Compressor off-***D***esign ***Op***eration (*CoDOp*) Project

Summary: Use advanced experimental and computational techniques with the purpose of predicting and understanding compressor surge

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Framework: CoDOp

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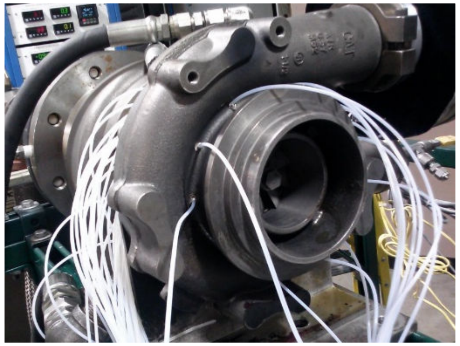
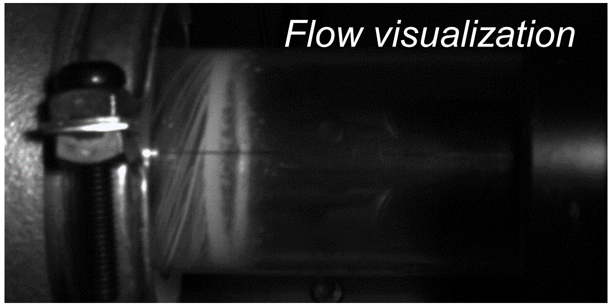
STEM & Swedish automotive industry supported project

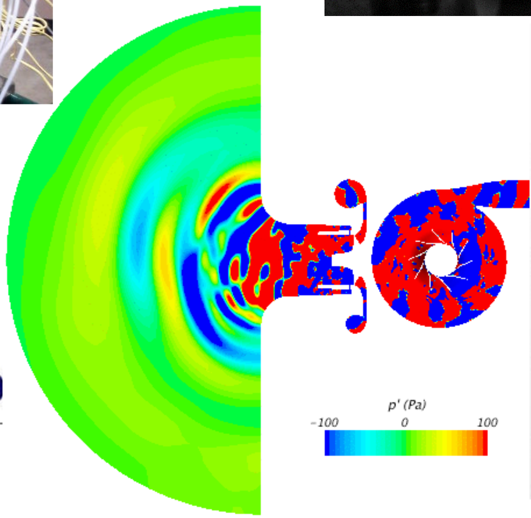
- *VT 2013 - HT 2017* "***CoDOp***" *project*
- *KTH-MWL, KTH-ICE, KTH-CICERO, KTH-Mek (applied CFD)*
- *Partners/Collaborators: SCANIA, Volvo Cars/GTT, BorgWarner, Univ. of Cincinnati*

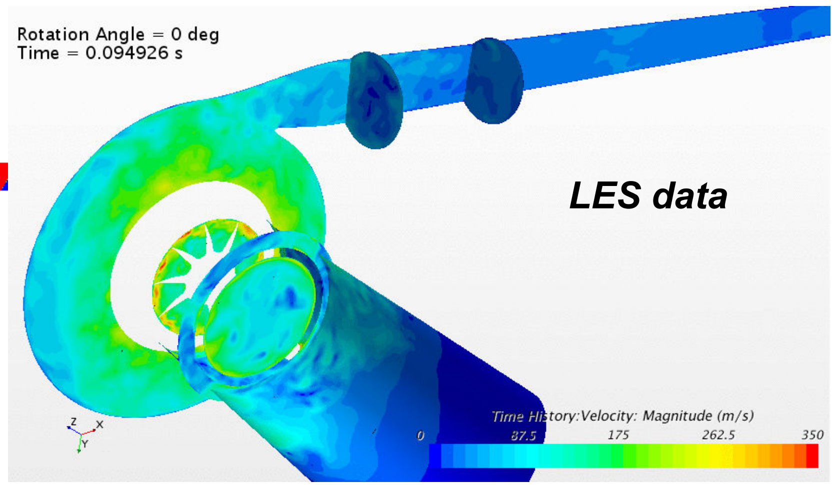
Pressure measurements





Swedish Energy Agency





Overview: CoDOp

WHY

Increase compressor operation range and efficiency using a physics-based approach for understanding the flow instabilities and surge inception phenomenon

Build knowledge for developing viable control technologies for flow instabilities to allow compressors operating safer and more silent over a broader operating range

HOW

- High-fidelity simulations & detailed experiments
- Develop methods for stall/surge identification

- Flow & Acoustic characterization
- System interaction, i.e. ICE & Turbocharger

Industry Input
Volvo Cars (engine maps)
Borg Warner (geometry, maps)
SCANIA & Volvo GTT

Activities

Compressor & ICE
Bertrand Kerres, PhD stud Exp,
CICERO/ICE; 0D/1D surge models

Compressor inlet piping

flow field

Turbomachinery response
- compressor map
- flow instabilities
- aeroacoustics

back pressure / pulses

Intake engine manifold

boost pressure

Internal Combustion Engine

CFD, surge, piping (Mek)
Elias Sundström, PhD stud
High-fidelity LES, models

Acoustics (MWL)
Raimo Kabral, PhD stud
Exp. Acoust. & 1D modeling

Aeroacoustics (MWL/Mek)
NN, Ind PhD stud Volvo CC
CAA & 1D modeling

Input/output to/from HOTSIDE project: on turbocharger assessment and holistic system view

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Project Aims

- Improve understanding of the flow at off-design conditions
  - high-fidelity simulations and experiments
  - quantify the flow instabilities with advanced mode decomposition techniques
- Quantify the geometry installation effects on the on-set of flow instabilities and surge
  - effect on compressor performance
- Aeroacoustics characterization of compressor surge
- Develop and /or adopt methods for stall/surge identification
- Surge inception scenario definition

