KTH ROYAL INSTITUTE
OF TECHNOLOGY

Compressor Flow Instabilities at Low Mass Flow Rates

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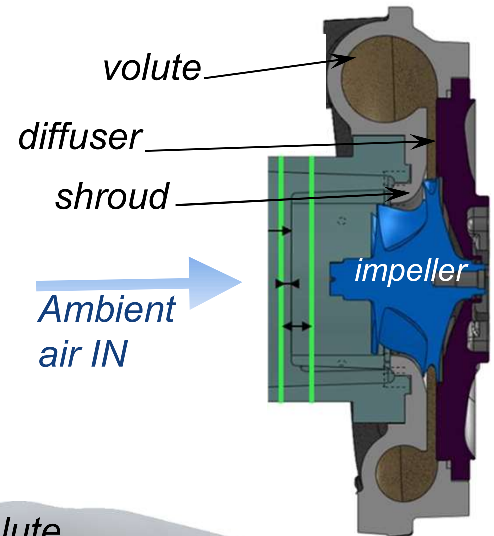
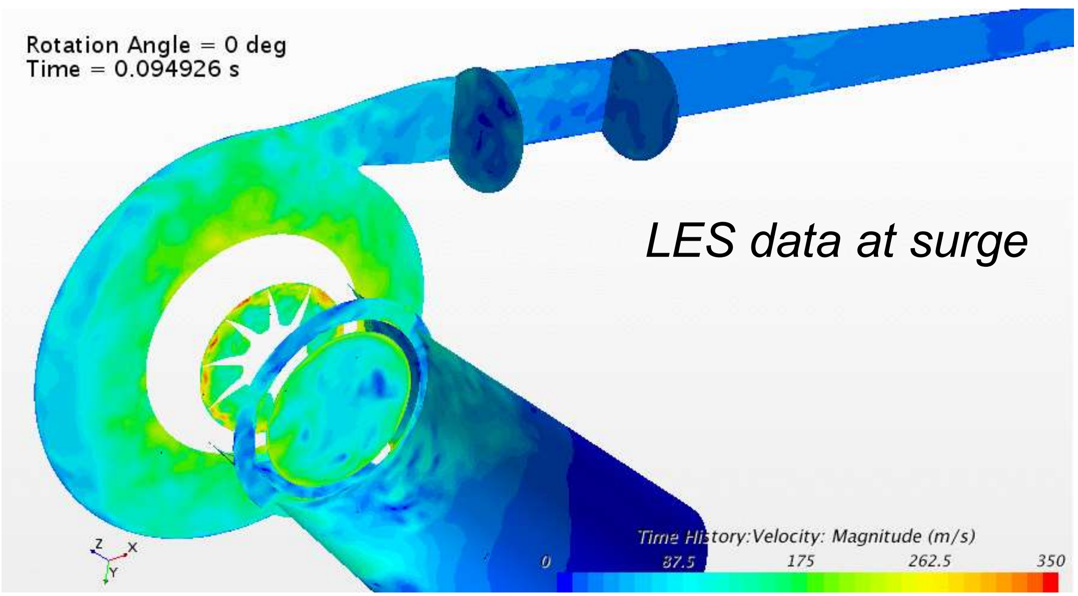
Energimyndigheten SCANIA VOLVO VOLVO BorgWarner

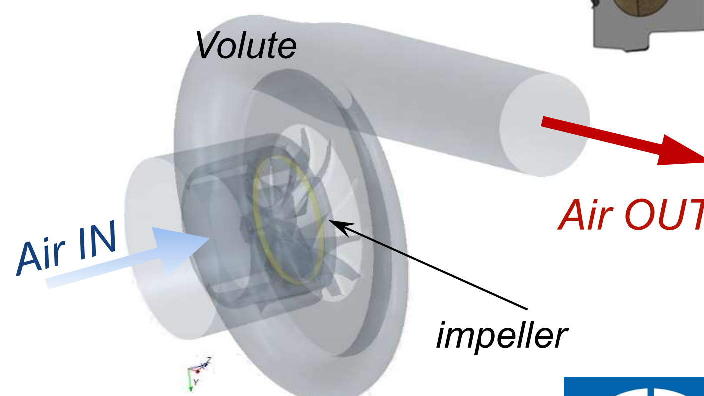
Centrifugal Compressor Flow Instabilities

