

Pre-stall prediction of a transonic engine compressor based on URANS and hybrid RANS/LES methodology[☆]

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ABSTRACT

This study provides URANS and DDES investigations of the transonic low pressure compressor of a two-spool unmixed turbofan engine operated at near stall conditions. The ability of both methodologies to resolve the pre-stall tip leakage vortex system is contrasted and evaluated against real engine data. Explicit relations between experimentally detectable irregularities in the blade pressure signature and numerically observed pre-stall disturbances of the tip leakage flow are presented. The study is guided by the principle to evaluate the modelling necessity for the transition from unsteady RANS calculations to scale-resolving methods for mapping real engine pre-stall perturbations and aims to enhance the design of future stall detection systems.

1. Introduction

Approaching the flow stability limit of an axial compressor is characterised by the formation of aerodynamic instabilities, which under certain conditions develop into a rotating stall inception of the compressor flow. Two main types of stall inception are distinguished (Day, 1993): modal stall and spike-type stall. Modal stall can be described as a long length scale wave-like distortion of the inflow velocity, which extends along the entire circumference. As throttling increases, the amplitude of the oscillating wave intensifies and causes the critical incidence to be exceeded, triggering a rotating flow separation (McDougall et al., 1990). The continuous amplification of the circumferential distortion usually allows sufficient pre-stall warning times (Garnier et al., 1991), covering several hundred rotor revolutions. Modal stall is frequently observed in low speed compressors. In contrast, spike-type stall tends to occur primarily in transonic compressors and also corresponds to the experimentally proven underlying stall mechanism of the compressor considered in this study (Stössel, 2017). Phenomenologically, spike-type stall is associated with short length scale disturbances. The presence of a spike is commonly related to the formation of a blockage zone in the tip region of a singular blade passage leading to a forward spillage of the passage flow and can be tracked by casing wall pressure data in terms of an immediate pressure rise upstream of the affected passage. However, the origin of the blockage zone is generally conceivable in the context of various previously developed flow scenarios. Scientific observations include a rotor suction side separation due to a local misflow (Emmons et al.,

1955), a leading edge (LE) spillage due to the tip leakage flow of the adjacent blade (Vo, 2001), a bursting of the tip leakage vortex due to a shock vortex interaction as well as the upstream movement of the tip leakage vortex with increasing compressor throttling (Weichert, 2012). A clear assignment of the case-dependent scenario, especially under engine-specific conditions, is still a subject of research according to the author's knowledge. This necessitates the formulation of pre-stall warning systems as implicit measures. Several methods have been introduced, such as the identification of aperiodicities in the blade pressure signature (Kern, 2022; Stössel, 2017) or the detection of disturbance frequencies caused by the circumferential movement of pre-stall perturbations using wavelet analyses (Zhang et al., 2016). The raw signal in each case is the unsteady recorded casing wall pressure data. The ability to correlate these detectable footprints of pre-stall irregularities in the wall pressure time trace with the actual flow scenario in the rotor tip region is an important motivation for this study. This is further emphasised by the generally very short pre-stall warning times associated with a spike-type stall initiation. Typically, the transition occurs within a few rotor revolutions (Kern, 2022).

The inherent unsteadiness of the tip leakage flow and in particular the high-frequency interaction of the blade tip vortex with the passage flow inspire the transition to advanced numerical methods. Recent studies indicate the potential increase in information when using hybrid RANS/LES methods to model compressor blade tip flow. Möller et al. (2024) achieved an improved agreement with experimental compressor performance data, particularly under throttled conditions for a transonic compressor test rig, by introducing a transitional DDES approach.

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Nomenclature

English symbols

c	Chord
c_p	Specific heat capacity
d	Diameter
E	Energy
F	Thrust
f	Frequency
$\dot{m}$	Mass flow
l	Length scale
Ma	Mach number
n	Spool speed
p	Pressure
T	Temperature

Abbreviations

<i>BPF</i>	Blade passing frequency
<i>DES</i>	Detached eddy simulation
<i>DDES</i>	Delayed DES
<i>ISA</i>	Int. standard atmosphere
<i>LE</i>	Leading edge
<i>LES</i>	Large eddy simulation
<i>LPC</i>	Low pressure compressor
<i>PPS</i>	Piezo pressure sensor
<i>SAS</i>	Scale-adaptive simulation
<i>TE</i>	Trailing edge
<i>URANS</i>	Unsteady Reynolds averaged Navier Stokes
<i>TS</i>	Time step

Greek symbols

α	Throttling state
η	Pitchwise wall unit
κ	Wave number
λ	bypass ratio
Π	Total pressure ratio
ξ	Streamwise wall unit
ζ	Spanwise wall unit

Subscripts and superscripts

$\wedge$	Amplitude
<i>acc</i>	accumulated quantity
<i>corr</i>	Corrected quantity
<i>exp</i>	Experiment
<i>pol</i>	Polytropic quantity
<i>red</i>	Reduced quantity
<i>rel</i>	Relative quantity
<i>sop</i>	Stationary operation
<i>t</i>	Total quantity

Table 1

Larzac 04C5 data at design conditions (Kern, 2022).

Global engine		LPC	
F	13 kN	Π_{LPC}	2.26
$\dot{m}_2$	27.6 $\frac{\text{kg}}{\text{s}}$	n_{LPC}	17.5 $\frac{1000}{\text{min}}$
$d_{2,tip}$	0.452 m	Ma_{tip}	1.37 (R1 rel)
λ	1.13	Blade count	
Π	10.4	R1/S1	23/61
T_{t4}	1403 K	R2/S2	29/43

continuously, quasi-stationary or dynamic throttling can be realised. The former enables compressor performance data acquisition at different, constant degrees of throttling, the latter allows for a reproducible run-up into stall events. The LPC stall mechanism is experimentally proven as spike-type, originating from the R1 tip region throughout the entire operating range (Stöfel, 2017). The measurement equipment is explicitly designed to record aerodynamic phenomena near the stability limit. High resolution piezo pressure sensors allow transient data acquisition through all stages. This includes an axially equidistantly distributed casing wall pressure 12-point-array extending from 40% of the axial chord upstream of the R1 LE to the R1 TE (PPS1-12; ref. to Fig. 10). All piezo pressure probes provide a sampling rate of $f_{exp} = 1\text{MHz}$. Total pressure and temperature data is available along all LPC stages. This study explicitly relies on radially distributed pitot probes attached to the leading edge of two stator blades of the first stage. Synchronisation between high frequency pressure data and engine performance data enables time-resolved classification in the overall engine context. Engine and LPC key data at design conditions is listed in Table 1. For additional information on the Larzac 04C5 engine and the LPC measurement equipment refer to Kern (2022) and Scheibel et al. (2024).

