Flutter-Free Turbomachinery Blades

Final Report Summary - FUTURE (Flutter-Free Turbomachinery Blades)

Executive Summary:

The propulsion of aircrafts is today almost exclusively based on turbomachinery-based engines, which is primarily due to their unprecedented power density. Turbomachines have progressively evolved since the middle of the last century and key advances have been made in increasing reliability, availability and environmental friendliness. Today’s aircraft engines consume on an average 12% less fuel than their late 1990-ies counterparts and are thanks to this much “greener”. Environmentally friendly aircraft engines are light, powerful, silent and produce low emissions of greenhouse gases and nitride oxides. This is achieved by having an efficient propulsion concept such as a high bypass ratio turbofan and by having an efficient power generation cycle. Reduced component counts and reduced weight of components among others are trends that make propulsion “greener”. There are however limits for how “green” and aircraft engine can become using traditional cycles largely affected by mechanical integrity. Of many phenomena
can become using traditional cycles, largely affected by mechanical integrity. Of many phenomena affecting the mechanical integrity of turbomachines, flutter is probably the most severe, as it can lead to the disintegration of components in very short time.

Within the FUTURE project, the phenomenon of flutter in turbomachines is addressed in a combined experimental and numerical effort, such as to increase the accuracy and reliability of turbomachinery flutter predictions. The focus of the project is put on the two primary areas of turbomachines, in which flutter is observed as are i) low-pressure compressors and ii) low-pressure turbines.

In the FUTURE project, a number of different aerodynamic test facilities are used as are:

- Non-rotating compressor cascade rig with controlled oscillation of blades
- Non-rotating turbine cascade rig with controlled oscillation of blades
- Rotating compressor rig (1 ½ stage)
- Rotating turbine rig (1 stage)

In addition, the following mechanical test rigs are used to characterize mechanical damping:

- Rotating in vacuo test rig for measurement of structural properties of a blisk
- Rotating in vacuo test rig for measurement of structural properties of a bladed disk with cantilevered blades and interlocked blades

State-of-the-art measurement techniques such as tip timing, optical vibration measurements, fast-response pressure transducers and Pressure-Sensitive Paint (PSP) have been used to characterize the structural properties and the unsteady aerodynamic behaviour during controlled oscillation and free flutter. Tests have been performed on a freely fluttering LPT rotor validating the potential for using structural mistuning to limit vibration amplitudes or suppress flutter completely. A variety of leading-edge computational activities have been performed in parallel to the experiments such as to validate numerical tools on high-quality test data acquired in the FUTURE project and to ultimately get a deeper understanding of the flutter phenomenon in turbomachines.

Project Context and Objectives:

Project Context

In modern aircraft engine design, where the driving forces are increasing aircraft safety, lowering weight, raising performance and cost-effective manufacturing, the challenge is to optimize for conflicting aerodynamic and structural demands. Increasingly thinner, lighter, but more loaded blades substantially raise the vulnerability towards flow induced vibrations such as flutter, leading to a high damage potential. By advancing the state-of-the-art in flutter prediction capabilities and design rules, the FUTURE project will lead to short term benefits in terms of decreased development cost in current engine programs, reduced weight and thus fuel consumption, and increased ability to efficiently manage flutter problems occurring on engines at service.

Mid-term and long-term benefits are that improved analysis and design aeromechanical methods for
Mid-term and long-term benefits are that improved analysis and design aeromechanical methods for aggressive lightweight blade design are an enabling factor for high efficiency future environmental friendly aero engines and gas turbines with maintained safety. In combination with a reduced time-to-market the project outcomes will have a strong impact on the competitiveness for the European aero engine module and stationary gas turbines manufacturers participating in the project. The project will give the partners access to experimental data that are not available in any other company in the world.

Project Technical Objectives

Design “Flutter-Free” Blades

Most of the cascade data available so far were obtained from generic experiments on two-dimensional attached subsonic and transonic flows with oscillating turbine and compressor cascade blades. New sets of data are now needed to further increase the understanding of the role played by the differences that exist between annular cascades and multistage configurations in the inception of flutter, data that FUTURE will supply. A parametric flutter study will be conducted for compressor profiles in a full annular oscillating cascade. A new suspension system capable of allowing for measurements of natural blade flutter will be used for the same compressor profiles in the annular cascade. An experimental parametric study on the blade aeroelastic behaviour will be carried out using oscillating rigid 3D blades in a sector annular cascade to study the influence of complex blade motions with the help of a pioneering excitation mechanism. As an additional effort to capture the physics observed in engine-realistic configurations, measurements on an innovative oscillating 3D flexible blade will also be conducted.

In order to assess the significance of the engine multi-row environment including wave reflections for the first time, a full scale VIGV-rotor-stator compressor test case will be designated to measure and assess sustained near flutter of the rotor.

The dependence of aeroelastic stability on relevant structural and aerodynamic parameters will be assessed in a full-scale single-stage rig using a blisk rotor that is representative of a modern ultra-high bypass fan design. The blade vibration will be actively controlled in terms of amplitudes and phases, allowing sophisticated aerodynamic measurement in great technical detail and with unprecedented flexibility concerning independent variation of the dominant parameters.

Breakthrough system for controlled forced vibration:

One device for excitation of a rotor in operation will be developed within the project.

The rotor will be designed so that no resonance-crossings occur in the operating range. Hence, one would not be able to assess the aerodynamic damping outside the flutter regime. The purpose of the controlled excitation device is to be able to excite rotor vibration to assess aerodynamic damping also in the stable regime.

The development of such a system is not only expected to lead to the advent of a new era in the experimental research of compressor and turbine aeroelasticity, it is also opens up for several new possibilities in the future. One is as a rational approach to investigate and assess the effect of incoming
possibilities in the future. One is as a rational approach to investigate and assess the effect of incoming
disturbances on turbomachinery performance and HCF. Another possibility is for investigation of using a
similar device on an aircraft engine for active control of damping.

Leading-edge measurement techniques:

Within the FUTURE project various sophisticated state-of-the-art measurements techniques will be used,
and further developed as well as validated. The novel PSP (Pressure Sensitive Paint) technique will
significantly enhance the resolution and quality of the experimental results. The high quality experimental
results will be essential for the validation and calibration of analysis and design tools and formulation of
improved design rules. As experiments and numerical calculations will be performed simultaneously it will
be possible to throughout the project identify experimental and/or numerical inaccuracies and thus during
the experimental campaigns gain insight into the governing physical phenomena. This is an enormous
advantage of having all the major European aeromechanical companies, research institutes and
universities involved in the same project. The database to be established will be world-wide unique.

Validated aeromechanical design and analysis tools:

The currently available numerical tools will be verified and benchmark tests will be performed based on the
new state-of-the-art experimental test data acquired in the FUTURE project, which include complex mode
shapes, 3D and multi-row effects. This kind of data does till today not exist. Based on the assessment of
prediction bottlenecks and the identification of the relevant flow physics and flutter controlling parameters,
potential routes will be identified to improve the design and analysis tools and the methods will be
calibrated accordingly.

