UNSTEADY FLOW PHENOMENA IN A HIGHLY BEND ENGINE INTAKE WITH PASSIVE AND ACTIVE FLOW CONTROL

P. Max*1, M. Stößel1, M. Krummenauer2, D. Kožulović1

1: University of the Bundeswehr Munich, Department of Aerospace Engineering, Institute of Jet Propulsion, Munich, Germany, philipp.max@unibw.de
2: Bundeswehr Technical Center for Aircraft and Aeronautical Equipment (WTD61), Manching, Germany

ABSTRACT
Highly bent intake systems cause unsteady flow phenomena which have a negative impact on the performance of the compressor system. In the present study, a serpentine intake is investigated experimentally with and without flow-stabilizing measures. The time-averaged measurement results show that the flow-stabilizing measures strongly reduce the separation bubble and the flow distortion in the intake. Unsteady pressure measurements indicate accordingly that dominant Strouhal numbers, associated with the Dean vortices, are weaker or not present at all in case of flow control. These unsteady phenomena are further analyzed in terms of their respective Strouhal numbers versus the power spectral density and compared to the configuration without any flow-stabilizing measures. The results demonstrate that without flow stabilizing measures, two dominant peaks occur at Strouhal numbers $0.32 \leq Sr \leq 0.39$ and $0.18 \leq Sr \leq 0.24$. Thereby, with increasing Reynolds numbers, the dominant Strouhal numbers decrease slightly.

KEYWORDS
highly bend engine intake, unsteady flow phenomena, active and passive flow control

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( \gamma )</td>
<td>relative radius of curvature</td>
</tr>
<tr>
<td>( r_{in} )</td>
<td>radius at the inlet cross section</td>
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<td>( DIP )</td>
<td>duct inlet plane</td>
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<tr>
<td>( IJP )</td>
<td>Institute of Jet Propulsion</td>
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<td>( MEIRD )</td>
<td>military engine intake research duct</td>
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<tr>
<td>( p_{\infty} )</td>
<td>ambient pressure</td>
</tr>
<tr>
<td>( d )</td>
<td>Duct outlet diameter</td>
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<tr>
<td>( x_{rel}, y_{rel} )</td>
<td>relative cartesian coordinates</td>
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<tr>
<td>( v )</td>
<td>velocity</td>
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<tr>
<td>( s )</td>
<td>Position at the centerline, percentage wise</td>
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<tr>
<td>( r_k )</td>
<td>radius of curvature</td>
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<tr>
<td>( Sr )</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>( DOP )</td>
<td>duct outlet plane</td>
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<td>( ETF )</td>
<td>engine test facility</td>
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<tr>
<td>( p_{rel} )</td>
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<tr>
<td>( x, y, z )</td>
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<tr>
<td>( L )</td>
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</tr>
<tr>
<td>( PSD )</td>
<td>power spectral density</td>
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<tr>
<td>( f )</td>
<td>frequency</td>
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<tr>
<td>( n )</td>
<td>spool speed</td>
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INTRODUCTION
Typically, the propulsion system of modern military aircraft is fully integrated into the airframe. In these configurations, s-shaped engine intake systems are commonly used. These intake systems have several design requirements which affect their aerodynamic performance.
To keep the structural weight of the aircraft low, the length of the intake is reduced leading to a strongly curved design of the duct. Furthermore, especially for military aircraft, a reduction of the radar signature in particular of the fan is required (Wong et al. (2006), Rabe (2003), Rao & Mahulikar (2002)). Resulting in intake systems that do not provide a direct line of sight between the duct inlet plane and duct outlet plane and thus require to additional offset the inlet and exit. Depending on the design of the intake system, flow separation and secondary flow phenomena are expected due to the strong curvature and eventual changes in cross-sectional shape (Bansod & Bradshaw (1972), Guo & Seddon (1983)). These flow phenomena are directly related to combined pressure and swirl disturbances at the duct outlet plane, which means a deterioration of the efficiency, as well as a reduction of the safe operating range for the subsequent compressor system (Giuliani & Chen (2016), Tu et al. (2018)). The formation of combined pressure and swirl disturbances is typically unsteady (Gil-Prieto et al. (2017), Tanguy et al. (2018)). This can result in additional stability losses that are neglected in a time-averaged analysis (Bowditch & Coltrin (1983)). Unsteady flow phenomena do not only cause local but also temporal inhomogeneity on the total pressure and velocity field. Therefore, there is great interest in improving the intake flow by flow-stabilizing measures and mitigating or eliminating the unsteady flow phenomena (Hamstra, J., Miller, D., Truax, P., Anderson, B., & Wendt, B. (2000), Burrows et al. (2019), Tanguy et al. (2017)).