Engine downsizing and turbocharging to maintain the same maximum power output

- to control emissions & improve fuel economy





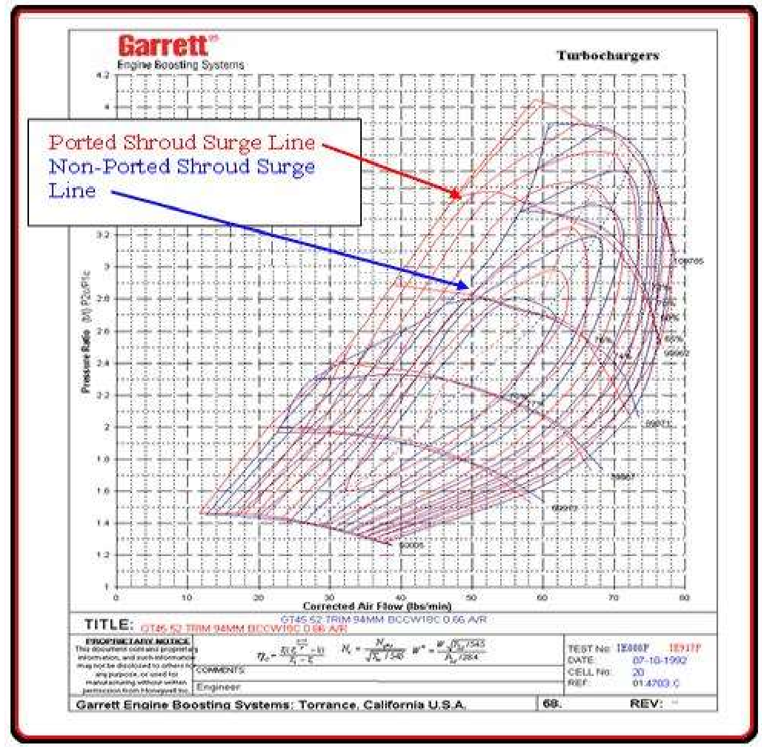


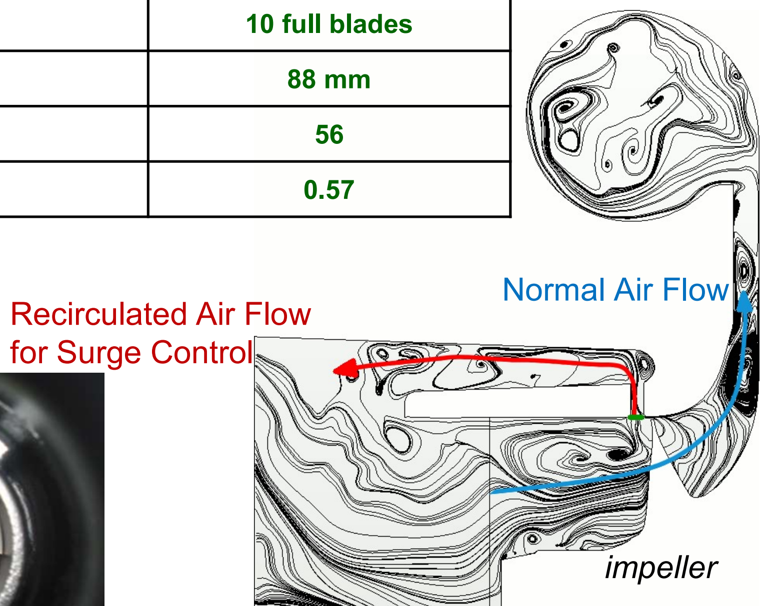
Energimyndigheten SCANIA VOLVO VOLVO BorgWarner GEx

Investigated compressor: GT40

- Problem: Instabilities at low mass flow rates which limit the compressor range of operation
- Ported Shroud solution used to extend this range

Turbo compatibility	Heavy truck engine
Power range	**400 to 850 kW**
Number of blades	**10 full blades**
Exducer diameter	**88 mm**
TRIM	**56**
Diffuser area ratio	**0.57**

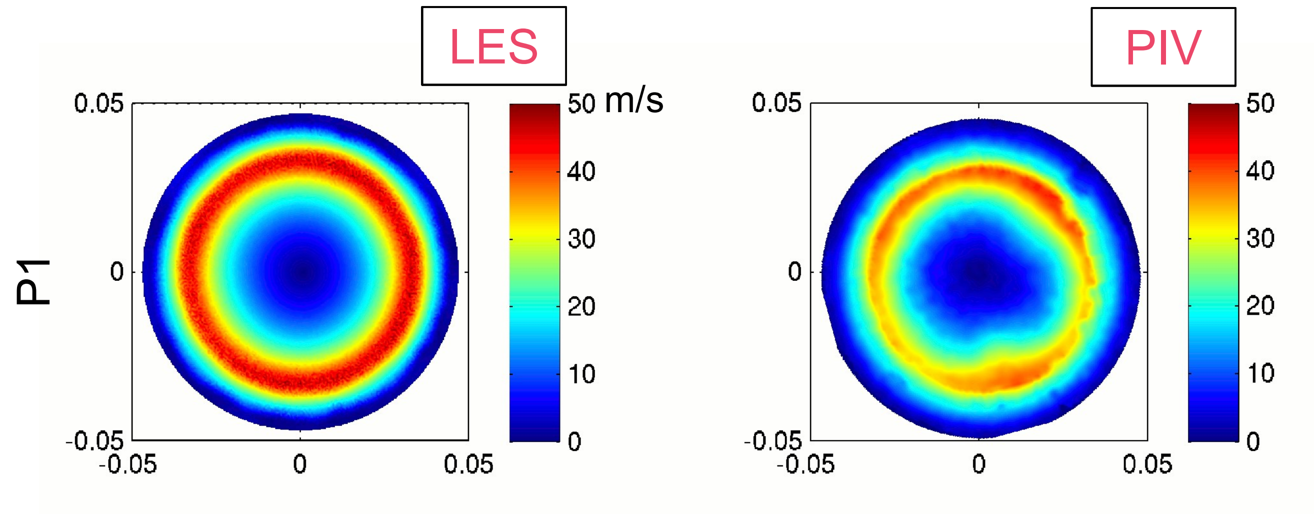




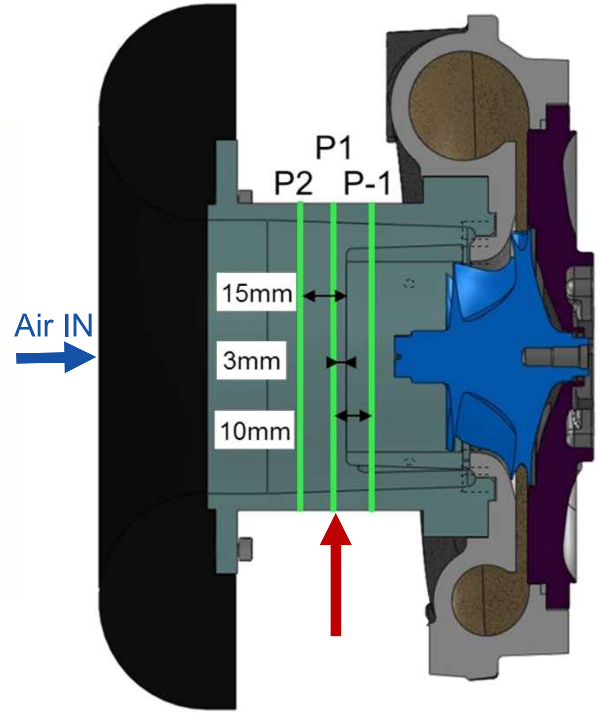
Ported shroud compressor supported by four unequally spaced ribs

Experimentally investigated compressor at UC

Closed ported Shroud: Stable operating condition (0.28kg/s); LES vs. experiments



Design Condition, 64k rpm; In-plane velocity magnitudes (m/s)



