AERODYNAMIC PERFORMANCE COMPARISON OF HIGH POWER TURBOPROP S-DUCT INTAKE ON CHANNEL WING AT VARYING AZIMUTH

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ABSTRACT

S-duct intake component for a highly loaded turboprop engine was investigated considering its installation on a channel wing of an active high-lift aircraft using computational fluid dynamics. The objective is to observe the interaction effects of the propeller-nacelle-wing on the S-duct intake aerodynamics, especially when the intake is positioned at different azimuth angles with respect to rotation axis. Single scoop wrap-around type S-duct was integrated into a representative nacelle body. The propeller was modeled as an actuator disc for the slipstream effects. Steady-state Reynolds-averaged Navier-Stokes simulations were run using negative Spalart-Allmaras turbulence model. Although the results showed that the reference S-duct position at $\phi = 270^\circ$ had the relatively higher recovery than the other variations, significant improvements in total pressure distortion and intensities were achieved at $\phi = 0^\circ$ and $90^\circ$ positions. Up to 3% decrease in swirl coefficient levels was observed when the wrap-around S-duct was positioned at $\phi = 90^\circ$ in comparison to reference position.

NOMENCLATURE

AIP Aerodynamic Interface Plane
CDI Circumferential distortion intensity
$DC(\theta)$ Total pressure distortion coefficient at sector $\theta$
$P_{t,i}$ Total pressure at ring $i$
$q$ Dynamic pressure, $\frac{1}{2}\rho V_a^2$
RDI Radial distortion intensity
$SC(\theta)$ Swirl distortion coefficient at sector $\theta$
$V_a$ Axial velocity
$V_c$ Circumferential velocity

Greek Symbol

$\alpha$ Highlight spread angle
$\theta, \theta_0$ Sector and initial angles on AIP
$\pi_i$ Intake total pressure ratio
$\phi$ Nacelle azimuth angle

INTRODUCTION

The progress of civil aviation is experiencing new challenges as the air transport volume of major hubs reaches their physical boundaries. Over capacity problems add to delay times and limits the market growth, as it is reported for the European air traffic flow (Eurocontrol, 2013). Small airports existing in the air transportation network can meet this challenge by introducing additional point-to-point connections. The Coordinated Research Center 880 (SFB
880) is investigating the design guidelines for future commercial aircraft to benefit from such networks distributed in Europe. The project focuses on short take-off and landing capability using active high-lift to benefit from short runways (Werner-Spatz et al., 2012), as well as passive high-lift by installing the nacelle on channel wing (Figure 1), morphing lifting surfaces on wing and reduced noise emission levels to mitigate the effects on population centers. The collaborative structure is formed in subgroups with the aforementioned research objectives regarding the aerodynamics, structural mechanics and airframe design.

![Figure 1: Turboprop nacelle installed on channel wing.](image)

The SFB 880 aircraft is powered with two turboprop engines in its first research period. Its specifications include flight mission with $Ma = 0.74$ cruise at 10.6km altitude in range of 2000km and active high-lift system for boundary layer control (BLC). Short take-off and landing within 800m runway is achieved by BLC using air suction and blowing to the Coanda flaps (Burnazzi and Radespiel, 2015). The BLC system includes electric-powered small compressors embedded in the wings, with their power supplied by the turboprops. The maximum power requirement was estimated as $\sim 10\text{MW}$ each of the SFB 880 aircraft turboprops, including the high-lift system power of $1.5\text{MW}$ at sea-level in the first research period. The high power rate of SFB 880 turboprop increases the importance of S-duct intake component, especially when installed on a channel wing. In this context, the Institute of Jet Propulsion and Turbomachinery (IFAS) at TU Braunschweig is investigating the turboprop intake aerodynamics and engine integration of SFB 880 aircraft.

