Aeroacoustic analysis of flow induced resonance in a gas pipeline

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ABSTRACT

Flow induced noise and vibration in the pipework of gas production platforms can lead to fatigue failures of attached small-bore pipes, and this can constrain the operating conditions of the platform. Typically, such problems comprise a source of turbulence in the flow, an aeroacoustic feedback mechanism due to acoustic resonances inside the pipework, and mechanical resonances which amplify the resulting vibration. The problem described here occurred in the gas metering system of a platform, with the source located in the header which comprised a bifurcation into two metering lines and sharp bends. Because of the cost of rectifying the problem, an in-depth study was carried out to analyse the flow and induct acoustic conditions. CFD modelling was carried out using the OpenFOAM software to predict the exact location and mechanism of the vortex shedding. The acoustic response of the complex ductwork was then modelled using the ACTRAN FEM tool to understand the feedback mechanism which led to resonance and high levels of response.

1. INTRODUCTION

The operation of a gas production platform has been constrained for many years by a flow induced vibration problem in the gas metering ductwork shown in Figure 1. Previous studies have indicated a number of possible causes, with the most likely source of excitation being flow instabilities in the header.

If flow instability occurred in the 30-35 Hz frequency range, it could potentially cause high levels of vibration by driving a mode of vibration of the structure which had been shown to occur at 34 Hz. In our review of all the historical data we confirmed that this was indeed a plausible explanation of the vibration problem, but that the exact mechanism and location of the flow instability needed to be confirmed in a follow-on study to ensure it is eliminated in any redesign of the system. In particular, it was unclear why there should be an apparently similar problem for both single and dual stream operation when the flow and acoustics were different.

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Hence the aim of the work reported here was to confirm the mechanism of the instability by carrying out numerical modelling of the flow through the system and acoustic characteristics of the ductwork that appear to provide an aeroacoustic feedback mechanism. Section 2 describes the details and results from the CFD modelling work carried out for the two flow configurations, and Section 3 describes results of the associated acoustic modelling.

Section 4 compares the test data gathered in several test campaigns on the platform with the modelling work.

Final conclusions from the study are then presented in Section 5.

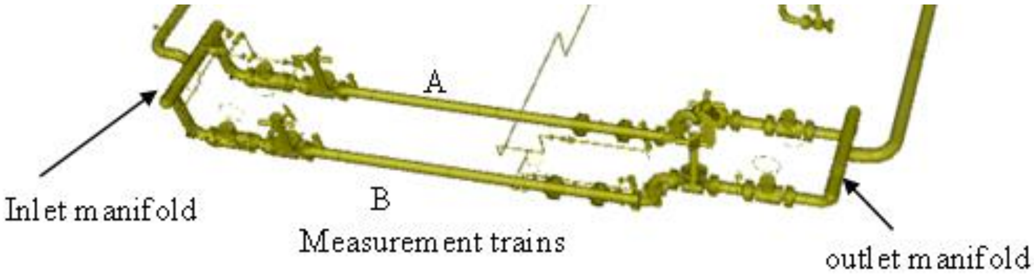

Figure 1: The export line and flow metering system.

2. CFD MODELS OF THE UNSTEADY FLOW

The pipework and components associated with the metering system are presented in Figure 1. Three compressors feed a 12" line to the inlet manifold of the metering system. From there the system may operate with only metering train A or B open (single stream), or A+B (double stream).

CFD analysis has been performed on a portion of the full pipeline with focus on the unsteadiness arising in the header and propagating into the metering ducts. The two models used to simulate the different flow regimes are presented in Figure 2. A velocity boundary condition was applied at the inlet. In the double stream case only a portion of the metering ducts was modelled, and a pressure outlet boundary condition was applied at both ends. In the single stream case duct B was closed at the valve position.