Various unsteady flow phenomena occur in pipe elbows, as well as highly bent engine intakes due to the strong bend. These are principally Shear Layer Instabilities and the oscillation of Dean vortices (Dean (1928)), known as Swirl Switching (Wellborn et al. (1992)). Rüttten et al. (2005) performed a large-eddy simulation in a pipe elbow and concluded that the shear layer between fluid with different velocities in the bend can also be unsteady and periodically throw off vortices. The so-called Swirl-Switching phenomenon was first described by Tunstill & Harvey (1968) conducting experimental investigations on a sharply bent pipe elbow. The mechanism of this phenomenon was explained by the asymmetry of the separation area. Gil-Prieto et al. (2016) presented the change from one dominant vortex to another in a time-resolved representation and analyzed the phenomenon of Swirl Switching in detail, Kalpakli Vester et al. (2015) and Hellström et al. (2013) investigated the phenomenon of Swirl-Switching on pipe elbows. They found that Strouhal numbers of 0.1 and 0.16 can be attributed to swirl-switching. While the Strouhal numbers associated with Swirl Switching differ by several orders of magnitude, the Strouhal number for Shear Layer Instabilities are typically between $0.2 \leq Sr \leq 0.3$ (Rüttten et al. (2005), Hellström et al. (2013)).

Sanders et al. (2013) used URANS simulations to calculate the unsteady flow in a highly contoured engine intake. The simulations showed an unsteady vortex pattern in the side region of the duct. In the present literature Shear Layer Instabilities in S-ducts are assigned to Strouhal numbers between $0.6 \leq Sr \leq 1.06$ (Gil-Prieto et al. (2016), MacManus et al. (2017)). Differences are presented by the investigations of Garnier (2015), who assigns a relatively broadband Strouhal number range of $0.25 \leq Sr \leq 0.625$ to the Shear Layer Instabilities in S-ducts. Swirl Switching phenomena in S-ducts are assigned to Strouhal numbers in the range of $0.4 \leq Sr \leq 0.7$ (MacManus et al. (2017)). In the CFD simulations performed by MacManus et al. (2017), two S-ducts with different curvatures were compared. The stronger curved intake presented a higher Strouhal number for both flow phenomena and, in particular, a broadband spectrum at low Reynolds numbers. In comparison, no dependency of the Strouhal number on the Reynolds number was observed in the less strong contoured S-duct.

Table 1 shows a summary of research studies dealing with flow instabilities in S-ducts. The
Strouhal numbers obtained on *Swirl Switching* and *Shear Layer Instabilities*, respectively, are shown in the first two columns. The relative radius of curvature $\gamma$ is also given as a measure of the strength of the curvature (Equation 1). It is calculated from the ratio of the radius $r_{in}$ at the inlet cross-section to the radius of curvature $r_k$.

$$\gamma = \frac{r_{in}}{r_k}$$  \hspace{1cm} (1)

In the case of an S-duct, the cross section from which $r_{in}$ was taken is immediately before the beginning of the first bend, $r_k$ refers to its radius.