Project Results:

2. Description of the main S&T results/foregrounds

WP1 – Turbine and Compressor Cascade Flutter

WP1 consisted in turbine and compressor cascade flutter experiment campaigns and provided detailed
measurements of relevant aeroelastic properties in a simplified and well controlled environment. The tests
completed the more complex rotating rig experiments of WP 2 (CTA turbine rig) and WP3 (TUD
compressor rig), and contributed to identify and isolate the effects of different aerodynamic and
mechanical design parameters. Two state-of-the-art facilities were employed in WP1, one at partner KTH
and one at partner EPFL.

Figure 1. Cascade test facilities used

In particular three different experiment campaigns were performed with the following objectives:

(A) KTH Turbine Experiments (on new airfoil geometry)

- assess the impact of complex vibration modes on aeroelastic stability, by testing a 3D rigid vs real
• assess the impact of complex vibration modes on aeroelastic stability, by testing a 3D rigid vs real deforming airfoil (requiring relatively high aspect ratio) and modes representative of rotor assemblies (requiring two Degree of Freedom (DoF) oscillation system, combining bending and torsion);
• assess validity of the stability maps approach and related linear superposition principle on simplified as well as complex vibration modes;
• apply and assess a novel type of Pressure Sensitive Paint (PSP) technique to measure timeresolved surface pressure, allowing high temporal and spatial resolution, such providing more detailed information on the unsteady flow behaviour.

(B) EPFL Turbine Experiments (on existing ADTurB cascade hardware)

• assess the impact of assembly vibration modes on aeroelastic stability of packeted airfoils (two jointly in pair and stator segment of engine configurations), by testing blade clusters modes (requiring an annular cascade).

(C) EPFL Compressor Experiments (on new airfoil geometry)

• perform detailed measurements of the vibration induced unsteady blade loading through controlled vibration experiments, complemented by assessment of the flutter boundaries under different flow situations in a freely vibrating cascade;
• identify and study flutter boundaries and address non-linear flow phenomena specific to compressor stall flutter, by gathering detailed information on the aeroelastic behaviour in all blades free flutter (requiring an annular cascade).

KTH Turbine Experiments

KTH AETR (Aerolastic Test Rig) is a set up composed by an annular cascade with 5 blades. The flow is directed using elastic walls that allow the periodicity assessment of the cascade.

Figure 2. KTH annular sector cascade test facility

The middle blade is oscillated in 3 orthogonal rigid body modes. The oscillation is achieved using a mechanical actuator beneath the hub of the cascade, which provides control on the vibration mode and frequency of the oscillation.

The objective of the setup is to perform flutter experiments in the influence coefficient domain. Within this purpose the oscillating blade and the adjacent are instrumented with fast response pressure transducers at 3 different span positions (10% 50% 90%). The motion of the blade is real-time measured using a set of 3 lasers. Consequently the pressure and motion are synchronized within the same timeline which allows the stability analysis.

Figure 3. LPT test object showing pressure measurement locations

KTH Controlled vibration on Rigid Blade
This section provides the technical information of the rigid blade oscillation campaign including the operating conditions, blade motion tracking and unsteady pressure data.

KTH turbine cascade has been assembled for rigid blade tests and the set-up has been calibrated dynamically. Unsteady pressure results have been acquired for:

- 4 different operating point (OP1, OP2, OP3, OP4)
- 3 rigid oscillating modes: Axial mode, Circumferential mode and Torsion mode.

Figure 4. Blade oscillation modes tested in KTH cascade

All tests have been performed as reported in the following test matrix:

Figure 5. KTH test matrix of controlled vibration tests

All data have been post processed and analyzed and proper uncertainty assessment has been done both for the steady analysis and the unsteady one, as shown in the following pictures where it is possible to see the axial distribution of the static pressure measured for different operative point and the unsteady pressure distribution.

Figure 6. Measured and predicted steady aerodynamic loading of the KTH cascade

Figure 7. Steady and unsteady test data; correlation of CFD results

KTH Controlled vibration on Flexible Blade

An elastic blade was designed, assembled and operated under restricted conditions and unsteady pressure measurements were performed using the unsteady PSP technique by partner Onera. However for safety reasons as well as due to limitations of the used measurement technique (PSP), the range of tested frequency was limited by an upper limit of 80Hz.

This section gives an overview of the results obtained using the Pressure Sensitive Paint (PSP) as an innovative investigation method to the usual pressure taps to provide pressure images on the blade surface in a turbine cascade. To achieve unsteady PSP measurements, several parameters have to be adjusted, like the blade material, the optical access, the intensity of excitation lamp, but the main issue concerns the blade deformation leading to changes in measurement conditions. The Pressure Sensitive Paint (PSP) technique has been used in the KTH flutter cascade as an innovative measurement technique with the aim to provide more detailed description of the unsteady aerodynamics governing flutter on the surface blade, and to push this technique to a higher TRL (Technology Readiness Level) for turbomachinery application. During a first test campaign, PSP measurements have been performed on rigid blades where one blade was oscillating in a controlled manner. Then a second campaign has been done on a flexible blade.

Figure 8. PSP measurement setup on KTH cascade
The PSP measurement technique uses a luminescent coating which is sensitive to air pressure variation. Even if the response time of the paint would allow quite fast acquisition rate (10kHz), the level of intensity emitted by the paint determines the signal-to-noise ratio (SNR) and thus the minimum exposure time for each image. The test matrix is reduced to one Operation Point (OP3) with the three oscillating modes: axial, torsion and circumferential. With the flexible blades, each configuration is performed twice: one with the pressure blade and one with the reference blade. Results obtained on rigid blade are consistent with the pressure taps measurements even if the quantitative values are not at the same level. In addition, the PSP images reveal an unexpected aerodynamic behaviour showing a stripe after the suction peak at (0.6 in arcwise) both on amplitude and phase of the complex pressure coefficient. This unsteadiness has not been revealed by the pressure taps measurements, neither by the CFD prediction, but was validated by oil flow visualization and associated to a separation bubble.

The results indicate that the PSP technique used is very challenging and that quantitative data can only be achieved with great care. In principle, the use of a second blade (coated with a paint which is insensitive to pressure) should be able to cope with the illumination variations due to blade deformation. But the processing of two set of images instead of one introduces additional noise on the images and no significant results can be obtained from these images.

EPFL Turbine Experiments
The Non-Rotating Annular Test Facility at EPFL-LTT that comprises twenty prismatic turbine blades allowed for testing of compressor or turbine cascades in sub- trans- or supersonic flow conditions with a large variation of inlet angles. It has been used for numerous investigations both steady state and unsteady.

The measurement have been conducted with the following techniques:

- Aerodynamic 5 hole probes
- Static pressure taps
- Unsteady pressure transducers
- Displacements sensors

The tests have been performed for: a single blade, a two-blade-cluster (Cluster A) and a four-blade-cluster (Cluster B).

The test campaigns have been designed in order to represent critical modes for those cluster configurations.
- Assembly system mode, which occurs when the assembly is deforming globally as a system and all the blades are moving simultaneously and synchronously. The cluster A bending mode was obtained by moving in phase the two airfoils in the packet along the same bending direction “e4”, while, The cluster B torsion mode is obtained by moving the four airfoils in the packet along the same bending direction “e1”, but with different amplitudes and phase lags.