3. Numerical approach

The numerical analysis is based on URANS and DDES simulations of a 45-degree segment of the first Larzac LPC stage. The numerical domain is shown in Fig. 1a. This choice is directly motivated by the experimental proof of compressor stall arising from perturbations of the R1 tip flow (Stöfel, 2017). To avoid the need to run a full annulus setup, the blade geometries are scaled to achieve a geometric multiple of the blade numbers (R1: 23→24, S1: 61→64). The scaling is performed in axial and circumferential direction, enabling geometrical blade profile similarity. This approach ensures that the ratio of pitch to chord remains constant, which is the key factor influencing the local pressure load on the compressor. The basis rotor blade geometry is extracted from a previously conducted fluid–structure-interaction study for each spool speed separately. All simulations are carried out with the 3D finite volume density-based solver TRACE, developed by DLR-AT and MTU Aeroengines AG. Both URANS and DDES calculations are based on the underlying two-equation $k-\omega$ turbulence model by Wilcox (1988). The URANS modelling approach is extended by a curvature correction approach by Wunderer (2024). Stagnation point turbulence is limited by using the approach of Kato and Launder (1993). A vorticity-based implementation by Shur et al. (2015) is used to determine the subgrid length scale of the DDES model. The DDES implementation follows Spalart et al. (2006). The calculation of inviscid fluxes is realised by a distributed blending of upwind and central schemes, enforcing a constant amount of 50% upwind second order scheme (Roe, 1981). This contrasts with the typically preferred choice of dynamic blending according to Travin et al. (2002), but proved to be mandatory to ensure numerical stability. This was observed in a very similar manner by Möller et al. (2024) in a comparable transonic compressor study. All URANS and DDES results are based on the identical mesh (structured OCH; 125 mn. cells). In the vicinity of both blade rows maximum near wall non-dimensional cell sizes of $\Delta\xi^+ < 360$ in streamwise, $\Delta\eta^+ < 1$ in

Riéra et al. (2016) demonstrated that the resolution of the tip leakage flow topology of a compressor rotor interacting with incoming stator wakes is significantly more detailed with a zonal DES method compared to averaged Navier–Stokes methods. The authors focused on transonic operation under design conditions. de Almeida et al. (2024) applied a scale-adaptive (SAS) approach to resolve circumferentially propagating pre-stall disturbances in a low-speed compressor stage, enabling quantitative mode decomposition.

This study intends to take the next consecutive step and provides an in-depth comparison of URANS and DDES results for a real engine compressor at different states of throttling. Key element is the assessment of the capability of a DDES approach to resolve compressor pre-stall behaviour in a real engine environment, at transonic design conditions as well as at subsonic off-design conditions. This explicitly includes the reproducibility of global compressor performance under throttling and the local formation of pre-stall irregularities as precursors to spike-type rotating stall compared to real engine data.

2. Test vehicle

The transonic low pressure compressor (LPC) of the two-spool unmixed turbofan engine Larzac 04C5 serves as test vehicle for all investigations conducted. The engine is operated on the institute's own engine test facility. The LPC comprises two stages with a tandem stator in the second stage and a prime number of blades in each row. Downstream of the LPC, the engine mass flow is divided into bypass and core mass flow. Both LPC rotor blade rows are designed for transonic operation ($Ma_{tip/R1(rel)} = 1.37$). At relative spool speeds below $n_{red,rel} = 81\%$, both rotors experience an entirely subsonic relative inflow, representing an off-design operation. Both flow regimes, transonic ($n_{red,rel} = 90\%$) and subsonic ($n_{red,rel} = 76\%$), are considered in this study. A mechanical bypass nozzle throttling device allows for LPC throttling beyond the surge line. With the option to close the bypass nozzle stepwise or

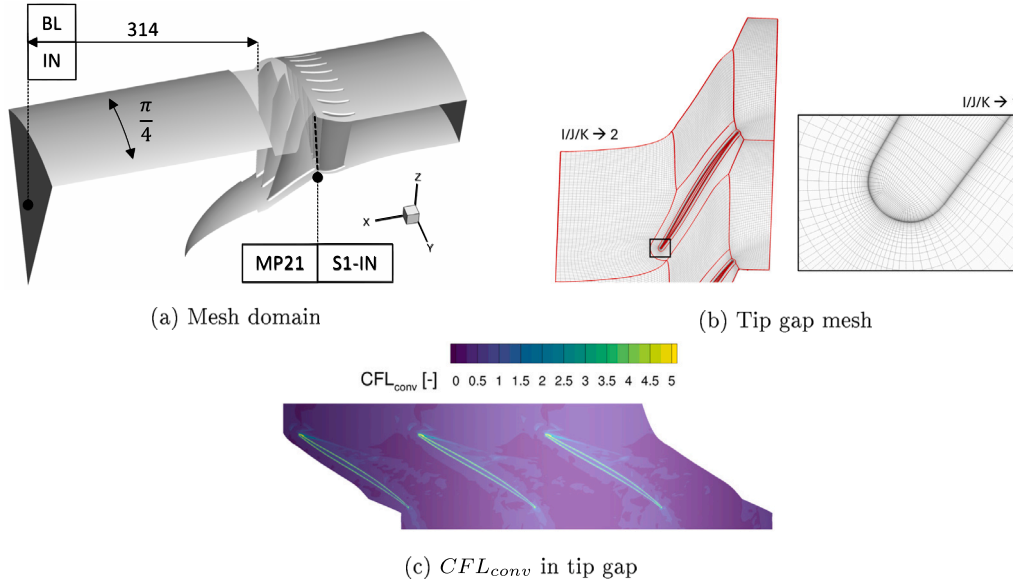


Fig. 1. Numerical domain with indication of measurement plane MP21 (a), tip gap mesh topology (b) and convective CFL_{conv} in tip gap (c)

Table 2

URANS grid sensitivity analysis for stationary operating point at $n_{red,rel} = 90\%$.

