Giornata di Studio sulle Turbomacchine

Bergamo 15 Luglio 2016

A survey of experimental and numerical analyses for turbomachinery applications: The UNIFI DIEF experience

Antonio Andreini Michele Marconcini

Dipartimento di Ingegneria Industriale – DIEF
Università degli Studi di Firenze
Turbomachinery research teams at DIEF

**REASE Group**
Prof. G. Ferrara
- Centrifugal compressors
- Advanced measurement systems
- Wind Energy

**TCR Group**
Prof. F. Martelli
- CFD modelling for gas turbines
- Combustor/Turbine interaction
- Centrifugal pumps and bearings

**HTC-Group**
Heat Transfer Combustion
Prof. B. Facchini
- Internal heat transfer, Film cooling
- Combustor/Turbine interaction
- Experiments and CFD

**T-Group**
TRAF Group
Prof. A. Arnone
- CFD e design
- Aeroacoustics, Aeroelasticity

**LSMM-Group**
Prof. M. De Lucia
- Experimental investigation of aeroacoustics
- Noise

**SERG Group**
Prof. G. Manfrida
- ORC cycles
- Wet Gas Test Facility
Part I

T-Group – TRAF Group
Prof. A. Arnone
- CFD e design
- Aeroacoustics, Aeroelasticity

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speaker
Michele Marconcini
T-Group – TRAF Group

Prof. A. Arnone

— Prof. R. Pacciani
— Assistant Prof. M. Marconcini
— Post. Doc.
  J. Bellucci, M. Checcucci,
  M. Giovannini, L. Pinelli,
  F. Poli, F. Rubechini
— 4 Ph.D. candidates
Long lasting collaboration with **GE Avio Aero**
for the **design** of **Low Pressure Turbine (LPT)** HL/UHL blades operated at low Re in steady and periodic unsteady conditions.

Collaboration with **Mitsubishi Heavy Industries (MHI)** for the analysis of turbochargers.

Collaboration with **Termomeccanica Pompe (TMP)** for the parametric design of industrial pumps.

Collaboration with **Avio** for the design of cryogenic pumps for rocket engines.
CFD applied to Turbomachinery Design and Analysis

T-Group – Prof. Andrea Arnone (andrea.arnone@unifi.it) – http://tgroup.unifi.it

Long lasting collaboration with **Ansaldo Sviluppo Energia (ASEN)** for the design of:
- Transonic axial compressors
- Heavy duty axial turbines
- High and low pressure steam turbines

Long lasting collaboration with **GE Oil&Gas** for the design of:
- HP and LP steam turbines
- ORC turbo expanders
- Centrifugal compressor
Aeroelasticity – Flutter & Forced Response

T-Group – Prof. Andrea Arnone (andrea.arnone@unifi.it) – http://tgroup.unifi.it

- **Study of the interaction** between **fluids and elastic bodies**
- **prevention of high cycle fatigue** (HCF) in turbomachinery due to flutter & forced response
- **Flutter** → “self-excited” aeroelastic blade vibration
- **Forced response** → vibration caused by external perturbations acting on the bladerows

**Campbell Diagram**
- O → Forced Response
- X → Flutter

**Compressor Row Deformation**

**Rotor/Stator Interaction**

**Partners:**
- Avio Aero
- ANSALDO ENERGIA
- General Electric
Aeroelasticity – Applications

T-Group – Prof. Andrea Arnone (andrea.arnone@unifi.it) – http://tgroup.unifi.it

- **Flutter stability assessment** with linearized & non-linear in-house codes
  - Fan, Low Pressure Turbine, Low Pressure Compressor, Steam Turbine
- **Blade flutter stabilization design**
  - Row mistuning
- **Forced response estimation**
  - Campbell diagram & input for dynamic analysis
- **EU projects on Aeroelasticity**
Aeroacoustics – Tone & Core Noise