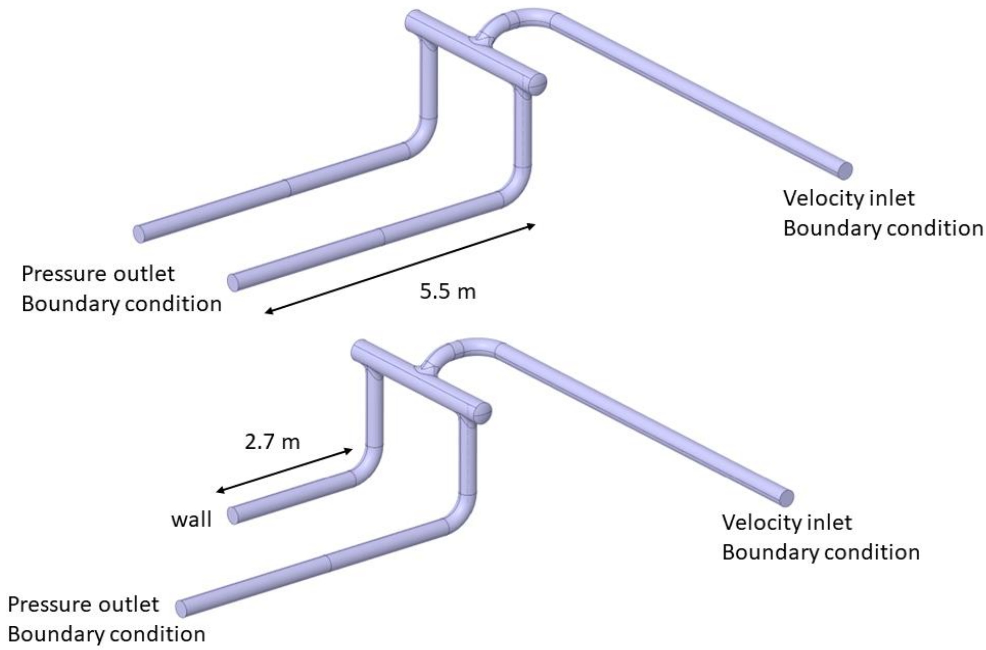

Figure 2: CFD models with boundary conditions and main duct lengths for the two flow regimes: double (upper) and single (lower) stream.

Unsteady Reynold Averaged Navier-Stokes (URANS) analysis, with the k-ω SST turbulence model, was carried out, using the open-source software OpenFOAM [1]. In the boundary layer, wall functions were employed to limit the number of cells, aiming at $100 < y^+ < 300$.

The average Mach number in the pipeline for all cases of interest did not exceed 0.1, which is typical of an incompressible flow. However, to model both the turbulent and acoustic pressure fluctuations, a compressible unsteady flow analysis was necessary.

In principle URANS is capable of modelling aeroacoustic feedback when the model is sufficiently accurate to predict the interaction between the two physics, which is generally achievable for tonal problems at low frequencies, as in this case. However, the accuracy strongly depends on the dissipation embedded in the numerical discretization, and the difficulty of modelling variables which are on two very different scales, as pressure perturbations arising from turbulence and acoustics. Therefore, two fully structured meshes were generated for both geometries to reduce numerical dissipation and cell count. The total number of cells was about 10 M in both cases.

The gas in the pipeline is a mixture of different natural gases. Static pressure was set up at the outlet as 11.3 MPa. Temperature and density, constant along the pipeline, were respectively 330 K and 80 kg/m^3. Combining the gas constant with the temperature, the speed of sound in the duct was then 430 m/s.

Two inlet velocity boundary conditions were considered for both cases: 10 and 20 m/s. This translates differently in the various ducts, as the flow bifurcates at the header (double stream) or deviates to the only open metering duct (single stream). Table 1 is a summary of the mean velocity through the system, evaluated by applying the mass flow rate conservation and using the area ratio of the various ducts.

Table 1: Summary of the mean flow velocity (m/s) along the ducts.

	Single stream		Double stream	
Inlet	10	20	10	20
Header	6	12	3	6
Metering	10	20	5	10

It is evident from the table that in both double and single stream cases there is a strong source of instability in the header, where the flow slows down and bifurcates or deviates to be redirected into the metering system. The study of this instability and its consequence on the acoustics is the object of the current study, as the vorticities generated by flow separations around bends and generated at expansions in duct area are a potential source of excitation for the flow induced vibration.

2.1. Dual stream flow

With dual stream flow, the velocity contour on a plane in the header presented in Figure 3 clearly shows vortices propagating downstream from the expansion and change of flow. It is interesting to note that the flow is oscillating asymmetrically.

Figure 4 shows the flow down the mitre bends, indicating that there is no additional vorticity generated there but it is only convected down from the manifold.

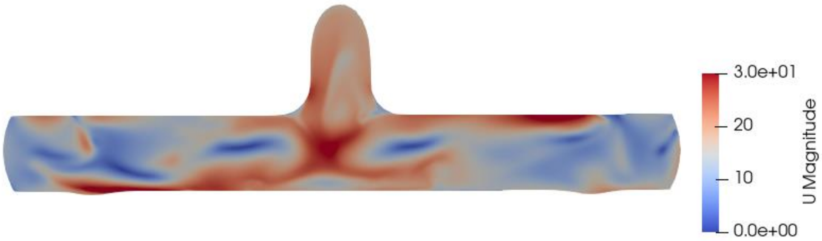

Figure 3: Asymmetrical pulsating flow velocity in the header downstream of the bifurcation on the cut-plane. Inlet velocity 20 m/s.