- ❑ Fair agreement with experimental data

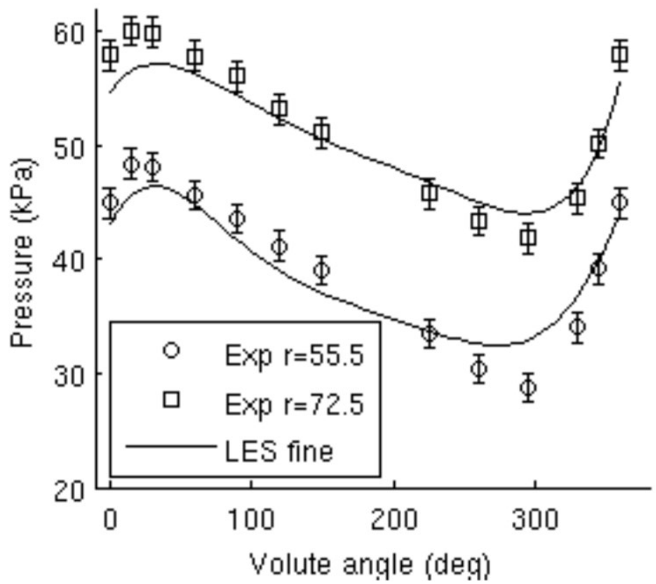
Semlitsch B., Jyothishkumar V., Mihaescu M., Fuchs, L., Gutmak E.J., Gancedo M., SAE Technical Paper 2014-01-1655, 2014, doi:10.4271/2014-01-1655.

UNIVERSITY OF Cincinnati

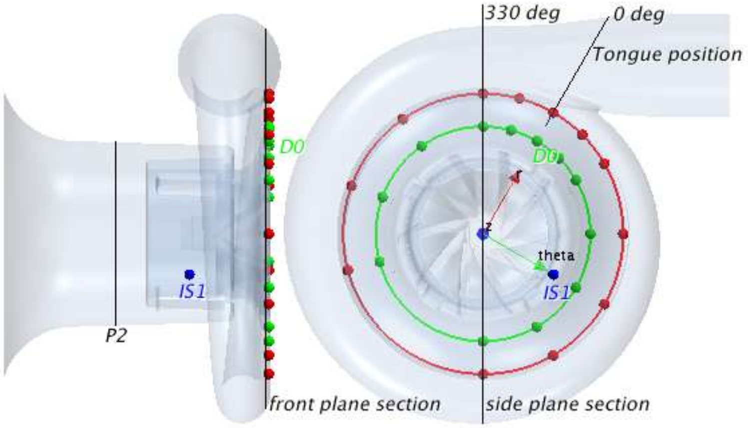
Experimental data provided by Dr. Gutmark and his team at Univ. of Cincinnati (UC)

Experimentally investigated compressor at UC

Stable Operating Condition (0.28kg/s); LES vs. experiments



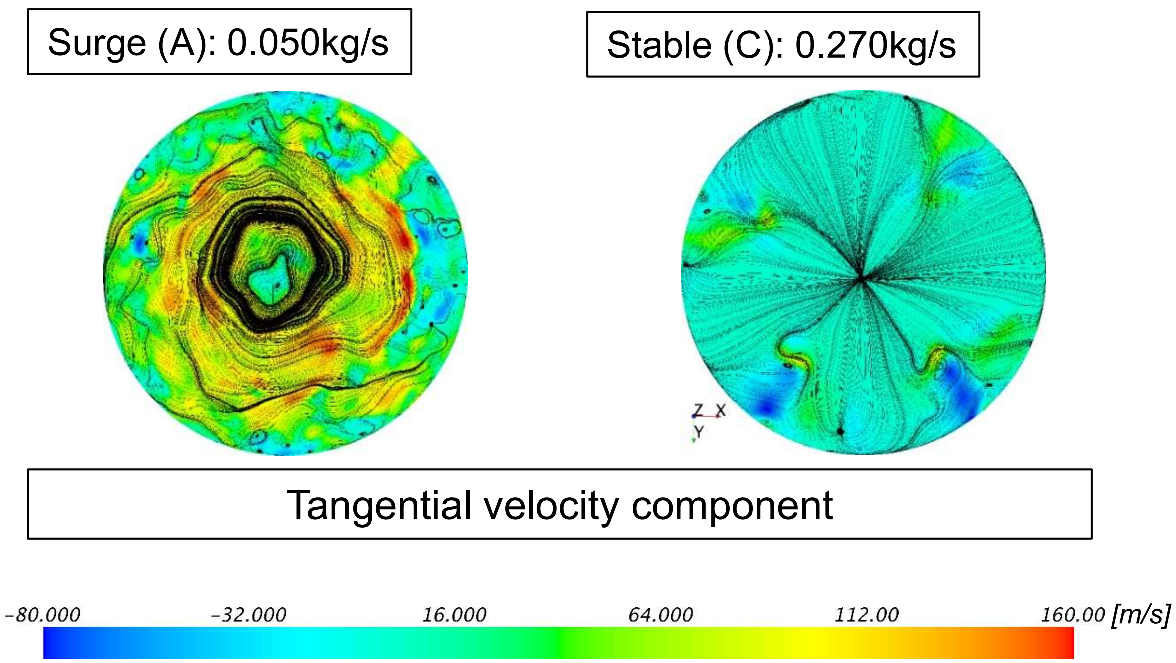
Design Condition; 64k rpm; Time-averaged pressure data on the diffuser's backplate (kPa)