Turboprop intakes in conventional tractor arrangement require serpentine type diffuser ducts (an S-duct) that accommodates the propeller gearbox offset by large curvature angles. S-duct intake design has to consider the interaction of propeller wake and nacelle contour along with the requirement of uniform air mass flow delivery through the curved duct to gas generator with minimum losses. High power demand of SFB 880 aircraft makes the external diffusion susceptible to highly loaded propeller slipstream. External drag is another concern due to the large core air mass flow requirement. In this regard, literature on turboprop intakes provided useful information for preliminary design choices. Little and Hinson (1982) compared different types of turboprop intakes and concluded with single scoop offset S-ducts being more advantageous than annular ones. Hancock et al.,(1986) confirmed the high performance of single scoops in their experimental study. On the other hand, both studies analysed the single scoop types at only one azimuth position. McDill and Tolle (1983) provided valuable information regarding integration of shaft penetration type S-duct intake, even though the high recovery of wrap-around type S-ducts was already observed experimentally by Little and Trimboli (1982). Intakes of different shaft connections were compared later by numerical investigation within SFB 880 (Atalayer et al., 2015), acknowledging that wrap-around S-ducts are preferable also for the high power turboprop specification of SFB 880 aircraft.
For the integration into nacelle, Fejtek et al. (1996) provided an optimisation methodology for intakes on a conventional tractor wing but at $\phi = 270^\circ$ azimuth angle. IFAS within the SFB 880 project also investigated installation effects of turboprop on channel wing as a passive high-lift solution. Müller et al. (2014) studied the nacelle and propeller interaction effects on wing. Their numerical study showed that the channel wing configuration significantly improves the lift-to-drag ratio while losing propulsive efficiency compared to tractor wing configuration; however, the study excluded the intake.

In this study, a single scoop, low pinion offset, wrap-around type S-duct was investigated for its aerodynamic performance using computational fluid dynamics. The intake was integrated into a representative nacelle model, installed on a channel wing. The objective was to analyse the performance effects on the S-duct flow when the intake azimuth position changed with respect to propeller rotation axis. It was expected that the intake recovery would be preserved with reasonably low rise in distortion levels. The results will serve as guidelines for the integration of high power turboprop S-duct intakes and as a preliminary analysis for wing-nacelle interaction effects using real propeller model with unsteady RANS simulations.

**ANALYSIS PARAMETERS AND INTAKE MODEL**

All averaged fluid properties of the steady-state simulation results were weighted by mass flow rate but mentioned only as average in this paper. The main analysis parameter was defined as the intake performance by total pressure recovery with respect to its inlet and outlet conditions. The outlet was assumed on the aerodynamic interface plane (AIP), therefore the recovery was evaluated by the ratio of average total pressures at AIP to inlet as $\pi_i$.

\[
\pi_i = \frac{\bar{P}_{t,AIP}}{\bar{P}_{t,in}}
\]  

(1)

The definition mentioned in Seddon (1999) was used to quantify the total pressure distortion coefficient $DC(\theta)$, which is based on parallel compressor theory. The lowest average total pressure found on $\theta$ sector (Figure 2) is subtracted from the average total pressure at the AIP and non-dimensionalised by the average dynamic pressure (Equation 2). In this investigation, the distortion extent was kept at $\theta = 60^\circ$ and the sector with the lowest average total pressure was found by pivoting along the AIP circumference.

Non-uniform total pressure distribution added to the wall friction causes the flow to swirl, which covers the shaft wall and reaches AIP. The loss caused by swirl was quantified using the coefficient $SC(\theta)$ from Seddon (1999) (originally proposed by Guo and Seddon, 1983). The maximum average circumferential velocity in the sector $\theta$ is used for the evaluation (Equation 3), which is non-dimensionalised by the average axial velocity through AIP as mentioned by Taskinoglu et al. (2003) (instead of average duct velocity as defined by Seddon, 1999). For this study, $SC(\theta)$ was observed for the complete AIP by pivoting $\theta = 60^\circ$ sector along the circumference in 5 rings.

\[
DC(\theta) = \frac{\bar{P}_{t,AIP} - \bar{P}_{t,\theta}}{\bar{P}_{t,AIP}}
\]  

(2)

\[
SC(\theta) = \frac{\bar{V}_{c,\theta}}{\bar{V}_{a,AIP}}
\]  

(3)
Additionally, distortion intensity descriptors of SAE (2014) were also applied by dividing the AIP into 5 rings and each into 20 equal sectors (Figure 2). Circumferential distortion intensity \(CDI\) compares the average total pressure of each ring \(P_{t,i}\) to the ring sectors with average total pressure values lower than the ring average \(P_{t,i,low}\). \(CDI\) values of all rings were further averaged for data reduction. Radial distortion intensity \(RDI\) compares the ring averages to the average total pressure of AIP \(P_{t,AIP}\). Data reduction was applied by taking the maximum \(RDI\).

