WP1: *Power-dense Contacts*. Leads: Hills & Nowell at Oxford.

Overview. This technical pillar represents a fundamental, experimentally calibrated but rigorous procedure for designing against fretting fatigue damage, as well as understanding, quantitatively, frictional damping, in all stationary contacts.

Background and motivation. Joint abound in a gas turbine, and although they are stationary, there is almost always some slip present, and that acts in opposing ways: one the one hand, it provides vibrational *damping* (see below), but, at the same time, it provides the right conditions to start off fatigue cracks. Fatigue is one of the more common forms of failure (although remote) in several elements of a gas turbine. Fir-tree roots (turbine), dovetail roots (fan, Figure 1) and shaft splines fatigue cracks have in the past been sources of concern. The *propagation* of cracks is well understood. Laboratory tests are used to determine the correlation between crack propagation rate and the stress intensity factor. What is found in the experiment is a material property, and the results may be applied with confidence to a crack of any geometry and in a component of any geometry, made from the same material.

However it is not the propagation of cracks which often consumes most of the component life, it is nucleation. Crack nucleation remains a very poorly understood phenomenon. What is needed is a procedure analogous to that used for propagation, but applicable to the nucleation of cracks from contact edges. **We have such a procedure in part-complete form**, and partially experimentally tested out [DAH1]. The stress intensity factor vs. propagation rate correlation works well because the former is the multiplier on a completely self-contained and precise eigensolution describing fully the state of stress at the crack-tip. A similar kind of analysis may be applied to contact edges, and the local state of stress, including the effects of frictional slip, has been found, and a quantity analogous to the crack-tip stress intensity factor, defined. These generalised stress intensity factors include size information about the contact, and control the rate of nucleation as well as an infinite life threshold.

Next Steps: The analysis of these problems has reached the stage where we have confidence in its correctness, and is fully worked out for the cases where the normal load on the contact is constant. Further, the process has been used to re-analyse historical fretting fatigue data and has been shown to collapse data well [DAH#1], and to define a threshold condition. So far, almost all of these results have been found for an aluminium alloy which has little relevance to gas turbines.

A new experimental apparatus is to be built to permit complicated, realistic loading (flight) cycles to be represented faithfully in the laboratory. It is important to emphasize that this philosophy means that the experiment will reveal material properties which can then be used to predict the strength of *any* contacts, and it therefore represents a real step in the streamlining of design procedures, No longer will it be necessary to test prototypical components, in just the same way as the crack propagation rate data have evolved. This new apparatus will build on >30 years of previous experience of developing fretting fatigue test apparatus, but incorporating extra features, requiring four servo-hydraulic actuators. Fretting fatigue tests will be carried out on titanium-6Al-4V, super CMV and nickel alloys (eg CMSX4) being representative of the fanblade dovetail root, main shafts and turbine firtrees respectively. These tests will establish threshold conditions and will also investigate the effectives of surface treatments and palliatives, although the goal will always be to eliminate these where possible, as they are both expensive to use and require repeat application, thereby adding to the service burden on the engine. Predictions of component lives made at Oxford will be tested, practically, in the scaled-spline apparatus used at

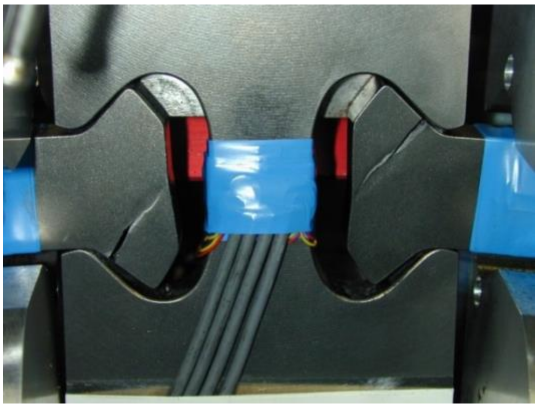

Figure 1 Fanblade root cracks laboratory experiment

Nottingham UTC. Prelimary tests on composite fanblade roots have already been conducted at Oxford using DIC to measure slip displacement, and further work on this material with evolving root geometries will be carried out. Further theoretical work to expand on our evolving understanding of realistic partial slip contact problems [DAH#2], [DAH#3] is also needed, to permit more realistic loading histories to be modelled.

