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SUPPRESSION OF AN AEROACOUSTIC FEEDBACK MECHANISM IN A COMPLEX PIPELINE

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ABSTRACT

This paper describes a study aimed at understanding and controlling an unsteady flow induced resonance in the metering system of a gas production platform, which had constrained the platform's operating conditions for many years. The resulting high-level vibrations posed a risk of fatigue failures in the attached pipework.
Various numerical flow and aeroacoustic modelling techniques were used to simulate the flow through the different parts of the system to identify the main physical excitation mechanism. This was found to be analogous to a so-called Rossiter tone, commonly occurring in grazing flows over cavities. In this case, vortex shedding at bifurcations in different parts of the pipeline were identified as sources of flow instability, associated with an aeroacoustic feedback mechanism from features further downstream. The numerical analysis also enabled an understanding of the persistence and varying strength of this mechanism along the entire pipeline, also depending on the flow regime at which the pipeline was operated.
The in-depth understanding provided by this analysis enabled recommendations for an efficient redesign of the entire system to control the problem at source.

Keywords: ***Aeroacoustics, resonance, numerical modelling, computational fluid dynamics.***

1. INTRODUCTION

A comprehensive review on resonance due to flow-induced pulsation in pipelines with various configurations of closed branches was presented in 2011 [1]. The review primarily focused on the aeroacoustic feedback mechanism, where boundary layer-excited vorticity couples with acoustic modes in the cavity. Many studies have investigated the aeroacoustics of cavities in pipelines, using both experimental and numerical approaches, with some of the most recent being [2-4]. Additionally, other aeroacoustic sources in a pipeline are T junctions, where vortex shedding from the junction can couple with an acoustic resonant mode of a nearby portion of the piping system [5-6].
The present study addresses a real-world problem, where for decades gas production on a platform has been disrupted by flow-induced vibrations in the gas metering ductwork, depending on flow regimes and velocity. At higher flow velocities, instabilities within the 30-35 Hz range triggered structural response in a mode of vibration at 34 Hz, causing significant issues.
The pipeline design includes an inlet duct where flow bifurcates into a header, then redirects into the metering system, and finally into the outlet duct (Fig. 1). Previous studies suggested various possible causes of instability, but our 2023 study [7] combined CFD and acoustic FEM analysis to confirm that vortex shedding and flow instability in the inlet header create an aeroacoustic feedback mechanism coupling with the pipeline's acoustic modes.
A follow-on study [8] extended the analysis to the outlet manifold, indicating a strong possibility of resonance in the outlet header, analogous to that previously identified in the inlet.
Based on our findings, the platform management company proposed a complete redesign of the entire pipeline aim to eliminate these issues at source.
After summarizing the aeroacoustic results and our proposed interpretation of the feedback mechanisms at the two different flow regimes in the current pipeline, this paper aims to present the equivalent results obtained for the redesigned pipeline and so demonstrate the improvements achieved by implementing the proposed modifications.

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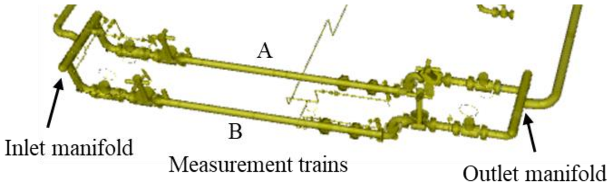

Figure 1: The current gas production pipeline.

2. AEROACOUSTIC MODELLING

In this study we utilised compressible Unsteady Reynolds-Averaged Navier-Stokes (URANS) simulations with the k-ω SST turbulence model to analyse turbulent and acoustic pressure fluctuations in the pipeline. Despite the average Mach number being characteristic of incompressible flow, compressible analysis was necessary to capture the relevant aeroacoustic phenomena.

We used the open-source software OpenFOAM [9], because it was the most efficient and cost-effective solution, in conjunction with High-Performance Computing (HPC).

Key Aeroacoustic Insights:

- The focus was on low-frequency interactions between vortex shedding and acoustic waves, which are crucial for understanding flow physics and providing design modification recommendations.
- Standard CFD tools face challenges such as dissipative numerical schemes that damp acoustic wave propagation and boundary conditions that reflect acoustic waves. Accurate modelling required careful treatment of these factors.
- Fully structured meshes were used to minimise numerical dissipation, allowing sound wave propagation without compromising stability. Non-reflective boundary conditions and progressively increasing aspect ratio meshes were employed to reduce wave reflection at inlets and outlets.