Doctoral students:
Elias Sundström, (CFD), Mek
Bertrand Kerres (Exp), ICE
Raimo Kabral, (Acoustics), MWL
NN, (Aeroacoustics), MWL/Mek

Reference group:
Lucien Koopmans, Volvo Cars
Magnus Knutsson, Volvo Cars
Ragnar Burenius, Volvo Cars
Johan Wallesten, Volvo GTT
Magnus Ising, Volvo GTT
Robert Eriksson, VCE
Said Tabar, VCE
Per-Inge Larsson, Scania
Thomas Svensson, Scania
Jonas Holmborn, Scania
Thomas Lischer, Borg Warner
Tom Heuer, Borg Warner
Marc Gugau, Borg Warner

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Highlights & Plans: CoDOp

PROJECT HIGHLIGHTS (start VT2013):

- Verification & Validation phase for LES solver completed (experiments: Dr. Gutmark, U. Cincinnati)
- Compressor noise assessment under design and off-design conditions (experiments & simulations)
- Compressor maps for two BorgWarner compressors covered by using RANS (VEP-MP & VEP-HP)
- Experimental assessment of upstream installation effects on surge line (Garrett)
- Preliminary evaluation of models for predicting compressor surge (Mek-MWL-ICE)

SHORT & LONG TERM PLANS:

- Detailed experimental and computational efforts on the BorgWarner compressor (flow & acoustics)
- Evaluation / calibration /development of compressor surge models
- Licentiate thesis for Elias Sundström is planned for VT2016; New Industrial PhD student on Compressor Aeroacoustics (VCC) to be recruted by VT2016
- Focus on BorgWarner geometries by BW TurboSystems Engineering GmbH
- Apply for EU project calls (Ho2020) and other national/international funding opportunities

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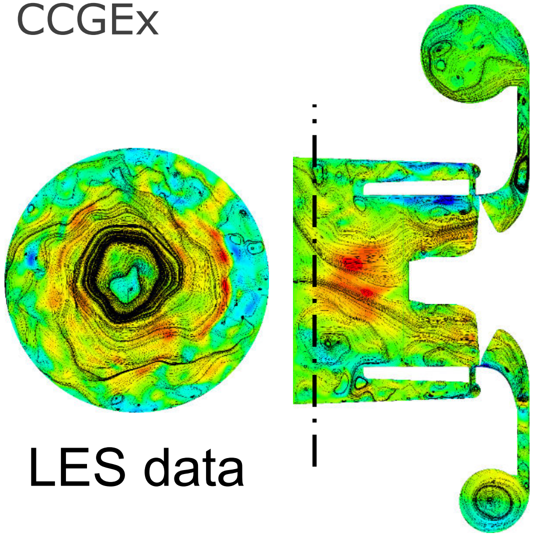
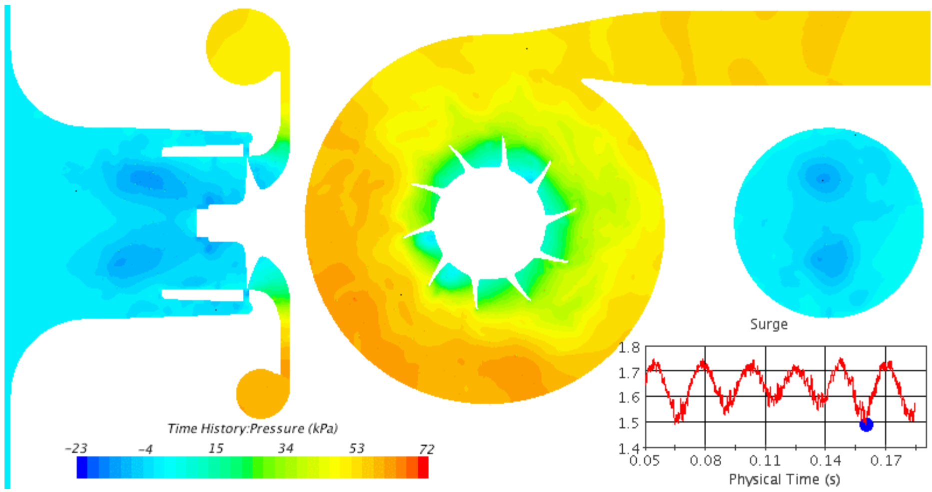
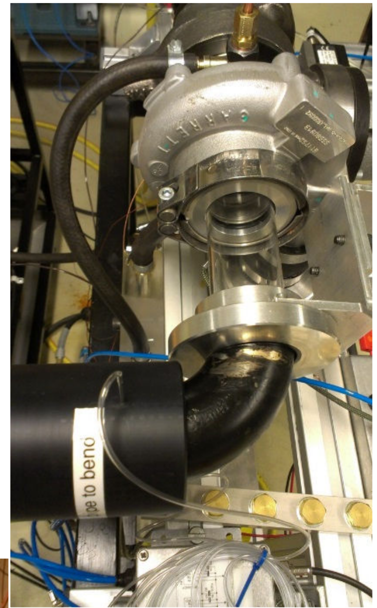
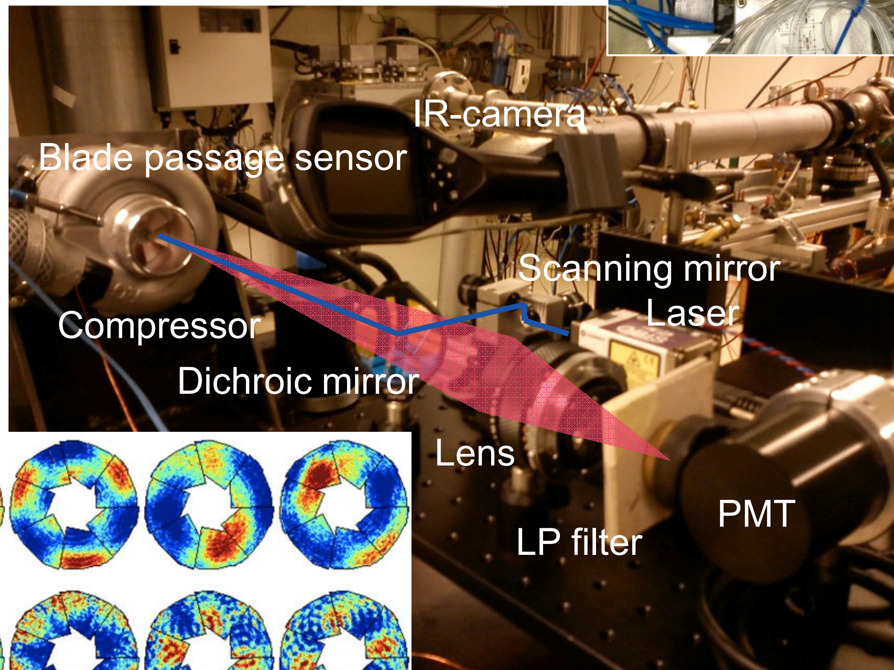
Interdisciplinary investigation of surge phenomenon in centrifugal compressors