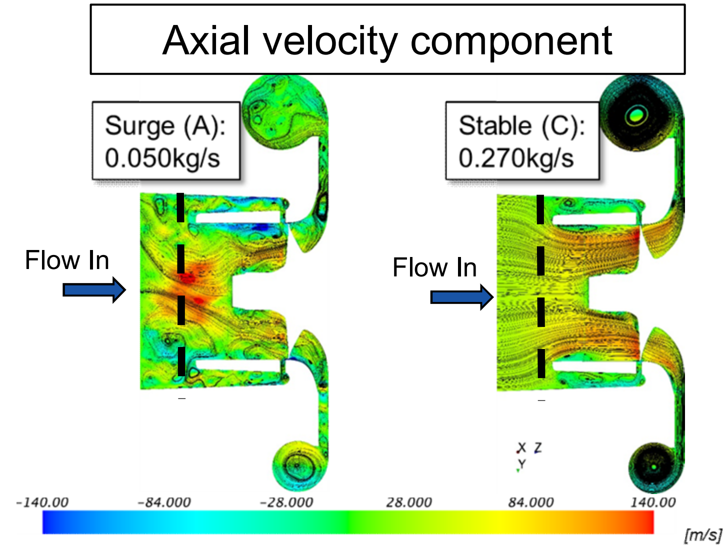


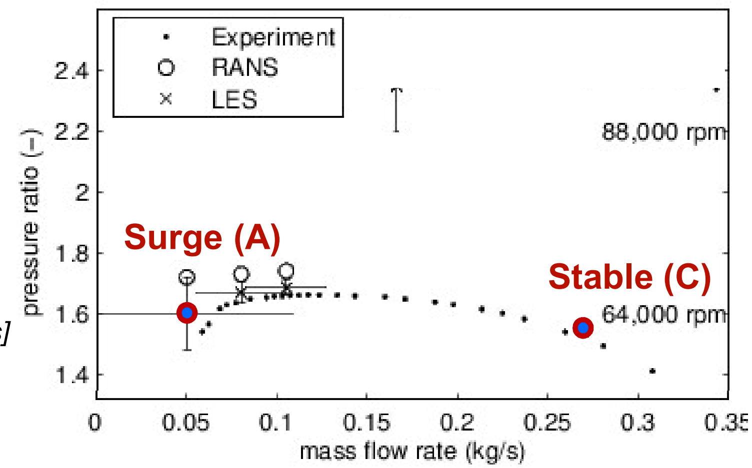
Sundström, Semlitsch & Mihaescu (2014) *SAE Technical Paper: 01-2856.*

- Possible causes for differences: case set-up simplifications (e.g. back-plate gap not included); the unavoidable mismatched w.r.t. Boundary Conditions

Velocity components: Compressor Inlet



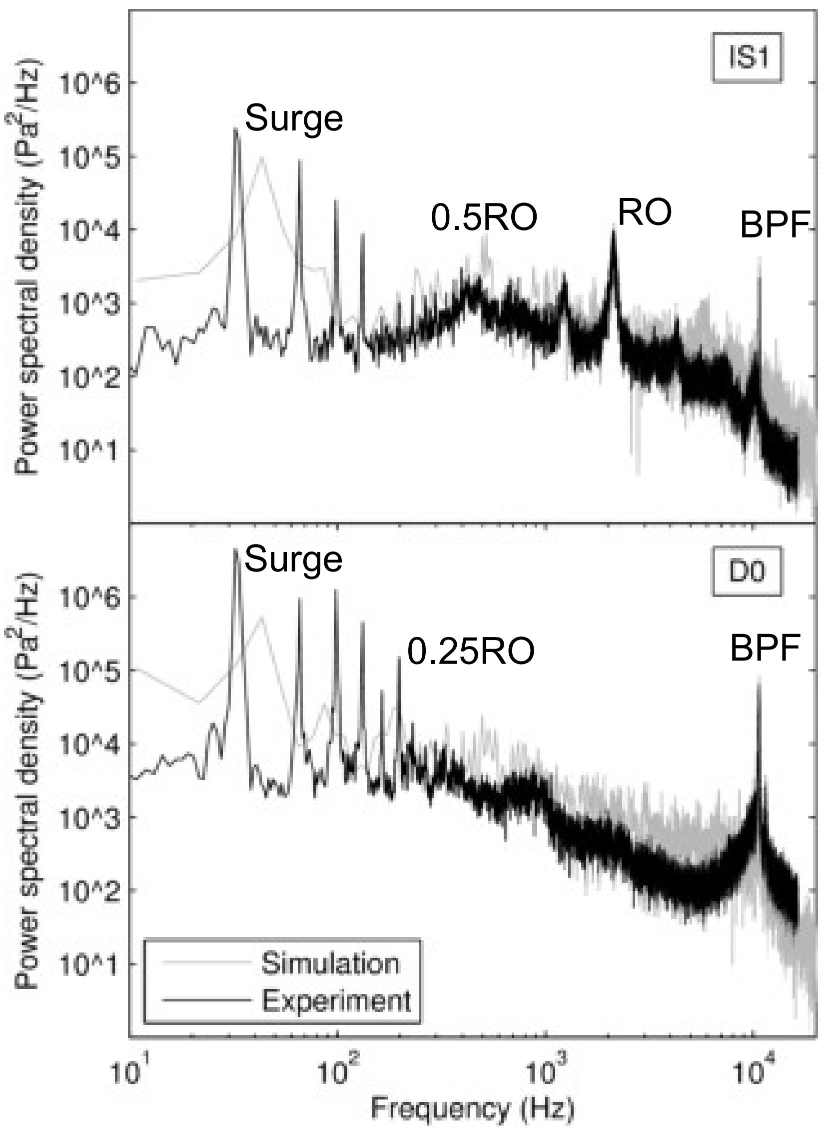


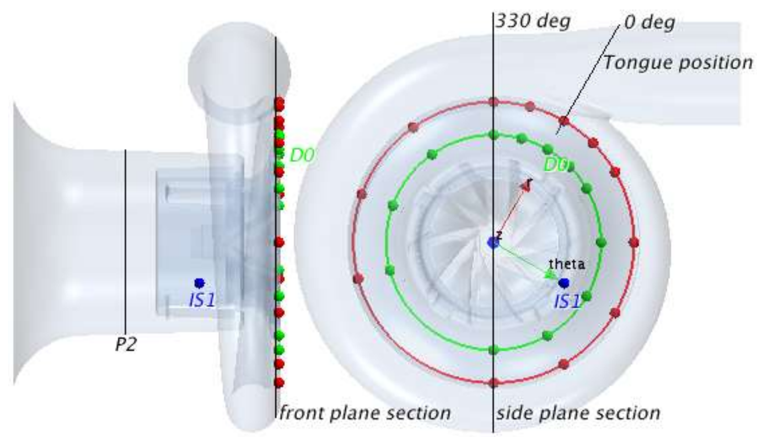


Semlitsch & Mihaescu (2016) *J. Energy*. 103: 572-587.