Figure 12. Assimilated system modes

- Assembly airfoil modes, that represents a family of assembly mode in which each airfoil of the cluster has a characteristic modeshape. The interaction between the blades in the packet may significantly impact on the single blade dynamic behavior. The cluster A mixed mode is obtained by rotating the first airfoil of the packet and by moving along the bending direction “e1” the second one, while The cluster B mixed mode will be obtained by rotating the first and third airfoil of the packet and by moving along the bending direction “e1” the second and fourth one.

Figure 13. Assimilated airfoil modes

Hence, the following measurement campaign have been performed:

- 1st measurement campaign: a two-blade-cluster of which both blades of the cluster move simultaneously and in phase (“e4” direction). Single blade controlled vibrations with a bending direction which is almost close to perpendicular to the blade chord (“e4” direction).

Figure 14. Tested two-blade-cluster

- 2nd measurement campaign: Single blade controlled vibrations with a bending direction which is parallel to the cascade test facility (“e1” direction). A four-blade-cluster which is controlled in phase and amplitude to simulate a movement similar to torsion (“e1” direction).

Figure 15. Tested four-blade-cluster

- 3rd measurement campaign: Two-blade-cluster and four-blade-cluster controlled vibration, both having in alternating manner bending “e1” and torsion vibration modes.

- 4th measurement campaign: Single blade controlled vibration in torsion mode. A two-blade-cluster of which both blades of the cluster move simultaneously and synchronously (torsion direction).

The following table summarizes the full test campaigns.

In the following the major aerodynamic values were determined via a digital post-processing code. All values relate to measurements at mid-span height with almost identical steady-state flow conditions. They comprise, among others: the local aerodynamic work coefficient, the global aerodynamic damping and the aerodynamic work per cycle as shown in the pictures below.
Figure 16. Steady aerodynamic test data; EPFL turbine cascade

Figure 17. Aeroelastic test data; EPFL turbine cascade

EPFL Compressor Experiments

This section provides the results of the tests performed in the frame of the EPFL compressor cascade controlled vibration experiment.

Figure 18. EPFL compressor test object

In association to the time dependant signals, steady-state flow fields and blade surface steady-state static pressures were measured. The steady-state and unsteady measurement positions are acquired at 20%, 50% and 90% of the blade span by the instrumentation shown in the picture below.

Figure 26 EPFL compressor instrumentation

The operating points selected for this test campaign are based on the steady-state data acquired during the first compressor measurement campaign (October 2010). Operating points of interest has been measured with the cascade vibrating to assess unsteady data. During the unsteady measurement campaign, the cascade’s blades are subjected to controlled vibration motion (first bending mode shape). All test have been performed following the test matrix below.

Figure 27 EPFL compressor test matrix

An example of results are presented below for some flow conditions. In figure 28 steady state pressure along the profile tip is presented.

Figure 28 EPFL compressor steady aerodynamic test data; left: blade loading, right: casing pressure

Unsteady pressure measurements on the blade are presented in figure 29 per several inter-blade-phase-angle.

Figure 29 EPFL compressor aeroelastic test data

WP2 – LPT Rotating Rig Flutter

Introduction

Two high aspect ratio aeronautical low-pressure turbine rotor blades sharing the same aerodynamic surface were designed to flutter in a rotating high-speed wind tunnel located at the CTA (Zamudio). The first rotor blade has plane not-contacting tip-shrouds and it is referred to as the cantilever configuration whereas the second features a z-shape shroud where there is a contact with the neighbouring blades and it is named the interlock configuration.
This is the first time that a bladed-disk has been specifically designed to flutter under controlled conditions and therefore it is believed that just the proper design of test vehicle itself would justify the whole project. The major technical difficulty was to design a rotor blade within the design space of an existing rig whose vibration amplitude were high enough to be measurable but not to compromise the safe operation of the rig and the facility.

Three more experiments were designed around this test. First, and more relevant, a vacuum spinning rig was designed and built in AVIO, as a separate project, to measure the mechanical damping of both bladed-disks. The main idea is that the rotor blades are excited in a vacuum chamber by means of stationary or rotating magnet system to control separately the frequency and nodal diameter of the excitation. The pull load of the rotor blade may be controlled independently also. This is possible using two rotating disks: the specimen and a second disk that contains the magnets. The rig is complex and a number of problems had to be solved to put in operation the whole system. The main objective of this test was to determine the mechanical damping and vibration frequency of each individual blade for different shaft speeds, nodal diameters and vibration amplitudes.

A third experiment was conducted in the KTH vibrating sector cascade using the 70% span section of the airfoil to experimentally characterise the aerodynamic damping of the rotor blade under different reduced frequencies and incidences. Finally a ping test of all the rotor blades was conducted at POLITO.

To complete the picture an experiment to validate the influence of mistuning due wearing or manufacturing imperfections on the rotor stability was designed. Rotor blade shrouds were designed to host mistuning masses with the objective of testing different mistuning patterns. Two patterns were designed and tested the first adding a mass in one out of two blade with the ultimate objective of completely suppress flutter and a second designed to half the vibration amplitude of the tuned bladed-disk and obtain clean signals of a mistuned fluttering configuration.

Experimental Campaign

Instrumentation. The LPT rotating rig experiment was designed to be measured with non-intrusive measurement techniques. Aerodynamic surfaces were not instrumented and therefore there is no direct measurement of the steady or unsteady pressures on the airfoils. Blade vibration measurements, both in the CTA wind tunnel and in the AVIO friction rig were performed using a blade tip timing optical system provided by RR to avoid the use of strain-gauges which are intrusive, induce an uncontrolled level of mistuning and provide incomplete information of the bladed-disk. Inlet and outlet aerodynamic boundary conditions of the rotor blade were obtained by radial and circumferential traverses of total pressure and angle using fast response five-hole probes. Inlet stagnation temperature and exit static pressure were measured also. Unsteady pressures in the casing were recorded using unsteady pressure transducers and therefore all the instrumentation used in the tests was non-intrusive.
Testing sequence. The cantilever bladed-disk was tested first at the CTA. The CTA wind tunnel allows an independent control of the rotor blade shaft speed, Mach and Reynolds numbers. Different shaft speeds and density levels were tested while the exit Mach number was kept constant. First low density levels and shaft speeds were tested to ensure the integrity of the hardware, once confidence was gained the different points of the test matrix were measured. Flutter could be clearly identified in a wide range of the test matrix and the experiment was considered by the consortium a great success. Then the two mistuning patterns were tested for the cantilever configuration. It could be verified that the design intent was correct and that the first pattern managed to completely suppress the flutter that had been intentionally created before, while the second reduced the vibration amplitude roughly to the half.

The cantilever configuration was sent to Avio while the interlock bladed-disk was being tested at CTA. The same test matrix was conducted for the interlock configuration but no signal of flutter was seen. This fact was aligned with the analytical predictions that showed that the interlock rotor was stable in spite of all the efforts that were done to design an unstable rotor within the constraints of the facility and the airfoil shape, that was the same for both configurations to keep the same aerodynamic steady loading. Stationary magnets were mounted in the outer casing but it was not possible to detect the vibration due to the forcing. In this sense the experiment was inconclusive.

Main Results and Conclusions

It has been shown for the first time that flutter of a realistic configuration may be reproduced under controlled conditions. This is a key element for the design of more complex experiments that will allow us to further understand the nature and limits of flutter. Coherent signals could be obtained by both the BTT and unsteady pressure probes. An example of this may be seen in Figure 4 where the harmonic content of a pressure transducer is represented. The frequency and range of unstable nodal diameter coincides very closely with those predicted analytically.