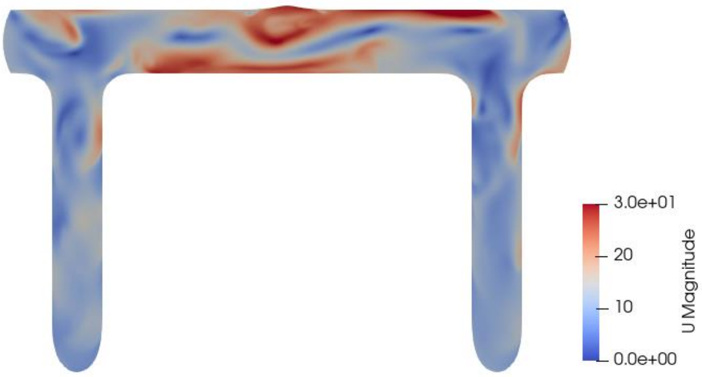

Figure 4: Unsteady flow down the mitre bends into metering ducts A and B.

Although the turbulence appears to be mainly generated at the expansion from the inlet pipe into the manifold, the process of scattering turbulent energy into acoustic energy could occur at either the bifurcation or at the entry to the measurement duct.

The latter is potentially a source of aeroacoustic feedback since it is analogous to the process that takes place with flow over a resonant cavity such as sometimes occurs with a motor car sunroof or aircraft equipment bays. Vortices from the upstream edge of the cavity are convected at the mean flow speed and create an acoustic source at the downstream edge. This causes aeroacoustic feedback at a frequency which increases in proportion to flow velocity, a so-called Rossiter tone [2], and when this coincides with the cavity resonance high amplitude response can occur. Some uncertainty in the model arises because the propagation distance is not precisely defined in this geometry, and the feedback frequency can lock-in to the cavity frequency.

The pressure spatial distribution in the various sections of ductwork may be used to analyse whether the perturbations are turbulence, which propagate at the speed of the flow, or acoustic waves which propagate at the speed of sound. This is known as wavenumber analysis, where for a wave of frequency f propagating at speed c, hence with wavelength $\lambda = c/f$, then the wavenumber k is given by $k = 2\pi f/c = 2\pi/\lambda$. For example, given a perturbation at a frequency of 35 Hz in a flow stream of 15 m/s, and with a speed of sound of 430 m/s, then an acoustic wave will have wavenumber k = 0.5 m^{-1}, whereas a turbulent wave will have wavenumber 14.7 m^{-1}.

The wavenumber analysis is carried out using a spatial Fourier transform, in an analogous way to frequency analysis being carried out by a temporal Fourier transform. The URANS time histories at the 256 points were first analysed into N frequency components from 0 to 2500 Hz using a time domain Fourier transform, and the resultant complex (i.e. amplitude and phase) data were converted to wavenumber spectrum for each frequency using a spatial Fourier transform. The resulting 256 x N matrix of wave amplitudes may then be plotted as a contour map as presented in Figure 5.

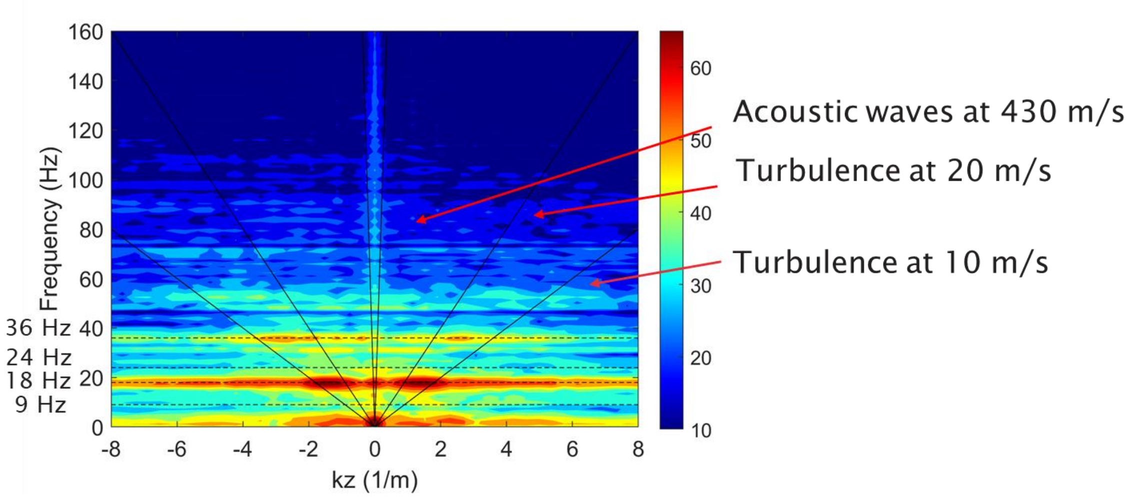

Figure 5: Wavenumber analysis of the pulsating pressure in the header. Dual stream flow at 20 m/s.