The pipeline system operates in single and dual stream regimes, with the inlet manifold feeding two metering trains. This study's findings aimed to mitigate flow-induced vibrations by addressing aeroacoustic feedback mechanisms in both regimes.

From test data measured on the platform, it was identified that the critical inlet velocity of 20 m/s triggered high vibration levels. In the dual stream case, this results in 10 m/s flow at each metering duct inlet, while in the single stream case, it remains 20 m/s at the single inlet. In the headers, due to expansion into a wider duct, the flow decelerates to 6 m/s in the dual stream case and 12 m/s in the single stream case.

The pipeline carries a mixture of natural gases, with a static outlet pressure of 11.3 MPa, and constant temperature and density of 330 K and 80 kg/m³, respectively. The speed of sound in the duct was 430 m/s.

3. ANALYSIS OF THE CURRENT PIPELINE

As reported in the previous studies [7] and [8], CFD analysis has been performed to identify the aeroacoustic feedback mechanism responsible for the resonance in the two different flow regimes.

We have employed wavenumber analysis to examine the spatial-frequency distribution of unsteady pressure perturbations. This powerful tool is used to plot the power spectral density of a wave over frequency *f* and wavenumber *k*, enabling the identification of standing and traveling waves and their propagation velocities. This method helps determine whether perturbations are turbulence, propagating at the speed of the flow, or acoustic waves, propagating at the speed of sound. More details on the application of this methodology were explained in our previous paper [7].

Using this method, we analysed both the inlet and outlet separately and surprisingly found both similarly problematic, despite the differences in flow patterns.

This is a summary of our findings and interpretations.

3.1 Dual Stream Case

The CFD model of the pipeline in this flow regime is shown in Fig. 2. The flow bifurcates at the inlet manifold, which feeds two metering ducts, and then rejoin in the outlet manifold.

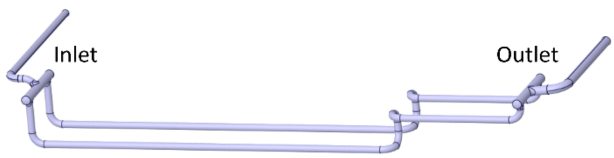

Figure 2: The current pipeline model in the dual stream flow regime.

Wavenumber analysis on the headers and metering ducts are shown in Figs. 3, 4, 5 and 6. In the headers dominant tones result from a combination of turbulence and acoustics. However, in the metering ducts the same tones are propagating as purely acoustic waves. Even if mechanisms differ significantly between the inlet and outlet manifold.

These are indications of vortex instability in the header triggering acoustic waves travelling in the metering duct.

In the case of flow over a cavity, discrete acoustic frequencies arise from the interaction between vortices formed over the cavity and the cavity's acoustic modes. This phenomenon is known as Rossiter tone feedback mechanism [10]. It is generally associated with shear layer vorticity generating acoustic waves when impinging on the downstream edge of the cavity, then travelling upstream through the cavity. The pressure disturbances are converted back into vorticity waves in the shear layer, completing the feedback loop, which is strongly dependent on the flow velocity. This mechanism is particularly critical when the pressure disturbances couple with the acoustic modes of the cavity.

The Rossiter formula calculates the Strouhal number (non-dimensional frequency) at which resonance occurs, as

$$St = \frac{fD}{U} = \frac{n - \alpha}{1/_k + M}, n = 1,2,3 \dots \qquad (1)$$

where:

- D is the cavity opening,
- U is the mean flow velocity,
- M is the Mach number,
- α is the phase delay (approximately 0),
- k is the ratio between the convection speed and the mean speed (experimentally 0.6).

In the current case, the flow is within the cavity rather than over it, but the vorticity generated by the flow instability can trigger the same aeroacoustic feedback mechanism.

Using Eq. 1, we can evaluate the critical frequencies. Given that both the headers have similar geometry, using D = 1.1 m (distance between the T-junction and the bifurcation), U = 6 m/s (mean speed in the header), and M = 0.014, the Rossiter frequencies are approximately multiple of 3.2 Hz. The wavenumber analysis of the inlet header (Fig. 3) shows dominant tones at 18 and 36 Hz, while the outlet header (Fig. 5) shows dominant tones at 12, 32, and 48 Hz. There appears to be an approximate 6 Hz factor, which can lock in with the header cavity modes. Specifically, 36 Hz corresponds to a quarter wavelength of the entire header, and the distance between the T-junctions of 2.3 m is a quarter wavelength at 48 Hz.