Cell count	Coarse factor	$\Pi / \dot{m}_{corr}$ [-]	η_{pol} [-]
125.0 mn.	1	0.0637	0.8786
99.2 mn.	$1/\sqrt[3]{2}$	0.0636	0.8790
78.7 mn.	$1/(\sqrt[3]{2})^2$	0.0637	0.8783
62.5 mn.	$1/(\sqrt[3]{2})^3$	0.0642	0.8742

pitchwise and $\Delta\zeta^+ < 460$ in spanwise direction are realised, whereby the spanwise resolution is additionally increased in the R1 tip region, featuring 37 nodes in the R1 tip gap resulting in maximum values of $\Delta\zeta^+ < 160$. The OCH topology of the R1 tip region mesh is shown in Fig. 1b. For visualisation, only every second cell node is displayed in the blade-to-blade view. The close-up illustrates the OH topology applied within the tip clearance. The strip surrounding the tip gap contains the near-wall resolution of the rotor blade, which is extruded towards the casing. This is standard practice in compressor simulations, as the small tip gaps ($\min(\Delta) = 0.2$ mm) do not allow for an O-mesh enclosing the blade tip, as is typically applied for propellers or un-ducted fans.

For URANS and DDES, the same temporal resolution (720 time steps (TS) per rotor blade passing period; 2160 TS per 45-degree segment) is used; a third-order implicit Runge–Kutta method (Ashcroft et al., 2013) is employed for temporal discretisation. The distribution of the convective CFL number CFL_{conv} in the tip region – the focus of this study – is shown in Fig. 1c. In general, a CFL_{conv} of less than one can be observed, the only exception being within the aforementioned band of extruded near rotor blade wall resolution. The maximum values of the convective CFL number at this point are $CFL_{conv} < 9$, which is considered sufficient with regard to the use of an implicit solver.

The choice of the grid discretisation is based on the spatial resolution required by the DDES approach and is also used for the URANS calculations to strive for maximum comparability between the models. Aiming for URANS grid insensitivity only would allow for a significantly coarser mesh. This is illustrated in Table 2 by a comparison of the URANS predictions based on four grid density levels (the highest level corresponds to the grid used in this study). The ratio of the corrected mass flow rate of the compressor to the total pressure ratio of the first stage, as well as the polytropic efficiency of the first stage, demonstrate that grid insensitivity was achieved even at 50% of the mesh count. The term ‘corrected mass flow’ refers to the correction of the absolute mass flow rate to International Standard Atmosphere (ISA) conditions.

An essential verification parameter for the basic DDES functionality is the shielding function f_d . Fig. 2 depicts the distribution of f_d , which blends between RANS mode ($f_d \rightarrow 0$) and potential LES mode ($f_d \rightarrow 1$). In general, the desired behaviour is demonstrated by shielding only attached boundary layers in RANS mode. A special situation occurs at the rotor tip gap close to the LE. Since the incoming boundary layer is larger than the radial extent of the tip gap, the tip gap is initially modelled in RANS mode. This is by construction a limitation of the DDES approach and needs to be mentioned. Nevertheless, the close-up views in Fig. 2 show the treatment of the tip leakage vortex in LES mode from its initial formation and a transition of the tip gap flow (between blade and casing boundary layer) into LES in axial direction at 30% axial chord. This encourages the authors’ assessment that the DDES approach is suitable, which is underlined by successful studies with very similar conditions at the tip gap onset (Riera et al., 2016).

In order to assess the spatial discretisation with regard to the ability of the DDES approach to switch to LES-like excitation, Fig. 2 shows additionally the DDES length-scale ratio l_{ratio} , defined as l_{RANS}/l_{DDES} . Values of $l_{ratio} > 1$ therefore indicate a DDES subgrid length scale that is smaller than the comparable RANS length scale. The larger the ratio, the greater the reduction in the modelled turbulent kinetic energy. The distribution in Fig. 2 refers to the rotor midspan. This position is considered the most critical, as the spatial discretisation in the spanwise direction is coarsened towards midspan in order to reduce the total amount of cells. The almost entire demonstration of $l_{ratio} > 2$ – with the exception of the near wall blade region, where RANS mode is intended – is desired and serves as an indication of adequate discretisation despite the moderate coarsening.

To finally ensure a sufficient temporal and spatial resolution of the DDES calculations, a minimum resolution of at least 80% of the total turbulent kinetic energy (sum of resolved and modelled TKE) is aimed for. This is checked and demonstrated by the visualisations in Fig. 3. Except from the near wall zones, modelled by URANS on purpose, the targeted resolution is achieved. This is shown for three axial positions, extracted at the R1 passage inlet, the R1 passage outlet and immediately downstream of S1. To complement the integral summation, Fig. 4 shows the recorded turbulence spectra at two numerical probe positions within the R1 tip region. The spectral analysis reveals the presence of an energy-carrying region, the inertial region, and a dissipative kink. This is considered important evidence that the hybrid RANS/LES approach implemented in this application-oriented context is capable of resolving the basic features of the turbulent energy cascade.

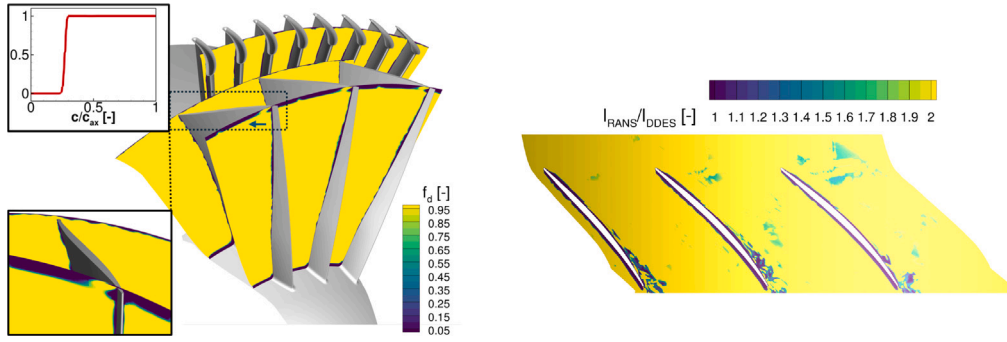


Fig. 2. Spalart shielding function f_d (left) and DDES length scale ratio l_{RANS}/l_{DDES} at mid-span (right).