- Stable condition: uniform tangential velocity distribution with indication of some activity in the ported shroud; flow goes relatively smoothly into the compressor
- Surge condition (0.050kg/s): Large tangential velocities; strong swirling flow motion sustained by the swirling reversed flow at the shroud

Single point Fourier Spectra



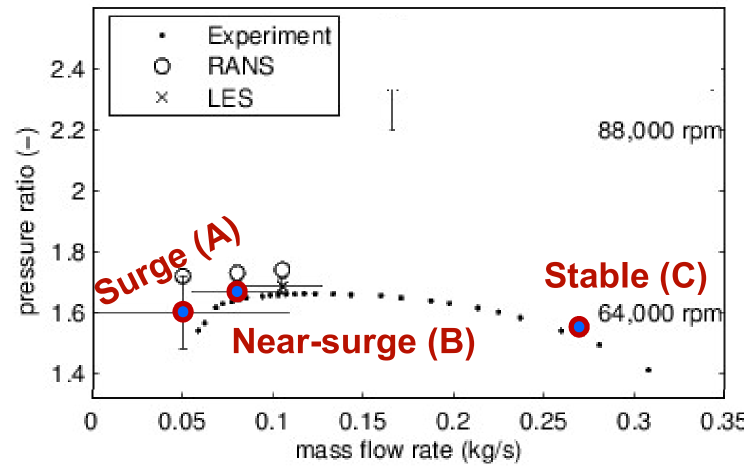


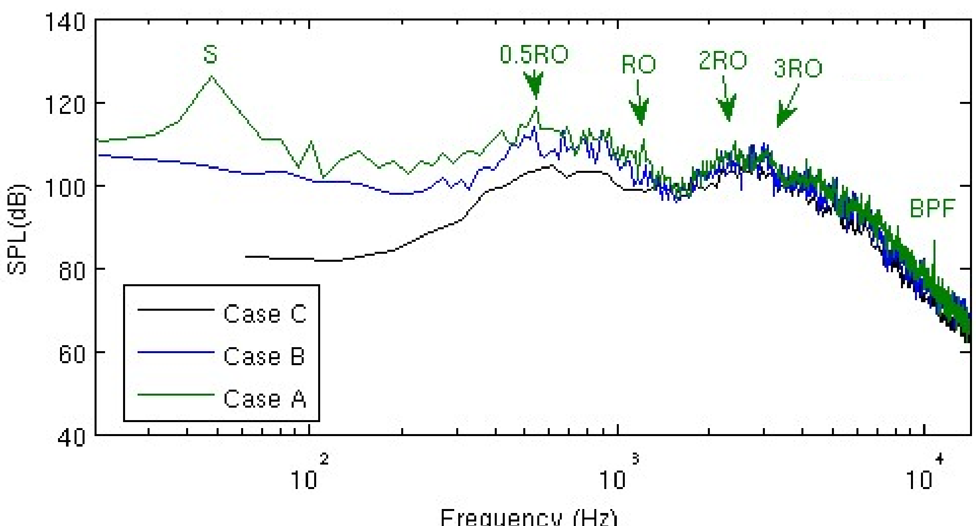
- Tonality at 43 Hz, 1st surge cycle harmonic, blade passing frequency and rotating order
- Broadband: mid-frequency range
- Narrowband: 250~600 Hz (peak at 0.5 RO)
- RO - rotating order of the shaft
- BPF - blade passing frequency

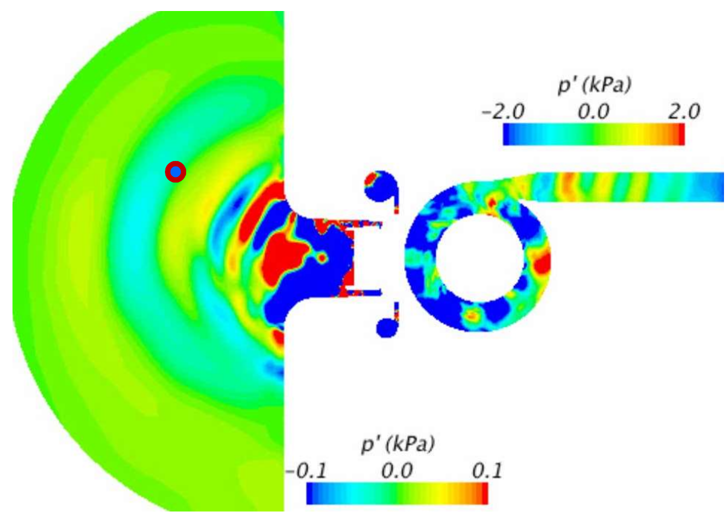
Sundström, Semlitsch & Mihaescu, SAE Paper: 01-2856, 2014

Extracting acoustic information

- SPL amplitude amplifies towards surge
- Broadbanded features around 0.5RO and 3RO, in agreement with other observations, e.g. Evans D. and Ward A., SAE2005-01-2485; Teng C. and Homco S., SAE2009-01-2053