T-Group – Prof. Andrea Arnone (andrea.arnone@unifi.it) – http://tgroup.unifi.it

- **Study of noise of aerodynamic origin** → generation & propagation
  - aircraft noise as environmental pollution
  - Fan, Core Engine, Turbine, Jet
- **Development of low-noise design methods**
- **Tone noise** → generated by rotor/stator interaction at BPF (Blade Passing Frequency)
- **Core noise** → direct & indirect noise coming from combustion chamber and interacting with turbine
- Partner: AvioAero
Aeroacoustics – Applications

T-Group – Prof. Andrea Arnone (andrea.arnone@unifi.it) – http://tgroup.unifi.it

- **Tone & core noise emission evaluation** in multi-stage environment with in-house frequency and time-domain solvers
  - High Pressure & Low Pressure Turbine
- **Semi-analytical methods for preliminary acoustic design**
- **Acoustic duct characterization**
  - Cut-on/Cut-off analysis
- **Numerical models for acoustic liner**
- **EU projects on Aeroacoustics**

**Tone Noise Generation & Propagation**
REASE Group

Prof. G. Ferrara

- Assistant Prof.:  
  L. Ferrari, A. Bianchini

- Post. Doc.:  
  F. Balduzzi, A. Fioravanti, L. Romani, I. Stiaccini, G. Vichi

- 5 Ph.D. candidates
Experimental and numerical analysis of rotating stall in centrifugal compressors

REASE Group - Prof. Giovanni Ferrara (giovanni.ferrara@unifi.it)

A several-years research cooperation is going on between GE Oil&Gas and DIEF (REASE Group) on Vaneless Diffuser Rotating Stall. Many aspects have been investigated so far, among which:

- Effect of the diffuser geometry, pinch, Reynolds number, etc. on stall inception and characteristics
- Development of new correlations for critical stall angle estimation
- Spatial reconstruction of stall pattern inside the diffuser
- Effects of the stall force on the rotordynamic behavior of the compressor
Test rig for advanced analyses in centrifugal compressors

**VISION:**

- **BE FLEXIBLE** → systematic use of multiple stage configurations with limited time and cost
- **PRODUCE RESULTS REALLY TRANSFERABLE TO ACTUAL MACHINES**
- **ENABLE ADVANCED ANALYSES**, both in terms of test methodology and of measurement systems
- **MINIMIZE STRUCTURAL COMPLEXITY, DIMENSIONS AND COST** → sustainable also in an academic context

**REASE Group - Prof. Giovanni Ferrara** (giovanni.ferrara@unifi.it)
Advanced measurement systems for turbomachinery

**REASE Group - Prof. Giovanni Ferrara (giovanni.ferrara@unifi.it)**

Development of innovative sensors and measurement techniques with direct application in turbomachinery analyses

- **Fast Response Aerodynamic Pressure Probes based on a Waveguide Approach**
  - Virtual 3-hole-probe with the sensors located far from the measurement point (waveguide)
  - Virtually insensitive to temperature effects
  - Tested to frequencies up to 5 kHz
LSMM-Group

Prof. M. De Lucia

— Post. Doc.

F. Taddei, G. Pierucci, M. Messeri

— 3 Ph.D. candidates
Experimental analysis of Aeroacoustic Noise in Aeronautical Turbines

LSMM-Group, prof. M. De Lucia

Relying on a 10-years-lasting partnership with GE Avio, the research activity of the LSMM group at DIEF is dedicated to the experimental analysis of aero-engine noise.

- Experimental analysis of aeroacoustic noise sources in aeronautical turbines:
  - DIEF Annular wind tunnel for tone noise analysis
  - Development of advanced noise measurement techniques
    - Set-up of radial/axial sensor arrays
    - Dynamic calibration of noise measurement devices

- Experimental investigation of passive noise reduction systems in aero engines
Experimental analysis of Aeroacoustic Noise in Aeronautical Turbines

LSMM-Group, prof. M. De Lucia

Relying on a 10-years-lasting partnership with GE Avio, the research activity of the LSMM group at DIEF is dedicated to the experimental analysis of aero-engine noise.