\[
CDI_{ave} = \sum_{i=1}^{5} \frac{1}{5} \left( \frac{P_{t,i} - P_{t,i,low}}{P_{t,i}} \right)
\]

\[
RDI_{max} = \max_{i=1:5} \frac{P_{t,AIP} - P_{t,i}}{P_{t,AIP}}
\]

**Integrated Intake at Varying Azimuth**

The power demand of SFB 880 aircraft amounts to \(\sim 10\ MW\) for its mission profile with \(Ma = 0.74\) cruise at \(10.6km\) altitude, as well as short take-off and landing using its active high-lift system. The intake diameter of its turboprop engines was estimated as \(D = 700mm\) (Figure 3(a)). Single scoop S-duct intake was modeled by spline guidelines to form the wrap-around, with the simplification of AIP assumed on the outlet. Area ratio was set as \(A_{AIP}/A_{inlet} = 1.19\) by compressible flow model on intake. The highlight spread angle was set as \(\alpha = 32.71^\circ\) for a narrow inlet width equal to AIP diameter \(D\) (Figure 3(b)). When a sensitivity analysis was made on the length aspect ratio of uninstalled, isolated, single scoop, shaft penetration S-ducts, total pressure recovery results suggested a slight trend of increase with higher \(L/D\) (Figure 3(c)). While the recovery was observed to rise \(0.5\%\) by increasing the \(L/D = 2\) to \(L/D = 3\), total pressure distortion coefficient decreased by \(58\%\). Therefore the length aspect ratio was set as \(L/D = 3\) for the integrated intake analysis.

For the analysis of interaction effects on the intake with channel wing installation, the selected S-duct was integrated into a representative nacelle body (Figure 4(a)). Its size was set as \(L_{nac}/D_{prop} = 1.6\) considering the preliminary engine design and the propeller size. The highly loaded propeller had a diameter of \(D_{prop} = 5m\) with a hub-to-tip ratio \(r_{hub}/R_{prop} = 0.26\), as modified from a similar project (Lenfers, 2012). Its pitch angle was set to \(\beta_{3/4} = 57^\circ\) at radius \(r/R_{prop} = 0.75\) at cruise and \(\beta_{3/4} = 29^\circ\) at take-off. An actuator disc model was used to represent the propeller slipstream for the steady-state simulations. The intake highlight distance
from propeller mid-plane was assumed as $t/D = 0.36$. Boundary layer diverter height was set as $h/D = 0.07$. Intake lip was simplified as a half elliptical profile.

The integrated wrap-around intake was installed on an unswept channel wing with a constant profile. Similar profile of Müller et al. (2014) was used as DLR F15 transonic airfoil with chord length $c \sim 3.8m$ (maximum thickness at 12.6%) to have comparable results for the SFB 880 project. Wing span was set as $b = 5c$. The actuator disc was embedded by $D_{prop}/6$ on a constant gap of $g/D_{prop} = 0.02$, located at $Z_n/D_{prop} = 0.35$. The nacelle was positioned at $X_n/D_{prop} = 0.3$ downstream of the wing leading edge. The reference azimuth angle of the S-duct integration was at $\phi = 270^\circ$ in polar notation as shown in Figure 4(b).

**COMPUTATIONAL SETUP**

Centaur software was used to generate the unstructured hybrid grids on the simulation models. Cylindrical domain with the wing span as the height of the side and $20c$ of radius for the base was applied using tetrahedral elements for farfield (Figure 5(a)). Hexahedral elements were used on critical regions as the outlet duct, while the solid surfaces were mapped with 30 prismatic layer elements. Initial height of prisms was set to $0.004mm$ in order to achieve $y^+ \sim 1$ to properly resolve the boundary layer. Higher grid density was applied in the region between nacelle-intake and wing (Figure 5(b)), in the wing wake, and on the intake lips (Figure 5(c)). Grid size was kept in average of $16 \times 10^6$ nodes.
DLR’s TAU solver was used for the steady-state RANS simulations. Second order central difference discretisation was used with scalar dissipation for the mean flow of the inviscid fluxes. For the turbulent components, second order Roe upwind discretisation was applied, coupled with Gauss divergence theorem to reconstruct the gradients. Viscous flux was evaluated with central discretisation with fully resolved gradients (instead of thin shear layer approach). Negative Spalart-Allmaras turbulence model (Allmaras et al., 2012) was applied in order to avoid non-physical negative vorticity due to low resolution. Internal domain of S-duct intake had finer grid resolution than the farfield; however, larger tetrahedral elements between the nacelle and the wing were considered when choosing this modification on the turbulence model. Convergence was achieved in 20000 iterations with time stepping scheme of $CFL = 1.5$.

