Institution: University of Liverpool

Unit of Assessment: 15 – General Engineering

a. Overview

Since RAE2008, the School of Engineering, within the Faculty of Science and Engineering, has been reorganised into three Research Centres: the Centre for Engineering Dynamics (CED), Centre for Materials and Structures (CMS) and Centre for Engineering Sustainability (CES). These Centres serve to place a new emphasis on high quality engineering research crossing the boundaries of the traditional engineering disciplines (Aerospace, Civil, Manufacturing, Materials, Mechanical). Hence this submission is made to the General Engineering panel for the first time. The Centre Heads, **Mottershead** (CED), **Chalker** (CMS) and **Badcock** (CES) carry the authority that comes with acknowledged research leadership in their fields as well as being University Heads of Departments.

CED encompasses the dynamics of flight, fluids and structures; CMS is centred on functional materials, manufacturing, lasers, structural materials and microscopy; and research in CES is concentrated on new interdisciplinary initiatives in risk and uncertainty and sustainable energy generation.

Strategic planning within the three centre structure has led to the emergence of two significant new inter-disciplinary research groupings. The first of these is the University-wide Liverpool Institute for Risk and Uncertainty (LIRU) led by **Beer** (CES) with membership that includes all three Centres. The second is the Biomedical Science and Engineering Research Group led by **Elsheikh** with colleagues from CMS and collaboration with the Faculty of Health and Life Sciences. A further new grouping in Nuclear Science and Engineering is planned.

b. Research strategy

The aim of the School of Engineering is to produce creative research and impact to the highest international standards. This is being achieved by the application of three guiding principles: (1) research should address major strategic and intellectual challenges with scope for continuing contributions and funding for the foreseeable future; (2) engineering research should be made relevant by meaningful interaction with industry; and (3) research that fulfils the requirements of (1) and (2) above generally requires teams of researchers of sufficient numbers and complementary skills to create critical masses of expertise.

In the School of Engineering research is developed on the basis of plans revised annually by the three Centre Heads. These plans are integrated into three year rolling plans at the School and Faculty levels, which in turn contribute to the overarching aims of the University Strategic Plan for 2009-14. Resources are provided in the School plan, and inter-disciplinary research is encouraged at the Faculty and University levels. The University has developed and supports seven inter-disciplinary research themes, including Materials, Energy, and Living with Environment Change, to which the School of Engineering makes substantial contributions.

Strategic planning based on the three guiding principles (above) has led directly to the establishment of LIRU and the Biomedical Science and Engineering Research Group within the assessment period. Plans are in development for a future Nuclear Research Group with contributions from across the Faculty of Science and Engineering.

LIRU membership extends to 40 academic staff spanning 10 Departments (including the Environmental Sciences, Financial Mathematics, Psychology and Engineering) across three Faculties with multidisciplinary PhDs already established between Engineering and all the above disciplines. The University plan includes refurbishment of its Chadwick Tower for co-location of all LIRU staff within two years. It will accommodate around 100 PhD students working in a common multi-disciplinary hub including teleconference facilities and hot-desks for visits (up to a month or more) by industrial partners, presently including Arup, Bechtel, JLR, Keppel Offshore (Singapore), NCK (Canada), NNL and Petrobras (Brazil).

Research in Biomedical Science and Engineering (with Faculty of Health and Life Sciences) promises a much needed instrument for the better quantification of intraocular pressure, the major risk factor for glaucoma. This work, funded by the National Institute for Health Research (NIHR), will enable the continuous monitoring of intraocular pressure leading to improved management of the disease and the avoidance of vision loss. An ERDF application is in preparation for a Centre for Research and Innovation in Biomedical Science and Engineering in partnership with North-West-based SMEs. Local collaborations are being fostered with eight Liverpool Hospitals. International collaborations (already established) include Universities of Bern, Hong Kong, New South Wales and Wenzhou Medical College and recent industrial funding includes Oculus (Germany) and UltraVision (UK).

Further **Future Plans** include a nascent Nuclear Engineering activity, led by **Patterson**, and developed together with the University of Manchester and the National Nuclear Laboratory to provide access to world-class facilities in the Dalton Cumbria Facility and the Central Laboratory (Sellafield) respectively. In addition, a dual PhD agreement with National Tsing Hua University (Taiwan) provides access to their THOR research reactor and a synchrotron. A Chair in Nuclear Engineering has been advertised and an appointment is expected in 2013-14 to be followed by additional appointments at the lecturer level.