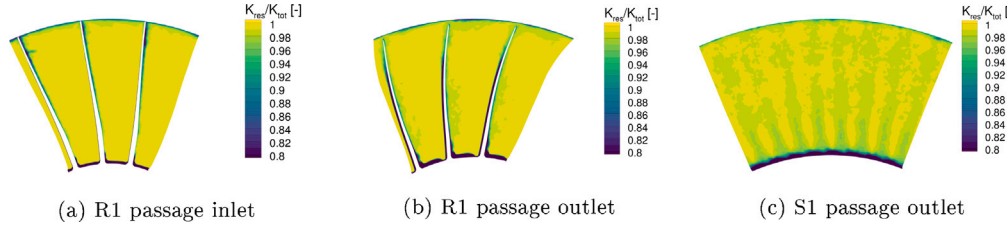


Fig. 3. Ratio of resolved and modelled turbulent kinetic energy K (viewing direction against the main flow direction).

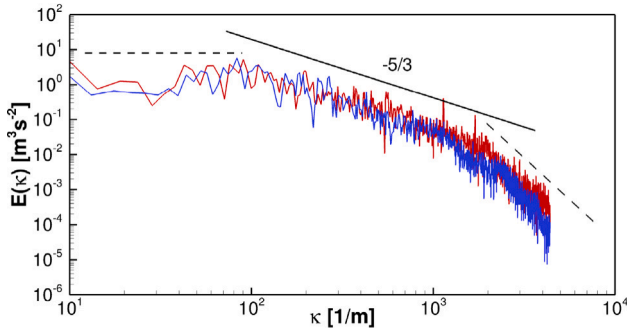


Fig. 4. Turbulence spectrum extracted from DDES at two probe positions in rotor tip region.

A 1D radial total pressure and temperature condition based on traversed boundary layer (BL) measurement data is prescribed at the domain inlet. A moderate turbulence intensity $Tu = 2\%$ and a constant turbulent length scale $tu_l = 0.0002$ m are defined. Turbulent perturbations are not prescribed, since the impact factor is regarded as low in the simulation of shear layer dominated flows He et al. (2021). At the domain exit, a 1D radial pressure condition is specified, which ensures a stator outlet pressure condition that is identical to LPC RANS calculations including all compressor stages (Scheibel et al., 2024). All unsteady simulations are initialised by RANS calculations. The initial RANS calculations are based on a mixing-plane interface between rotor and stator, this is switched to an unsteady zonal interface for the time-resolving simulations. The operational fluid is prescribed as air relying on an ideal gas condition with constant specific heat capacity c_p .

The statistical analysis, including time averaging, is started after two rotor revolutions. The decay of the initial transients is verified using the rate of change of the moving average (over one domain period) of the three quantities compressor mass flow rate $\dot{m}_{corr}$, total pressure ratio Π and polytropic efficiency η_{pol} . Fig. 5 illustrates the conservative choice of the cut-off value for the initial transients in the course of the moving average of the corrected mass flow $\dot{m}_{corr}$ during operation on the stationary operating line ($\alpha = 1.00$) and under throttling ($\alpha = 0.90$) at transonic speed $n_{red,rel} = 90\%$. The definition of the throttling

parameter α is given in Section 4.2 (refer to Eq. (1)) and serves here solely as an operating condition marker. The statistical analysis is based on at least five rotor revolutions following the initial transient cut-off. This corresponds to 40 domain periods (45-degree segment). Statistical convergence was verified by quantifying the two-sided 95%-confidence interval for each quantity under consideration. This was assessed based on period-averaging, yielding the confidence interval $CI_{95,period}$ from the distribution of the domain period mean values, and on the autocorrelation analysis, yielding the effective confidence interval $CI_{95,eff}$ based on the integral autocorrelation time scale and the resulting effective number of statistically independent samples. Table 3 lists the calculated 95%-confidence intervals for $\dot{m}_{corr}$, Π and η_{pol} for both operating conditions shown in Fig. 5.

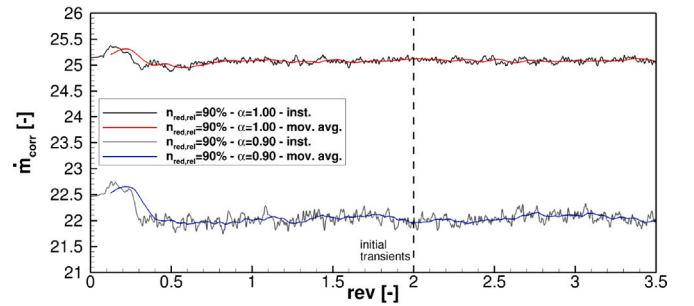


Fig. 5. Initial transient indication for corrected mass flow at $n_{red,rel} = 90\%$.

Table 3

Statistical convergence metrics for $n_{red,rel} = 90\%$ stationary operating point and throttled condition.

α [-]	Quantity	Mean	$CI_{95,period}$	$CI_{95,eff}$
1.00	$\dot{m}_{corr}$ [kg/s]	23.86	± 0.0079	± 0.0091
1.00	p_t/p_{t-IN} [-]	1.552	± 0.0003	± 0.0004
1.00	η_{pol} [-]	0.830	± 0.0008	± 0.0008
0.90	$\dot{m}_{corr}$ [kg/s]	20.96	± 0.0292	± 0.0366
0.90	p_t/p_{t-IN} [-]	1.523	± 0.0009	± 0.0008
0.90	η_{pol} [-]	0.740	± 0.0025	± 0.0032

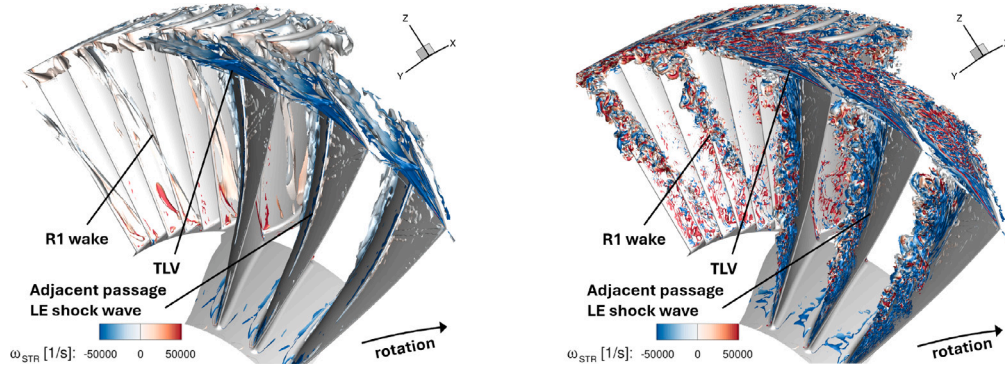


Fig. 6. Iso-surface of instantaneous rotor row vortex structures (λ_2 criterion) coloured by streamwise vorticity ω_{STR} for URANS (left) and DDES calculation (right).