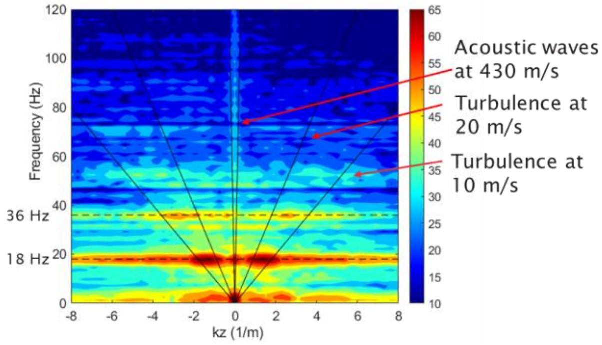

Figure 3: Wavenumber analysis in the inlet header.

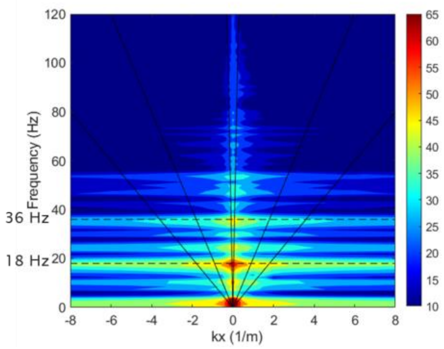

Figure 4: Wavenumber analysis in the metering duct, when only the inlet header is modelled.

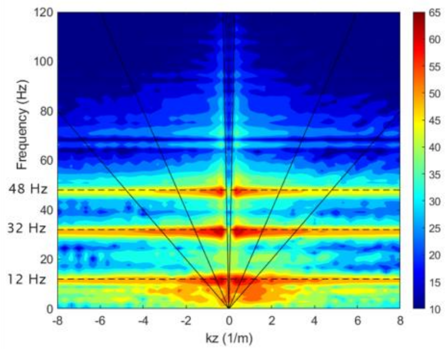

Figure 5: Wavenumber analysis in the outlet header.

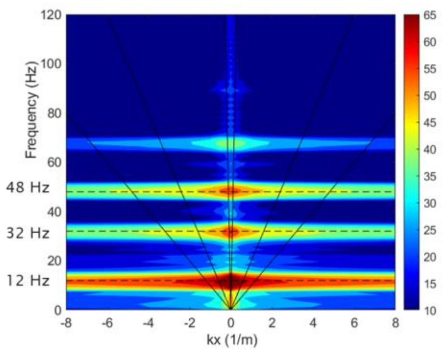

Figure 6: Wavenumber analysis in the metering duct, when only the outlet header is modelled.

3.2 Single Stream Case

The CFD model of the pipeline in this flow regime is shown in Fig. 7. With only one metering duct open, branches are present on the closed line.

For brevity, only the wavenumber analysis on the headers are shown in Figs. 8 and 9. The instability is even more pronounced in both the inlet and outlet headers, as the mean velocity is effectively doubled in this case. There is also evidence of the same Rossiter feedback mechanism, with a similar 6 Hz factor, which is further amplified by the presence of the closed branches. In fact, the two dominant tones 12 and 20 Hz are the same in both headers, as the two branches have similar lengths, approximately a quarter wavelength at 20 Hz.

Figure 7: The current pipeline model in the single stream flow regime.

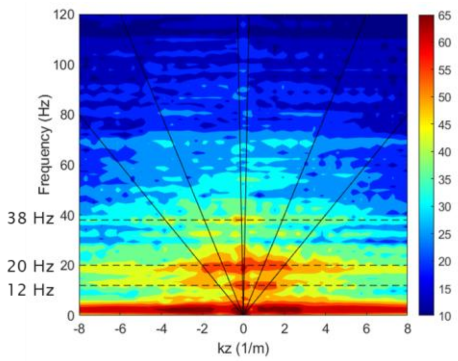

Figure 8: Wavenumber analysis in the inlet header.

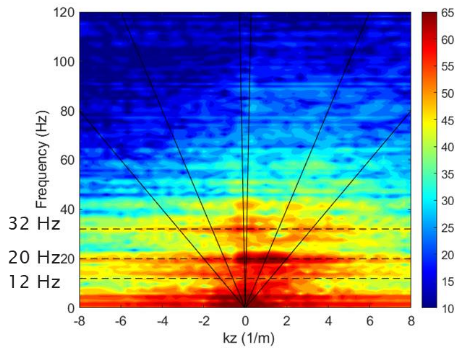

Figure 9: Wavenumber analysis in the outlet header.