It has experimentally been shown that flutter severity increases with the density level, but the trend with the shaft speed for this experiment could not be clearly explained. Further analytical work is needed fully.
shaft speed for this experiment could not be clearly explained. Further analytical work is needed fully understand this behaviour.

Figure 22. Unsteady pressure as a function of the nodal diameter and density for low shaft speeds

The stabilizing effect of mistuning has been demonstrated experimentally for the first time under controlled conditions. Trends are predictable using current analytical tools but absolute values difficult to predict. The difference in the vibration amplitude of the three cases is clearly visible and the trend steady.

It has experimentally been shown that the vibration amplitude is controlled by non-linear mechanisms, dry friction in particular. Figure 5 (left) displays the response of the blades of the cantilever configuration as a function of the frequency. It can be clearly appreciated that the response of the rotor blade is non-symmetric about the resonance, which is the classical response of a non-linear damper. In this particular case the friction of the system is solely due to the fir-tree attachment but more complex experiments can be devised where contributions from other contacts, such as the interlock, may be expected.

It has also been shown that the mechanical damping changes significantly with the shaft speed as it is outlined in Figure 5 (right). This change of the damping with the pull load needs to be properly retained in the simulation for a correct prediction of the vibration amplitude.

Figure 23. Blade vibration amplitude as a function of the frequency (left) and mechanical damping (right) as a function of the shaft speed measured by the BTT equipment obtained in the Avio friction rig

WP3 – Multi-Row Compressor Flutter

Introduction

Within WP3 the physical understanding of engine relevant compressor flutter will be enhanced by performing flutter experiments in a rotating 1 ½ stage compressor rig at TU Darmstadt. The focus is on flutter at or near stall. In contrast to the common design route, to design for avoidance of flutter, a rotor blisk will be specially designed to reach a well-defined rotor-blade flutter within the operating domain of the compressor. In free flutter tests the time-evolution of vibration amplitude and unsteady pressure will be measured at onset of flutter. Free flutter tests will give a direct determination of the flutter limit as function of operational conditions with no assumptions or model uncertainties involved. The free flutter experiments are complemented by forced response experiments to assess the aero damping characteristics at stable operation using an excitation system developed within the WP. The use of the excitation system allows measurements in a wider range of running conditions, and data at extended operation that may be inaccessible in free flutter regions.

To assess the aerodynamic damping from the measured total damping there is need for a well determined mechanical damping. Hence, a state-of-art method previously developed with the support of European Community in ADTurB II will be re-used and adapted to measure mechanical damping of the blisk under rotation. The data gained from the two compressor test campaigns in conjunction with the data from the mechanical characterization will provide valuable insight to the parameters controlling flutter in an engine relevant environment and also directly give a measure of the reliability of the flutter prediction methods.
relevant environment and also directly give a measure of the reliability of the flutter prediction methods
used in the design of the rotor.

Achievements

The measurements of the total damping from forced excitation with subsequent ring-down tests are seen
as the key outcome of this work package. It allows the partners to directly correlate their aeromechanical
simulations on test data and to conclude on prediction accuracy of aerodynamic and mechanical damping
with the additional test data from the ECL spin pit tests. Figure 24 shows the total damping as a critical
damping ratio for different operating points and different nodal diameter patterns. The predicted trend of
the damping versus nodal diameter as it has been shown in earlier reports agree well with test data. There
are however differences that are not fully explained to date and further analysis of the data is needed here.

Figure 24. Measured total damping in the TUD compressor from blade tip timing data at various operating
points

Figure 25. Free-flutter experiments in TUD compressor; operating points denoted “critical” featured higher
blade vibration amplitude

In addition to the forced excitation experiments, the compressor operating range has been screened for
free flutter occurrences. A series of operating points have been identified that featured higher vibration
amplitude as depicted in Figure 25 (points denoted with “critical”). This is a substantial result as it
represents a very rare test case that comes with detailed measurements of blade vibration amplitudes,
accurate mechanical characterization and total damping measurements from ring-down experiments.

Figure 26. Correlation of measured and predicted damping of the TUD compressor (OP20)

Last, a comparison of measured and predicted damping is shown in Figure 26. The comparison shows
that the predictions are close to test data in terms of values and trends, but that differences exist of the
order of 100-200% of the measured value. This might seem as an unacceptably high value but still the
order of magnitude of damping is about the same. The observed differences come to some degree from
different mean aerodynamics, to some degree from the prediction of the mechanical vibration and to some
degree from the varying treatment of the unsteady aerodynamics. The test data acquired during the TUD
tests include also detailed measurement of the unsteady casing pressures, which is used by the partners
to identify the source of the discrepancies and then to use this information to improve their aeroelastic
prediction capabilities.

WP4 – Synthesis of Experiments and Computations

The work package WP4 “Synthesis of Experiments and Computations” was aimed to

• do the Post-Test Predictions of Experiments

  o TUD compressor
  o EPFL Compressor cascade
• Establish a database containing a set of flutter experimental data for the calibration of numerical methods
• compare the measured and analytical results for all five experiments
• Calibrate numerical tools for flutter and forced response predictions through direct comparisons with high-quality experimental data from all test programs in work packages 1-3, encompassing unique engine-representative configurations for turbomachinery blade instability measurements
• Derive best practice guidelines

Elaborate improved and/or new flutter design criteria for compressors and turbines

Establishment of Data Base containing Experimental and Numerical Data

A web-based data base for the numerical and experimental data has been established at the begin of the project. According to the data standardization agreement, also elaborated within WP4, this data base has then been filled throughout the FUTURE project with the measured results from the five experiments and the corresponding analytical results from all partners. This form of communication proved to be very efficient. The resulting data base is of high value to all partners to improve their numerical methods, even after the end of the project. All deliverables, technical reports and progress reports have also been stored in the data base in a clearly laid-out and easy-accessible manner.

In addition to that, the data-base was designed such, that it could be used as a general communication platform between the partners. For that purpose each work package had a separate folder which could be structured according the needs of the involved partners. This feature was very helpful and improved the quality of the data exchange.

Post-Test Predictions / Comparison with experimental Data

TUD compressor

Goal of TUD compressor experiment and corresponding calculations was to validate aerodynamic damping of specific travelling wave modes and free flutter in a multi-stage environment.

In order to excite the blades in the travelling wave modes of interest, an excitation system (air injection system) was design within the FUTURE project and incorporated into the rig.

Figure 27. TUD compressor with air injector (excitation system)

A first interesting finding when comparing measured and analytical results is that the measured..
A first interesting finding when comparing measured and analytical results is that the measured compressor map is relatively well captured by the calculations (Fig 4-2) even though differences in the radial flow profiles of the distinct calculations were observed, probably due to different secondary flows at the tip. This also leads to slightly different shock characteristics. (Fig 4-3).

Figure 28. Compressor map: TUD: measurement – others: calculation

Figure 29. Steady tip pressure field OP19: TUD picture: measurement – others: calculation

Figure 30. Flutter curve: TUD experimental results - others: calculation

Measured and calculated damping curves for one operating conditions are exemplarily depicted in Figure 4-4. There exist also cases with more variation between the various calculations and measurement. This is probably due to the different steady solutions (shock characteristics).