<table>
<thead>
<tr>
<th>Sr Swirl Switching [-]</th>
<th>Sr Shear Layer Instabilities [-]</th>
<th>Re $\times 10^4$ [-]</th>
<th>Geometry</th>
<th>$\gamma$ [-]</th>
<th>References</th>
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<tr>
<td>-</td>
<td>0.25 - 0.625</td>
<td>75 u. 150</td>
<td>S-duct</td>
<td>0, 16</td>
<td>Garnier (2015)</td>
</tr>
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<td>1, 06</td>
<td>71</td>
<td>S-duct</td>
<td>0, 16</td>
<td>Gil-Prieto et al. (2016)</td>
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<td>0.4</td>
<td>0.75</td>
<td>110</td>
<td>S-duct</td>
<td>0, 1</td>
<td>MacManus et al. (2017)</td>
</tr>
<tr>
<td>0.4</td>
<td>0.75</td>
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<td>0, 9</td>
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<td>0, 16</td>
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<tr>
<td>0.5 u. 0.7</td>
<td>0.6</td>
<td>170</td>
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Table 1: **Summary of various studies on the subject of Shear Layer Instabilities and Swirl-Switching in S-ducts**

For many years unsteady investigations in intake systems were considered of low importance despite some earlier suggestions made in the 70s to include the time-variant element of inlet total pressure distortion in the characterization of an engine’s stability degradation (Jacocks (1972)). However, in fact, it was found that the unsteady part of the distortions can add as much as 30% range to the steady-state measurements (Cousins (2004)). In this paper four piezoelectric pressure sensors have been installed in a serpentine engine intake. The aim is to characterize the dominant pressure frequencies in a Baseline case (intake without flow control) and then apply passive and active flow control measures to the duct and analyse if the frequencies are damped or amplified.

**EXPERIMENTAL SETUP**

The experiments were performed on the engine test facility (ETF) at the Institute of Jet Propulsion (IJP) (Bindl et al. (2009)). For investigations on aerodynamic intake compressor interactions, the Military Engine Intake Research Duct (MEIRD) was designed and built at the IJP (Rademakers et al. (2016)) (Figure 1, Figure 2). It was developed with the scope to intentionally provoke a severe pressure-swirl distortion on the compressor system of the Larzac 04 test engine.

The centerline is shown in Figure 2 with the corresponding geometric parameters. The inlet-outlet diameter ($D_{DOP}$) is 0.454 m. With this diameter, the length in the x-direction, as well as the contour of the centerline, can be defined. The centerline is determined by four cross-sections (Figure 2):
Figure 1: Schematic overview of the instrumentation within the MEIRD as well as the position of the piezoelectric pressure sensors

Figure 2: Basic geometric parameters of the intake duct (Ceterline: Red; Inlet section: green); Contour of the cross-sections depicted in blue
CS₀: entrance cross-section (DIP - Duct Inlet Plane)

CS₄₀: cross-section at 40% centerline-length

CS₇₂: cross-section at 72% centerline-length (highest point)

CS₁₀₀: Duct outlet cross-section (DOP)

The cross-sections are positioned along the centerline in their centers of area. The cross-section (CS₀) at the inlet represents a kidney shape. This kidney shape changes via the cross-section at 40% centerline-length (CS₄₀) to a rectangular shape at the cross-section at 72% (CS₇₂) centerline-length. At the DOP, the cross-section is a circular profile. A surface has been overlaid on these cross-sections, which result in the MEIRD geometry. As can be derived from Figure 2, the inlet investigated here has a length in the x-direction of 3 · D_DOP and a diffusion factor of A_DOP/A_DIP = 1.17. Furthermore, the geometry is symmetric about the vertical plane of the duct. The MEIRD does not provide a direct line of sight from the duct inlet plane (DIP) to the DOP at any angle of attack, thus reducing the radar signature of the compressor to a maximum. Consequently, unlike most of the S-ducts studied in the open literature, the MEIRD has no round cross-section trajectory, hence no relative radius can be specified. As CFD simulations by Haug et al. (2018) demonstrated, the intake possesses a flow separation in the area of the second bend (cf. Figure 1 c) letter A). To investigate the separation region in more detail, three removable panels are located in this area (cf. Figure 1 a) and c)). Panel 1 is located just upstream of the separation location while panel 2 is placed in the area of the separation bubble and panel 3 is located partially in the separation area. To evaluate the measurement data, the measured static wall pressure Δp is given as a relative value \( p_{\text{rel}} \) in relation to the ambient pressure \( p_\infty \).

