9th Osborne Reynolds Colloquium
and Research Student Award

Department of Aeronautics
Imperial College London
Roderick Hill Building
16th June 2011

GAS TURBINE SHAFT OVER-SPEED / FAILURE PERFORMANCE MODELLING

Dr. Luis Gallar
Luis.Gallar@Rolls-Royce.com

Rolls – Royce University Technology Centre in Performance Engineering
Cranfield University, Cranfield, MK43 0AL, Bedfordshire, United Kingdom

The aviation industry has witnessed staggering technological advances in the past decades that have permeated very often to other sectors of the industry. The development of such novel and disruptive technologies is fuelled in most cases by the very competitive markets that aerospace companies operate in. Gas turbine engine design in particular is driven nowadays by the pursuit of greater fuel efficiency and smaller overall operational costs. There is, however, an overriding requirement behind any design that cannot be subordinated to fuel and cost economy. In Civil Aviation safety is, and will always be, the ultimate requirement than cannot be obliterated. As a safeguard of safety, the Aviation Authority must be satisfied that a new type or mark of engine is safe to be operated within declared limits, even in the event of certain component or control system failures. Hence, significant effort and resource are invested in industry and academia on attaining such high standard of airworthiness.

Shaft failures in particular result in a more or less sudden decoupling of the compressor and turbine, with no instantaneous change in the aerodynamic power flow. The compressor will slow down and the turbine over-speed very rapidly; if the engine is running at high power, the turbine disc will burst in a very short time, of the order of 100-200 milliseconds, unless surge occurs or fuel is shut off. Shaft failure events are characterised by the strong and complex interrelation existent between engine components and the dependency of the progression of the event on the particular failure and engine geometry under analysis. The speed at which the event progresses and the deficient understanding of the performance of the various engine components at these far off-design conditions make the modelling of a shaft failure one of the most difficult problems in the engine to analyse.

The accurate modelling of shaft failure events has become a pushing issue for engine manufacturers because of two main reasons: new certification threats coming from changes in legislation and the need to optimise the engine to minimise fuel burn. Engine certification requirements are prone to change over time, usually to become more stringent. With regards to shaft failure, whereas in the past the engine has gained certification on the basis of the historically extremely remote occurrence of such events, this claim is no longer acceptable and the engine manufacturer is now required to demonstrate, either by test or analysis, that the failure will not hazard the aircraft safety by releasing energetic fragments or result in uncontrollable fires. Although engine shaft over-speed/failure tests would satisfy the Authority, large scale tests under those conditions tend to be prohibitively expensive and complex. On the other hand, today's poor understanding of the event leads to the conservative design of turbine discs with an obvious penalty on weight and fuel burn. It is within this context that the need for an analytical approach that accounts for all the heavily interrelated phenomena arises to model the progression of the event.

The operation of the gas turbine at over-speed conditions remains substantially unexplored. To the best of the author's knowledge, there is currently not one tool which considers all the important physical phenomena and that can address the modelling requirements identified (table 1). No reference to the event can be found in the public domain and the very limited data available is proprietary. The research presented here is the starting point of a long term research collaboration between Rolls-Royce and Cranfield University that aims at enhancing the performance modelling capability of shaft failure events. The final objective is the development of an inexpensive automated computational tool to model the behaviour of gas turbine engines during shaft failure and over-speed scenarios (fig. 1). The initial intent of the tool is twofold: on the one hand, the tool will be employed in the certification of gas turbines against core shaft failures and on the other a better over-speed assessment will promote an improved design capability to account for shaft failure early in the engine design process.

Component	Behaviour	Modelling requirement identified
Compressor	The compression system is likely to surge either because of the high vibrations induced on the engine that affect the tip clearance, variable geometry malschedule or because of the speed mismatch between shafts	1. Compressor characteristics in reverse flow 2. Compressor maps for a malscheduled VSV system 3. Dynamic model of the compression system able to cope with stall and recovery
Turbine	Turbine capacity and efficiency will change substantially due to flow incidence being very far from design conditions	1. Extended turbine characteristics at high negative incidences
Internal air system	In failures where the shaft loses its axial position the turbine disc can be displaced rearwards and close some of the discharge ports of the internal air system. Pressure build ups in the turbine cavities will act as cushions avoiding the contact and friction between structures that would dissipate energy and help arrest the over-speed	1. Time accurate model of the performance of the internal air system

Table 1: Engine component behaviour during a shaft break and modelling requirements identified.