This contour map shows three areas separated by six lines, which are the areas delimited by the flow and acoustic propagation speed, to identify which frequency peaks are associated to an acoustic or a turbulent perturbation wave. This confirms that in the header the pulsations are dominated by turbulence, propagating at a mean flow speed between 10 and 20 m/s, which is the range in the header, but the acoustic waves are also apparent.

The fundamental frequency of the pulsations is f = 18 Hz which, based on an inlet velocity U = 20 m/s and duct diameter D = 0.273 m, corresponds to a non-dimensional Strouhal number of St = 0.25, where $St = f\ D\ /\ U$.

For vortices shed by a simple expansion from a duct into free space the Strouhal number is normally taken as 0.2, and so the fact that the expansion here is into the constrained space of the header, and with a bifurcation, has apparently increased the frequency with which vortices are generated.

The data in Figure 5 also shows significant energy at the 36 Hz harmonic frequency. This occurs because the vortex shedding is not purely sinusoidal, and it is to be expected that as the energy of the flow increases, or where aeroacoustic feedback occurs as discussed in Section 6, then the relative importance of the 36 Hz component will increase.

To check the Strouhal scaling of the vortex shedding process, a prediction was also made for an inlet flow velocity of 10 m/s. The contour map in Figure 6 indicates that the fundamental frequency is now 9 Hz, which corresponds to the same Strouhal number of 0.25.

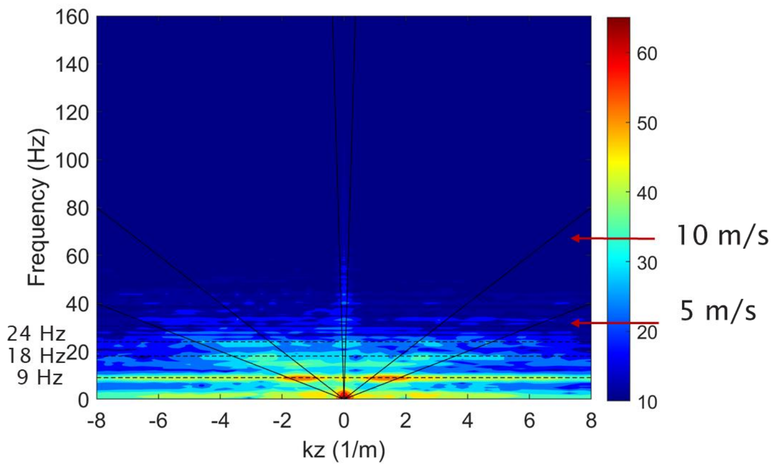

Figure 6: Wavenumber analysis in the header for dual stream flow at 10 m/s inlet velocity.

There is also the question whether vortex shedding could also occur at the mitre bend. In that case turbulence would be shed into the measurement duct, whereas the wavenumber analysis in Figure 7 shows that the pulsations there are dominated by acoustic waves.

A specific feature of interest apparent in the power spectrum of Figure 7 is the peak at 9Hz. This half harmonic of the vortex shedding frequency probably arises from low level oscillatory flow behavior between ducts A and B. The same 9 Hz frequency can also be detected in the inlet duct upstream of the expansion into the header.