Free flutter could not be validated. Even though some experimental results indicated some sort of asynchronous vibrations, none of the computational results showed flutter. An exact explanation could not yet be found for the measured effect.

EPFL annular compressor cascade

A modern geometry 3D-rotor which is susceptible to flutter was designed within the FUTURE project for the transonic compressor rig at TU Darmstadt. A typical 2d-section of this rotor was investigated in the non-rotating annular test facility at EPFL. Due to the extensive instrumentation a better understanding of the unsteady flow was expected.

The controlled vibration experiments allow the understanding of the unsteady surface pressures for the selected cascade geometry, mode shape and frequency as a function of operating conditions, and inter-blade phase angles. Due to the non-rotating setup of the tests, the effort required to extract this information from the cascade tests is significantly lower than for the rotating rigs, so that a larger range of aerodynamic and aeroelastic parameters can be covered by the cascade tests.

Figure 31. Cavities of EPFL compressor cascade

The comparison between the experimental and numerical results showed that it is necessary to include the cavities of the EPFL compressor cascade into the CFD model in order to get the steady aerodynamic results right. This holds true for the results at inlet, outlet and blade surfaces. In the context of the FUTURE project this is extremely important, since the numerical aeroelastic results can only be correct if the steady flow field is captured correctly. In former projects numerical inlet boundary conditions had to be artificially adjusted in order to get a good agreement with measured surface pressures. Due to incorporation of the cavities within FUTURE such a non-physical modification is not necessary any more.

Figure 32. Unsteady results of subsonic operating point FMU150; left: measured and calculated flutter curves (for all IBPAs), right: measured and calculated unsteady blade surface pressures (example for one IBPA)
An extensive and comprehensive data base of unsteady pressures and aerodynamic damping has been created for a modern geometry compressor profile. This data base consists of

- 5 Operating Points (subsonic, transonic)
- All (20) IBPAs
- Unsteady surface pressures for 3 span positions
- Unsteady casing wall pressures

All the experimental efforts have been complemented by corresponding numerical analysis, thus enabling a fruitful exchange of information between the experimentalists and the analytical workers.

The accuracy and resolution of the measured unsteady pressures was sufficient to understand deviations between numerical and experimental damping results better. Global damping effects could be explained by local pressure effects. This is mandatory to improve the quality of the analytical tools further.

CTA turbine / AVIO Star Gate Rig

A series of free flutter experiments were performed at CTA at different aerodynamic operating conditions as part of the FUTURE project WP2 LPT Rotating Rig Flutter. In these experiments a complete turbine rotor row was tested with two different blade configurations (cantilevered and interlocked), and with several mistuning patterns:

- Tuned
- 0-1 Mistuning (alternate mistuning)
- 1-1-1-1-0 Mistuning (4 equal blades, 1 distinct)

The blade oscillations have been measured with an optical tip-timing system. Additionally unsteady hub wall pressures have been measured.

The mechanical damping of the rotor configuration was measured in a very sophisticated manner under rotation with a co-rotating magnetic excitation system in the vacuum at the AVIO rig.

The rotor was designed within the FUTURE project such that it should flutter in its tuned, cantilevered configuration at certain operating conditions and to be stable in the cantilevered, alternate mistuning configuration.

WP4 of the FUTURE project includes the realization of the post-test numerical computations (modal analysis, steady aerodynamics, and unsteady aerodynamics) required to reproduce the aeroelastic and dynamical behavior of the CTA experiment and AVIO experiment.

One major success in terms of validation was that for the cantilevered configuration

- In the tuned case both, the CTA experiment as well as the numerical results showed aerodynamic
In the tuned case both, the CTA experiment as well as the numerical results showed aerodynamic instabilities (flutter, limit-cycle oscillations)

In the alternate mistuning case both, the CTA experiment as well as the numerical results showed aerodynamic stable behavior

In the 1-1-1-1-0 mistuning case both, the CTA experiment as well as the numerical results showed approximately have the instability of the tuned case

Another very interesting finding is that in case of aerodynamic instabilities (flutter, limit cycle oscillation) several nodal diameters (or inter blade phase angles) can become unstable at the same time. In case of the experimental results this could be seen nicely in the unsteady hub pressure signal (see. Fig 4-8) since in the steady frame of reference (probe system) each nodal diameter corresponds to a different frequency, while in the rotor frame of reference the frequencies are almost identical. The analytical results of all partners (see Fig 4-9) all show a wide range of unstable nodal diameters (negative critical damping values), too.

In Figure 4-9 in addition the comparison of the numerical damping results to the measured mechanical damping from the star gate rig is shown: In case of the (measured) limit cycle oscillation the mechanical damping (black squares) is expected to equal the aerodynamic instability.

KTH turbine cascade

The KTH non-rotating turbine cascade comprises an annular sector of five blades one of which was made oscillating in controlled rigid-body modes. The unsteady pressure was measured during controlled blade oscillation on the oscillating blade itself and on two neighbour blades. The testing of the aeroelastic properties was hence done in the influence coefficient domain. Data were acquired at nominal operating conditions and severe off-design condition such as to force induce a massive separation on the pressure side. The intent was to assess the effect of this separation on the unsteady behaviour of the flow during blade oscillation. The figures below shows a sample comparison of the measured and predicted steady and unsteady pressure on the oscillating blade.

EPFL annular turbine cascade
The EPFL non-rotating annular turbine cascade comprises 20 oscillating blades, each one controlled by an independent excitation system. Three different experimental campaigns were conducted, for a total of nine distinct controlled vibration tests. The EPFL annular turbine tests served especially to validate the analytical prediction of the flutter behavior of packages of vanes or blades. In case of vane rows this is important since LPT vanes are often assembled out of vane clusters. In case of blades there exist concepts to have welded pairs of blades. The oscillating behavior and aeroelastic behavior of a cluster differs from that of a single vane or blade. In the EPFL annular turbine cascade such cluster modes have been excited in a controlled manner and unsteady pressures could be measured more easy and in more detail than in a rotating rig. Integrating over the airfoil surfaces allowed to derive aerodynamic damping values which in addition to the unsteady pressure fields could be compared for each blade between measured and experimental results. For a real engine application the resulting aerodynamic damping for one mode of a cluster of airfoils is obtained integrating over all surfaces within the cluster. The EPFL turbine experiment allowed to validate how much of the overall damping of one cluster mode is caused by which blade. An example for the comparison of numerical and experimental damping results of a 2-blade cluster mode is given in Figure 4-10.

It is validated that the participation of each of the blades to one cluster modes is distinct. The spreading of the numerical results as well as the difference to the experimental results show that there is still room for improvement of the tools.

Best Practice Guidelines

Best practice guidelines have been established for aeroelastic experiments and calculations. Both based on the lessons learned collected at the aeroelastic workshop at the end of the project. The partner expect those to be helpful when continuing research in following projects.

Potential Impact:

The project contributes directly to creating lighter, more efficient and safer aircraft engines.

In this perspective the main societal impact is related to reduced cost for design and manufacturing (keeping competition high and secure skilled jobs in Europe), reduced cost for airfares (allowing people easier travel) and reduced emissions (less environmental impact).