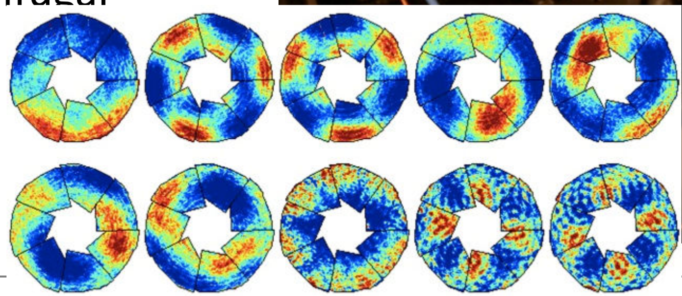






- PSP/TST measurements carried out for the first time on a rotating compressor wheel
- Compressor flow instabilities quantified using POD/DMD analysis of data
- Assessment & enhanced understanding of noise generation process associated with centrifugal compressors
- http://www.ccgex.kth.se/publications





Pastruhoff M., (2014) "Measuring with presure sensitive paint in time-varying flows", PhD Thesis, ISBN: 978-91-7595-246-8

LES of Flow Instabilities related to Compressor Surge

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Doctoral student:
Elias Sundström (CFD), Mek

Supervisors:
Mihai Mihaescu
Laszlo Fuchs

DOCTORAL PROJECT CONTENT/SCOPE:

1. Understand flow instabilities in centrifugal compressors precursor to surge
2. Understand flow and acoustics coupling phenomena related to compressor surge
3. Define possible criterion for surge inception based on advanced unsteady data analysis
4. Assess installation effects on compressor flow instabilities and surge
5. Assess analytical models for prediction of compressor surge

PROJECT RESULTS:

- Flow instabilities at off-design conditions quantified based on high-fidelity simulations (Honeywell compressor); the responsible modes were exposed. Noise generation and propagation phenomena captured. Good agreement with experimental data from Univ. of Cincinnati (SAE 2014-01-2856, AIAA 2015-2674)
- Compressor maps for two different BorgWarner compressors computed with RANS. Good agreement with gas-stand experiments. Similarities in flow phenomena exposed. (ICJWSF2015 conference contribution)

FUTURE PLAN, SHORT & LONG TERM:

- Analyze, compare, and summarize the flow & aeroacoustics data on Honeywell compressor; assess the noise generation mechanisms; write journal-quality manuscript.
- Licentiate thesis defense planned for VT2016
- Complete the analysis of RANS data (BW) to identify loss mechanisms in the compressor for different operating conditions
- Assess the upstream pipe installation effects on compressor surge (BorgWarner compressor)