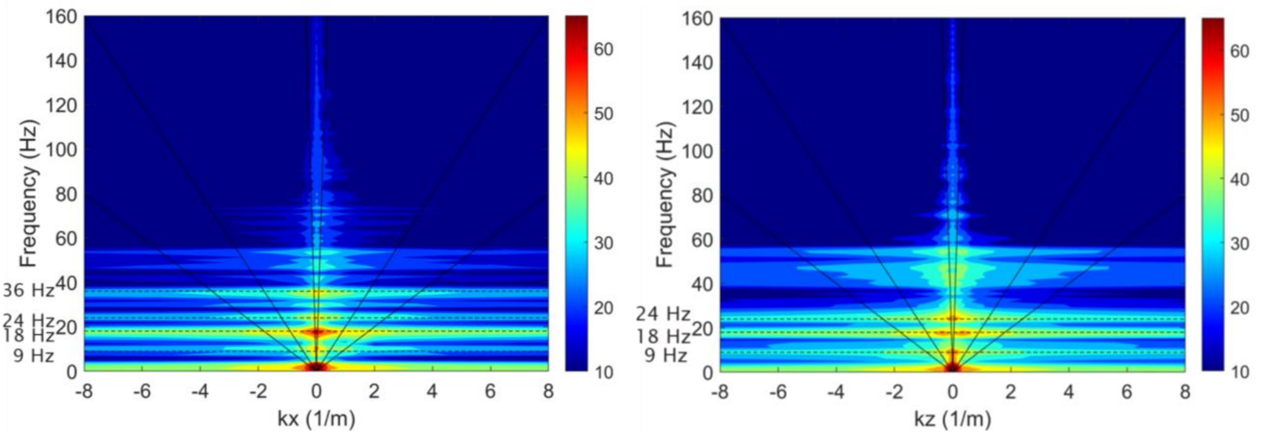

Figure 7: Wavenumber analysis in the measurement duct (left) and inlet duct (right) for dual stream flow at 20 m/s inlet velocity.

The relative phase of the pressure pulsations in the two measurement ducts are compared in Figure 8 using the time signals at the inlet to the ducts as predicted by the CFD analysis, showing that the signals are out of phase, which was crucial to set up the acoustic FEM analysis, and confirming the oscillating nature of the turbulence shedding process at the manifold inlet.

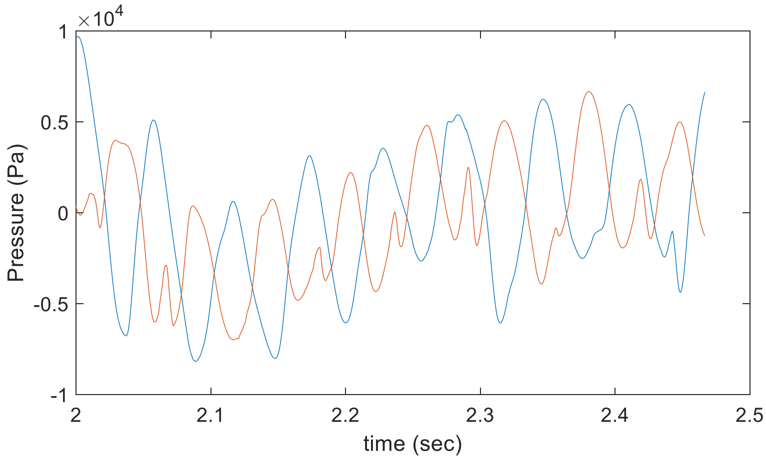

Figure 8: Phase relationship between points at the start of the two measurement ducts in the time domain.

2.2. Single stream flow

Changing the configuration of the measurement ducts from dual to single stream flow causes several major changes to not only the flow distribution but also the acoustic characteristics of the ductwork.

Figure 9 shows the flow down measurement duct A. As noted above the mean flow in the open section of the manifold must be 12 m/s, but there is a significant spatial variation. The mean flow into the measurement duct is the same as the mean flow from the inlet duct, 20 m/s.

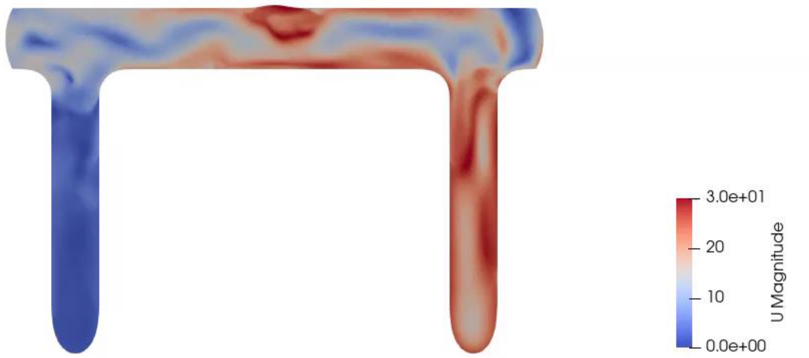

Figure 9: Flow velocity distribution with duct A only open.

The URANS model predicts the pressure perturbations in the manifold, measurement and inlet duct, and as for the dual stream flow these have been analysed as wavenumber maps in Figure 10 and Figure 11.

The comparison of the result for the header in Figure 10 with the same result for the dual stream flow in Figure 5 shows some significant differences:

- The dominant frequency of 20 Hz is somewhat higher than the 18 Hz frequency noted in Figure 5. This frequency is assumed to be the Strouhal frequency for vortex shedding with the single stream flow.
- Another peak is apparent at 12 Hz, which appears to comprise a combination of asymmetric turbulence (with positive wavenumbers propagating downstream) and acoustic waves. Although a small peak at 10 Hz was noted in Figure 5 for the dual stream flow case, this is far more prominent, and could plausibly be the result of the proposed aeroacoustic feedback mechanism.
- There is also an acoustic peak at 38 Hz, approximately 3rd harmonic of the 12 Hz frequency, which could again be due to the aeroacoustic feedback mechanism. A peak at 24 Hz should also be present, but this is presumably hidden by the 20 Hz vortex shedding frequency.

