Understanding the phenomenon of Rotating Instability: An opportunity to improve aero engine safety?

Interaction between Rotating Instability and Rotating Stall in Axial Compressors

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In Short

- Rotating Instability (RI) is an aerodynamic instability occurring in gas turbines such as aero engines
- RI may lead to structural vibrations and precedes surge, posing a threat to safe engine operation
- Our goal is to understand the interaction between RI and other turbomachinery phenomena such as rotating stall through numerical simulations executed in parallel with experiments

Gas turbines are essential machines in modern societies. Applications are found in aero engines, power generation plants and many industrial processes. These turbomachines are likely the most efficient way to burn fuel in a relatively compact setup which demands high power density. Understanding the complex flow phenomena present in gas turbines is key to achieve a more efficient design. Additionally, operation and safety issues may arise if flow instabilities are not prevented or contained.

One of the aerodynamic instabilities present in turbomachinery is the Rotating Instability (RI). It has been shown to cause non-synchronous vibrations, a potentially dangerous aeroelastic phenomenon which poses a threat to structural integrity. Additionally, RI may also lead the development of rotating stall cells in compressors, which can in turn affect the whole operation if it enters the surge regime. The latter condition implies a sudden drop of pressure ratio and mass flow rate and severe low-frequency pressure pulsation in the axial direction.

The most prominent RI features are: first, it occurs largely during off-design engine operation, near the machine stability limits; second, it is measurable near the tip of rotor blades, more explicitly, the tip clearance (see Fig. 1); third, its frequency spectrum is characterized by a broad chain of peaks at approximately 40% of the blade passing frequency.

Some of the open questions in the research of RI include: what is its exact origin? How does it relate to tip clearance vortices? What role does rotor-stator interaction play in the development of RI? What is the interplay between RI and rotating stall cells?

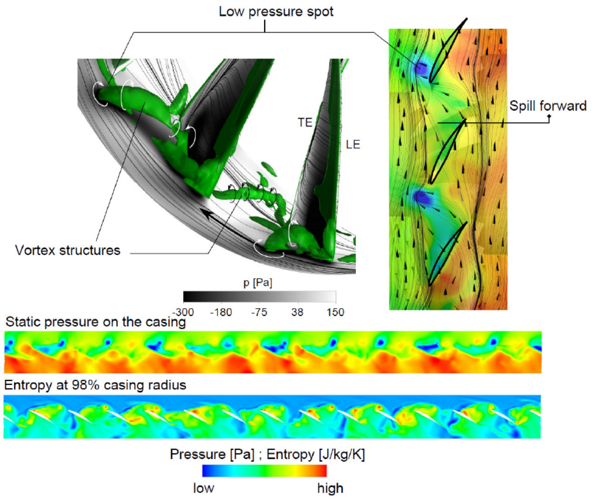


***Figure 1:** Depiction of the RI phenomenon in the analyzed rotor. Vortex structures pinpointed with green λ_2 surfaces.*

This project addresses these knowledge gaps by carrying out numerical simulations in parallel with experiments in a wind tunnel. The test rig located at the Chair for Aero Engines represents an axial compressor stage, shown in Fig. 2. A total of 14 rotor blades followed by eight stators vanes produce RI scenarios with diverse circumferential modal counts and amplitudes [1]. Throttling enables setting the operating point by varying the channel mass flow. The Mach number reaches 0.47 at the design speed.

The flow behavior at the tip clearance is directly related to the RI pressure signature. Figure 3 illustrates the change in tip blade loading. Starting from a stable tip clearance vortex (TCV) at Fig. 3(a), part