\[
p_{\text{rel}} = \frac{\Delta p + p_\infty}{p_\infty}
\]  

(2)

The x-axis is expressed as a relative value \( x_{\text{rel}} \) with respect to the total length of the MEIRD \( L \) (Equation 3).

\[
x_{\text{rel}} = \frac{x}{L}
\]  

The high-frequency instrumentation is the basis for the identification of unsteady flow phenomena. Piezoelectric pressure sensors from Kulite were used in this test setup. The positions of the Kulite sensors are marked as black dots in Figure 1 b) and displayed as green lines in Figure 1 d). Two Kulite sensors are located within the xz-symmetry plane at the front (\( p_{\text{Kul, front}} \)) and rear (\( p_{\text{Kul, rear}} \)) end of the duct. The other two sensors are oriented symmetrically to the xz- symmetry plane (\( p_{\text{Kul, left}}, p_{\text{Kul, right}} \)) (cf. Figure 1 b)). This arrangement was chosen to be able to assess pressure variations due to longitudinal and lateral flow fluctuations. Kulite sensors of the XCS - 093 model series with an absolute operational mode, a pressure range of 1 bar, a sensor diameter of 2.4 mm and a maximum eigenfrequency of 200 kHz were used. The sampling rate was 100 kHz. In addition, four Kulites are mounted in circumferential direction approximately 10 mm upstream of the leading edge of the low-pressure compressor. Their exact position can be seen in Figure 1 d). Only pressure fluctuations with a maximum frequency of \( f = 292 \) Hz (\( Sr = 0.55 \)) which corresponds to the maximum rotational frequency of the low-pressure compressor of the Larzac 04 test engine were considered in the investigations. According to experimental investigations by Plourde & Brimelow (1969), higher-frequency fluctuations have no influence on compressor operation. To proof this statement higher Strouhal
numbers were also evaluated once. However, purely mechanical effects and no fluid mechanical effects from the MEIRD could be observed. Therefore, higher-frequency fluctuations than the rotational frequency of the low-pressure compressor have not been taken into account.

The absolute pressure measured by the Kulite sensors is not used for unsteady flow assessment. Solely the frequency with which the pressure varies is of interest here. Hence, the time-resolved pressure measurement uncertainty was validated in that respect. A conventional speaker was used to generate tones with a defined frequency, which are basically pressure fluctuations. The Kulite sensors were used to measure these fluctuations. In average the absolute difference between the tone generator frequency and the measured peak in the data from the Kulite sensors was below \( 0.1 \text{ Hz} \) for the range of frequencies which are of interest for the investigations in this study.

To ensure the comparability of different experiments with different S-duct geometries, during the evaluation of the experimental data the Strouhal number \( Sr \) (Equation 4) was plotted over the power spectral density (PSD).

\[
Sr = \frac{f \cdot d_{\text{hyd}}}{v}
\]

(4)

The Strouhal number was referred to the DIP and the hydraulic diameter \( d_{\text{hyd}} \) of the DIP was used as the characteristic length. Whereby the velocity \( v \) is also referred to the DIP.

Three different panel configurations were investigated on the MEIRD. First a Baseline configuration where no flow stabilizing measures are applied in the MEIRD was analyzed. In the second configuration panel 1 is solely replaced by a panel with vortex generators (VG)(cf. Figure 3). The vortex generators have been designed by Kachele et al. (2018) in a design of experiment study. In the third configuration, starting from the Baseline configuration solely panel 2 was exchanged by a panel with a Coanda nozzle slot and air was actively injected into the MEIRD (Blo)(cf. Figure 3). The blowing mass flow rate was increased from 1% in 0.5% steps to 2% of the intake inlet mass flow rate. The Coanda nozzle slot was placed slightly upstream of the separation location. The vortex generator panel with the most relevant geometric parameters, as well as a cutaway view of the blowing configuration panel, is shown in Figure 3.