Symmetry conditions were applied on the circular bases of the farfield domain at wing tips. The engine on-design condition was cruise with $Ma = 0.74$ at 10.6 km altitude; however, for this flight condition, the farfield domain was set at $Re = 18 \times 10^6$ based on the wing chord length and freestream at $Ma = 0.6$. The reduction in freestream velocity for cruise was necessary as the simulations with $Ma > 0.6$ showed local sonic regions at actuator disc tips and TAU code was unable to converge at this range. This “off-design” cruise condition with $Ma = 0.6$ at 10.6 km altitude was referred as cruise in the results section for simplicity. Freestream $Ma = 0.172$ at sea-level was applied for the end of take-off run at level flight, referred as take-off in the results for simplicity.

AIP of the S-duct intakes was defined as a static pressure boundary condition (“engine inflow” in terms of TAU code) with an initial estimate for mass flow rate. As the on-design for the turboprop was cruise with $Ma = 0.74$, the pressure and mass flow rate on AIP were scaled for the $Ma = 0.6$ cruise freestream and $Ma = 0.172$ take-off as off-design conditions. Actuator disc model in TAU solver calculates the thrust and torque distributions at the desired revolution per minute to simulate the steady-state slipstream. The model requires pitch angle and lift-drag polar distribution inputs on the surface boundary as it is coupled with a blade element theory.

**RESULTS**

**Total Pressure Recovery and Distortion Coefficient**

Total pressure recovery comparison in Figure 6(a) showed that the reference azimuth position of the S-duct intake at $\phi = 270^\circ$ achieved higher $\pi_i$ than the rest at cruise, with the exception of $\phi = 135^\circ$, which had less than 0.2% increase over the reference. The average loss in $\pi_i$ remained about 0.5% for other positions when compared to the reference intake; however, the lowest occurred when the intake was at $\phi = 315^\circ$, showing 1% lower $\pi_i$ when compared to...
the reference at cruise. Take-off condition influenced the performance with an expected sharp drop of 5% and the intake at $\phi = 0^\circ$ remained the highest by only 0.4% over the reference. The difference between the maximum $\pi_i$ and the rest at take-off remained as low as 0.3%. It can be argued that $\pi_i$ is almost insensitive against the azimuth position of the S-duct intake at take-off, with the notable exception of loss at intermediate position of $\phi = 315^\circ$.

Results in Figure 6(b) were achieved by taking the maximum of $DC(60^\circ)$ over the complete AIP circumference. Large difference was observed between the reference and the other positions, as the highest $DC(60^\circ)$ achieved with the reference $\phi = 270^\circ$ at cruise. The lowest distortion of $\phi = 0^\circ$ experienced 13% drop of $DC(60^\circ)$ in average compared to the other cases at cruise, while having close values to the positions above the y-axis. This comparison changed in favor of reference intake position at take-off but the lowest $DC(60^\circ)$ occurred at $\phi = 45^\circ$.

Figure 6: **Performance and distortion comparison of S-ducts by varying azimuth.**

$DC(60^\circ)$ distribution was investigated on AIP circumference of intakes at cardinal positions as in Figure 7. The reference intake position showed the highest at the AIP sector $30^\circ \leq \theta_0 \leq 90^\circ$ at cruise. The AIP distribution of other cardinal positions confirmed the maximum $DC(60^\circ)$ results by showing lower distortion than the reference within the AIP circumferential extent of $15^\circ \leq \theta_0 \leq 90^\circ$ at cruise. It should be noted that the intake at $\phi = 90^\circ$ position experienced a shift in its maximum $DC(60^\circ)$ sector to initial sector angle $\theta_0 = 20^\circ$.