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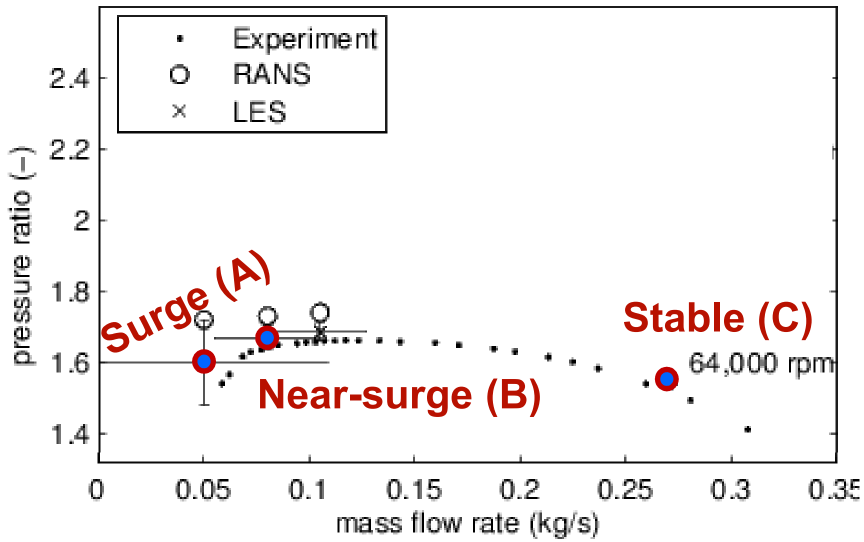
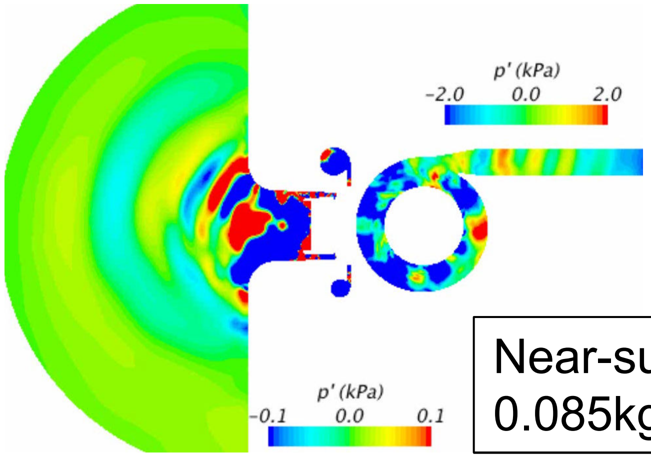
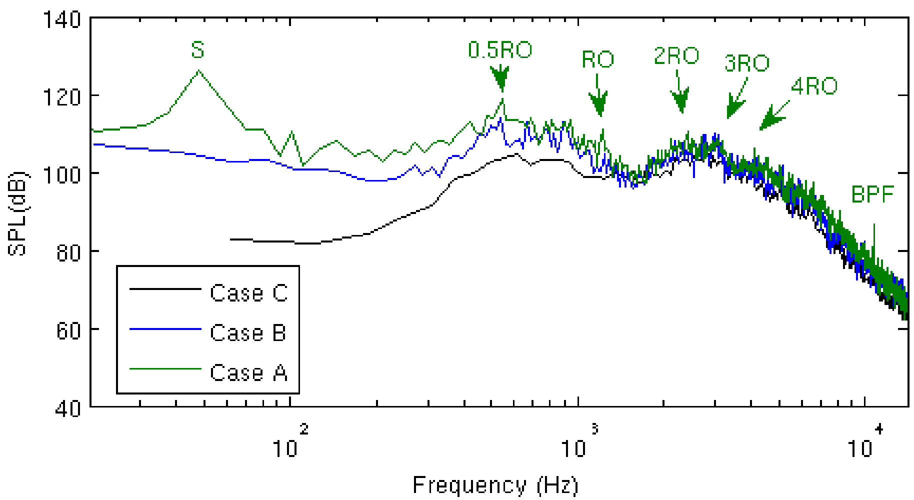
Flow and Acoustics Assessment (Honeywell compressor)

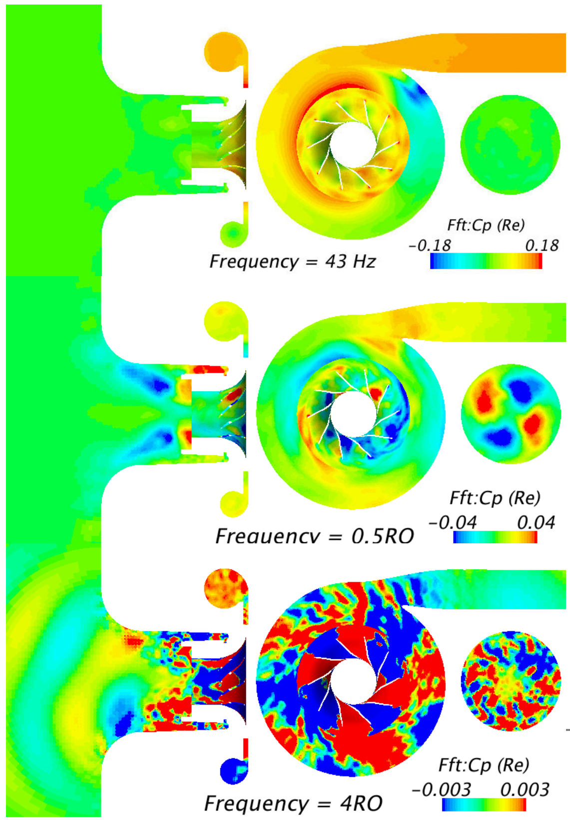
- Amplified SPL towards surge
- Broadbanded features around 0.5RO and 3RO
- Wave generating mechanisms captured with LES. Assessment with surface spectra and flow decomposition (POD/DMD)

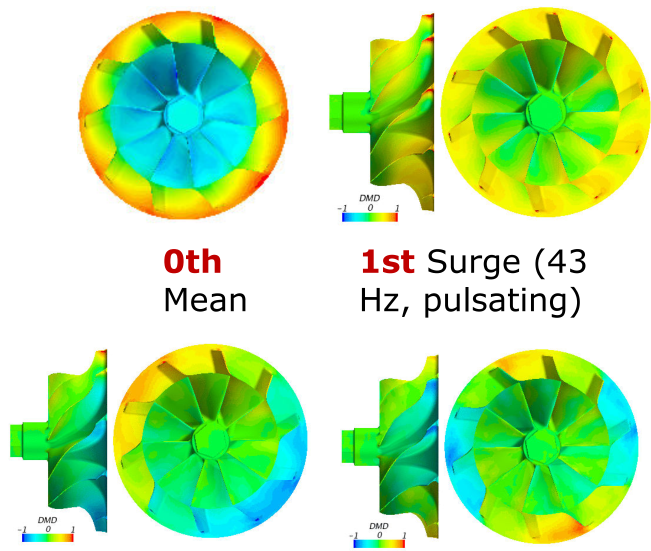




Near-surge (B): 0.085kg/s







0th Mean

1st Surge (43 Hz, pulsating)

2nd RO (1069 Hz, spinning mode)

6th 2*RO (spinning mode)

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Compressor maps for engine installations

DOCTORAL PROJECT CONTENT/SCOPE:

1. Understand the effect of different inlet geometries on compressor surge
2. Investigate parameters for the detection of surge onset
3. Evaluate theoretical models for compressor performance prediction and surge dynamics
4. Compare compressor characteristics on cold gas stand with on-engine measurements

Doctoral student:
Bertrand Kerres (Exp), ICE

Supervisors:
Andreas Cronhjort
Mihai Mihaescu

PROJECT RESULTS:

- Evaluation of a theoretical compressor surge model for the CICERO test bench
- Effect of reduction of inlet diameter and inlet bend, including bend clocking, on compressor map

ONGOING INVESTIGATIONS:

- Impeller backflow in operation close to surge
- Hurst exponent as indicator of compressor surge (w. Vineeth Nair & Raimo Kabral, MWL)
- Evaluation of theoretical compressor performance models using LES data (w. Elias Sundström, Mechanics)

FUTURE PLAN, SHORT & LONG TERM:

- Impeller backflow for bend inlet
- Change compressor to BorgWarner compressor (Volvo VEP HP)
- On-engine measurements of compressor characteristics

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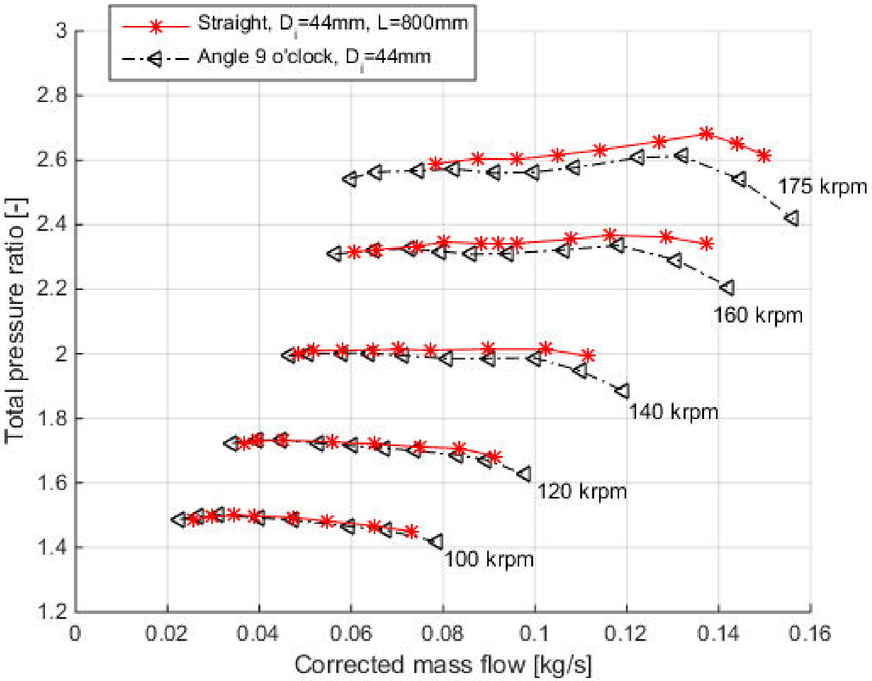
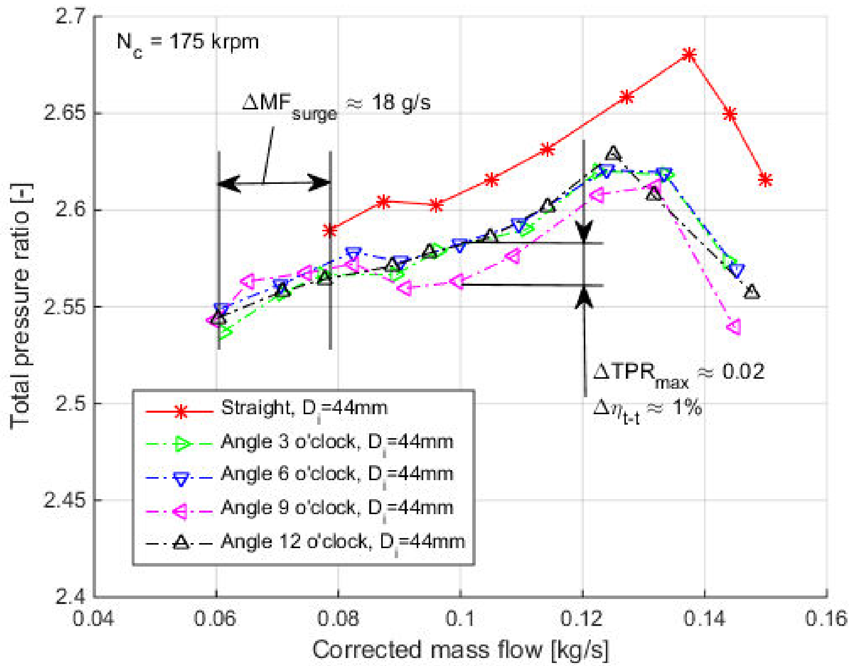
Effects of an upstream bend on compressor map



Left half of map for straight and bend inlet

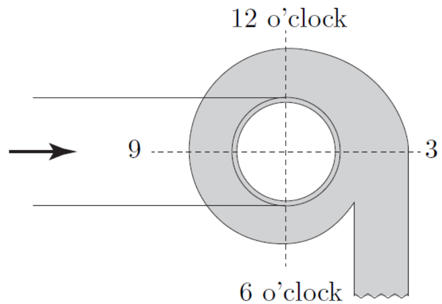


Effects of clocking at the highest speedline

Bend effects:

- lower pressure ratio and efficiency at high mass flows (mainly due to bend losses)
- Surge line shifted to lower mass flows at high impeller speeds