More specifically:

There is a significant need for well documented experimental data of various kinds related to aeroelasticity in turbomachines. Among these, results related to flutter as well as low engine order (LEO) excitations and structural mistuning / damping are highly difficult and expensive to obtain. Once these data exist it is of high importance to safe-keep and exploit them in appropriate matters. Properly taken into account, such data will be of significant scientific and industrial importance over more than a decade. Furthermore, it is
Data will be of significant scientific and industrial importance over more than a decade. Furthermore, it is important to have trained people who can understand the results and use them at the maximum benefit.

Although experimental data are of "real nature", they should always be accompanied by numerical calculations to detect any kind of missing information so that the experiments can be re-directed towards the eventual differences found between numerical and experimental results. This kind of experimental information is very expensive to obtain, and joint collaboration over national boundaries is almost a necessity.

Once the data have been obtained there should be exploitation in a coherent and organized way by different researchers. The amount of information is so large that it is difficult for a single company to consider all important aspects. The knowledge should also be transferred to "beginning engineers" as well as students in universities.

The main purpose of this exploitation strategy report is to chart and document the current and planned exploitation of the projects outputs. Exploitation will generally fall in one of three different categories, namely industrial, academic, and consortium, and this report aims to cover each of these categories. Further, the report discusses the possibilities for a wider dissemination of the project, i.e. the strategy for communicating the project objectives and results to a broader range of industries.

The partners have the following intentions related to dissemination and exploitation:

1: ALSTOM

1.1: Use of the FUTURE results

- Turbine configuration
  
o Understand differences between Flutter CFD prediction methods (an uncertainty of the CFD flutter method)
o Understand differences between FEM frequency prediction methods (an uncertainty of FEM prediction process, in particular frequency level)

- Turbine cascade configurations
  
o Validation case for Flutter CFD methods

- Flutter testing
  
o Best practice for detailed cascade measurement of flutter
o Best practice for measurement of turbine flutter, both mechanical and aeromechanical

2: TUD:

2.1: Use of the FUTURE results
2.1 Use of the FUTURE results

- the FUTURE project implemented a new field of research at the TUD transonic compressor
- the such established research focus is continued in nationally funded research projects (e.g. AG Turbo 2020, Vorhaben 1.2.3 „Aeroelastische Vorgänge im Blattspitzenbereich hochbelasteter Verdichter“, Förderkennzeichen 0327719D)
- and further continued in the Deutsche Forschungsgemeinschaft (DFG) funded research “Untersuchung der Wechselwirkung zwischen Blattspitzenströmung und Schaufelschwingungen in einem hochbelasteten Axialverdichter”, GZ: SCHI 913/5-1)
- for educating students in the field of aeroelasticity through bachelor/master theses and tutorials both experimentally (transonic compressor) and numerically (TRACE)
- for a new European commission co-funded research project proposal ARiAS for excellent collaboration in aeroelasticity on a European level
- for a new Deutsche Forschungsgemeinschaft (DFG) funded “Forschergruppe” in aeroelasticity with both cascade and rotating rig experiments for excellent collaboration in aeroelasticity on a national level (Germany)
- FUTURE results will also enable S. Leichtfuß and F. Holzinger to finish their doctoral theses

2.2 Dissemination of the FUTURE results

(In addition to the already mentioned 8 bachelor/master theses plus the input to the lecture “Verdichtertechnologie” plus CFD tutorials):

- 2012, ISUAAAT13, “Commissioning of the FUTURE Compressor”, Holzinger, F., Leichtfuß, S., Schiffer, H.-P. Östlund, J., Kharyton, V.
- 2013, Rolls-Royce University Technology Center Review, “Aeroelastic research on a transonic compressor”, Holzinger, F., Schiffer, H.-P.
- Yet to come (in 2014):

- journal publication of the FUTURE compressor experimental results
- conference publication of the FUTURE compressor experimental results
- doctoral thesis of F. Holzinger, TUD, that will in parts be based on FUTURE results
- doctoral thesis of S. Leichtfuß, TUD, that will in parts be based on FUTURE results
- post-project workshop at SIT
- post-project workshop at IC (this is not yet decided)
- continued numerical work on the FUTURE compressor geometry as part of bachelor/master theses

3: RR:

3.1 Use of the FUTURE results
3.1: Use of the FUTURE results

- Validation of RR flutter prediction capability for LPT
- Confirmation of impact of frequency mistuning on stability of LPT
- Validation of RR tools for predicting Limit cycle amplitude with different blade arrangements
- Refinement of BTT algorithms for processing noisy data
- Gained confidence for incorporating mistuning ideas into engine demonstrators

3.2: Dissemination of the FUTURE results

- Potential collaboration with IC/ITP/UPM on conference papers
- Build knowledge into in-house aeromechanics training

4: ECL:

4.1: Use of the FUTURE results

- It has been shown experimentally how gyroscopic effect affects resonance frequencies. This result suggests that mode calculations at high rotating speeds should be taken into account to provide reliable margin evaluations.
- Experimental modal parameters evaluation has been associated with specific uncertainty quantification. Automation of the procedure will be a valuable spin-off of Future for further analyses.
- The tests performed under vacuum at ECL on a rotating blisk have provided experimental FRFs at various rpm. Qualitative effect of rotation on mistuning has been characterized. Then, extra exploitation of experimental results will consist in building a representative model of this phenomenon.
- Mistuning identification has been processed following the best achievable eigenvectors strategy but other methods are available, especially inside the Future consortium (SIT, MTU). It is planned to compare mistuning identification methods on the basis of Future experiments.

4.2: Dissemination of the FUTURE results

- The steps of WP3 blisk design procedure are already included in academic material dedicated to engineers following initial training. They especially provide realistic values and orders of magnitudes concerning components that are usually not given to students for confidentiality reasons.
- A simplified FE model of WP3 blisk is already used to calculate modes. It enables students to split numerically the different effects governing rotating blading disks frequencies evolution.

Different standards of modal data exchange have been used with partners during the Future project, and will be reused more extensively in other works, making dialog easier between aerodynamics and solids mechanics specialists.

- Several lessons have been drawn from ECL’s Future experiments concerning the ideal modal characterisation of a rotating blisk with the perspective of assessing flutter risk: pre-test simulations, measurement strategy and validation issues have been addressed and they will be used for other projects such as those concerning the PHARE platform that is under construction in Lyon (http://www.ingenierie.at).
Such as these concerning the PHARE platform that is under construction in Lyon (http://www.ingenierie-at-lyon.org/accueil/equipex-phare/).

5: UPM:

5.1: Use of the FUTURE results

- CTA rig FUTURE flutter computational results will be used to set-up and check, new aeroelastic codes for both structural and aero computations.
- The results on the CTA rig (both, experimental and numeric) are extremely valuable as realistic examples for the aeroelasticity lectures.
- Also, the mistuned vs. tuned results of the CTA rig (both, experimental and numeric, and their very good agreement) are extremely good examples that will be used to improve the (frequently quite obscure) lectures on mistuning effects.
- The friction measurement on the CTA blades will be also used to improve turbomachinery aeromechanics teaching.
- And, finally, the whole set of results within all workpackages of FUTURE constitute an excellent dataset (both, experimental and numeric) that we will surely profit from in future Master Thesis and PhDs.