The vortex generator height \( h_{VG} \) in relation to the reference boundary layer thickness \( \delta_{ref} \) is 1.3. The VG chord length \( c \) referred to reference boundary layer thickness is 9.3. And the y-distance over the reference boundary layer thickness is 2.8. During the investigations, the engine was kept constant at different speeds while the measurement data were recorded \( (N_{\text{red,rel}} = 54\% \text{ to } N_{\text{red,rel}} = 86\%) \). The constant reduced spool speed is defined as follows\(^2\)

\[
n_{\text{red,rel}} = \frac{n}{n_{\text{max}}} \cdot \frac{\sqrt{T_{ISA}}}{\sqrt{T_t}} \cdot 100\%.
\]

(5)

Those spool speeds are corresponding to a Reynolds number range related to the DIP of \( 1.7 \cdot 10^6 \leq Re \leq 3 \cdot 10^6 \) and Mach-numbers between \( M_{54\%} = 0.24 \) and \( M_{86\%} = 0.44 \) at the DIP.

\(^1\)The boundary layer thickness on the bottom of the MEIRD within CS3 at \( n_{\text{red,rel}} = 90\% \) is used as reference value \( \delta_{ref} \).

\(^2\)The reduced spool speed is corrected with the ambient temperature at sea level according to the International Standard Atmosphere \( (T_{ISA} = 288.15 \text{ K}) \) and relative to the maximum spool speed of the Larzac 04 LPC \( (n_{\text{max}} = 17,500 \text{ 1/min}) \).
PROCEDURE FOR DATA ANALYSIS

The focus of the analysis was the transformation of the data from the time to the spectral domain, where they have been investigated for typical frequencies of unsteady flow phenomena. For this purpose, the mean value was subtracted from the recorded data before the spectral analysis and a 6th order Butterworth filter with a cutoff frequency of $40 \text{kHz}$ was applied. The Short-Time Fourier Transform (STFT) was then calculated from this data vector. A Hamming window with an overlap of half a window width was used as window function for the calculation of the STFT. The window width was $0.5 \text{s}$ and the sample frequency was set to $40 \text{kHz}$. In order to smooth the data, for each spool speed five tests were carried out with a recording time of $20 \text{s}$. From each of these tests, the power density spectrum was calculated via the Strouhal number and then arithmetically averaged with each other. This averaging procedure smoothed out random fluctuations in the spectrum, which means that only peaks that were present during all tests at all times are shown. This makes it easier to identify the main flow phenomena in the spectrum.

RESULTS AND DISCUSSION

Time-averaged measurement

Figure 4 shows the relative static wall pressure profiles in the xz-symmetry plane of the MEIRD with and without flow-stabilizing measures at a constant engine speed of $N_{\text{red,rel}} = 76\%$. The internal wall contour is displayed in gray. Furthermore, the relative positions of the three panels, as well as the area of flow separation (A) are depicted in shaded color. The orange arrow marks the exact blowing position of the Blo configuration. The static wall pressure profiles of the different configurations at the upper wall of the intake deviate only slightly and show no aerodynamic critical features. Aerodynamically more significant are the wall pressure differences at the lower wall of the MEIRD. Up to $x_{\text{rel}} = 0.69$ the wall pressure profiles of all configurations is nearly identical. All configurations show a relatively constant pressure...
gradient from $x_{rel} = 0.1$ to $x_{rel} = 0.6$. Between $x_{rel} = 0.6$ and $x_{rel} = 0.69$, the flow accelerates towards the narrowest cross-section of the duct. Subsequently, the static wall pressure of the Baseline configuration increases before a pressure plateau between $x_{rel} = 0.75$ and $x_{rel} = 0.85$ develops which, according to the CFD simulations from Haug et al. (2018), can be attributed to flow separation. In the VG configuration, the pressure drops to $p = 0.8$ at $x_{rel} = 0.72$ and then increases continuously up to DOP. A pressure plateau which might indicate a flow separation is not visible. The profile of the blowing configuration (Blo) depicts the lowest static wall pressure due to the accelerated injected air. Downstream, the pressure increases constantly and a detachment area in the shape of a pressure plateau does not occur.