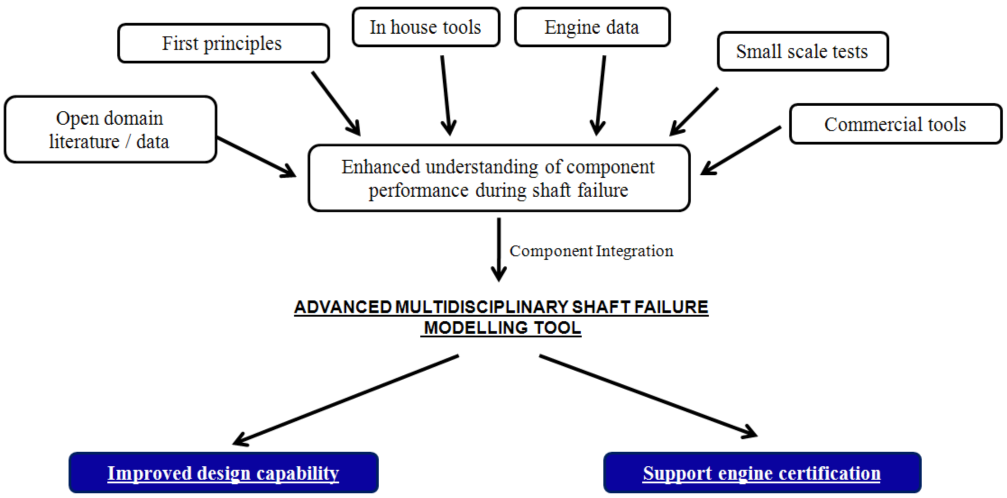

Figure 1: Research scope and intent.

The experimental and modelling work carried out encompasses two separate tasks. First, engine component models have been developed for the provision of extended component characteristics that cover the wide range of operating conditions present during the over-speed. The second task is the vertical integration of all the findings and engine components into a modular "all in one" whole engine performance transient model.

The main milestones achieved by the research hitherto can be broadly summarised as follows:

1. A novel stage stacking technique has been developed to derive axial compressor characteristic lines in reverse flow (figure 2). The technique is based on first principles across blade rows in conjunction with high fidelity CFD simulations that are used to validate some of the modelling assumptions. This is fundamental to enable the prediction of the stalled operation of the compression system that is likely to follow a core shaft failure.

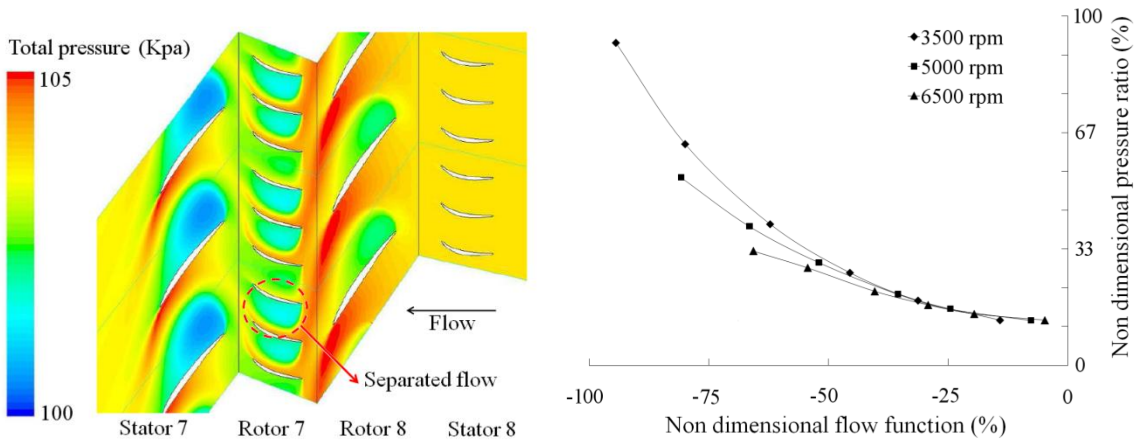

Figure 2: 3D CFD derived total pressure contours at mid span in reverse flow over the last two stages of an eight stage axial compressor (left) and reverse flow compressor map derived by the stage stacking technique (right).