- Development of noise-data processing tools:
  - Modal decomposition of 3D acoustic fields
    - Tone noise analysis
    - Broadband noise analysis
  - Signal enhancing methods for rotating machinery
Part II

SERG Group
Prof. G. Manfrida
– ORC cycles
– Wet Gas Test Facility

TCR Group
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Prof. B. Facchini
– Internal heat transfer, Film cooling
– Combustors
– Combustor/Turbine interaction
– Experiments and CFD

speaker

Antonio Andreini
SERG Group

Prof. G. Manfrida

- Prof. D. Fiaschi
  - Post Doc
    - Riccardo Secchi
  - PhD Candidates
    - Lorenzo Talluri, Karolina Petela
Wet Gas Test Facility

SERG Group – Prof. G. Manfrida, Prof. D. Fiaschi

- Wet Gas Test Facility
- THT Lab premises (Prof. Facchini)
- Rig designed to test Oil&Gas equipment operating with wet/gas fluids

Air

<table>
<thead>
<tr>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air flow rate</td>
<td>0 - 0.9 [kg/s]</td>
</tr>
<tr>
<td>Air flow Temperature</td>
<td>0 - 150 [°C]</td>
</tr>
<tr>
<td>Operating Pressure</td>
<td>101 - 550 [kPa-a]</td>
</tr>
</tbody>
</table>

Water

<table>
<thead>
<tr>
<th>Range</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water flow rate</td>
<td>0 – 4.16 [kg/s]</td>
</tr>
<tr>
<td>Water line pressure</td>
<td>400 - 1200 [kPa-a]</td>
</tr>
<tr>
<td>Number of Atomization nozzles</td>
<td>1 - 17</td>
</tr>
<tr>
<td>Drop diameter</td>
<td>150 - 800 [μm]</td>
</tr>
<tr>
<td>Liquid Mass Fraction</td>
<td>0 – 72.5 [%]</td>
</tr>
</tbody>
</table>
Mini and micro Radial turboexpanders for ORC

SERG Group – Prof. G. Manfrida, Prof. D. Fiaschi

- Low to Micro size (5 – 50 kW)
TCR Group

Prof. F. Martelli

- Research fellows
  - S. Salvadori
  - A. Cappelletti, M. Insinna

- 1 PhD candidate
Unstructured in-house CFD code for compressible flows

TCR Group – Prof. Francesco Martelli, Dr S. Salvadori, Dr M. Insinna

- In-house HybFlow CFD code developed since 1999
  - Finite Volume approach for hybrid unstructured mesh
  - 2nd order accurate in space and time, 2nd gradient reconstruction
  - Implicit time-marching and explicit Runge-Kutta approaches
  - Turbulence modeled using eddy-viscosity assumption (k-ω, SST)
  - Transition modeled using intermittency function (γ-Reθ) or k-ε-kl
  - DNS-, LES- and DES-able code with inlet fluctuation methods
  - Able to perform conjugate heat transfer analysis in HPT
  - Fully coupled unsteady approach (phase lag and domain scaling)
  - Parallel computing, optimized for CINECA HPC resources
  - Used in Uncertainty Quantification analysis (MCM, PCM)

Energy Procedia 10.1016/j.egypro.2015.12.133

WSEAS Trans Fluid Mech 6(3):160-173

ASME J Turbomach, 10.1115/1.4007836

UQ-NLES
Combustor/turbine interaction with in-house methodologies

TCR Group – Prof. Francesco Martelli, Dr S. Salvadori, Dr M. Insinna, Eng. D. Griffini

- In-house development of methodologies for the study of aero-thermal combustor/turbine interaction
- Use of coupled solvers (ANSYS Fluent®/HybFlow) with various approaches (RANS or URANS, Hybrid SAS/URANS)
- Study of complex real-machines effects
  - Complex geometries (fillets, clearances, etc...)
  - Real cooling configurations
  - Realistic boundary conditions at the turbine inlet
- High-fidelity reproduction of turbine inlet conditions for metal temperature prediction and aerodynamic analysis

J Turbomach 2016
DOI: 10.1115/1.4031864

Swirl migration (ASME GT2014-25433)

Metal temperature with combustor swirl

ASME GT2012-69038
Numerical prediction of the Morton effect

TCR Group – Prof. Francesco Martelli, Dr S. Salvadori, Eng. D. Griffini

- Developed in cooperation with GE Oil & Gas and the MDM Lab of DIEF, the in-house data processing tool SNAPSHOT allows to individuate the presence of rotordynamic thermal instabilities using a quasi-steady approach. The code is coupled with an in-house CFD tool for the thermo-hydrodynamic analysis of tilting-pad journal bearings, originally developed for Worthington.