Summary of Progress: The School of Engineering has benefitted from large-scale re-building and refurbishment at a cost of £36M (completed 2008) and its organisational structure has been re-modelled to place greater emphasis on research than was envisaged at RAE2008. Strategic planning has resulted in the emergence two completely new significant inter-disciplinary research groupings and another major new grouping is planned. 23 staff have been appointed in the current assessment period with the purpose of developing critical masses of researchers in existing and new research fields. This is evident in increased research income (per FTE, the per annum average over the assessment period was £128k, compared with £75k over the last three years of the RAE2008 assessment period) and numbers of PhD students graduating (per FTE, the per annum average number of doctoral awards over the the REF assessment period was 0.75, compared with 0.30 over the last three years of the RAE2008 assessment period).

Selected Achievements:

CED: In the assessment period 26 EPSRC research grants and 12 EC Framework 6 or 7 projects have been active. Highlights include: (1) The £3M research programme of the Agusta-Westland Liverpool Advanced Rotorcraft Centre (**Barakos**#3,#4 and **Steijl**#2,#3). (2) New simulation methods developed in a €1.8M single-partner Marie Curie excellence team (**Badcock**#1,#2, **Mottershead**#1,#3 and **Timme**#1), enabling for the first time routine Computational Fluid Dynamics (CFD) based flutter prediction. These were implemented into the Airbus CFD code, and successfully tested on a model of an in-development aircraft towards a modified industrial process. (3) Development of an active pole placement method for vibration suppression (**Mottershead**#2) and the successful demonstration on an Agusta-Westland airframe. (4) Development of Bayesian techniques to estimate modal properties from ambient excitation, with applications to very large buildings with Arup (**Au**#1,#4). (5) Explanation of mechanisms for the development of elastic flow instabilities in Non-Newtonian fluids (**Poole**#1,#3) leading to the design of microfluidic devices capable of measuring fluid relaxation times down to less than 1 ms, and the influence of polymer additives on the impact of droplets on solid surfaces (**Bertola**#1) with the potential via EPSRC-grant funding to control or improve the effectiveness of a range of single-drop and spray applications in additive manufacturing processes.

CMS: In the assessment period 30 EPSRC research grants and 3 EC Framework 6 or 7 projects have been active. Highlights include: (1) EPSRC Centre for Innovative Manufacturing on Laser Based Production Processes. **Sutcliffe** leads Additive Manufacturing activity, including a CDT awarded 2013 and led by Nottingham, with Newcastle and Loughborough. Methods for monitoring and control of tolerances and surface finish in additive manufacturing, achieving significant impact for the development of industrial processes and their use for biomedical manufacturing applications (**Sutcliffe**#1-3, Impact Case Study #1). (2) Functional thin films research embedded in the current UK power electronics initiative - EPSRC platform grant with NXP and IQE (**Chalker**#2, Impact Case Study #3). (3) The £2.5M NiCAL Electron Microscopy centre has been established, and funding secured for the next five years of development of SuperSTEM at the Daresbury

Laboratory. The research advances in microscopy have been in the combination of analytical methods within aberration corrected transmission electron microscopy to yield atomic scale compositional information (**Romani** #1, #2); (4) Instigation of a new £1.5M activity in ophthalmology (Biomedical Science and Engineering Research Group) into methods for the measurement of intraocular pressure in cooperation with clinicians (**Elsheikh**#1-4) and successful clinical trials of a non-contact instrument for the accurate measurement the eye's internal pressure. (5) Research with Airbus on optical strain measurements for damage detection, and the validation of computation solid mechanics models with the US Air Force and via a Framework 7 award with the Swiss Standards Institute (SNV), Fiat , NNL (**Patterson**#4).