![Figure 4: Static wall pressure within the xz-symmetry plane of the MEIRD at $N_{rel} = 76\%$ and a blowing mass flow rate of 1.5%](image)

**Unsteady measurement**

With the Kulite arrangement in this study the most dominant unsteady flow phenomena can be detected and the effect of flow stabilizing measures can be investigated. Figure 5 and Figure 6 show the power spectral density (PSD) determined from a time averaged short time Fourier transformation of the measurement data for several engine operation points. Current data is evaluated for $Sr < 1$ solely since flow fluctuations with frequencies higher than the one per revolution fan rotation are not expected to influence engine operability (Plourde & Brimelow 1969). The diagrams have two x-axes due to the different magnitudes of the occurring phenomena. The Baseline configuration is plotted on the blue x-axis, while the VG
and _Blo_ configurations are plotted on the black x-axis. The measurement results of Kulite front ($p_{Kul\_front}$) and Kulite rear ($p_{Kul\_rear}$) and the two dominant peaks I and II, which mainly occur in the _Baseline_ configuration are depicted in [Figure 5](#).

**Kulite front**

Peak I can be attributed to Strouhal numbers between $0.32 \leq Sr \leq 0.39$ and peak II can be assigned to Strouhal numbers between $0.18 \leq Sr \leq 0.24$. As the engine speed increases, the Strouhal number of both peaks (I and II) decrease and the amplitude of the PSD increases. Furthermore, it can be observed that the flow stabilizing measures strongly damp the amplitude of the PSD. The _Blo_ configuration shows no significant peaks at all, while the _VG_ configuration shows peaks in the similar Strouhal number range as the _Baseline_ configuration but only at 76% and 86% speed, and strongly damped.

**Kulite rear**

Analyzing the Kulite rear data shows that Peak I is within the same Strouhal number range as already observed at Kulite front ($0.32 \leq Sr \leq 0.39$) (cf. [Figure 5](#)). Peak II can be assigned to Strouhal numbers in the range $0.18 \leq Sr \leq 0.18$. Since the Strouhal numbers and thus the frequencies between peak I and II are no multiples of each other, two different phenomena are concluded. As already noticed at Kulite front, the injection eliminates all dominant Strouhal numbers and the vortex generators damp them strongly. Considering the entire operating range the Strouhal number varies with the engine speed and thus the apparent fluctuating flow phenomena seem to be Reynolds number related.

**Kulite left**

Kulite left shows different dominant peaks depending on the engine speed ([Figure 6](#)). At $N_{red,rel} = 54\%$, a dominant peak at a Strouhal number of $Sr = 0.2$ is visible (peak III). This peak is dominant in all recorded speed ranges. A second smaller peak at $Sr = 0.6$ is only visible at $N_{red,rel} = 54\%$ (peak VI). At $N_{red,rel} = 76\%$ and $N_{red,rel} = 86\%$, peak IV is observed within a Strouhal number range of $0.32 \leq Sr \leq 0.34$. Peak III and IV correlate with peak I and II at Kulite front and rear. At $N_{red,rel} = 86\%$, peak V occurs at a Strouhal number of $Sr = 0.44$.

**Kulite right**

Kulite right shows exactly the same dominant peaks at the same Strouhal numbers like Kulite left. No phase shift of the data sets was found. Therefore, it is concluded that the phenomena are fluctuations of the flow in longitudinal direction.