Clocking: Angle posistion opposite of volute reduces pressure ratio and efficiency



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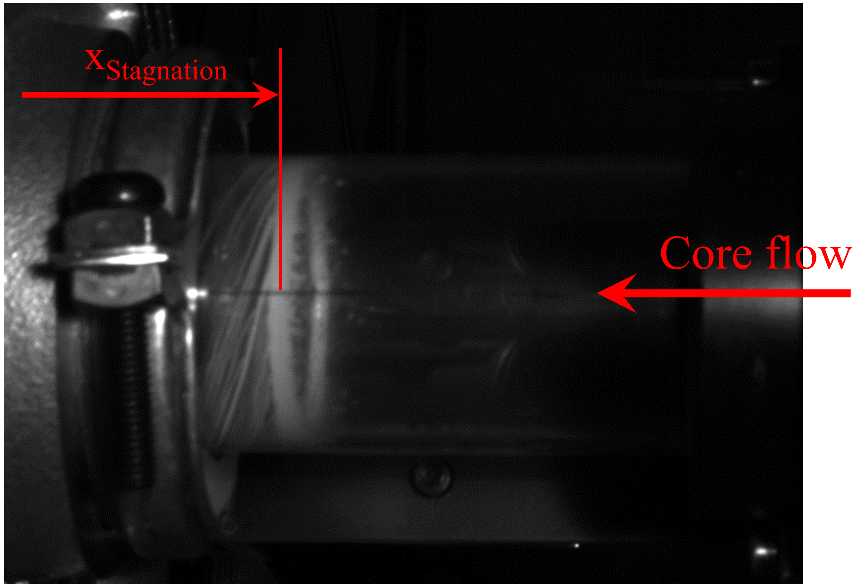
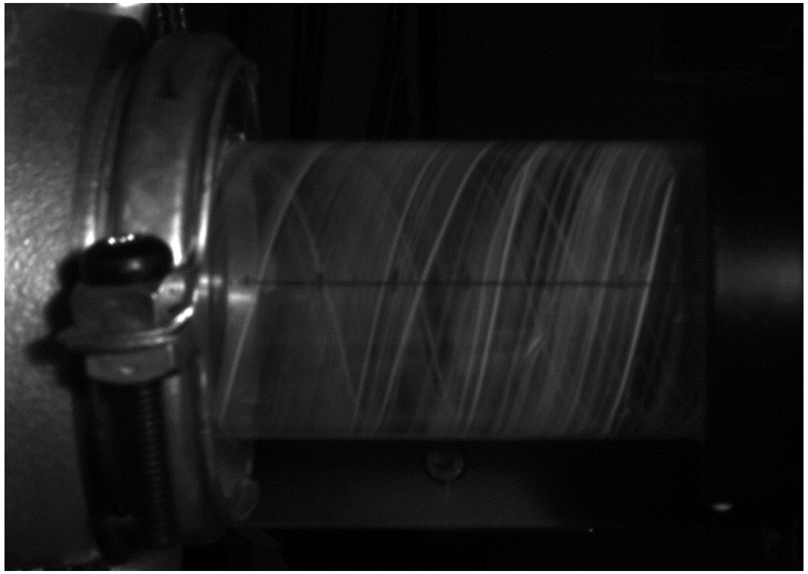
Impeller backflow wall streamlines



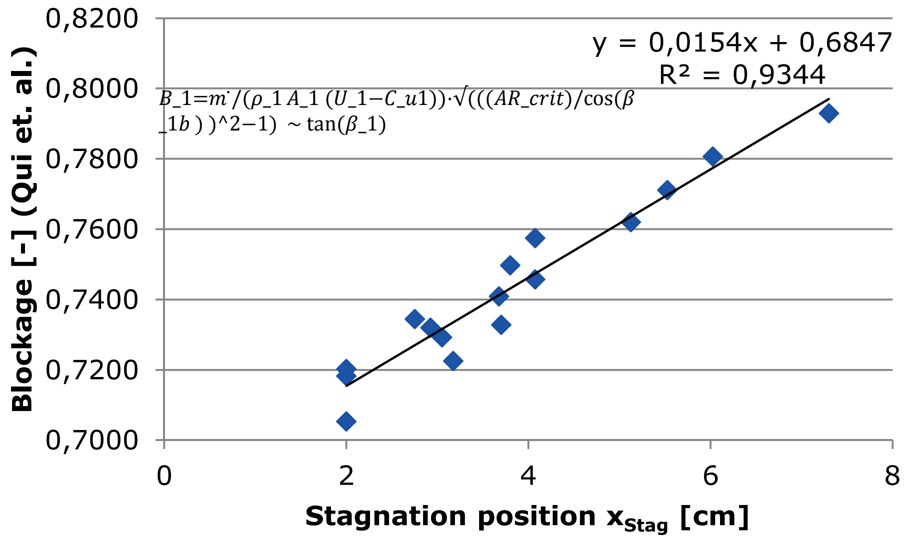
N_c = 80 krpm, near surge



N_c = 100 krpm, surge

- Experimental data can be used to verify theoretical inlet blockage models, and CFD simulations

- Flow angle of the backflow can be estimated



Rotating machines and innovative noise control

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Doctoral student:
Raimo Kabral (Exp/Sim), MWL

Supervisors:
Mats Åbom
Hans Boden

DOCTORAL PROJECT CONTENT/SCOPE:

1. To understand the role of acoustic field in the TC surge initiation process.
2. Determine the impact of coupling duct-system acoustic properties to the TC surge margin.
3. To develop innovative noise control techniques for the downsized engine inlet.
4. To understand the impact of so called modified Cremer acoustic impedance at the flow-duct wall to the acoustical damping.