The same interesting combination of frequencies is apparent in the analysis of the measurement and inlet ducts, Figure 11, which shows the dominance of acoustic waves. A particular feature to note in the data for the inlet ducts are the peaks at both 20 and 24 Hz, whereas the equivalent plots for the dual stream flow only show a single peak.

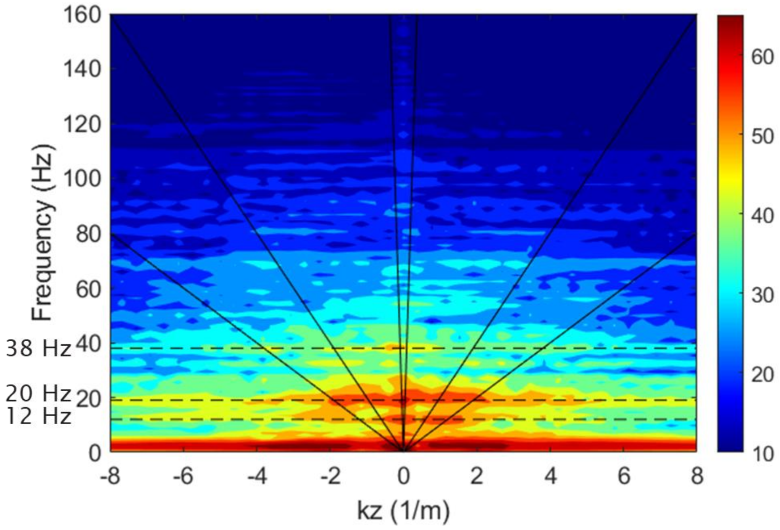

Figure 10: Wavenumber analysis in the header duct for single stream flow at 20 m/s inlet velocity.

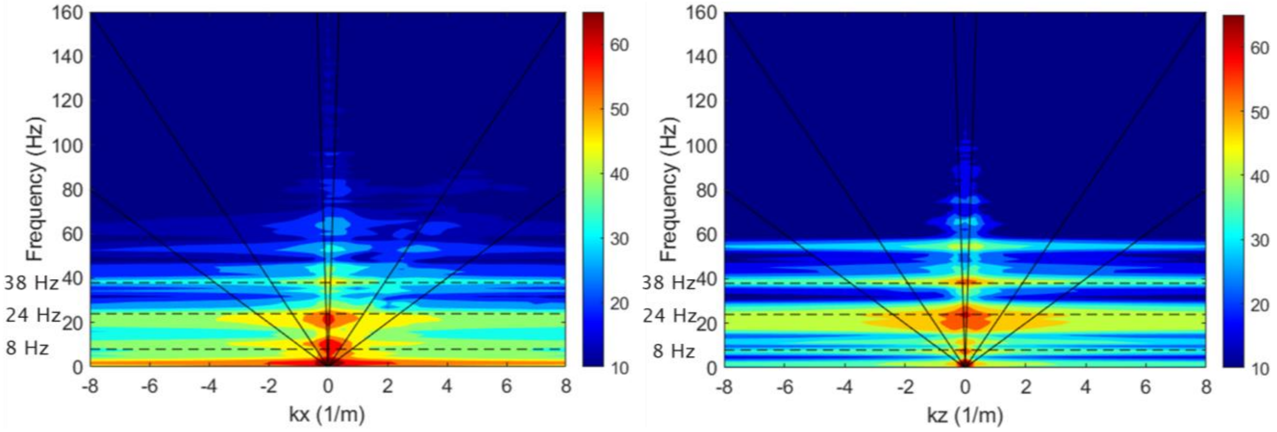

Figure 11: Wavenumber analysis in the metering duct A (left) and inlet duct (right) for single stream flow at 20 m/s inlet velocity.

3. ACOUSTIC FE ANALYSIS OF THE DUCTWORK

Acoustic FE modelling was carried out using the ACTRAN software tool [3], with the aim of interpreting how aeroacoustic feedback could cause an increase in the intensity of the flow pulsations.

3.1. Dual stream configuration

Figure 12 shows the geometrical model and the boundary conditions used in the simulation. At both pipes entering the header manifold and at the end of the outlet a no reflection boundary condition was assumed. In order to simulate an acoustic source of the same nature of the pulsating flow in the manifold (Figure 8), two out-of-phase point sources at the inlet to each measurement duct were used as acoustic excitation.