Figure 7: **Total pressure distortion on S-duct AIP sectors (phase-aligned); comparison by varying azimuth.**

At take-off condition, the reference intake at $\phi = 270^\circ$ retrieved its favorable stand amongst the other cardinal positions for the maximum $DC(60^\circ)$, which was at $\theta_0 = 45^\circ$ (Figure 7(b)).
The total pressure loss was doubled of the cruise in the same sector, and it was revealed that the extent of the distortion exceeded 60°. By the definition of the parameter, negative \( DC(60°) \) values indicate the sectors with higher total pressure than the AIP average. At cruise, two distinct sectors with \( DC(60°) < 0 \) could be identified, whereas at take-off, this corresponded to a continuous sector with the extent of \( 105° \leq \theta_0 \leq 315° \).

![Figure 8: Total pressure contours on AIP at cruise condition.](image)

When the total pressure contours on the AIP of intakes were compared at cruise condition (Figure 8), the greatest change was observed on the thick boundary layer at the bottom half. When the intake was rotated from \( \phi = 270° \) to \( \phi = 0° \), the boundary layer weakened, and it was further diminished as the intake azimuth angle was \( \phi = 90° \) (Figure 8(c)). This reduction was not observed in \( DC(60°) \) analysis, as the parameter is evaluated by averaging in the complete radial direction of \( \theta = 60° \) sector.

The reference azimuth \( \phi = 270° \) has high recovery similar to the \( \phi = 135° \) case but it also suffers from the highest \( DC(60°) \) at cruise. The intake at top position (\( \phi = 90° \)) showed lower total pressure distortion at cruise, while keeping its recovery 0.6% less than the reference. As the total pressure distribution in the actuator disc downstream field was compared for the cardinal positions (Figure 9), influence of the slipstream was observed to be significant. The sector roughly between \( 90° \) and \( 180° \) of the actuator disc downstream had the favorable total pressure increase due to the rotation. The intakes close to this sector are exposed to the high energy flow (Figure 9(b)). In contrast, the intake positions far from this sector capture the flow with larger gradients, introducing loss starting from their inlet plane. However, it should be noted that the simulations were run with the steady-state assumption. The unsteady nature of the flow downstream of an actual propeller would introduce more severe up- and downwash effects varying in time.

**Circumferential and Radial Distortion Intensities**

\( CDI_{ave} \) results in Figure 10(a) showed the most favorable intensity distribution for the intakes at positions of \( \phi = 0°, \phi = 90°, \) and \( \phi = 315° \) for cruise flight. The reference position and \( \phi = 180° \) cases remained amongst the highest. The intermediate position of \( \phi = 45° \) affected its intake worst by producing 37% higher \( CDI_{ave} \) than the one at \( \phi = 90° \). At take-off condition, these two positions exchanged their stands against each other; however, S-duct intake at \( \phi = 90° \) experienced only 16% higher \( CDI_{ave} \) than the \( \phi = 45° \) azimuth position. Similar change in behaviour due to flight conditions was observed for the \( \phi = 0° \). This contradiction
Figure 9: Actuator disc downstream flow at \( x/D_{prop} = 0.33 \); cruise condition.

can be explained by the non-uniform total pressure distribution within the slipstream, that was augmented by the higher thrust at take-off condition. A simpler reason could be the data reduction applied on \( CDI \) by averaging, which normalises the intensity distribution between the rings.

![Figure 9](image)

Figure 10: Distortion intensity comparison of S-ducts by varying azimuth.

On the other hand, radial distortion intensity results in Figure 10(b) confirmed the preferable performance of \( \phi = 90^\circ \) position for the S-duct intake, showing 10\% lower \( RDI_{max} \) than the reference at cruise. This low \( RDI_{max} \) was also observed at take-off condition for \( \phi = 90^\circ \) position for the S-duct intake, being the second lowest distortion intensity in radial direction. The highest \( RDI_{max} \) was observed with the \( \phi = 315^\circ \) position. At this point, it can be argued that the S-duct intakes at cardinal azimuth positions are more preferable than the intermediate angles.