4. Results

The discussion of results is introduced with a comparison of the calculated vortex structures based on the URANS and the DDES approach under identical fluidic boundary conditions (see Fig. 6). The considered operating point refers to a stationary operating line condition at the transonic relative spool speed $n_{red,rel} = 90\%$. Basically, both approaches reflect the main flow features: tip leakage vortex (TLV), adjacent passage leading edge shock wave and the R1 wake entering the downstream located stator domain. However, the URANS approach is only capable of reproducing the large-scale integral structures. The DDES result visualises the resolution of small-scale interacting turbulent structures rather than a concentration of turbulent kinetic energy on singular structures. This corresponds to the expected result and confirms especially with regard to the TLV resolution the motivation of this study to take a scale-resolving approach into account.

4.1. Integral speedline data

Two spool speeds are considered, $n_{red,rel} = 90\%$ close to design speed and $n_{red,rel} = 76\%$ representing an off-design condition with subsonic rotor blade tip inflow. For each spool speed one condition close to the stationary operating line and two throttled conditions were calculated. Each 3-tuple ((U)RANS, DDES) relies on exactly the same boundary conditions. The resulting stage 1 total pressure build-up Π is plotted against the corrected compressor mass flow $\dot{m}_{corr}$ in Fig. 7. For reference, steady RANS calculations including both LPC stages are added (light grey — Scheibel et al. (2024)). These reference simulations rely on the original blade count without domain scaling

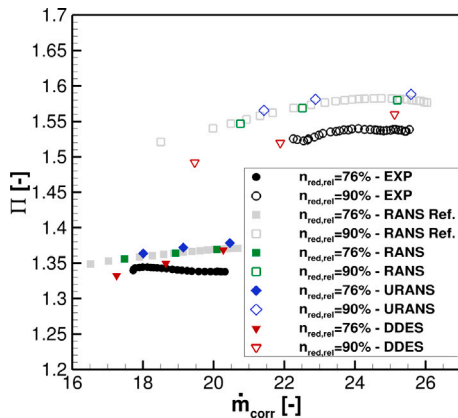


Fig. 7. Computed time-averaged LPC operating points at relative spool speeds $n_{red,rel} = 76\%$ and $n_{red,rel} = 90\%$ using RANS, URANS and DDES methodology.

and are set up using a mixing plane condition between rotating and stationary domains. The comparison of the single-point RANS results (green) with the reference line confirms that both the reduction to a first stage only configuration and the geometry scaling due to the assimilation of the blade numbers have a negligible influence. In general, RANS and URANS predict similar characteristics for the respective speedlines, including a consequent shift towards higher pressure build-up and higher mass flow rates from RANS to URANS. In contrast, the transition to DDES leads to a shift of the speedline in terms of slope and absolute values, resulting in an improved agreement with the experimental reference, with the exception of the stationary operating point at $n_{red,rel} = 76\%$. The differences between (U)RANS and DDES increase with increasing throttling. In fact, the most throttled DDES operating point at $n_{red,rel} = 90\%$ exhibits a continuously decreasing mass flow over time and cannot be considered stable in terms of flow rate. In contrast, the (U)RANS prediction, which is based on identical boundary conditions (3-tuple), determines a stable behaviour with regard to the moving average of mass flow and pressure ratio. The DDES result is consistent with the significantly higher stall mass flow of the experimental reference. The (U)RANS results do not enter an unstable regime and underpredict the stall mass flow. An exact determination of the stall mass flow rate associated with the individual numerical approaches is not part of this study. The periodic configuration enables the simulation of initially excited pre-stall perturbations. This is demonstrated in the further course of this paper and is the design application of the chosen setup. An accurate prediction of the stall mass flow rate requires a full annulus configuration to resolve the formation of rotating separations propagating in the circumferential direction. This capability is limited by the assumption of periodic boundary conditions and will not be addressed here. However, the compressor map footprint of the 3-tuples suggests that the pre-stall behaviour resolved by the DDES method differs significantly from the averaged Navier–Stokes approaches.

4.2. Integral radial distributions

The comparison of DDES and URANS prediction is continued with the radial total pressure build-up evaluated downstream of R1. The simulations are designated with the throttling state α_{BC} of the respective RANS initial condition: defined as the quotient of the simulated total pressure ratio Π and corrected mass flow $\dot{m}_{corr}$, relative to the experimental quotient on the stationary operating line (SOP):

$$\alpha_{BC} = \frac{\frac{\dot{m}_{corr,start-sim}}{\Pi_{start-sim}}}{\frac{\dot{m}_{corr,sop-exp}}{\Pi_{sop-exp}}} \quad (1)$$

The calculation of the throttling parameter α_{BC} refers to the initial condition to point on the identical boundary conditions and identical start solution of the simulations compared. As analysed in the previous Section 4.1, the final predicted state of throttling differs depending on the numerical approach. For comparison, the predictions derived at

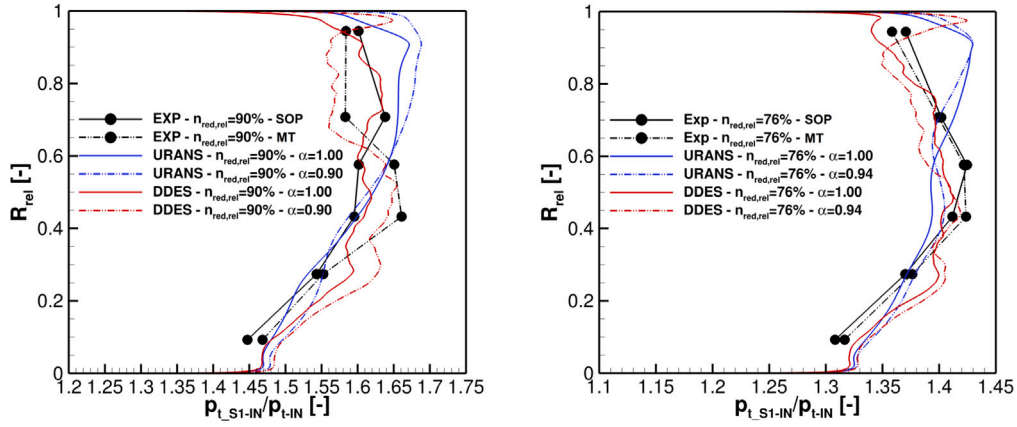


Fig. 8. Time-averaged radial distributions of absolute rotor total pressure build-up extracted at MP21 for $n_{red,rel} = 90\%$ (left) and $n_{red,rel} = 76\%$ (right).