A quantified understanding of fretting and contact damage is very important for Rolls-Royce at the moment. Its new engine architectures implies that contacts will be loaded more heavily than ever before. This is especially true in the transmission shafts of *Advance3* and *UltraFan* engines (Fig. 2 of CfS) and in the longer term, will apply equally to all blade root contacts which also evolve to minimise weight, so that contact conditions are increasingly severe. **Interface Modelling and Validation for Improved System Performance.** It is now relatively straightforward to predict the dynamic performance of a single component to a very high degree of accuracy, but the same cannot be said of complex assemblies such as those comprising gas turbines. Contact interfaces between components introduce localise stress and may contribute to crack nucleation, but they also additional compliance and damping, which affects both resonant frequencies and has the beneficial effect of reducing response amplitudes. Numerous aspects of this are important for future aircraft engines: (a) the need to predict performance at the design stage, (b) the need to understand effects of assembly order, (c) the need to understand effects of surface topography evolution. Hence there is a clear need for improved models of frictional interfaces which would allow (i) better understanding of existing joints, including the evolution of behaviour with time, and (ii) improved design of joints in a holistic manner, to make them more deterministic, and to optimise the joints through understanding dynamics, structural integrity, and wear of the interface.

This requires an interdisciplinary approach, including elements of; dynamics, contact mechanics, and tribology. The UTCs at Oxford, Imperial, and Nottingham are ideally placed to make a major contribution in this area, based on their existing understanding and facilities and on a proven track record of collaborative research. Recent projects have run on fretting fatigue/fretting wear (EPSRC: Nottingham/Oxford) and on friction measurement and modelling (EPSRC: Oxford/Imperial). Current work supported by Rolls-Royce is taking place in the area of wear (Oxford/Nottingham) and contact stiffness (Imperial/Oxford).

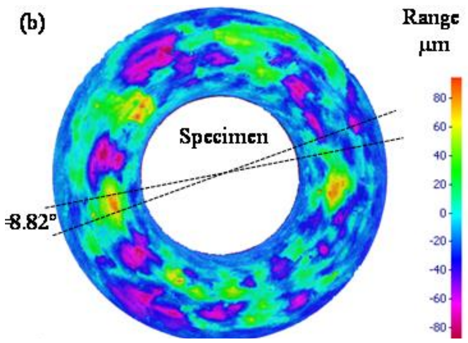

Figure 1 Surface characterisation

The proposed work will involve all three UTCs in developing and validating improved models of frictional joints. At Oxford, work will take place at both micro- and macro- scales, Figure 2. Existing DIC techniques will be employed on images collected at a range of length scales, including from experiments carried out in the scanning electron microscope [DN1]. This will involve the development of new rigs, capable of providing the required contact loads in-situ. In parallel with the experimental work, existing asperity scale models will be developed and used as the basis for a macro-scale model of contact stiffness, which will be validated using the experimental results.

Main Elements of Work Early tasks: Task #1 (months 1-6) Design new test apparatus and procure controllers/actuators. Task #2 (months 1-12) Extend range of partial slip contact solutions to reveal damping characteristics and match to engine flight cycles. Task #3 (months 1-11). Develop micro positioning apparatus for Alicona Task #4 (months 6-14) Construct and commission new test apparatus. Task #5 (months 14-30) carry out initial fretting fatigue tests and use to calibrate nucleation life for material 1 (super CMV). Task 6 (months 11-30) Make specimens and measure evolving tangential stiffness in existing apparatus. Examine surfaces.

[DN1] Nowell, D., Mulvihill, D.M., Parel, K., and Paynter, R.J., 'Measurement and modelling of contact stiffness for rough contacts, Proc 42nd Leeds-Lyon Symposium on Tribology, Lyon, Sept 7-9 2015.