**Kulite Sensor 1.1 (44°)**

The _Baseline_ configuration shows a peak at $Sr = 0.2$ and $Sr = 0.55$. A slightly higher amplitude of the PSD can be observed in the _Blo_ configuration, but no dominant peaks occur. In total, sensor 1.1 is relatively inconspicuous as far as dominant peaks are considered. This is to be expected for the position which is far away from the separation bubble and the resulting total pressure fluctuations.

**Kulite Sensor 1.2 (188°)**

The _Baseline_ configuration shows a significant peak at $Sr = 0.2$, which correlates with peak II shown in [Figure 5](#). The _VG_ configuration shows a spike at $Sr = 0.27$ but remains
Figure 5: Spectral analysis of Kulite data for Kulite front and Kulite rear at several engine operating points
Figure 6: Spectral analysis of Kulite data for Kulite left and Kulite right at several engine operating points
damped without further peaks for the remaining Strouhal numbers. The Blo configuration runs almost without peaks. However, two peaks appear at $Sr = 0.53$ and $Sr = 0.79$, which are also observed at sensor 1.3 and 1.4 (Figure 7). But, the peak in the Baseline configuration at $Sr = 0.18$, which is present at the Kulites placed in the MEIRD too, is completely suppressed.

**Kulite Sensor 1.3 (260°)**
The Baseline configuration of Kulite sensor 1.3 shows similar behavior (peaks) as already observed with Kulite front and rear. Again, the flow stabilizing measures effectively suppress these undesired peaks onto the compressor system.

**Kulite Sensor 1.4 (332°)**
With sensor 1.4, a clear peak can be seen in the Baseline configuration at $Sr = 0.2$, but this can be suppressed by flow-stabilising measures.

![Figure 7: Spectral analysis of circumferential Kulite data at $N_{red,rel} = 76\%$](image)

From the unsteady measurement data it can be summarised that the unsteady flow phenomena arise from the separation bubble occurring in the MEIRD and indicate a Strouhal number between $0.32 \leq Sr \leq 0.39$ and $0.18 \leq Sr \leq 0.24$. The flow stabilization measures thereby not only suppress the detachment bubble, in addition they reduce the unsteady flow phenomena onto the compressor system. At the same time, these measures do not create any additional unsteady flow phenomena. A comparison of the Strouhal numbers obtained in this study with the Strouhal numbers given in the literature for ShearLayerInstabilities and SwirlSwitching is not immediately possible due to the strong Reynolds number discrepancy between the experiments. The Strouhal numbers given in the literature for SwirlSwitching and ShearLayerInstabilities are significantly higher. However, the results show that the Strouhal number of the dominant peaks decreases with increasing Reynolds number. This means that the results shown here cannot directly match the literature due to the significantly higher Reynolds number.
CONCLUSIONS

The experiments were conducted on a highly bent S-duct that is typically for low observability aircraft. The flow phenomena occurring were recorded using both time-averaged and unsteady pressure measurement techniques. Flow-stabilizing measures (vortex generators and blowing) were further installed and investigated within the duct. The time-average measurement results demonstrate that the flow separation occurring in the intake can be avoided with both vortex generators and active flow stabilization using air injection. The unsteady results show that mainly two dominant Strouhal numbers occur. One in the range of $0.32 \leq Sr \leq 0.39$ and the second in the region of $0.18 \leq Sr \leq 0.24$. With applied flow stabilizing measures, these dominant Strouhal numbers are strongly damped or eliminated. These unsteady effects must therefore be triggered by the separation bubble. The flow-stabilizing measures damp the corresponding unsteady flow phenomena in the same manner as the flow separation bubble is reduced. However, there are some peaks that cannot be explained with the current instrumentation of the experimental setup. This is the subject of further research. Future work will be based on higher-order numerical simulations which are expected to provide a full description of the flow topology and dynamics. Furthermore, experimental investigations with an SAE Kulite measuring rake are planed for the future.

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