CES: Research in this Centre is concentrated on new and emerging inter-disciplinary initiatives for the exploration of new research fields, including risk and uncertainty (LIRU) and renewable energy with the Faculty-wide Stephenson Institute for Renewable Energy (SIRE). In the assessment period 10 research council grants have been active. The main initiatives are: (1) The establishment of LIRU as a University-wide Institute drawn from 10 departments for the study of risk and uncertainty. Achievements include imprecise probabilities presently being used by Dynamore GmbH in crashworthiness design of cars (**Beer**#2), global sensitivity calculations for large structural models, for example applied to European Space Agency Gravity field and steady-state Ocean Circulation Explorer (GOCE) satelite (**Patelli**#1) and the development of the classical Path Integral (introduced by Wiener and reinvented by Feynman) for application to stochastic nonlinear dynamics problems in engineering (**Kougioumtzoglou**#1). (2) Thin-film solar cells (SIRE), recent demonstration of a new design of nanowire solar cell device (**Durose**#2), and development of new and sustainable photovoltaic (PV) materials, suitable for mass-market production for the vastly expanded solar market, forecast for the next 10 – 20 years. Also a CDT in *New and Sustainable PV* awarded 2013 and led by Liverpool (PI **Durose**), with Bath, Cambridge, Loughborough, Oxford, Sheffield, and Southampton (total value £9M with £5.5M EPSRC contribution) for the training of 70 PhDs over 5 cohorts.

c. People, including:

i. Staffing strategy and staff development

The staffing and research strategies are inter-connected by the shared purpose of recruiting excellent people to form critical masses capable of outstanding research. Of 23 appointments in the period, fifteen are ECRs, amounting to 28% of the full-time academic staff population. Examples of appointments to the three Centres include the following.

CED: Au, from Hong Kong City University, was appointed to a joint chair in CED and LIRU. His expertise is in the output-only modal identification of Civil Engineering structures from ambient excitation by Bayesian inference. This complements the research of **Mottershead** on stochastic model updating. **Zuev**, from Southern California was appointed to a lectureship. He shares a research interest with **Au** on the development of fast Bayesian algorithms, typically Subset Simulation (SS), and strong links to the work of **Beer** and others in LIRU. **Diaz De La O**, appointed to a lectureship, from Swansea, has a background in morphing aerostructures, to complement research by **Badcock** and **Mottershead**, and Gaussian process emulators, to connect with LIRU interests. The appointment of **Paoletti** to a lectureship in Control, from Harvard, complements and creates links between previously separate research activities in the areas of structural and flight dynamics, CFD and IC engines. **Steijl** and **Timme**, both appointed to lectureships from internal post-doc positions, strengthen the CFD research on rotorcraft and transonic fixed-wing aerodynamics by combining with **Barakos** and **Badcock** respectively. **Bertola,** appointed to a senior lectureship, from Edinburgh, and **Kubiak** appointed to a lectureship, from Leeds, have interests in the internal dynamics and mixing of non-Newtonian fluid droplets. This complements the research of **Poole** on large-scale pipeflow of non-Newtonian fluids, as does the research of **Dennis**, appointed to a lectureship, from Cambridge, with expertise in the experimental investigation of the structure of turbulent flows.

CMS: Patterson came from Michigan State to take the AA Griffith Chair of Structural Materials and Mechanics. A Royal Society Wolfson Research Award holder, his expertise in full-field techniques for strain measurement complements **Mottershead's** research on image analysis of full-field vibration data. **Patterson** provides leadership across the Faculty of Science and Engineering on Nuclear Science and Engineering. **Elsheikh**, from Dundee, was appointed to a chair in a

Biomedical Science and Engineering. The subject of his research is ocular biomechanics with interest in ocular material characterisation and numerical simulation of ocular biomechanical performance. His appointment was supported by three lectureships in Biomedical Science and Engineering to achieve critical mass and strengthen links with the Faculty of Health and Life Sciences; **Akhtar**, from Manchester, and **Curran**, from the Faculty of Health and Life Sciences, an expert in the control of cellular function by the engineering design of surfaces and scaffolds. Her research is complemented by the appointment of **D'Sa** from Ulster whose research is in the field of surface engineering to control the adhesion of biological materials. **Edwardson** from the Lairdside Laser Centre was appointed to the Manufacturing Research area on the ultrafast processing of material surfaces to work with **Dearden**.