4. REDESIGN OF THE PIPELINE

Our study has identified that the main cause of flow instability leading to aeroacoustic resonance is the flow bifurcation and convergence occurring in the header, coupled with the expansion of the flow from a narrower to a wider duct.

Therefore, we have recommended eliminating the headers and finding alternative, smooth solutions to redesign the pipeline avoiding sharp edges, which are strong sources of turbulence. Figures 10 and 11 illustrate the proposed design for the new inlet and outlet, which primarily utilise T-junctions only, as T-junctions itself have not shown potential to be a source of vortex shedding, when using smooth rounded joints.

Further analysis of the proposed design has demonstrated significant improvements in both the flow stability and acoustics of the pipeline.

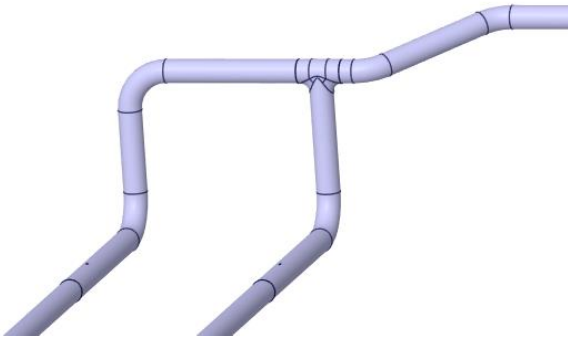

Figure 10: New design of the inlet header.

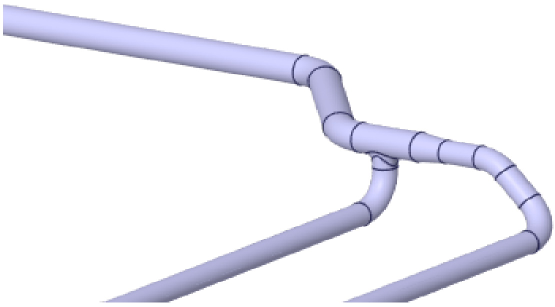

Figure 11: New design of the outlet header.

4.1 Dual Stream Case

The wavenumber analysis shown in Figs. 12 and 13 reveal a complete absence of strong tonal components. There is no evidence of a potential aeroacoustic problem.

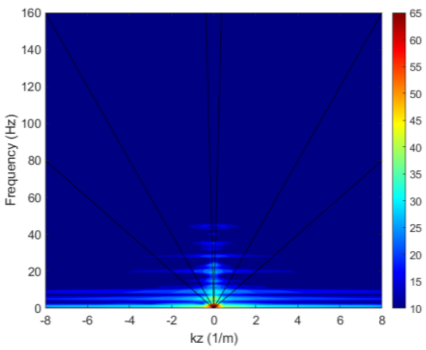

Figure 12: Wavenumber analysis in the inlet header.

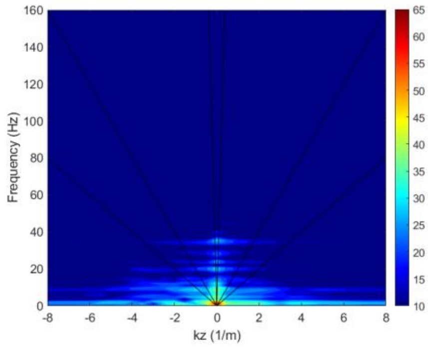

Figure 13: Wavenumber analysis in the outlet header.

4.2 Single Stream Case

Despite showing an overall improvement on the tonal content, the wavenumber analysis (Figs. 14 and 15) in this case still reveals some evident tonal components.
Flow analysis (Fig. 16) indicates that flow instability arises from the expansion occurring upstream of the T junction. This expansion is necessary as the outlet duct is wider than the metering ducts, but we have argued that moving the expansion downstream of the T junction would be beneficial to stabilise the flow.

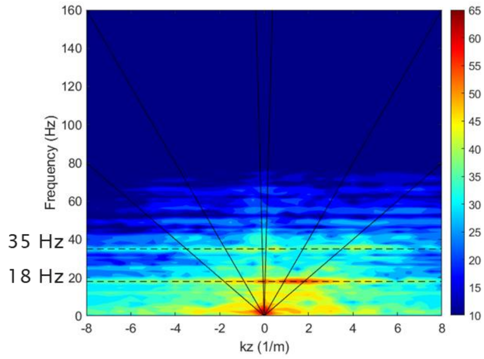

Figure 14: Wavenumber analysis in the outlet header.