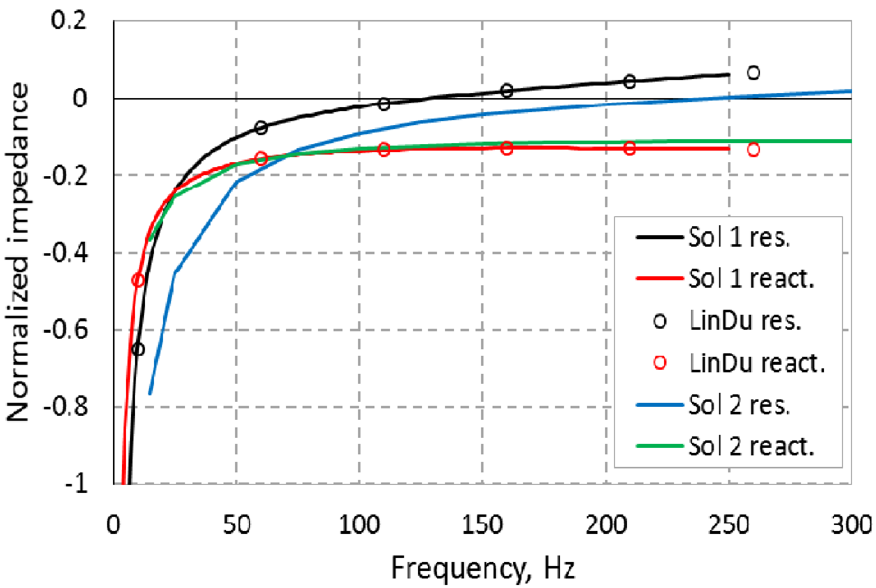
PROJECT RESULTS:

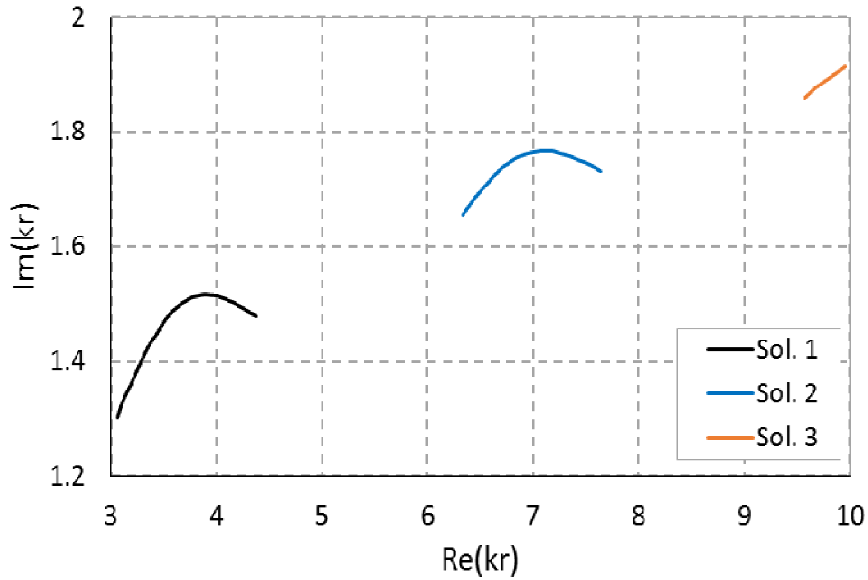
- Acoustic measurements and compressor assessment at design and off-design operating conditions
- The accuracy of the simplified FEM model of the Compact silencer have been extended by solving the convective wave equation including the vital flow effects.
- The first three solutions of the Cremer condition for the first duct radial mode pair *(m* = 0*)* have been numerically determined and corresponding acoustic impedance spectra have been also computed and studied.

FUTURE PLAN, SHORT & LONG TERM:

- Short term future plans: finalize the investigation on the Compact silencer and publish the findings (Journal of Acta-Acustica).
- Prediction of TC surge by means of Hurst exponent criterion (MWL-ICE). Work with Volvo Cars on prototype silencers.
- Long term: complete the analyzes on the acoustic field experiments of the TC.
- PhD degree during Q3 2016.

The investigation of modified Cremer impedance in the low frequency range





- The resistance of the revised Cremer impedance tends to be negative in the very low frequency range i.e. a source instead of sink.
- On a complex plane the solutions are well separated i.e. the modified Cremer impedance is consistent throughout the frequency range and not switching from one solution to the other.
- The resistance of the second solution is significantly lower compared to the first solution while the difference in the reactance is much smaller.

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Students; timeline (est): CoDOp

Turbocharging Research Area	2015				2016				2017				2018			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Compressor Off-Design Operation Project																
Bertrand Kerres, PhD student, ICE, Exp/1D									PhD							
Elias Sundström, PhD student, Mek, CFD					Lic							PhD				
Raimo Kabral, PhD student, MWL, Exp							PhD									
NN, Ind. PhD stud Volvo Cars, MWL/Mek													Lic			

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Publications: CoDOp project

(selective)

Kalpakli Vester, A. (2014) *Vortices in turbulent flows—rocking, rolling and pulsating motions*. **PhD thesis**, KTH Mechanics, Stockholm, Sweden.

Pastuhoff, M. (2014) *Measuring with pressure sensitive paint in time-varying flows*. **PhD thesis**, KTH Mechanics, Stockholm, Sweden.

