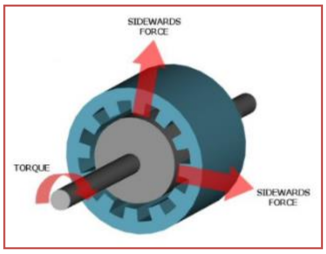
WP6: *Integrated electro-mechanical actuation*. Lead: Garvey @ Nott'm.



Overview. This technical pillar focuses mainly on exploiting the ability of any rotating electrical machine to develop a controllable transverse force between the "stator" and the "rotor". This has two main applications: (1) it can produce oscillatory force to remove vibration energy or (2) it can provide a steady force (relative to one frame) to counteract either weight loads or loads caused by gyroscopic couples. This WP will also include extended examination of how fine adjustments in torque profile can be used to minimise oscillations in shaft-trains and a grass-roots re-examination of electrically powered actuation in aircraft.

Background and motivation. Electrical machines are certain to play a major role in future aero propulsion systems. They will appear as propeller drives in distributed propulsion, as generators powered from gas turbine engines and as drives for flight control surfaces. Services such as cabin climate control, air-oil separation and fuel pumping will also be electrically driven. Hundreds of smaller machines will deliver secondary functions but are not relevant for this investigation.

The main body of this work is most relevant for electrical machines integrated directly into gas turbines on relatively long slender shafts. These machines present great challenges - dominated by cooling considerations (aspects of this are explored in WP6). They also present great opportunities through the ability to achieve transverse actuation (in two independent directions) without any significant sacrifice. The fraction of net aero-engine power consumed in electricity generation is rising steadily. Boeing's 787 has ~500kW of generation on each of its two Trent1000 engines - a small percentage of total engine power. The bulk of net engine power is deployed in the fan to propel the aircraft. These engines transmit power from the engine core out to a gearbox where it is spread to oil-air separators, hydraulic pumps, fuel pumps and two large generators. The 787 is presently the "most-electric" large aircraft but the trend is towards running more/all of the ancillary services electrically and, longer-term, to power the propulsion itself indirectly in distributed configurations. In the short term (10-15 years), generators on-board engines will simply be larger.

Further into the future, the aero gas turbine of the future may have no fan or it may be a very small unit compared with the fans of engines such as the Trent XWB[1]. Then most of the net engine power will be dispatched electrically and re-converted into mechanical power locally at propulsor sites. The generators will necessarily be much larger and it will be impractical to transmit the power away from the turbine rotor before converting it. **The ability to control net transverse force on rotors will completely remove what is presently a major limitation in gas turbine engine design – having major (rotordynamic) critical speeds in the middle of running range.** Critical speeds are currently avoided religiously in engine design because unbalance forces can be amplified by factors of >100 at these rotational speeds unless some measure is present to remove vibration energy before it accumulates to dangerous levels. **This transverse force control will also enable propeller drives to suppress rotor vibrations will allow operation in regions where they would otherwise suffer flutter instability.** Overall, it will essentially mean we can do more with less.

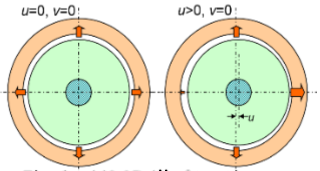


Fig 1 : UMP Illustration

UMP and controlling it. All electrical machines with ferromagnetic material on both rotor and stator experience unbalanced magnetic pull (UMP). Fig. 1 illustrates this and shows why UMP generally has a strong associated negative stiffness effect – tending to reduce critical speeds. UMP can be controlled by deliberately changing the pattern of MMF (magneto-motive force) across the airgap. Historically, this has been done either by (a) realising machines having two completely different sets of windings (one for torque production and one for developing transverse force) or (b) using concentrated windings on the stator poles with completely independent current-sources for each concentrated winding. Two different groups have developed two different solutions that enable transverse force to be controlled completely independently from torque, where exactly the same loops of copper lie in the same machine slots as a conventional machine winding and where completely separate inverters can supply the torque-producing and force-producing functions independently. Both solution sets are applicable in any electrical machines where each stator coil has a diametrically-opposite coil.

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[1] The Trent XWB has a 3m diameter fan – the largest fan on any engine yet built.

