WP2: *Impact and Intelligent Failure Management.* Lead: Petrinic, Oxford

Overview. This technical pillar focuses on the fundamental aspects of impact generated by rapid rebalancing of energy and momentum possessed by power-dense new-generation of large civil aviation gas turbine engines induced externally (by ingesting foreign objects) or internally (due to process or component failures). Thus generated rates of strain in the bulk of underlying materials and the rates of relative displacement along their contact interfaces, ultimately, exceed considerably those in normal operations comprised of vibrations responsible for fatigue and wear. However, their transient characteristics can be very similar, which offers opportunities for development of bespoke experimental setups capable of simulating, in controlled laboratory environment, the extreme as well as common in-service conditions characterised by interactions and sequences of non-linear physical phenomena, otherwise commonly simulated in separate experiments, without offering clear understanding on their spatial or temporal interactions. The corresponding development of proposed new predictive modelling capability is key to gaining the understanding required to design airworthy and reliable future power-dense systems also readily found in different incarnations within the defence sector, as the most important other beneficiary of the proposed research.

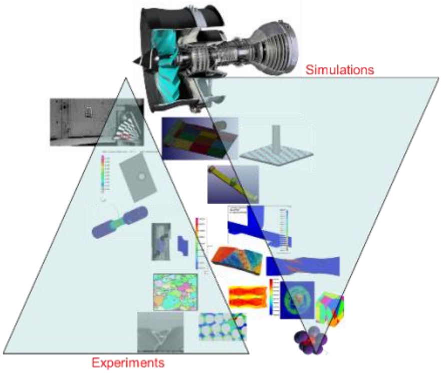
The background and motivation. In addition to the more frequent than commonly known, major impact events (bird strike or fan blade containment), a number of small scale rapid interactions occurs during nearly every flight cycle (blade tip rubbing), or even during every rotation (geometric interaction of contact assemblies). When combined with relevant rapidly changed thermal (as well as magnetic, in the case of electro-mechanical actuators) conditions, the challenge of developing the corresponding predictive modelling design tools (material selection, topology and shape/size optimisation, stress analysis), gains the *multi-physics* and *multi-scale* attributes.

The main focus of this work is relevant to designers who require validated tools capable of simulating the behaviour of advanced materials and systems subjected to impact loading, across a wide spectrum of magnitudes, from small ones (causing just incremental deterioration in material performance), to major ones (resulting in large energy and momentum rebalancing that lead to catastrophic loss of integrity of individual components or the system as a whole). The ability to address a range of novel material systems, from fibre reinforced polymer matrix systems, via a range of metallic and cermet systems to ceramic matrix composites, as well as their joining into inevitably hybridised components and structures is at the core of this proposal. The corresponding academic challenges, on the experimental side, range from the ability to apply (rapidly) the representative thermo-magneto-mechanical loads through to the ability to observe and measure the responses of materials and their joints under consideration [NP#7, NP#8]. On the modelling side, the key related challenge is in the ability to conduct multi-physics and concurrent multi-scale computations capable of simulating non-linear material responses leading to strain localisation and fracture, only where needed and when needed within the domain during the computation. The objective of this research to is to enable simulations of relevant phenomena at the corresponding length scale [NP#16, NP#17, NP#20], concurrently, i.e. without having to perform many separate computations or analyse sub-models in isolation at the risk of not being able to furbish them with correct initial and/or boundary conditions.

The proposed fundamental research objectives are expected to amount to the unique capability to address advanced design topics such as that of force-fusing of significant sub-systems (e.g. large hybrid fan) when the rapid rebalance of the respective potential and kinetic energies and momentums threatens to cause catastrophic loss of integrity of the whole power-dense engineering system under consideration. The nature of such ultimate exploitation aims and the cumulative complexity of required experimental support and related modelling capability calls for collaborative engagement and cross-disciplinary understanding of related physical phenomena, as proposed here. The proposed development must also be fit to generate data and methodologies which, in this context, must align with principles of *Digital Materials* for *Digital Design* within *Industry 4.0* in order to actually make the required exploitation impact.