Sundström, E., **Semlitsch B.**, **Mihaescu, M.** (2015) *Centrifugal Compressor: the Sound of Surge*, AIAA Paper 2015-2674. arc.aiaa.org/doi/abs/10.2514/6.2015-2674

Kalpakli Vester A., **Örlü R.** and **Alfredsson P. H.** (2015) *Pulsatile turbulent flow in straight and curved pipes – interpretation and decomposition of hot-wire signals.* Flow Turbul. Combust., 94, 305–321. dx.doi.org/10.1007/s00348-015-1926-6

Kalpakli Vester A., **Örlü R.** and **Alfredsson P. H.** (2015) *POD analysis of the turbulent flow downstream a mild and sharp bend.* Exp. Fluids, 56, 57. dx.doi.org/10.1007/s00348-015-1926-6

Semlitsch B., **Jyothishkumar V.**, **Mihaescu M.**, **Fuchs L.**, **Gutmark E.J.**, and **Gancedo M.** (2014) *Numerical Flow Analysis of a Centrifugal Compressor with Ported and without Ported Shroud.* SAE Paper, 14PFL-0797. dx.doi.org/10.4271/2014-01-1655

Sundström E., **Semlitsch B.**, and **Mihaescu M.**, (2014) *Assessment of the 3D Flow in a Centrifugal Compressor Using Steady-State and Unsteady Flow Solvers*, SAE Paper, 2014-01-2856 papers.sae.org/2014-01-2856/

Kabral R., **Du L.**, **Åbom M.**, and **Knutsson M.** (2014) *A Compact Silencer for the Control of Compressor Noise*, SAE Int. J. Engines 7:1572–1578, dx.doi.org/10.4271/2014-01-2060

Kabral R., **Åbom M.**, (2014) "Investigation of flow-acoustic interaction in automotive turbocharger," *Online Proceedings of the ISMA 2014*.

Åbom M. and **Kabral R.** (2014) Turbocharger noise - generation and control. *SAE Technical Paper Series 2014-10-25*.

Semlitsch, B., **Jyothishkumar, V.**, **Mihaescu, M.**, **Fuchs L.**, and **Gutmark, E. J.** (2013) *Investigation of the Surge Phenomena in a Centrifugal Compressor Using Large Eddy Simulation.* ASME Paper, IMECE2013-66301. dx.doi.org/10.1115/IMECE2013-66301

Open Questions on Surge

- Which are the key factors (dynamic changes & mechanisms in the flow) responsible for surge?
  - Flow assessment (e.g. instabilities, hysteresis), sensitivity to BCs
- Is there a similarity in mechanism for surge at different operating conditions? (compressor speed & mass flow/volume flow)
- How does the rotor-system inertia affects instabilities?
- How does the piping system influences surge?
- Does flow-acoustics coupling play a role within the process of inducing instabilities?
- How one can avoid / control unwanted phenomena?

Working Packages (I)

- **WP1: Compressor choice and installation (CICERO Lab.)**
  - *Compressor calibration rig; Choice of compressors (Rotrex & BorgWarner); Instrumentation of compressor rig; Upstream installation effects on compressor map; Compressor under pressurized (high/low) conditions (under close loop)*
- **WP2: Instrumentation to determine surge (CICERO Lab. & MWL)**
  - *Dynamic pressure transducers; external microphones, accelerometers; Detailed study of mild surge: measurement of scattering matrix data close to surge*
- **WP3: Velocity field determination (CICERO Lab.)**
  - *Decision about instrumentation; LDA, PIV, hot-wire; Design and construction; Flow visualization; velocity field characterisation upstream compressor inlet under stable and surge conditions w/o installation effects (e.g. bended pipe)*
- **WP4: Pressure sensitive paint (PSP) / Temperature sensitive paint (TSP) development for use on rotating compressor blades (CICERO Lab.)**
  - *Proof of concept of life-time method; Temperature measurement: Temperature measurements in calibration chamber using lacquered PSP (LPSP); Apply PSP/LPSP(TSP) on rotating compressor blade; Use PSP/LPSP(TSP) on fixed compressor blade with flow; Using PSP/LPSP(TSP) on rotating compressor blade*

Working Packages (II)

- **WP5: Installation & Instrumentation of the Engine-Compressor rig (ICE Lab)**
  - *Identify the most suitable engine - turbocharger system; Instrument the compressor side (upstream and downstream piping systems); Instrument the turbine side*
- **WP6: Characterise the compressor under steady operating conditions on the engine rig (ICE Lab)**
  - *Reproduce points on the compressor map generated by the CICERO lab for steady engine operating conditions and standard intake system to the compressor; Upstream installation effects on the compressor map under steady operating conditions.*
- **WP7: Characterise the compressor under surge conditions on the engine rig (ICE Lab)**
  - *Provoke surge; Identify suitable measurement methods to define whether the compressor is running in surge mode or not; Compare the effect of different compressor inlet conditions (already tested in the CICERO lab); Manipulate downstream pressure pulsations, and map how they affect surge.*
- **WP8: Characterise the compressor under transient operating conditions on the engine rig (ICE Lab)**
  - *Design a way to run the engine under transient operating conditions; Perform transient experiments to determine the delay time for surge to establish*

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Working Packages (III)

- **WP9: Verification and validation of the LES approach (CFD)**
  - *Verify the solver for different spatial and temporal resolutions; Solver validation for stable operating conditions; Assess solver's sensitivity to the operating conditions*
- **WP10: Unsteady LES for compressor surge characterization (CFD)**
  - *Solver validation under surge condition(s) by comparing with measured data; Data comparisons between the flow associated with surge and the flow associated with the stable operating conditions.*
- **WP11: Unsteady LES for mapping the near-surge flow behaviour (CFD)**
  - *Analyse and characterize the flow behaviour near the surge using POD/DMD;*
  - *Study of surge under different rotational speeds and mass flow rates; Identify the mechanisms for surge;*
  - *Surge Aeroacoustics*
  - *Quantify the modes leading to the transition between the stable and the unstable stages;*
  - *Identify and quantify the effects of the inlet/outlet piping system*