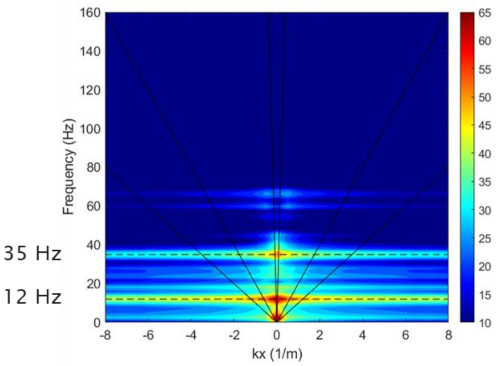

Figure 15: Wavenumber analysis in the outlet header.

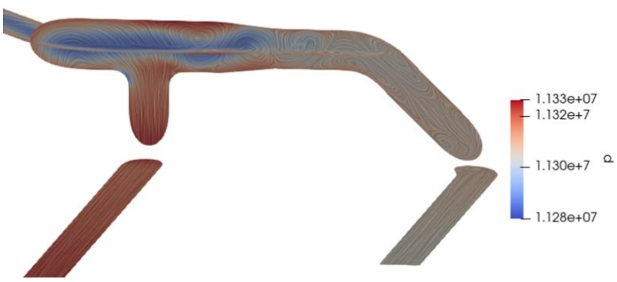

Figure 16: Pressure instability arising at the flow expansion.

5. REDESIGN OF THE OUTLET EXPANSION

To prove our hypothesis with the minimum effort, instead of redoing the full CFD analysis on a redesigned outlet, which would have required issuing an updated CAD and remeshing it, we modified the inlet model by adding an expansion duct to transition from the metering duct to the outlet duct size.

This model is shown in Fig. 17 and was used as an outlet with flow only inlet into the metering duct connected by the T junction to demonstrate the beneficial effect of the smooth transition downstream of the T junction.

Wavenumber analysis in the header of this fictitious outlet (Fig. 18) confirms our assumption, by showing a lack of tonal component.

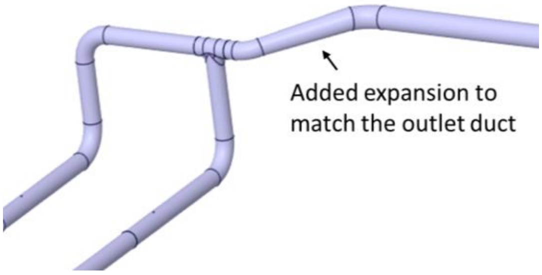

Figure 17: Using the inlet header to prove the effect of moving the expansion downstream the T junction.

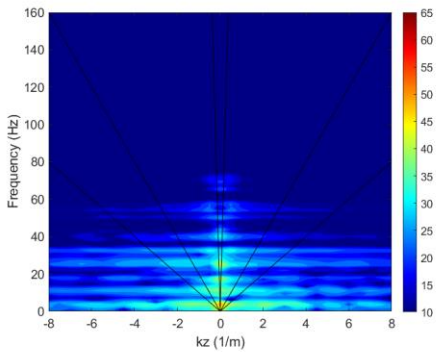

Figure 18: Wavenumber analysis in the header.

6. CONCLUSIONS

The CFD analysis successfully identified the aeroacoustic feedback mechanisms responsible for resonance in two distinct flow regimes. By employing wavenumber analysis, we examined the spatial frequency distribution of unsteady perturbations and revealed that both the inlet and outlet headers exhibited similar problematic behaviour despite differences in flow patterns.

The wavenumber analysis indicated dominant tones resulting from a combination of turbulence and acoustics, with evidence of vortex instability triggering acoustic waves. The single stream case showed even more pronounced instability, amplified by the acoustic modes of closed branches.

To address these issues, we recommended eliminating the headers and redesigning the pipeline using only T-junctions, which have not shown potential to be a source of instability. Further analysis of the proposed design demonstrated significant improvements in both flow stability and acoustics.

However, in the single stream case, despite overall improvement, some evident tonal components remained. Further analysis confirmed that moving the expansion downstream of the T-junction removed the strong tonal components.

This numerical modelling approach provided powerful insights to identify the physical mechanisms involved in this complex engineering problem and has the potential to be applied to a wide range of other aeroacoustic problems.

7. ACKNOWLEDGMENTS

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