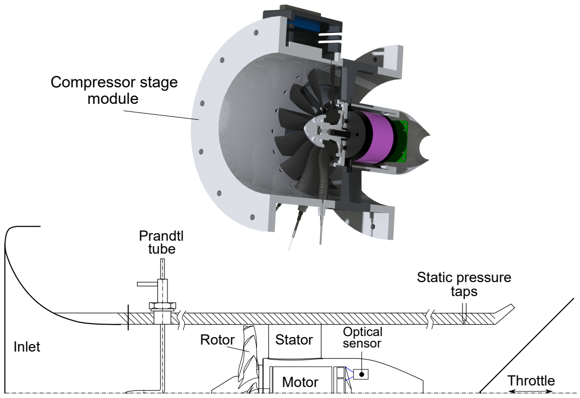
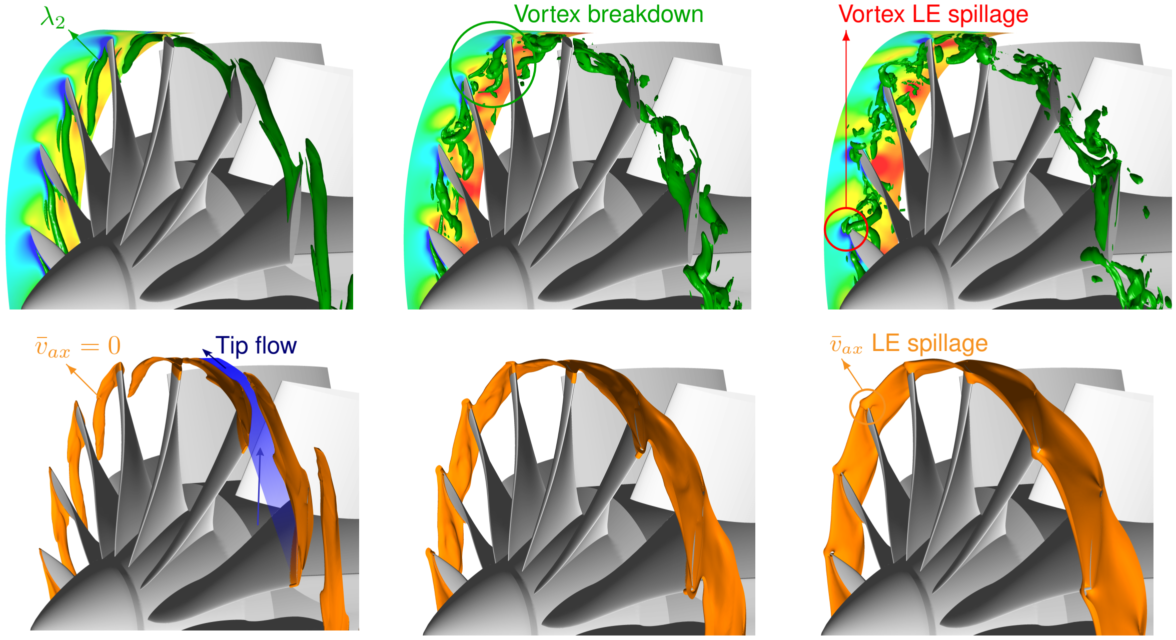


***Figure 2:** Compressor stage test rig at the Chair for Aero Engines, investigated experimentally in parallel with the CFD computations.*



(a) Stable (reference) (b) Prestall disturbance (c) Rotating (part-span) stall

Figure 3: *Selected operating points. Top: λ_2 surfaces in green, pressure on casing wall. Bottom: Orange surfaces where temporal average of axial velocity is null.*

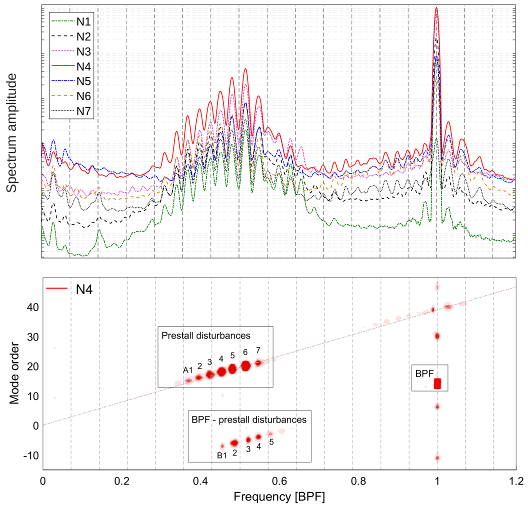


Figure 4: *Top: circumferential mean of pressure spectrum for numerical probes in the absolute frame of reference. N1 to N7 correspond to different axial positions (each with 360 uniformly distributed sensors). Bottom: corresponding circumferential mode order for probes at midchord position N4.*

of the main flow (in a time-average sense) is still allowed to stream through the vortex and the adjacent blade. Further throttling brings the TCV into break down, as shown in Fig. 3(b). The break down envelope is however still contained within each single passage. Lower mass flow levels produce part-span stall, as shown in Fig. 3(c). Now the vortex filaments traveling in the circumferential direction continuously spill over the leading edge, inducing local tip flow separation on the suction side.

Further RI indicators are seen in Fig. 4. The data is obtained by computing spectra in space and time of pressure probes flush mounted to the rotor casing. The presence of consecutive azimuthal modes with increasing frequency around half the BPF is a clear evidence of RI. Additionally, the nonlinear interaction between the BPF and the RI band is also evident in the region labeled "BPF - prestall disturbances". Other RI metrics such as signal coherence and phase distribution were also capable of confirming the presence of the flow instability. For more details and results, refer to [2].

WWW

`https://tinyurl.com/InteractionBetweenRIandRS`

More Information

[1] M. Eck, R. Rückert, D. Peitsch, M. Lehmann. Prestall Instability in Axial Flow Compressors. *J. Turbomach.* **142(7)**, 071009 (2020). doi: 10.1115/1.4046447

[2] V. B. C. de Almeida, E. Tüzüner, M. Eck, D. Peitsch. Numerical characterization of prestall disturbances in a compressor stage. *ASME 2023 Turbomachinery Technical Conference & Exposition*. ASME2023-101101.

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