Near-surge (B): 0.070kg/s

1714932504369567E+001 -0.2905418864187805E+000 -0.2594992850901339E+001 0.2165052065572526E+000 -0.1679391845766783E+001 -0.1908220271117915E+001
4566163276669246E+000 -0.1359533712925901E+001 -0.9965247058572034E-001 0.1241793463445173E+000 0.1014655448678995E+001 -0.6924593705265936E+000
1510533199273222E+001 -0.2127958244029155E+001 -0.4227684621401136E+000 0.3710858969313868E+000 0.2283014859033826E+001 0.7761446761242569E+000
.5280267819854909E+000 -0.5108666412758146E+000 0.2075898106239340E+001 0.5241022323248168E+000 0.1374713382896179E+000 -0.5337802884200349E+000
3044806051969037E+000 0.1169041911020979E+001 0.2156038848406716E+001 -0.6718804681606541E+000 0.3529630182887514E+000 0.8964087223265369E+000
4905974760479341E+000 -0.8194505202469221E+000 0.1038110498510081E+001 -0.1435081928902869E+001 0.9084744260336521E+000 0.5748709129076505E+000
9070928900452501E+000 -0.5329628899406734E+000 0.1482995884309786E+001 -0.1646342927529616E+001 0.1231103814637809E+001 0.8416370259150291E+000
2848338376119138E+000 0.1795480494777467E+000 0.1539468439025070E+001 -0.4050179067712828E+000 -0.1339382891786914E+000 0.5927480418798319E+000
.9807779547375255E+000 -0.1394496598324647E+000 0.1739926353170235E+001 0.4065388059281782E+000 0.9622799439272496E-001 0.3499978910169286E+000
1707015919118012E+000 0.1340020801550425E+001 -0.6375521057226133E+000 0.5811587020667498E-001 0.8983864461818228E+000 0.1448164114623678E+000
.4338519999554551E+000 0.1111044600270708E+001 0.2027390446188566E+001 0.1375913902645972E+001 -0.8164649711040699E+000 0.9882500436498212E+000
.9765600845600121E+000 0.7260016745789110E+000 0.4941447514124727E+000 0.4537654142767285E+000 0.1229820596082329E+000 -0.6665016446921797E+000
3043816923741196E+000 -0.1500334102999711E+001 0.1139729423921510E+001 -0.1600969655156742E+001 -0.1165549494097412E+001 0.7638934423847696E-001

Which are the developed flow structures responsible for the frequencies observed?

How do they look like?

7883329220394073E+000 -0.6073061126404413E+000 0.4867482383004425E+000 0.6297608136518367E+000 0.1282316167618620E+001 0.1183484130236984E+001
3952144054185681E+000 0.5403455684754255E-001 0.5221133179348365E+000 -0.1183307934637142E+001 0.6612180565226793E+000 0.1561603260521766E+000

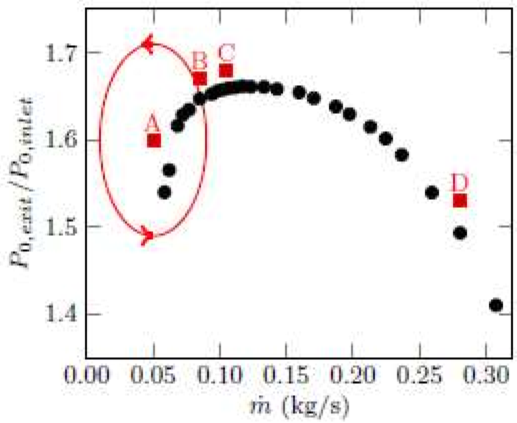
- ❑ Fourier transform; surface spectra analysis
- ❑ Proper Orthogonal Decomposition (POD)
- ❑ Dynamic Mode Decomposition (DMD)

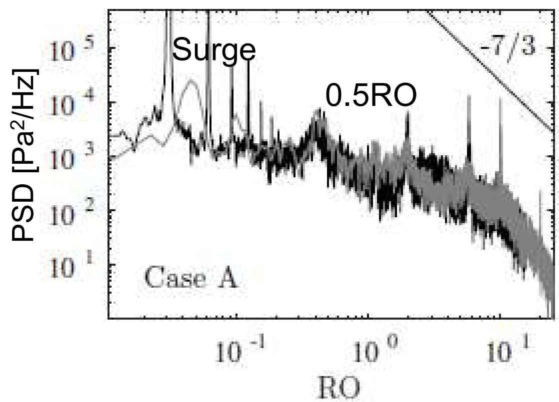
1678085180148728E+000 -0.8974652136016332E+000 0.4394310181546791E+000 -0.1382462638366333E+000 0.1282918228279874E+001 0.2723427863758062E+000
8297789050924536E+000 0.4333294316098687E+000 0.6904840077230876E+000 0.1001052318311551E+001 0.6719075349282833E-001 0.9560772898324014E+000
.5695939675069468E+000 0.3363863655934451E+000 -0.8148108873267246E+000 0.1068680403658729E+001 -0.2774425791077422E+000 0.7445932159049169E+000
3490141499624635E+000 -0.6215363191464524E+000 -0.2069986953316328E+000 0.8011127224935998E+000 0.1040307287734328E+001 0.8342398260989168E+000
4504845061376628E+000 -0.7880908433295245E+000 0.2217668788173476E+000 -0.1175412648114819E+000 -0.1328817227492283E+000 -0.6800434501498382E+000
.3285184567164951E+000 -0.5273048023327482E+000 -0.6119552599033192E+000 0.1539150093989716E+000 -0.5094655126108473E+000 0.4062669242717574E+000
.1755681502506868E+000 -0.5579955833949024E+000 0.3132722483282956E+000 0.1550061528399211E+001 0.4622446161091939E-001 0.9498300914071518E-001
.2903553913857778E-001 0.6314059985265221E+000 -0.4198555065641163E+000 -0.6924429354910319E+000 -0.1019500247889173E+001 0.7794482436222597E+000
.4115228127214182E+000 -0.1892927138034795E+000 -0.5222025794880164E+000 -0.4836721724617783E-001 0.2422256143103053E+000 -0.5450941778294977E-001
.4420845590293802E+000 0.1066964105526146E+001 -0.1541521671333963E+000 -0.1975527416005975E+000 -0.1032774511580742E+000 0.3160998613566801E+000
.6839795630218847E+000 0.2121380284987645E+000 0.9070094839132090E-001 0.6539685248026905E-001 -0.2644868201953798E+000 -0.1925589945246452E+000
5126457665746844E+000 0.6420498967321981E+000 -0.4034813472051998E+000 0.7326858867438858E-001 0.5044421965361592E-001 -0.3133514736821236E+000
.4205934112737866E+000 0.7050905408515271E-001 -0.4766058178278074E+000 -0.2230848736476515E+000 0.1110115964849385E+000 -0.4543613457353777E+000