Swirl Distribution

After performance and distortion analysis, it was assumed a reasonable decision to compare the swirl distribution of the intakes at cardinal azimuth positions of \( \phi = 0^\circ, 90^\circ \) and \( 180^\circ \), as they performed with higher recovery and lower distortion levels. \( SC(60^\circ) \) distribution was investigated by pivoting the sector in 15\(^\circ\) increments over the AIP for 5 rings. \( SC(60^\circ) \) on the tip rings of analysis cases were shown in Figure 11(a). It was observed that the \( \phi = 0^\circ \) intake position suffered from the highest swirl in anticlockwise direction, while \( \phi = 180^\circ \) position experienced the highest in clockwise direction. In contrast, intake at \( \phi = 90^\circ \) azimuth
angle showed the lowest swirl in both directions. It can be argued that the S-duct intake at reference azimuth $\phi = 270^\circ$ experiences adverse effects of its location between the nacelle and the channel wing. Its axisymmetric case of $\phi = 90^\circ$ achieves lower swirl due to not only the different propeller slipstream but being free of channel wing flow. This effect was also observed on $\phi = 0^\circ$ position, which deteriorates when rotated to its axisymmetry at $\phi = 180^\circ$.

The comparison of maximum swirl coefficients in anticlockwise direction confirmed the low $SC(60^\circ)$ of $\phi = 90^\circ$ azimuth angle for the wrap-around S-duct intake (Figure 11(b)). Wrap-around intakes were observed to have their highest swirl on their tip rings as it was addressed previously in Atalayer et al. (2015). By positioning the intake at $\phi = 90^\circ$ on the nacelle, 8% decrease in $SC(60^\circ)$ on AIP tip ring was achieved (Figure 11(b)), as well as 3% average drop over the 5 rings.

**CONCLUSIONS**

Interaction effects on turboprop S-duct intake at varying azimuth angles on channel wing were investigated by applying steady-state RANS simulations. Single scoop, low pinion offset, wrap-around type S-duct intake was integrated on a representative nacelle at different azimuth positions. The propeller was approximated as an actuator disc. The simulations were run at cruise and take-off conditions. The S-duct aerodynamic performance was compared in terms of recovery and distortion on its AIP.

Comparison of total pressure recovery revealed the reference intake position at $\phi = 270^\circ$ has higher $\pi_i$ than the rest of the analysis cases at cruise. The exception was $\phi = 135^\circ$ position, which showed only a slight increase of 0.2% that requires further confirmation. Sharp drop in recovery was observed for all cases at take-off condition with the highest recovery observed at $\phi = 0^\circ$. The positions at $\phi = 0^\circ$ and $90^\circ$ showed lower $DC(60^\circ)$ levels than the reference at cruise but this advantage did not hold for the take-off condition. The increase in distortion behaviour due to take-off was confirmed by plotting the distribution over the complete AIP.

On the other hand, comparison of distortion intensities reassured the choice of $\phi = 0^\circ$ and $90^\circ$ as favorable intake positions. The highest $CDI_{ave}$ was observed with the $\phi = 45^\circ$ position, having 37% more distortion intensity than $\phi = 90^\circ$. At take-off condition, contradicting $CDI_{ave}$ levels were observed again but $RDI_{max}$ results confirmed choice of preference case $\phi = 90^\circ$ for its lower levels at both cruise and take-off.

Swirl coefficient was investigated as a distribution over the AIP by pivoting the sector $\theta =$
60° in 15° increments in 5 rings. It was observed that $\phi = 90°$ position achieved lower $SC(60°)$ at AIP tip ring of wrap-around S-duct in both anti- and clockwise directions when compared to reference $\phi = 270°$. Detailed investigation over the 5 rings revealed that 3% drop in $SC(60°)$ could be achieved when the intake was positioned at $\phi = 90°$.

Based on the results, it can be suggested that $\phi = 90°$ and $0°$ azimuth angles can be used for S-duct intake integration with the SFB 880 turboprop nacelle. However, it should be noted that the study excluded the means of nacelle connection to the wing, i.e. pylon effects should be considered before proceeding. The investigated wing-nacelle interaction effects on the intake will be verified with unsteady RANS simulations using real propeller model and further validated by wind tunnel tests.

ACKNOWLEDGEMENTS

The SFB 880 is a joint project with collaborating partners of Technical University of Braunschweig, University of Hannover and German Aerospace Research Center (Deutsches Zentrum für Luft- und Raumfahrt – DLR), funded by German Research Foundation (Deutsche Forschungsgemeinschaft – DFG). All simulations were run using the computational resources of North-German Supercomputing Alliance (HLRN) in Hannover and Berlin.

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