Figure 12: FE model of the dual stream configuration.

We evaluated the forced frequency response of the system at the position of two pressure transducers in ducts A and B that have been installed on the platform. Results are presented in Figure 13. The close correspondence with the peak frequencies shown in both the CFD predictions (Figure 5) and the test data presented in Figure 17 is remarkable, in particular with the strong peak at the problem frequency of 34 Hz.

This appears to confirm that the mechanism causing high response in the dual stream configuration with an inlet velocity of 20 m/s is as follows:

- Vortices are shed from the manifold inlet. Figure 5 predicts dominant frequencies of 18 and 36 Hz, but with energy at multiples of 9 Hz.
- The vortices are convected through the manifold and turbulent energy is scattered into acoustic energy at the entry to the measurement duct.
- Because the inlet flow is oscillating, the acoustic sources at ducts A and B are out of phase. This drives a series of modes in the coupled ducting system which are also approximately at multiples of about 9 Hz.
- In particular the modes at 17.3 Hz and 34.4 Hz align very closely with the predicted vortex shedding frequency at 20 m/s.

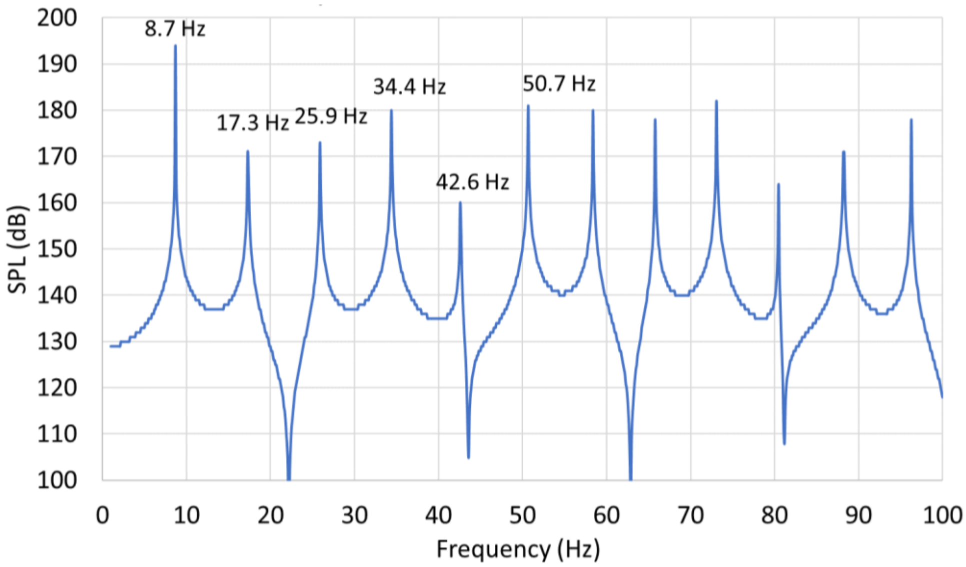

Figure 13: Forced response at the pressure transducers in ducts A or B.

3.2. Single stream configurations

The model for the single stream case is presented in Figure 14. The flow is down line A and both valves are closed in line B. In this case an incident plane wave is assumed as acoustic excitation as there is no suggestion in the CFD results of a more complex interaction of pulsating pressure in the header and in the frequency range of interest only plane waves are cut on in the various ducts.

Figure 14: Duct layout with only single stream A operating and both upstream and downstream valves closed in line B.

The ductwork may be considered as a system of discontinuities which acts as a reactive silencer, blocking certain frequencies and allowing others to pass. There are two expansion chambers (the inlet and outlet manifolds), with a single linking pipe, and there are sidebranches off each chamber, with the upstream sidebranch being located very close to the source at the inlet duct.

Figure 15 shows the forced response in duct A. As for the dual stream case, there are regular dips at resonances of the overall system length, but a key feature now is the twin dips corresponding to frequencies where the sidebranch lengths are 1/4, 3/4 and 5/4 times the wavelength. The lower frequency dip of each pair corresponds to the slightly longer length of the downstream sidebranch, and the higher frequency one comes from the upstream sidebranch.

Since these sidebranch resonances are not in the 30-35 Hz range, they cannot be responsible for the high response experiences on the platform in this configuration at 20 m/s. Hence a plausible mechanism for high response in this case is as follows:

- Vortices are shed from the manifold inlet at the frequencies given in section 2.2. Peaks are shown particularly at 12, 20 and 38 Hz, although other frequencies are also noted in the analysis.