The proposed collaborative activity is envisaged to complement a set of projects (DYNAPIN-EP/M012905/1, PROFILE-ATI/113078, DELICE-ATI/113106, UNICAM2-DSTL/AGR/00507/01) addressing detailed mechanical performance of several classes of advanced materials as candidates for significant improvement of the performance of future power-dense engineering systems (such as gas turbine engines and structural armour) thus making it timely and offering even greater potential to make significant impact as it would provide deeper fundamental underpinning as well as the platform for integration of individual outcomes of other projects.

Core proposed development. Task #1: Assessment of force fusing requirements in aircraft engines (months 1-3): This task is expected to provide the understanding of the challenge posed upon the designers who need to force-fuse sub-systems when their relative motion become incompatible and threatens to cause catastrophic failure of the system as a whole. Understanding the descriptions of these incompatibilities and criteria for force-fusing are the expected outcomes. Task #2: Design of new experimental setups (months 1-9): The analysis of force fusing challenge with emphasis on vibration characteristics and on options of controlled material failure will lead to the design of experimental setups. Two key rigs will be built to establish the foundations for controlled laboratory simulations of key physical phenomena. Firstly, a spin rig which should provide the platform for studying relevant vibration characteristics of progressively damaged rotors and for quantification of proposed criteria for force-fusing. Secondly, two types of rigs capable of generating impact (rapidly rising mechanical) loading by colliding solid projectiles or through fluid-structure interaction (gas gun . shock tube) and by pulse laser ablation. A number of sub-rigs will be built in order to hold the specimen or systems under investigation, such that the same setups could be quickly dismantled and rebuilt in other laboratories (Oxford Physics Department, Oxford-Harwell, Imperial College or Nottingham), thus promoting further the desire to execute a number of different experiments by sharing rigs aimed at the same range of applications. At least three journal papers are expected to be generated as a result of activities comprised within this task. Task #3: Experimental activities (months 4-36): This work will be divided into two main streams. Firstly, material characterisation experiments, mostly at length scales up to the size of typical Representative Volume Element of materials under consideration. Secondly, structural experiments will be carried out to study the motion and thus generated forces. Journal papers focused on controlled fracture processes are expected to result from this work. Task #4: Development of new numerical simulation tools (months 7:48): The work in this task will draw specific constitutive and cohesive relations from other parallel research projects thus allowing the focus here to be placed on concurrent multi-scale (and multi-physics, as the next level of desired detailed analysis features). This will provide the bridge between detailed small scale analysis and holistic (e.g. Whole Engine Modelling) calculations. Task #5: Development of Digital Materials and Digital Design tools (months 10-60): The significant exploitation route and thus created impact is expected by establishing the database of experimental results and corresponding numerical simulations which are going to reduce (if not completely remove) the possibility of introducing human errors at all stages of calibration and validation of design tools.



Overall, in addition to already mentioned expected journal papers, two doctoral theses and two rigs (spin, gas gun) established strong access routes to in-house and national facilities (pulse laser ablation) and a number of portable experimental fixtures will be delivered. Education and development value of the project is expected to be demonstrated through graduation of two doctoral students and promotion of two postdoctoral research associates and one tenure track faculty position.

Interactions with other technical pillars. Interaction with the Imperial-led WP3 is and Nottingham-led WP6 will focus on understanding and quantification of non-linear vibrations comprising small-scale impact events and on post impact vibration as well as on quantification of material behaviour during transient phases of impact and vibration loading by combining detailed numerical modelling with experimentation relying upon ultra-high speed photography and high-frequency 3D laser vibrometry. Similarly, the interaction with Nottingham-led WP5 will provide the platform for development of better understanding of thermal (particularly adiabatic) characteristics of earmarked advanced materials under consideration, while the joint development of numerical algorithms for processing high power-density contacts, in the context of concurrent multi-scale analysis, will be carried out with Oxford-led WP1.

Interactions with other Universities. Important existing relevant concurrent joint research carried out with UTCs in Bristol (on through-thickness reinforcement of carbon fibre polymer matrix reinforced composite laminates) and in Swansea (on ductile Titanium alloys), as well as with Imperial College (on rate dependent behaviour of adhesively bonded joints of dissimilar materials) and with Cambridge (on comminution processes in impact loaded ceramics for armour) will be incorporated wherever possible to complement the proposed research and prevent duplication.