) expertise in measuring interface conditions during vibrations with the help of high speed cameras will be used for Task 4. Further overlaps occur in the later modelling stages of the program, where collaborations with project WP1, WP4 and WP6 will support the nonlinear model development of the whole engine.

Interactions with other Universities.

Work conducted at the University of Bristol on large nonlinear structural vibration testing and scanning LDV techniques, and large scale vibration data analysis from Virginia Tech, will be highly useful in the development of the distributed nonlinear vibration testing techniques for the assembled structures.

[1] Butlin, T., Woodhouse, J., Champneys, A.R., 'The landscape of nonlinear structural dynamics: an Introduction', Proceedings of The Royal Society, 2015
[2] Neild, S.A., Champneys A.R., Wagg D.J., Hill T.L. & Cammarano A 'The use of normal forms for analysing nonlinear mechanical vibrations'. Philosophical Transactions of the Royal Society (2015)
[3] Carri, A, Weekes, B, Di Maio, D & Ewins, D, 'Extending modal testing technology for model validation of engineering structures with sparse nonlinearities: A first case study'. MSSP, 2016.
[4] Baldacchino, T., Cross, E.J., Worden, K. , Rowson, J., 'Variational Bayesian mixture of experts models and sensitivity analysis for nonlinear dynamical systems', MSSP, 2016.