Stability Analysis Results

Data from Taniguchi et al., ASME J Tribology, 1990, 112:542-550
Analysis of centrifugal pumps

TCR Group – Prof. Francesco Martelli, Dr S. Salvadori, Dr A. Cappelletti

- Long term cooperation with WEIR-Gabbioneta SRL for the development of numerical tools for analysis and design:
  1. Experimental and numerical analysis
  2. Residual axial thrust evaluation with uncertainty quantification
  3. Cavitation modelling
  4. Component interaction
  5. Leakage flows characterization

EACFM, 10.1080/19942060.2012.11015420
HTC-Group – Heat Transfer and Combustion

Prof. B. Facchini

– A. Andreini, Prof. C. Carasci
– Post Docs
  • A. Picchi, L. Mazzei
  • A. Innocenti, L. Winchler, T. Fondelli
– 10 PhD candidates
Experimental analysis of turbine internal cooling

HTC-Group – Prof. B. Facchini – www.htc.unifi.it

- TLC and IR thermography of cooling schemes
  - Heat Transfer coefficient measurement
  - Static and rotating rigs

Collaborations
- AnsaldoEnergia
- Avio Aero
- GE Oil & Gas

Research Projects
- EU FP6, FP7 programs (2001-2013)
- PRIN2007, PRIN2010
Film cooling investigations

HTC-Group – Prof. B. Facchini – www.htc.unifi.it

- Measurement of adiabatic film effectiveness
  - Pressure Sensitive Paint (PSP) technique

- MS5002E S1B, S1N

- Trailing Edge film
Secondary Air System

**HTC-Group – Prof. B. Facchini – www.htc.unifi.it**

- **Stator Rotor cavities**
  - heat transfer, sealing, windage losses

- **Seals**

**MAGPI**

**Avio Aero**

Effects of cooling air supply geometry on sealing and cooling performances

- Windage losses
- Heat transfer
  - Thermocromic Liquid Crystals
- Internal flow field
  - Traverse system
    - Hot wire anemometry
  - PIV

**Rotating rig for investigation on fundamentals**

- Friction factor analysis for flow leakage prediction
- Acoustic analysis

**Honeycomb seals for centrifugal compressors**
CFD investigation of turbine cooling

HTC-Group – Prof. B. Facchini – www.htc.unifi.it

- RANS and Scale-resolving methods (SAS, DDES, LES)
  - Support experimental tests
- Film Cooling modelling

Test rig geometry

Scale-resolving CFD of impingement cooling

FCM – Film Cooling Modelling

Replace of film cooling holes by localized source clouds

PRIN 2010/2011 INSIDE
Aerothermal Investigation of cooled Stage turbine: Design optimization and Experimental analysis

NASA C3X 1988
MS5002E
Conjugate Heat Transfer

HTC-Group – Prof. B. Facchini – www.htc.unifi.it

- Decoupled iterative methodologies
  - Thermal design tools
- Full CHT

Recent development → BANKS 3D (GE Oil&Gas)
- Coupling with 3D FEM and 3D CFD through Ansys Workbench environment
- New Flow-Network solver
- Validation with actual engine data and literature tests (NASA C3X)

Since 1993 with...

NASA C3X 1988
Windage and lubrication in gear boxes

HTC-Group – Prof. B. Facchini – www.htc.unifi.it

- Testing and modelling of windage losses in high speed power gearboxes

High speed rotating test rig (15000 rpm)

Meshing gear modelling

Flow field

Lubricating oil jet

High speed camera

CFD VOF
A survey of experimental and numerical analyses for turbomachinery applications:
The UNIFI DIEF experience

Antonio Andreini         Michele Marconcini

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