CES: Beer, from the National University of Singapore, was appointed to a professorship in Risk and Uncertainty and became Director of LIRU in 2012. A von-Humbolt fellow, his research is on non-traditional models of uncertainty, such as fuzzy probabilities, with emphasis on reliability analysis, risk and robust design. His appointment and the subject of his research was reinforced by the appointment to lectureships of **Kougioumtzoglou**, from Rice, and **Patelli**, from Innsbruck, as well as **Au**, **Diaz De La O** and **Zuev** (mentioned above). **Kougioumtzoglou** is an expert on stochastic systems exhibiting nonlinear behaviour with exposure to risk or hazard, and **Patelli** has a background in Nuclear Engineering, risk management and optimisation. **Durose**, from Durham and an expert in thin-film solar energy materials and solar cells, was appointed to a chair in Renewable Energy. His research connects with complementary activities in CMS (**Chalker** and **Romani**).

Career Development for Academic Staff: Academic staff are assigned to one of the three Research Centres, and processes such as individual planning, reviewing and approval of research proposals, and the Performance and Development Review are carried out within this structure, placing a strong focus on research planning and career development. Training and development programmes are available for research team leaders, while academics in senior management positions undertake a leadership development programme. A wide range of online courses are provided and training requirements are discussed, recorded and monitored regularly through the University's Professional Development Review scheme as a mandatory part of the development of all staff.

Each research active member of staff has an allocation from the School operating budget to support their engagement with the wider research community, and the School Management Committee (Head of School and Centre Heads) makes further investments in facilities and studentships aligned with the School plan. Each of the Centres runs a programme of workshops and seminars aimed at stimulating new research ideas. An example of the outcomes of this is the development of LIRU, which was started following a two day workshop attended by 70 staff from 16 different Liverpool Departments. A second example is the Biomechanics network that meets six times a year, and has initiated research in the ocular, skeletal and manufacturing fields.

Fellowships: **Barakos** to a Russian Federation Eminent International Scientist Fellowship, 2011; **Ouyang** to a RAEng Leverhulme Trust Senior Research Fellowship, 2010; **Patterson** to a Royal Society Wolfson Research Merit Award, 2011; and **Poole** to a Michelin Materials Science Chair 2011-12 at Ecole Superieure de Physique et de Chimie Industrielles, Paris.

Promotions: **Barakos** and **Ouyang** to Chairs; **Zhao, Shenton** and **Dearden** to Readerships; and **Poole** and **Potter** to Senior Lectureships in the assessment period.

Specific Support for New Staff: All new staff are given support, and mentors are appointed to ensure the successful integration of ECRs into research groups in the three Centres. The role of the mentor includes advice on aspects of research-career development, such as preparing grant applications and the choice of journals and international conferences for the presentation of research results. A gradual increase in teaching is typical for new appointees (around half are given one year completely free of teaching), leading to a full contribution after three years. New professors all receive individually negotiated start-up packages, and other staff, including ECRs, receive support on a case-by-case basis to establish the facilities required for their research.

This start-up investment has established new laboratories in Biomedical Science and Engineering and Optical Strain Measurement and computing facilities for LIRU, and has significantly enhanced

instrumentation in non-Newtonian fluid mechanics and dynamics (robotics). ECR appointments include: **Kougioumtzoglou, Patelli, Diaz De La O** and **Zuev** to LIRU, **Edwardson** to Manufacturing and Lasers, **Akhtar, Curran** and **D'Sa** to Biomedical Science and Engineering, **Dennis** to Fluid Mechanics and **Steijl** and **Timme** to CFD.

Research Assistants: The University is a signatory to the Concordat to Support the Career Development of Researchers and the efforts to provide a supportive environment have been recognised by the award of the European Commission's 'HR excellence in research' badge. An annual University conference is organised to build the community of researchers, with topics covered in recent years including research impact, attracting funding and public engagement, and a researcher development programme offers courses to researchers to assist them with their career development.