5.2: Dissemination of the FUTURE results

- A description of the FUTURE project results will appear in the official UPM research web page.
- A description of the FUTURE project results will also appear in the web page of our research group (http://web.fmetsia.upm.es/denlia/)
- The FUTURE project will be presented to the students when its results are used in graduate and undergraduate lectures.
- We are finishing several research works that started from FUTURE results; mainly related to Asymptotic Mistuning Model improvements for flutter calculations when the mistuning is not too small. In all the resulting presentations and papers, the seminal role of the FUTURE project will be appropriately acknowledged.

6: SUN:

6.1: Use of the FUTURE results

- The FUTURE project provided us with an enormous amount of test data for our own facility (velocity profiles, pressure data, etc) that can be used for the verification of future research.
- If required the FUTURE results can be used to upgrade and improve the operation of the blade excitation system.
- The FUTURE results obtained on the SUN rig will specifically be used for further research to model and investigate fluid-structure interaction on rotating compressor blades.
- The results will also be used to expand our local research to consider the deflection of large diameter axial flow fan blades under load.
- The results will be used as a starting point for research studies on turbomachinery flutter at SUN.
6.2: Dissemination of the FUTURE results

- Research lectures on project results to be given to students.
- Inclusion of section on aeromechanics in undergraduate teaching schedule.
- Project technical scope to be used as reference literature for post graduate students investigating aeromechanics.
- Relevant project report to be made available to post graduate students.
- The two MSc projects completed on the subject will be available on the SUN research repository.

7: CERFACS:

7.1: Use of the FUTURE results

- enhance harmonic balance predictions
- perform uncertainty quantification of the imposed phase lag on EPFL compressor cascade (360 simulation with a small shift of phase lag from one blade to another)

  o focus on TUD 1.5 stage configuration:
  o perform full 360 reference simulations

- test and assess new reduce order methods not available during FUTURE:

  o multi-frequecy harmonic balance on single blade passage
  o multi-phaselag simulations (developed at onera) on single blade passage

- use cascade cases for CERFACS internal turbomachinery training (mainly for new trainees and PhD students)

7.2: Dissemination of the FUTURE results

- submit a journal paper on expe/simu comparison on EPFL compressor cascade
- write a conference paper (ETC or Turbo Expo) to promote the paper
- show some test cases at ISAE engineering school lectures (http://www.isae.fr/en) and emphasize the scattering
- use one test case (a cascade) on practice works by ISAE students

8: TECHSPACE Aero:

8.1: Use of the FUTURE results

- An experimental reference for today aeroelastic tools calibration,
- An experimental reference for future aeroelastic tools calibration,
- A benchmark to compare TA performances in terms of flutter predictitons with respect to other companies on the market.
8.2: Dissemination of the FUTURE results

- Results are available at the aerodynamics department,
- Results were presented and are available to the projects having concerns about aeroelastic phenomena,
- Results are available at the department dedicated to vibrations analyses.

9: CTAero:

9.1: Use of the FUTURE results

- To prepare experiments for new European project proposals that will enable further understanding of flutter phenomena
- To use the lessons learned during the project in order to improve future test campaigns and reduce possible risks within them
- To qualify the laboratory technically, implementing measurement techniques utilized during FUTURE project
- To perform experiments in other technical fields that will benefit from the experience gained in FUTURE project
- To become part of a European industry, research institute and university group, that will focus on improving the competitiveness of European turbomachinery industry and research, in the field of turbomachinery aeroelasticity

9.2: Dissemination of the FUTURE results

- Through meetings with local universities
- Through description to partners in regional research projects (Airhem II)
- Through meetings with SME-s of the area

10: PCA:

10.1: Use of the FUTURE results

- The PCA capability in this area has been validated by participation in the Future programme.
- During the Future programme methods have been developed which are both more capable and much faster.
- These developments make activities in this area more attractive to clients.
- The activities being more attractive, we can expect greater activity.
- Greater activity will have benefits to PCA, clients(manufacturers) and end users.

10.2: Dissemination of the FUTURE results

- PCA are actively promoting this capability through discussion with clients.
  There is an article on their website explaining flutter together with a reference to the Future programme.
- There is an article on their website explaining flutter together with a reference to the Future programme.
- Dissemination will occur through client based active projects.
- PCA intend to publish results.
- PCA will train staff (and possibly the staff of clients) in the methodology.

11: UniFi:

11.1: Use of the FUTURE results

- improved knowledge about aeroelastic phenomena enhances flutter analysis
- numerical code validation against experimental data is an essential part of solver development and extension

11.2: Dissemination of the FUTURE results

- in scientific papers
- in master theses and PhD theses
- in courses for students

12: EPFL:

12.1: Use of the FUTURE results

- Based on the results develop/create new topics to investigate further in the specific field, probably leading to new projects
- Improve measurement techniques to avoid problems encountered during testing
- Use the results to teach, for example: use one of the problem descriptions as in FUTURE, discuss with students possible solutions to the problem, present employed solution technique done by the specialists worked in FUTURE, discuss results/encountered problems
- By using the results extend the content of Turbomachinery lectures
- Student projects

12.2: Dissemination of the FUTURE results

- Publish the results on conferences (presentation & papers) / journals / PhD thesis
- Teaching, include the FUTURE results
- Start a discussion forum for unsolved problems in the project
- Highlight main results on the lab homepage (of course if agreed by the consortium)

13: ONERA:

13.1: Use of the FUTURE results

Future project was a framework to assess the high-fidelity numerical tools used and developed at
- Future project was a framework to assess the high fidelity numerical tools used and developed at ONERA for turbomachine aeroelastic stability predictions.
- The experimental results data basis will be useful for the calibration of Onera elsA/AEL code and alternative method (reduced models, linearized approaches) for turbomachine aeroelastic simulation.
- Regarding new measurement techniques, Future was a good opportunity to implement the PSP measurement technique in a new field of application.
- The opportunity also to show the turbomachinery community the existence of this technique, its potential and its limitations.

13.2: Dissemination of the FUTURE results

- Publications with experimental/numerical comparisons using Future database.
- Dissemination of the elsA/ael code, subject to discussion and agreement for each cases.

14: CSIR:

14.1: Use of the FUTURE results

- The experience of building the excitation system will be used to develop other flutter excitation systems that the CSIR is actively developing
- The results from FUTURE have already led to a comprehensive plan for the improvement of the current system for testing turbomachinery systems
- The results, human resource development and experience from FUTURE have already been fed into the limited turbomachinery design capability within South Africa and will ultimately lead to safer and more efficient products in the field of turbomachinery
- The link between Stellenbosch University and the CSIR has been built most effectively through the FUTURE programme and further collaboration in related fields is anticipated.
- The networks developed with European partners will benefit European and South African research and development in future.

15: DLR:

15.1: Use of the FUTURE results

- Systemization and optimization of our numerical flutter predictions process (WP1 & WP3 results)
- Validation of interfaces between CFD and FEM codes (WP1 & WP3 results)
- Improvement of our physical understanding of EPFL Non-Rotating Annular Test Facility experiments (WP1 results)
- Comparison and analysis the quality our numerical tool with other numerical approaches (WP1 & WP3 results)
- Handling of complex mode shapes (WP3 results)
- Improved understanding of flutter physics?