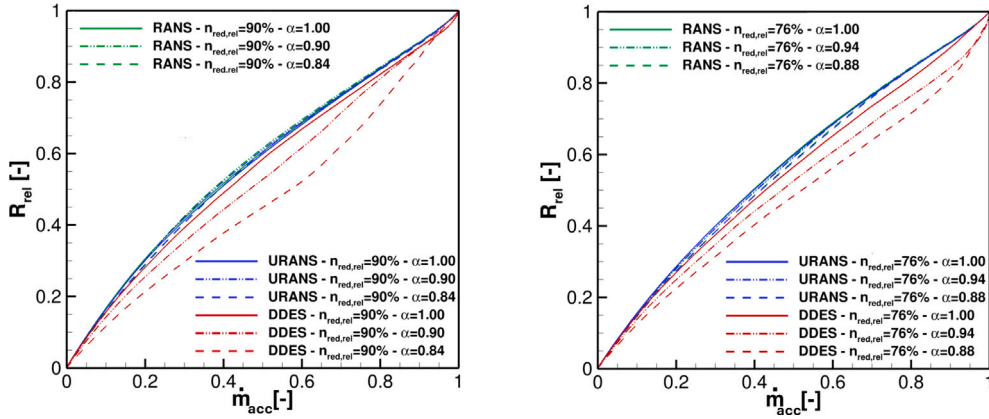


Fig. 9. Time-averaged radial distributions of accumulated hub-to-tip mass flow distribution extracted at MP21 for $n_{red,rel} = 90\%$ (left) and $n_{red,rel} = 76\%$ (right).

the stationary operating line and at a moderately throttled condition are selected (ref. to Fig. 7: 3-tuples with medium and highest mass flow). Experimental radially distributed pitot probe validation data are available in measurement plane MP21 (see Fig. 1a), consistently also for the SOP and the moderately throttled (MT) condition (derived from quasi-stationary throttling procedure). Fig. 8 states the comparison of the calculated URANS and DDES radial pressure load distributions with the experimental reference data.

At stationary operating point conditions, the total pressure build-up in the tip region is overestimated by URANS for both spool speeds. This deviation is not present in the DDES result, which leads to a significantly improved agreement with the experimental reference. Furthermore, when throttling at $n_{red,rel} = 90\%$, URANS predicts an increase in total pressure near the tip, which is contrary to the experimental trend. Based on DDES, the shift of the total pressure maximum towards midspan is predicted in analogous manner to the measurement data. Similarly, throttling at $n_{red,rel} = 76\%$ results in an exposed URANS total pressure maximum near the tip, which is not present in either the experiment or DDES. The URANS approach is not able to accurately model the throttling behaviour of the compressor, while the transition to DDES allows for a significantly improved agreement with measurement data. This is an important finding for assessing the need to rely on scale-resolving methods to predict the pre-stall behaviour of the LPC.

An examination of the radial accumulative mass flow distribution $\dot{m}_{acc}$ is depicted in Fig. 9. For clarification, the term $\dot{m}_{acc}$ is defined as the mass flow fraction summed from hub to tip relative to the absolute stage mass flow. The DDES approach reveals a shift of the tip mass flow towards midspan with increasing throttling. This can be directly attributed to the resolution of an increased blockage caused by the R1

tip leakage vortex system. Under throttling, the TLV trajectory moves upstream, resulting in an expansion of the blocked area (to be shown in Section 4.3/ Fig. 12). The trend is present at both spool speeds, but is more pronounced at the transonic $n_{red,rel} = 90\%$ condition. Both the unsteady and steady RANS models do not capture this redistribution and remain almost unchanged under throttling. Actually, the inclusion of unsteady effects from RANS to URANS does not lead to a macroscopic change of global performance characteristics. The prediction of a mass flow redistribution in correlation with the TLV expansion is considered the main reason for the improved DDES results compared to (U)RANS.

4.3. Casing wall pressure correlations

Moving forward from the assessment of the prediction of integral compressor data, this section focuses on the representation of unsteady casing wall pressure data. This is essentially motivated by the use of these blade pressure signature data in pre-stall warning algorithms and the reflection of small scale turbulence resolution in high frequency data. Three piezo pressure sensors (PPS) are selected from the 12-point array above R1 (see Fig. 10): PPS1 is located 40% of the axial chord upstream of the R1 LE, PPS7 40% of the axial chord downstream of the LE, and PPS12 near the TE. Fig. 10 depicts a comparison of simulation and measurement data at the stationary operating line at $n_{red,rel} = 76\%$. In principle, both numerical approaches reflect the main features visible in the piezo data: a periodic sequence of pressure maxima and minima representing the signature of the rotor blade pressure and suction side passing the stationary probe PPS1, an increase in the mean pressure level in streamwise direction (PPS1 $\rightarrow$ PPS7 $\rightarrow$ PPS12), and high-frequency oscillations at PPS12. However, the URANS data remain

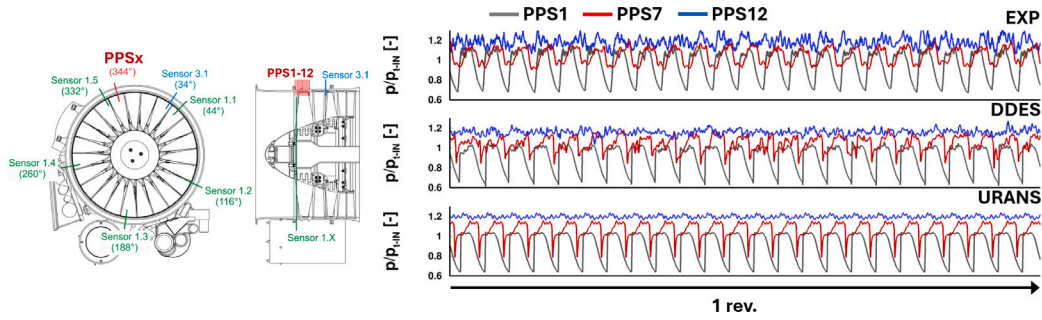


Fig. 10. Comparison of unsteady experimental piezo casing pressure data with numerical results derived from URANS and DDES approach.