Equality and Diversity: The University gained the Athena Swann Bronze Award in 2010 and the School submitted an application for a Departmental Bronze Award in November 2013. All academic and research staff are eligible to access a range of family friendly options (e.g. maternity, paternity and adoption leave, parental, compassionate, domestic and personal leave). The University has a flexible working policy to allow individuals to vary or adjust their pattern of work based on their personal circumstances. A start has been made on redressing the School's gender imbalance by the appointment of four female staff to lectureships since 2008. The two ticks guaranteed interview scheme is operated for applicants with disabilities.

ii. Research students

A major advantage of the re-building and refurbishment of the School of Engineering buildings was the introduction of large open-plan desk-type work spaces where PhD students are accommodated in clusters belonging to research groups with staff offices nearby. This has led to a culture of shared research objectives, open discussion of problems and methods, with Post-Docs and the more senior PhD students providing scientific advice and guidance to more junior colleagues in a structured approach to PhD training, including seminar programmes organised by the three Centres, PhD workshops and an annual PhD conference. Of 173 PhD students who started during the period of assessment, 156 (90.2%) have progressed successfully either to completion to the next year of their studies.

Recruitment of PGR Students: Priority has been, and continues to be, given to increasing the number and quality of PhD students and to ensuring a high-quality student experience. The total number of new registrations has been in the range 20-30 in each year of the assessment period, with support for HEU students derived from the EPSRC doctoral training grant, CASE awards (e.g. from BAE SYSTEMS, Stirling Dynamics, Airbus, QinetiQ), and funding from the School operating budget, which has been increased significantly in the last three years, matched from external sources (e.g. the Spanish Renewable Energy Agency and A*STAR Singapore). In addition, the development of a University International Graduate School has been supported to provide additional opportunities for staff and students to collaborate with several overseas institutions (e.g. Ocean University of China and National Tsing Hua University, Taiwan) within a framework of dual PhD agreements. Of the 93 currently registered PhD students, 35 are UK nationals, 20 from other EU countries, 19 from China and 19 others. The number of self-funded OSI students has been 48% of the total over the assessment period.

Training and Monitoring of PGR Students: Student progress is monitored and feedback delivered at regular intervals. This includes the definition of a research plan after three months, the recording of notes on 12 student-supervisor meetings per year, the assessment of draft thesis-style reports after nine, 21 and 33 months, annual presentations to staff and students which are assessed and the annual recording of generic skills training undertaken. The latter is drawn from the University's Skills Programme aimed at developing career skills, choosing from a range of three day modules, participating in a University-wide poster day and attendance at a regular Engineering seminar programme. Entrepreneurial activity is promoted through participation in the Research Council YES programmes, and an annual residential Enterprise School with Lancaster University.

Example PGR Student Outcomes: **Gomez-Iradi**'s research resulted in a wind turbine aerodynamic prediction code that is now in production use at the Spanish Renewable Energy Centre, where he now works (**Barakos**#2). **Timme**'s work was implemented into an Airbus/DLR code, and demonstrated on an Airbus aircraft model (**Timme**#1), with him later being appointed to a lectureship at Liverpool. **Haddad-Khodaparast**'s research on interval model updating (**Mottershead** #3) led to the demonstration of the method with DLR on a generic aircraft model and to his appointment to a lectureship at Swansea University. **Ghandchi Tehrani** implemented a vibration controller, based on modal test data, on a helicopter airframe (**Mottershead**#2) and was appointed to a lectureship at ISVR, Southampton. Work on spatial light modulation for laser processing was undertaken by **Liu** (**Dearden**#4), who took up a lectureship at Hubei University of Technology. **Clare** did work on the rapid prototyping of electrodes for miniature quadrupole mass spectrometers which has been subsequently commercialised (**Chalker**#4), and he has taken up a lectureship at Nottingham. **Tao** joined the National Institute of Metrology of China and established a new laboratory in materials, becoming Head of the Division of Nanometrology and Metrology for Advanced Materials in 2011. In total, 22 PhDs/Post-Docs have gone to University lectureships in the assessment period, including Queen's Belfast, Liverpool, Loughborough and two to Southampton.

d. Income, infrastructure and facilities

Research planning and targeted appointments to form clusters of researchers in identified areas of growth was matched by the development of **major new laboratory facilities** established since RAE2008:

CMS. Additive Manufacturing: Facilities are some of the most complete in the world with 14 machines (total value c. £3.5M), including four Selective Laser Melting (SLM) platforms (one of which is the SLM500, the largest of its kind available), two inkjet printing systems one with quad materials facilities, one photo polymer system, two Fused Deposition Modelling (FDM) systems and one ink on powder system (Impact Case Study #1). Laboratory-developed machines include spiral growth manufacturing and several blown powder laser cladding systems. Firm plans include the installation of an Arcam A1 Electron Beam Melting machine (Stryker) with Nottingham (High Value Manufacturing Catapult) and a 1kW SLM system (Renishaw). Optical Stress Analysis: Major equipment includes a high-speed digital image correlation system, thermoelastic stress analysis system and custom-designed optical microscope to support objectives on (i) macro-scale quantitative validation of computational mechanics models (AFRL-Wright-Patterson, NNL); (ii) meso-scale understanding of damage propagation mechanisms (Airbus UK); and (iii) nano-scale exploration of interaction of metallic nanoparticles with biological cells (EC JRC, Ispra). Biomechanics Laboratories: Includes one of the best equipped ocular biomechanics laboratories in the world and two new biological tissues laboratories. Equipment includes an inflation rig for testing corneas, scleras and whole eye globes under controlled inflation conditions and an Instron 3366 testing machine for low load levels and facilities for digital image capture (NIHR with Faculty of Health and Life Sciences). A new Agilent G200 Nanoindenter and a refurbished Bruker Mulitmode 8 Atomic Force Microscope are used for the characterisation of biological tissues with state-of-art microbiology and tissue culture facilities. Nuclear Engineering: Access to nuclear facilities at Sellafield is exceptional and underpins future research plans (Section b) in this area.

CES. LIRU Computer Laboratory: 25 servers for 248 cores and 290Gb of Memory and free access to the STFC-Hartree Blue Gene Q HPC.

Established laboratory facilities were enhanced by targeted investment, improvements to existing facilities and the development of new rigs.

CED. Dynamics and Control Laboratories: An arena with one hundred programmable robots (kilobots), camera and projector, and dedicated computing resources, provided by the School of Engineering, for new research into robot-swarm dynamics. New rigs for active vibration control of multi-span bridges and flutter suppression in aeroelasticity, including a rigid aerofoil (USAF EOARD) and a new flexible-wing wind-tunnel model, under development (EPSRC). Fluid Mechanics and Hydraulics Laboratories: High-speed stereoscopic particle image velocimetry for

investigation of spatial organisation of turbulent structures in non-Newtonian pipe flow, with 100 mm precision bore borosiliciate glass pipe flow facility, capacity 1000 litre. A 80,000 litre, 6m/s, recirculating water flume (working section 0.84 x 1.4 x 3.5 m) used for tidal stream turbine project (EPSRC), helicopter ship interaction (EPSRC) and to investigate "subskimmer" hybrid surface/subsurface craft (TSB/EPSRC KTP, Marine Specialised Technology). CFD Computer Laboratory: 1300 cores funded from by TSB grants with AgustaWestland Helicopters and access to the N8 Polaris cluster, the UK Hector, the STFC-Hartree Blue Gene and JUROPA Blue Gene (Germany) systems as well as the University Chadwick cluster. Flight Simulation: A new moving base flight simulator to add to the existing one owned at the start of the assessment period, both with hexapod bases to provide motion cueing and used to support research on three EC projects as well as EPSRC and US Army funded research during the assessment period.

CMS. Electron Microscopy: The campus-based *Nano Investigation Centre at Liverpool* (NiCAL) (£2.45M ERDF) houses a range electron microscopy facilities including aberration corrected TEM, SEM and state-of-the-art field ion beam specimen preparation. NiCAL enables nanoscale chemical analysis of engineering materials, such as graphene heterostructures (**Romani**#1). This is complimented by the *SuperSTEM* facility at Daresbury (Nion UltrastemTM 100), providing atomic-scale chemical analysis. Nanofabrication: The *Royal Society – Wolfson Cleanroom* houses Atomic Layer Deposition and Aixtron CVD systems, as well as a STS semiconductor processing cluster tool. Lasers: Ultra short-pulse laser systems for micromachining, surface texturing and precise parallel processing. Pulsed Nd:YAG lasers used for ignition in IC test engines with Ford Motor Company (collaboration with CED) with funding from the Carbon Trust; CO_2 and fibre laser based Direct Write facility used to explore processes for fabrication of antennas and sensors for BAE Systems and Alstom. Impact: A range of high-energy impact rigs and blast facilities for the development of new blast-resistant composite-metal hybrid structures (**Cantwell**#3, **Guan**#1).