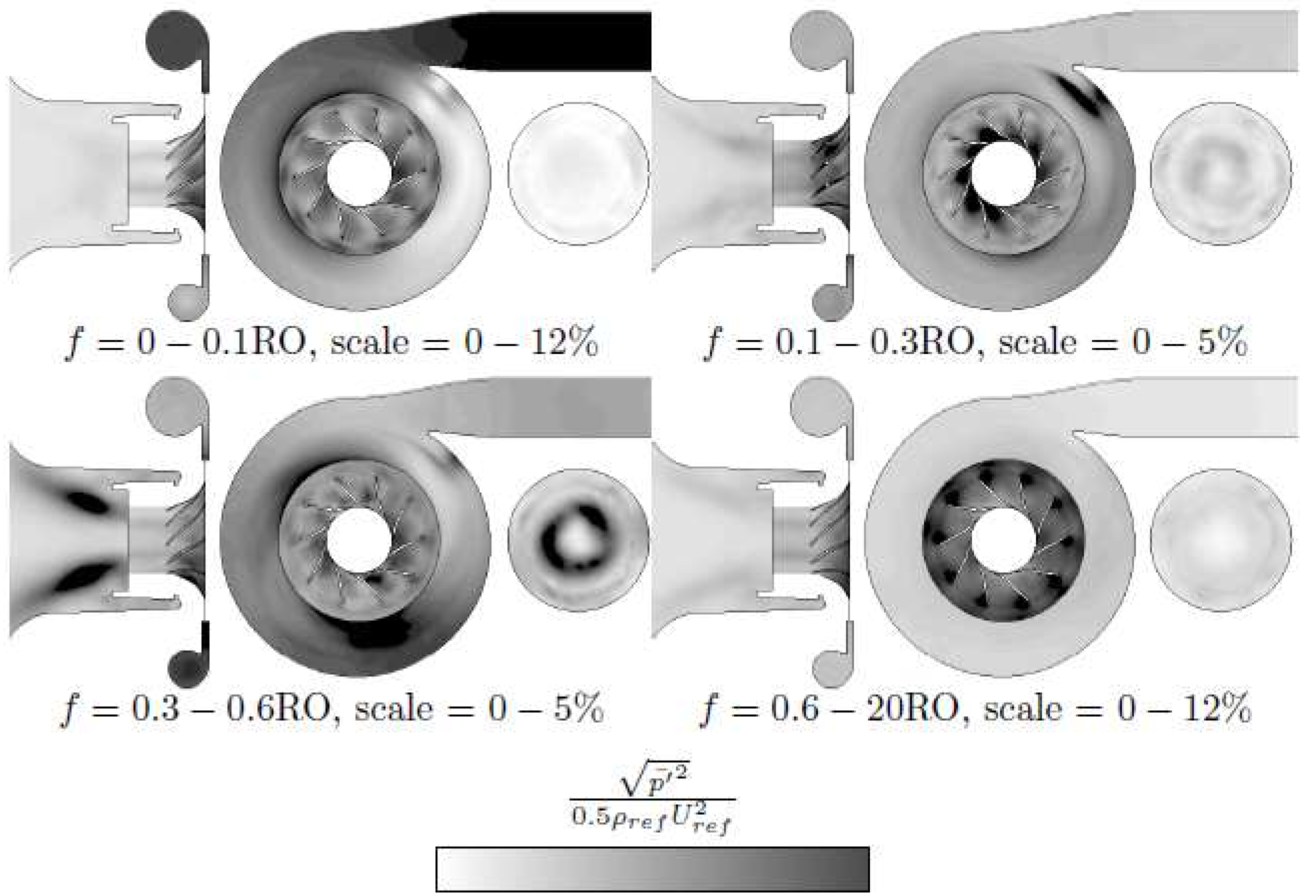
Surface spectra: pressure fluctuation (RMS), unstable (Case A)

Sundström, Semlitsch & Mihaescu, *J. of Sound and Vibration* 434: 221-236, 2018.

Unstable ← Stable





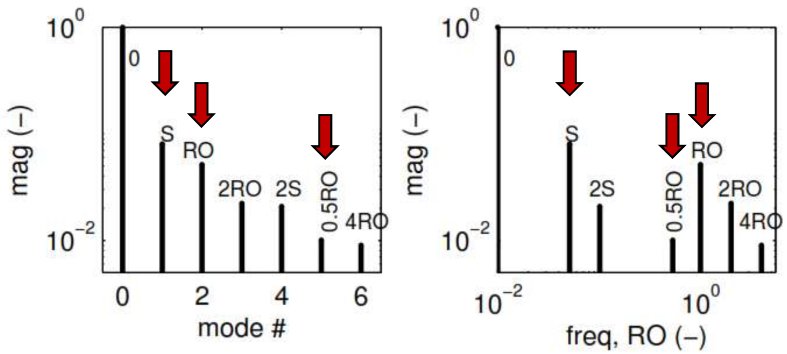


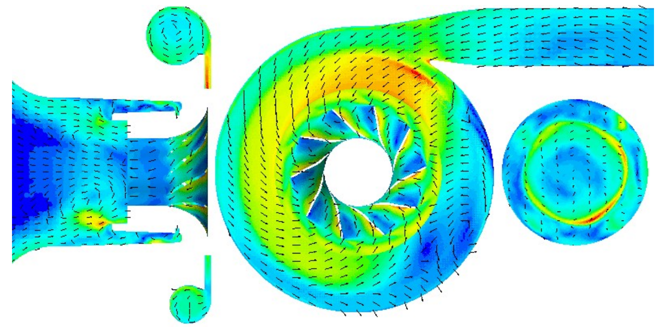
How do these modes evolve in space and time and how energetic they are?

Flow modes @ Case A /surge condition

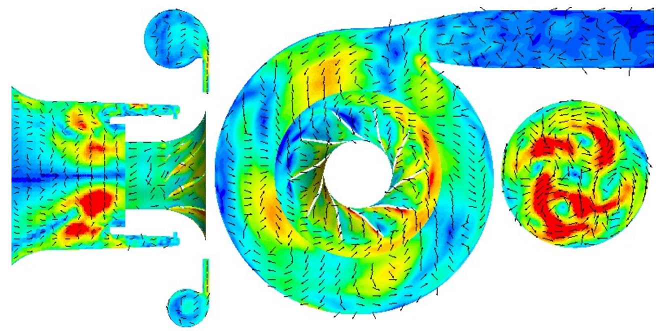
- Quantification of flow instabilities observed
- Dynamic Mode Decomposition at surge (velocity)

Sundström, Semlitsch, *and* Mihaescu (2018). *Flow, Turbulence and Combustion*. 100(3): 705-719.