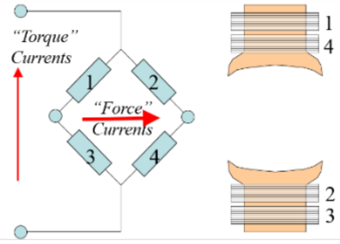

Fig 2 : Garvey *et al* concept

Together with PhD students Khoo and Kalita, Garvey pioneered and proved a solution class where each one "coil" in a conventional machine winding would be divided into a pair of "half-coils" [SDG#12],[SDG#16]. Then a series-connected pair of coils on opposite sides of a machine would be connected instead in Wheatstone bridge format (Fig 2). The attraction of this arrangement is the "force-inverter" has very low ratings for both current and voltage. Two slight restrictions are that each "coil" must have an even number of turns and all ends of the "half-coils" must be brought out. The "force inverter" is a current-source drive and the machine returns to a completely conventional design if this is simply disconnected. Chiba[2] and co-workers [1], [2], recently developed a competing scheme (Fig. 3). This can be retrofitted to (almost) any machine where all coil ends are brought out. A disadvantage is that the "force inverter" must carry large currents. This inverter must be a "voltage-source". The machine reverts to completely conventional design if the inverter is simply short-circuited.

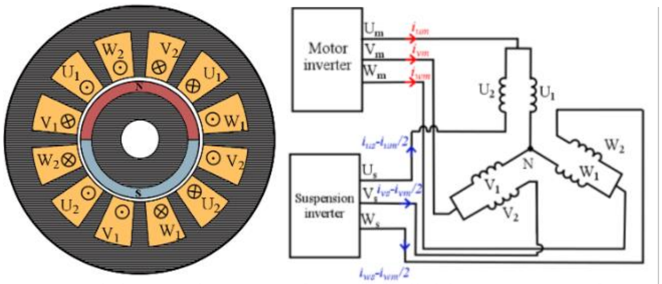

Fig 3 : Chiba *et al* concept for controllable transverse force.

Main elements of work.

Task #1: (months 1-28): A fundamental review of the potential positive and negative implications including inline electrical machines within gas turbine engines. Task #2: (months 1-8): the connection patterns of Figs. 2 and 3 have both been trialled in separate cases but not compared in detail on a common case. This comparison will comprise the first element – the only element to comprise mostly electrical engineering content. This will deliver a journal paper. Task #3: (months 9-20): These force-control arrangements will then be explored in the aero context – with specifications being drawn up for relevant force capacities and bandwidths. A summary document will be deposited in the project repository. Task #4: (months 21:56): to exploit this actuation in the context of WP2, we will explore whether high levels of force can be realised in very short timespans (possibly discharging capacitors across the force circuits). This task will include some experimental work. A video, PhD thesis and associated journal paper will emerge. Task #5: (months 21:32): this task will explore the highly interesting possibilities of exploiting the non-linearities in assembled systems through parametric excitation as an alternative route to stabilisation. This can potentially offer control of some very high-frequency phenomena using relatively low-frequency excitation. This task has especially strong relevance to the "cross-excitation" problem which has been understood only very recently in aero-engines and which presents extreme challenges to verifying that certain engines are safe. The work will deliver a report and journal paper based on experimentation at Imperial College on the "assemblo-dynamics" rig.

Overlaps with other parts of the programme.

Interaction with the Oxford-led WP2 is and Imperial-led WP4 is obvious. Through Task#5 above, there will also be strong overlap with the Oxford-Imperial focus on *assemblo-dynamics* in WP1 and WP3. Clearly, there will be essential connections with the thermal management activities of WP5 to ensure that the (small) additional losses caused by the "force-currents" do not lead to thermal runaway problems.

Interactions with other Universities.

Important relevant work has been done at UTCs in Sheffield (self-bearing machines and high-temperature machines) and in Strathclyde (fault-tolerant power-electronics) that can blend in here and will be highly useful in developments of this work towards incorporation. Since Nottingham's own electrical engineering department has been very strongly involved in CleanSky and CleanSky2 projects centred on high power-density machines for aerospace, we will exploit indigenous expertise and experience to the full in these areas.

[1] R. Oishi, S. Horima, H. Sugimoto, and A. Chiba, "A Novel Parallel Motor Winding Structure for Bearingless Motors," *IEEE Transactions on Magnetics,* 49, 2287-2290, 2013.

[2] A. Chiba, S. Horima, and H. Sugimoto, "A principle and test results of a novel bearingless motor with motor parallel winding structure," *Energy Conversion Congress and Exposition (ECCE), 2013 IEEE*, 2013, pp. 2474-24

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[2] Chiba can rightly claim to be the world authority on self-bearing machines.