CES. Solar Energy Materials and Solar Cells: Equipment for the fabrication and testing of thin-film solar cells, and studies of the factors that limit the efficiency of solar-cell materials. These include: a) thin film crystal growth equipment (five sublimation chambers and three RF/DC sputtering chambers for semiconductors and transparent conductors, plus processing furnaces) b) solar cell testing (two AM1.5 solar simulators, External Quantum Efficiency spectroscopy) and c) materials investigations equipment (optical transmission/reflectance, mapping van der Pauw, thickness profiler, variable temperature/variable field Hall effect, Seebeck effect, impedance analysis and thermal admittance spectroscopy, temperature dependent conductivity measurements).

Research Funding: The per FTE per annum average over the assessment period was £128k, compared with £75k over the last three years of the previous assessment period. Of the £22M income in the current assessment period, £10.5M was from Research Councils, £3.6M from other UK government sources, £2.9M from UK industry and £3.8M from the European Union. Additional external funding not recorded as research funding to the amount of £8.02M was received in the current assessment period to support the Knowledge Transfer centres discussed in REF3a (the Virtual Engineering Centre, Lairdside Lasers Engineering Centre and the NiCAL microscopy centre). The deliberate development of new critical-mass research grouping in key areas of RCUK funding (LIRU, Biomedical Science and Engineering, Nuclear Engineering) as well as other established strong groups with excellent industrial partnerships (e.g. Renishaw, Stryker, AgustaWestland) places each of the three Centres in strong positions to compete for research funds in the future, from, for example, Horizon 2020.

e. Collaboration and contribution to the discipline or research base

Major collaborations include:

NATO Scientific working group AVT-113 measured/computed the vortical flow on an unmanned air vehicle model. The group, including NASA, Boeing, BAE SYSTEMS, German Aerospace Centre (DLR), produced journal publications (including **Badcock**#3) and an international conference. Liverpool was a significant contributor to the computations and organisation of this activity, and the follow-on AVT-161 and 201. The Liverpool PhD student (**Vallespin**) was a co-recipient of the NATO Scientific Achievement Award 2012 for the outcomes of AVT-161.

EC Framework projects: Aerodynamics: SimSAC, ECERTA, UFAST, FFAST, TFAST, IMESCON, GoAHEAD; Flight Simulation: MyCopter, ARISTOTEL, OPTIMAL, NICE-TRIP; Materials: PARSEM, CELPACT, LASMICROTOK, GETMAT; Vibration and Strain Measurement: ADVISE; VANESSA. As an example, the GoAHEAD project, including DLR, ONERA, Eurocopter, Stuttgart University and Agusta Westland, involved wind-tunnel measurement and the computation of flow around a complete helicopter configuration (**Barakos**#4). Liverpool contributed a full set of calculations for the planning of a complicated and large scale wind tunnel campaign and final evaluation of the results.

Materials with Chemistry: Chalker#1,#3 and **Potter**#1 with Chemistry (Rosseinsky, Cooper, Aspinall) in the Knowledge Centre for Materials Chemistry; the 'Complex Materials Discovery Portfolio Partnership' (EP/C511794/1); the platform grant 'Chemical Synthesis of Transformative Extended Materials' (EP/H000925/1); and the TSB project 'Improved Processes and Materials for Energy Saving Glazing' (TP11/LIB/6/I/AM092J). All of these developments have focused on the development of new thin film materials for engineering applications. SuperSTEM researchers have collaborated with the Manchester Nobel Prize winners (**Geim** and **Novoselov**) on the imaging of graphene and elucidation its various property/structure relationships (**Romani** #1).