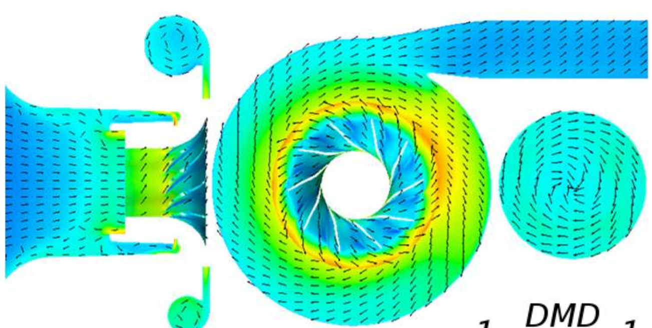




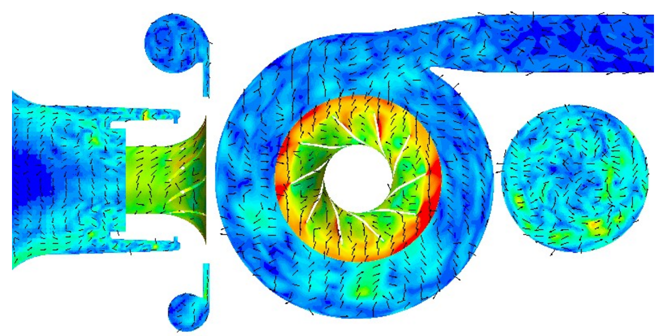
Surge (43 Hz, pulsating)



0.5RO (rotating stall in the diffuser)



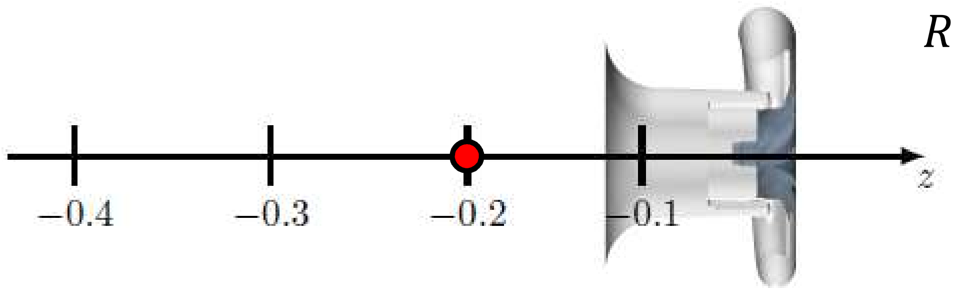
M0 Mean

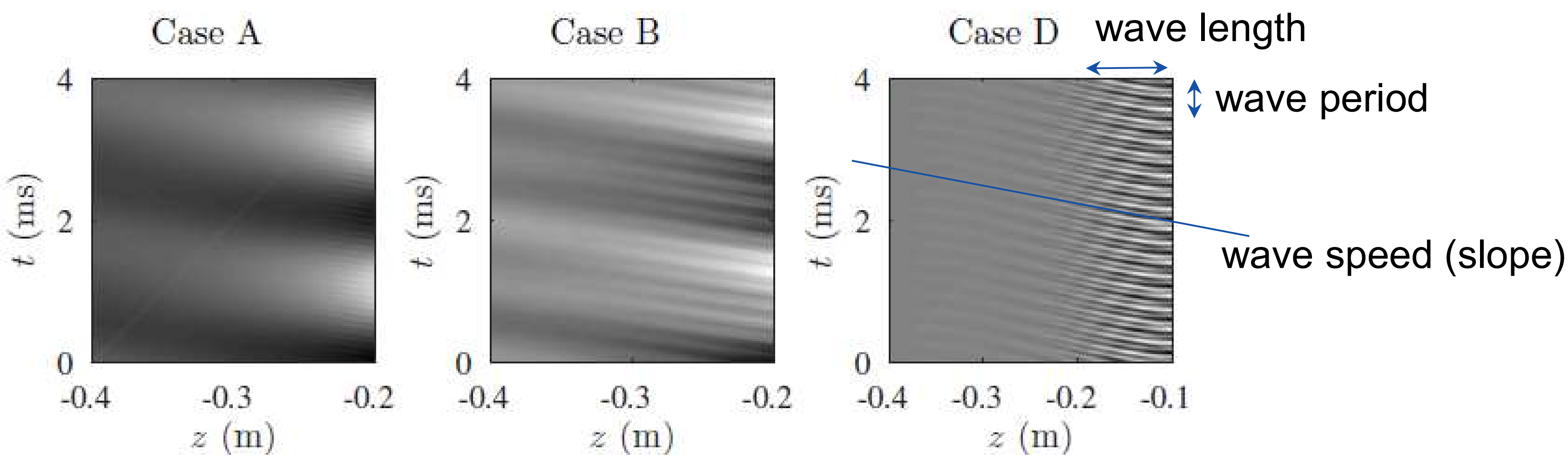


RO (spinning mode)

Upstream acoustic domain: Space-time correlations based on pressure

$$R(r_i, \Delta t) = \frac{< p'(x_i, t)p'(x_i + r_i, t + \Delta t) >}{\sqrt{(p'^2(x_i, t)}\sqrt{(p'\hat{}2(x_i + r_i, t + \Delta t)}}$$





- Propagation wave speed ~ 340 m/s (reference point z = -0.2)
- Waves propagate upstream (negative slope)
- Longer wave length/period disturbances for unstable conditions

Outlook

- 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 upstream and downstream flow perturbations impact the onset of instabilities?
- How does the compressor installation (piping system & volume) influence surge?
- How one can avoid / control unwanted phenomena?

Acknowledgements

SNIC

PDC @ KTH

Cray XC40 system 53632 cores
(1676 nodes with 32 cores/node)

Energimyndigheten

SCANIA

VOLVO

BorgWarner

Competence Center for Gas Exchange

CCGEx

"Charging for the future"

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