Steady-state CFD Solution: static pressure distribution on the blades is important to judge the quality of the flow prediction in the passage, especially at transonic flow conditions.
the flow prediction in the passage, especially at transonic flow conditions.

- For structural dynamic simulations of configurations, especially with a strong structural coupling between the blades like interlocked blade configurations, the FEM modeling approach should include complex modes formulations.

- Education of PhD students within the 4 years of the project:

  - DLR educated one PhD student during the project (duration: 4 years). From this point of view, the FUTURE project was efficient: the average duration of PhD education at DLR is rather within the range of 5 to 7 years but due to the wide panel of experiments (non-rotating, rotating, compressor, turbines,…), the student developed a wide overview of the turbomachinery aeroelasticity domain in a reduced amount of time.

- Short-Term Exploitation. In the short term, the following project outcomes are expected to be exploited by the industrial partners:

  15.2: Dissemination of the FUTURE results

  - Formation of students and PhD students
  - Validation of TRACE code
  - Experience in the design of future flutter experiments
  - Better understanding of former discrepancies between measurements and CFD results for EPFL test rig (for future experiments associated to the test rig)
  - Data standardization to ease and optimize the communication between the partners
  - Common Database for More Effective Exploitation and Dissemination. After the end of the project:
    - The project results will be used for the validation of the CFD codes used at DLR and the improvement of aerodamping prediction methods.
    - The results will also be compared between several partners.

16: KTH:

16.1: Use of the FUTURE results

- PhD, Tek Lic, MSc students have had the possibility to participate in the research in various ways
- The Pressure Sensitive Paint progress have already allowed the methodology to be used in another test-rig. This has been part of a Tek Lic thesis. The methodology will be explored more in the future
- Lecture material from different partners has been collected and will be introduced into a Massive On-line Open Course through a new e-learning platform under development (E3L)
- The FUTURE collaboration was instrumental in the preparation of the THRUST MSc program
- There will be an attempt for an application towards a PhD program THRUST+ within ERASMUS+
- The knowledge obtained in FUTURE will be essential as background for the preparation of the Horizon2020 application “ARIAS”
- The knowledge is applied in two national projects involving PhD students (Turbopower; National Aeronautical Research Program)

16.2: Dissemination of the FUTURE results
16.2: Dissemination of the FUTURE results

- Results from FUTURE have been used in 3 PhD theses
- And in one Tek Lic thesis
- 6 MSc thesis projects have been performed directly related to the FUTURE project, and several more indirectly related.
- Knowledge and results introduced into MSc and PhD level courses

17: Turbomeca:

17.1: Use of the FUTURE results

- First of all: finalizing the construction of the data bases and (ideally) distributing them to the consortium
- Continuing the exploitation of these data bases to validate codes and new methodologies
- Extend the initial fields of interest to other components (LPT for Turbomeca for ex)
- Strong basis for new projects

17.2: Dissemination of the FUTURE results

- TM technical internal review realized six months after the end of the project: involving research program team, compressor and turbine design teams

18: SIEMENS:

18.1: Use of the FUTURE results

- Analytical findings vs. experimental results have highlighted critical flaws in the in-house flutter prediction tool for engine-relevant transonic compressor blade operation, including mesh sensitivity and boundary treatment.
- Numerical tool validation efforts are underway, including in-house and commercial flutter codes.
- Improvement of the aeromechanical prediction process, i.e. linking of involved numerical tools such as FEM and CFD programs, scripts, etc., to enhance and ensure consistency, quality, and speed.
- Aeromechanical prediction and design guidelines for low pressure turbines will be critically reviewed based on FUTURE experimental findings.
- Performed tip-timing data acquisition identified a definite need to improve signal processing and analysis techniques to reduce uncertainties in damping quantification. Ongoing work.
- Performed tip-timing data acquisition further identified a need to improve signal processing and analysis techniques to properly quantify modal contents during severe non-synchronous events such as stall. Ongoing work.
- Short-comings became evident related to proper procedures for performing high cycle fatigue assessments in the finite life regime, which are now being addressed.

18.2: Dissemination of the FUTURE results

Data and findings have been shared within the aeromechanical community inside Siemens to ensure
Data and findings have been shared within the aeromechanical community inside Siemens to ensure quality validation over a wide range of tools and applications. A number of conference publications have been and will be issued, both by SIT alone and jointly with FUTURE partners, that are based on FUTURE experimental data and associated numerical work. The educational material connected to an internal course on “Turbomachinery Technology” will be improved with examples of evaluations based on FUTURE data. The presentation material related to industrial guest lectures within the THRUST and Energy Technology M.Sc. programs at KTH will be updated with evaluations and findings stemming from the FUTURE project.

19: SNECMA:

19.1: Use of the FUTURE results

- Results from KTH and EPFL test cases: analysis of fundamentals aerodynamics phenomenon involved during flutter
- Results from WP1: used to improve modeling practices regarding numerical parameters (turbulence modeling, temporal resolution, ...)
- Results from WP2: used to improve understanding of flutter in low pressure turbine (which configuration(s) seem(s) prone to flutter)
- Results from WP3: used to quantify the importance of modeling the surroundings of the rotating row during flutter prediction calculations
- Results from WP4: used to sort modeling practices currently used for flutter prediction and attempt to quantify their pertinence

19.2: Dissemination of the FUTURE results

- Incorporation of FUTURE deliverables into the Snecma documents Data Base
- Presentation of the results during internal meetings (SAFRAN Group internal)
- Raw experimental results made available to anyone on the company so further analysis can be made using Snecma tools for experimental data post processing
- FUTURE test cases used for internal PM (Pratiques de Modélisation or Modeling Practices) documents updates

20: GKN Aerospace:

20.1: Use of the FUTURE results

- Validation and improvements of aero design and verification tools
- Validation and improvements aeroelastic design and verification tools
- Implement findings in ongoing and future development programs of rotors
- Implement developed experimental methods in ongoing and future development programs of rotors
- Update GKN design practice for aeroelastic analysis
- Further analysis and exploitation of results in national (e.g. TURBOVIB and TURBOKRAFT) and future international research programs
- Use findings as input to gap analysis and definition of roadmap for continued aeroelastic research work
20.2: Dissemination of the FUTURE results
- Continue to support publishing of FUTURE results done by the academic partners
- Use results in future research programs and participate in conferences and workshops
- Present FUTURE results findings at seminars and lectures to students
- Use results in thesis works

21: ITP:

21.1: Use of the FUTURE results
- EPFL data has already been used to further validate the linearized code know as MusT-L which is currently used in production
- CTA rotating turbine mistuned configuration data have been used to obtain TRL4 for the use of mistuned configurations and to convince the management to go for a dedicated proof of concept of a mistuned configuration inside Clean Sky in the SAGE3 demonstrator. TRL6 will be obtained by means of the testing of this mistuned configuration.
- TUD compressor data has already been used to validate MusT code for compressors. The whole compressor map has been simulated and compared against experimental data in a side dedicated effort.
- Flutter simulations of the TUD compressor are planned in the short term.
- Systematic use of the STARGATE friction data to derived and calibrate friction models is planned but activities have not already started

List of Websites:

www.future-project.eu

Related documents

![final1-ftr-5-93.pdf](final1-ftr-5-93.pdf)

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