There are numerous cases of collaborations that show evidence of research leadership. Selected examples include: **Au** with Bou-Zeid (Princeton) using heat transfer simulation models together with an advanced Monte Carlo simulation method called Subset Simulation. The latter is a powerful method invented by Au for investigating rare events in complex systems, which is otherwise computationally prohibitive. The work provided important insights for meteorological, urban canopy, problems, for which existing strategies are found to be inadequate for complex models. It led to a publication in *J App Meteorology & Climatology*. **Timme** (ECR) with DLR, Germany, and Airbus UK on flutter and gust analysis. The collaboration included a one month placement working with CFD experts at DLR Göttingen and a demonstration of Fast-Flutter simulation at the Airbus UK Advanced Simulation Research Centre (ASRC) in Bristol. The Fast-Flutter demonstration was one of the first projects where a real-life model of an Airbus was provided for university researchers to demonstrate the feasibility of applying academic simulation tools to very large-scale industrial problems, and led to further collaborative projects on gust response simulation. **Mottershead** with Dantec Dynamics and Centro Ricerche Fiat on image processing of full-field vibration data acquired typically by digital image correlation. Tens (or hundreds) of thousands of data points were reduced to just a few tens of image descriptors, thereby achieving an efficiency (without loss of accuracy) that had not been obtainable previously. The technique, invented at Liverpool, was applied to a car bonnet, a difficult test because of the irregular shape (**Mottershead**#4), and is presently being applied to press-fitted car wheels with Bonisoli (Politecnico di Torino).

Awards and Prizes.
Akhtar (ECR): Outstanding paper prize IEEE T-UFFC (Ultrasonics), 2012. **Badcock**: EC Marie-Curie Excellence Team Award (Project ECERTA) 2007-2010. **Barakos**: AgustaWestland Outstanding University Researcher Award, 2010. **Dearden**: Best Paper prize, International Conference on Manufacturing Automation and Systems Technology. **Elsheikh**: Best paper in the Journal of Royal Society Interface 2009. **Ouyang & Mottershead**: Paper selected for special review in commemoration of the 50th anniversary of the Journal of Mechanical Engineering Science (Proc. I.Mech.E., Part C, 233(1), 175-187, 2009. **Patterson**: EC Joint Research Centre Best Paper Award 2008; Best paper in the Journal of Strain Analysis for Engineering Design, 2009; Frocht Award from Society for Experimental Mechanics, 2010.

Editorships of Journals.
Patterson: SAGE Open Engineering (Patterson is founding editor of this open access journal for all areas of engineering); Fatigue and Fracture of Engineering Materials and Structures; Journal of Strain Analysis for Engineering Design.

Associate Editorships.
Badcock: Aeronautical Journal. **Barakos**: Aerospace Science and Technology. **Beer**: International Journal of Reliability and Safety; ASCE-ASME Journal of Risk and Uncertainty Analysis. **Dearden**: Journal of Laser Micro and Nanotechnology. **Mottershead**: Mechanical Systems and Signal Processing. **Ouyang**: Journal of Sound and Vibration (Subject Editor); International Journal of

Vehicle Noise and Vibration.

Keynote & Plenary Papers.
Au:Asian-Pacific Symposium on Structural Reliability and its Applications, Singapore, 2012. **Barakos**: 2nd Asian-Australian Rotorcraft Forum, Tianjin, China, 2013. **Beer**: American Society of Mechanical Engineers, International Mechanical Engineering Congress and Exposition, Denver, USA, 2011; 5th International Conference on Reliable Engineering Computing (REC2012), Brno, Czech Republic, 2012. **Guan**: 1st International Conference on Advanced Composites for Marine Engineering, Beijing, 2013. **Elsheikh**: 8th International Congress on Corneal Cross Linking, CLX2012, Geneva, 2012; Ocular Biomechanics Symposium - 8th European Solid Mechanics Conference, Gratz, 2012. **Mottershead**: American Society of Civil Engineers, Engineering Mechanics Institute, EMI2011, Boston, USA; 10th International Conference on Vibration Problems, ICoVP2011, Prague. **Ouyang**: 15th Asia Pacific Vibration Conference, Jeju, Korea, 2013; Northeast China Conference on Mechanics, Dalian, 2013; Chinese Congress on Theoretical and Applied Mechanics, Xian, 2013. **Patterson**: 9th International Automotive Composites Conference, Troy, Michigan, USA, 2009; 4th Iberian Conference on Fracture, Porto, Portugal, 2010; Convegus Nazionale dell' Associazione Italiana per l'Analisi delle Sollecitazioni, Vicenza, Italy, 2012; International Union of Theoretical and Applied Mechanics, Taipei 2012; 9th International Conference on Advances in Experimental Mechanics, Cardiff, Wales, 2013. **Poole**: Workshop on Instabilities and Turbulence in Viscoelastic Fluids, the Lorentz Centre, Lieden, 2010.