2. Development of a fully flexible and modular tool to simulate the performance of the secondary air system during rapid transients. The study of the transient behaviour of the internal air systems of gas turbines has not been reported previously in the literature. This tool constitutes an excellent starting point to analyse not only shaft failure scenarios but other transients of interest like the loads exerted on bearings in industrial machines for sudden changes in load.
3. Analysis of turbine aerodynamics at the high negative incidences typical of over-speed events. High fidelity 3D CFD studies have been carried out supported by a low speed experimental rig of turbine vanes. These studies led to the development of a stage stacking technique to derive turbine maps for over-speed conditions. Moreover, flow visualisation techniques over the vanes allowed the identification of flow patterns not described before in the literature. As an example of this, figure 3 shows how at an incidence of -113 degrees (1) the flow separates from the leading edge of the vane (2) and rolls up from the endwalls into two vortices over the pressure surface of the vane.

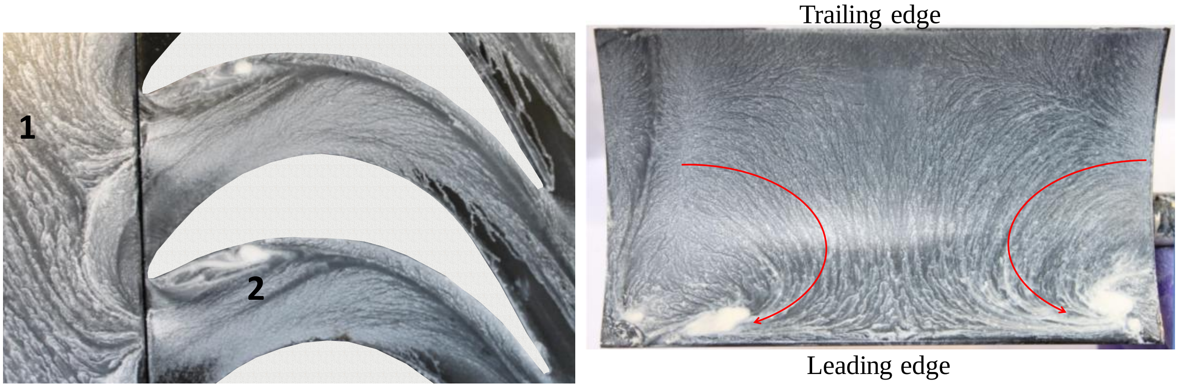

Figure 3: Flow visualisation on the turbine vane cascade rig on the bottom endwall (left) and on the pressure surface of the vane (right) for a 0.25 Mach number flow at -113 degrees incidence.

4. The results from the turbine aerodynamics studies have made possible the development of a pressure loss model significantly more accurate at far off-design conditions than the widely used model due to Ainley and Mathieson. This allows the rapid estimation of pressure losses across turbine vanes without the need for time consuming numerical simulations.

The current work focuses on the integration of all the findings, models and maps into a single “all in one” engine transient performance model that will be validated against engine data available from the industrial partner. The final tool will prove invaluable in the support engine certification and will allow optimising the engine discs against shaft failure events.

The author has been particularly active trying to divulgate the findings of his work within the scientific community. Further to monthly technical meetings and presentations with the sponsor and to the delivery of the doctoral thesis, the transfer of technology developed by the research has taken place in the form of tools, data bases, models and manuals delivered to the company in various workshops during an industrial placement in the last stage of the doctoral programme. In addition to this, the research has produced valuable knowledge and data for the research community in the form of three journal papers (two published [1,2] and one currently under review [3]), six peer reviewed papers presented by the author at international conferences and two seminars given by the author to two foreign universities. This work was also recognised with the 2008 Eric Beverly award from The Worshipful Company of Coach Makers and Coach Harness Makers of London.

References

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