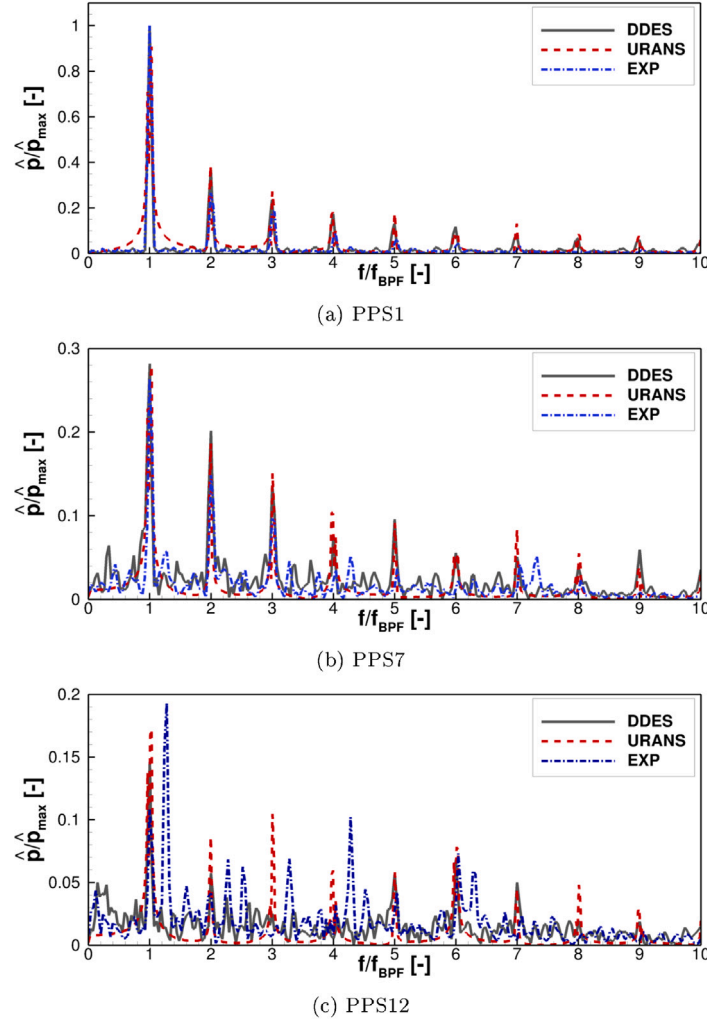


Fig. 11. FFT spectra of time-resolved casing pressure data.

in a strictly periodic regime for all three probe positions, while the DDES resolves an irregular oscillation behaviour that is in significantly improved agreement with the measurement data.

To quantitatively assess this observation, Fig. 11 presents the fast Fourier transform (FFT) spectra of the signals shown in Fig. 10. The spectra are grouped according to the probe location. The FFT amplitude $\hat{p}$ for all three probes is normalised to the corresponding maximum PPS1 amplitude $\hat{p}_{max}$ observed. For PPS1, the blade passing frequency and its harmonics can clearly be identified as the dominant frequency components. These characteristic peaks are consistently captured by both numerical approaches and are in good agreement with the experimental reference.

The FFT spectra at PPS7 and PPS12 further confirm the observations made from the time-domain signals in Fig. 10. For both probe positions, the URANS results remain dominated by discrete spectral peaks associated with the BPF and its harmonics, while almost no additional broadband spectral content is observed. This behaviour differs significantly from the experimental measurements, which exhibit substantially higher spectral energy in between the BPF harmonics. In contrast, the DDES approach reproduces the experimentally observed spectral distribution considerably more accurately. In particular, the streamwise change in spectral energy distribution is captured in good agreement with the measurement results.

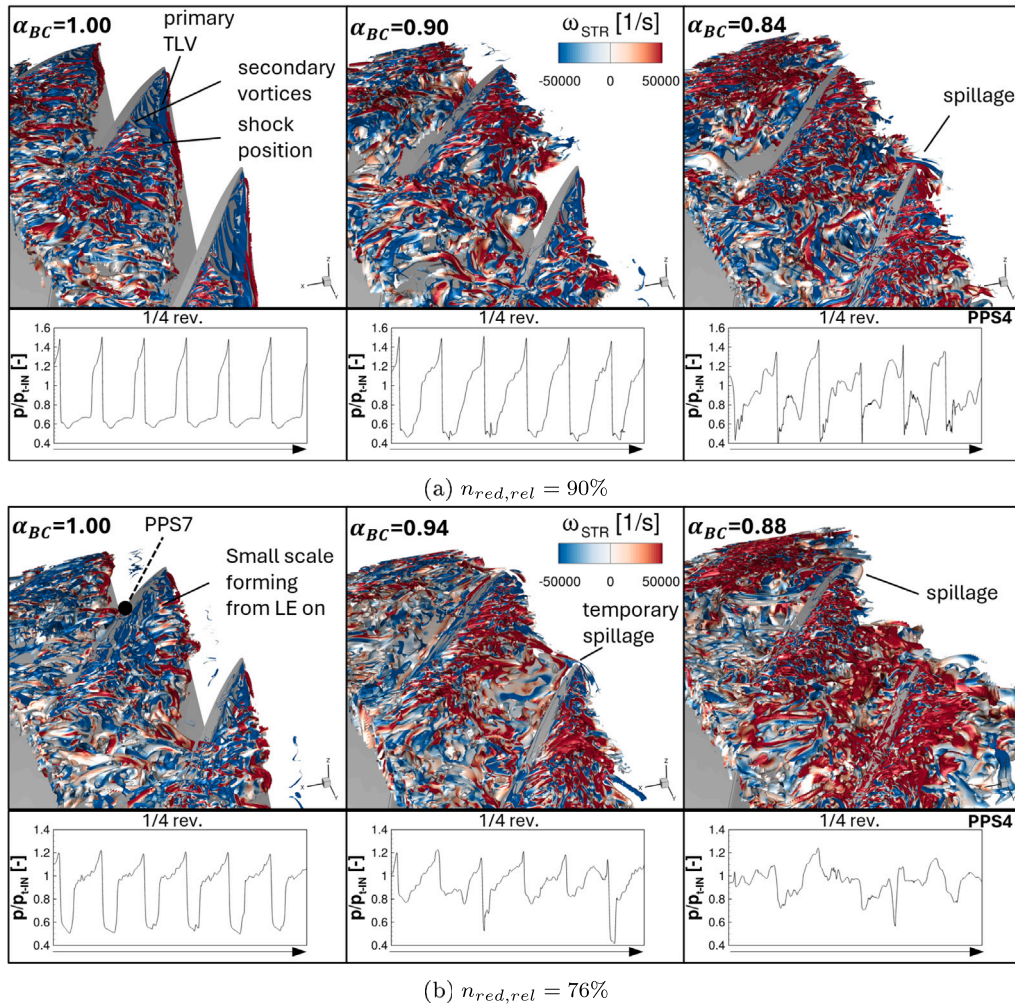


Fig. 12. Correlation between DDES resolved instantaneous rotor tip vortex structures and DDES blade pressure signature extracted at probe position PPS4 at time frame of snapshot; view direction from aft to front.

The tendency of URANS to suppress and the ability of DDES to resolve irregularities in the blade pressure signature is assumed to be a significant advantage of the scale-resolving approach with regard to a proper representation of a real engine spike-type stall initiation process. In combination with the capability of the DDES approach to resolve the integral compressor performance tendencies under throttling – as elaborated in the previous Sections 4.1 and 4.2 – the prerequisites for a correlation of the current tip leakage vortex topology with the resulting footprint in the casing wall pressure data appear to be given. In other words, the final objective of the present study addresses the demonstration of the possibility of using the DDES approach to achieve a link between implicit pre-stall indicators and causal changes in the tip leakage flow system.

In Fig. 12 instantaneous snapshots of the rotor tip vortex structures (based on λ_2 criterion) are depicted for both spool speeds considered in each case for three different states of throttling. The snapshots are referred to numerically predicted casing pressure data extracted at piezo sensor point PPS4 (immediately at R1 LE). The pressure time traces cover a time frame of a quarter rotor revolution. The instantaneous snapshot has been extracted at half of the time of the considered period (1/8 rev.). The throttling conditions correspond to the operating points in Figs. 7/8/9 and are denoted by α_{BC} respectively. For the near design speed $n_{red,rel} = 90\%$, the tip leakage vortex system is located deep inside the passage under stationary operating conditions ($\alpha_{BC} = 1.00$). Close to the LE, the formation of the primary TLV is clearly visible, surrounded by secondary vortices that roll up around the main TLV. Additionally,

an induced vortex rotating in opposite TLV direction is resolved directly next to the primary TLV. These observations are similar to the findings of Riéra et al. (2016). Downstream of the shock position, a bursting of the TLV can be observed, which is accompanied by a slight deflection of the primary TLV trajectory and leads to the formation of small turbulent scales. A purely periodic, undisturbed pressure sequence is observed at the probe position PPS4. This situation remains unchanged with moderate throttling ($\alpha_{BC} = 0.90$). However, the area affected by dominant TLV scales is shifted significantly upstream, but remains completely within the rotor passage. Additional throttling causes a spillage of the neighbouring blade LE ($\alpha_{BC} = 0.84$). This situation is now reflected in the casing pressure data in the form of ambiguous detection of pressure maxima. The deviation from a clearly recognisable blade passing frequency serves as a pre-stall indicator in classic stall warning measures (Stöfel, 2017).

When switching to the off-design subsonic speed $n_{red,rel} = 76\%$ at stationary operating condition ($\alpha_{BC} = 1.00$), the development of small scales that form the TLV system can be observed directly at the LE. With regard to the transonic speed $n_{red,rel} = 90\%$, the presence of the strong passage shock appears to damp the upstream development of small scales. The axial position of probe position PPS7 is additionally marked in the snapshot. For this operating point, PPS7 is the first axial position that shows irregularities in the periodic sequence of pressure maxima and minima (PPS1-6 with sharp maxima/minima). This is visible in Fig. 10. The sensor position corresponds well with the point of impact of the

first TLV structures on the adjacent blade pressure side and provides a possible explanation for the arising reduced periodicity of PPS7. Moderate throttling ($\alpha_{BC} = 0.94$) at $n_{red,rel} = 76\%$ leads to a situation in which the entire TLV system is generally contained within the passage, but a temporary spillage of singular structures occurs around the adjacent LE. This seems to be reflected in the PPS4 signal by shifted pressure minima, whereby the general distinction between pressure maxima and minima is still possible. Kern (2022) achieved significantly increased pre-stall warning times by detecting elevated pressure minima. The DDES result provides indications that these shifted minima could be related to temporary spillage preceding a spillage by a large number of scales, as can be observed with further increased throttling ($\alpha_{BC} = 0.88$). This follow-up situation is accompanied by a complete collapse of the periodicity of the wall pressure signal, which triggers conventional warning systems.

5. Conclusions

DDES and URANS investigations of the LPC first stage of a two-spool unmixed turbofan engine were conducted. The capability of the numerical approaches to predict the LPC pre-stall behaviour was contrasted by a comparison against real engine measurement data. This refers to time-averaged global compressor performance data as well as to high resolution unsteady casing wall pressure data. Two spool speeds were considered, a transonic design speed and a subsonic off-design condition. Three different states of throttling were analysed per spool speed.

The study reveals a significantly improved representation of the compressor map characteristics and radial pressure load distributions when using the scale-resolving method, with only the DDES approach covering the experimental trends at near stall conditions. In general, the deviations between the numerical approaches increase with increasing degree of throttling. DDES predicts a significantly larger blockage area caused by the resolved tip leakage vortex system, leading to a mass flow redistribution under throttling that is not captured by URANS. This is considered to be the main reason for the model deviations. Although the use of a scale-resolving approach to represent integral compressor performance data is not generally considered mandatory, the results presented show significant advantages in the context of a tip-sensitive rotor system.

The DDES approach proved suitable for resolving irregularities in the blade pressure signature, very similar to the occurrence in the experimental reference data. In contrast, URANS showed a strong tendency to remain in a periodic regime without revealing the experimental behaviour. In FFT spectra of casing pressure data, the capability of URANS was mainly limited to the prediction of the blade passing frequency and the corresponding harmonics. The DDES approach was shown to cover a broadband spectral energy distribution in close agreement with experimental test data. This capability of DDES is considered a key enabler in representing real engine pre-stall perturbations and in supporting the enhanced development of pre-stall warning measures. The ability to establish correlations between the blade pressure signature recorded on the rotor casing and the causative disturbances of the tip leakage vortex system was explicitly demonstrated for both spool speeds.

The study provides indications for the necessity to use a scale-resolving approach for the numerical representation of a real engine compressor.

CRedit authorship contribution statement

Julian A. Scheibel: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marcel Stöbel:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Dragan Kožulović:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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