- The vortices are convected downstream and generate an acoustic wave which propagates back up the manifold to interact with the source. For this distance the aeroacoustic feedback is predicted to occur at harmonics of about 10-12 Hz.
- There is also an acoustic mode of the header and closed sidebranch at about 30 Hz (Figure 16) which could amplify the 3rd harmonic of the aeroacoustic feedback mechanism.

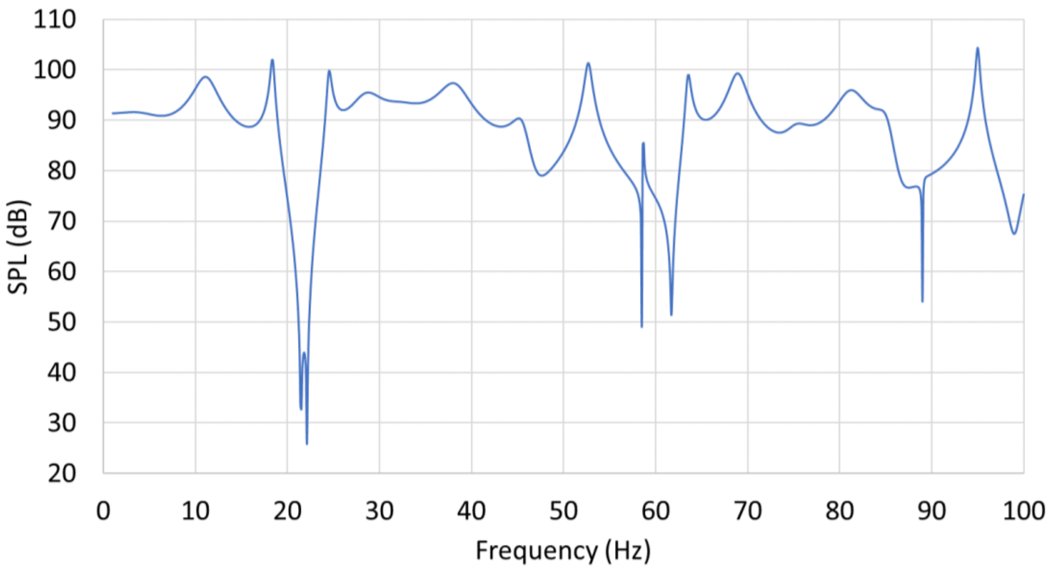

Figure 15: Frequency response at pressure transducer in duct A.

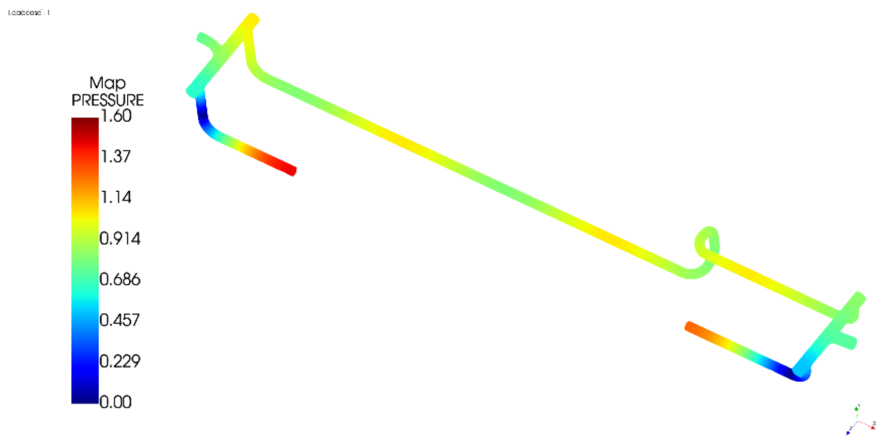

Figure 16: Standing wave pattern at 32 Hz, showing a ½ wavelength standing in the inlet manifold.

4. TEST DATA ANALYSIS

With the insight provided by the results of the CFD and FE models, it was possible to identify many of the peaks observed in spectra that were acquired from the transducers in ducts A and B during field trials, and this has helped to confirm the interpretation of the sources mechanisms.

Considering first data for the dual stream flow shown in Figure 17, the close correspondence with the predicted frequencies in Figure 13 is remarkable. Furthermore, carrying out cross-spectral analysis between transducers A and B also confirmed that the signals were out of phase as demonstrated in Figure 8.

This confirmed that the source of excitation for the dual stream flow is turbulence from the manifold inlet impinging on the end of the manifold and outlet leading to the measurement ducts. High levels are observed because there is a coincidence between the vortex shedding frequencies of the inlet pipe and the natural frequencies of the duct, when driven by out of sources at the header outlet pipes. There is some evidence of the Rossiter mechanism, but this is relatively low level because of the lower speed flow compared with the single stream case.

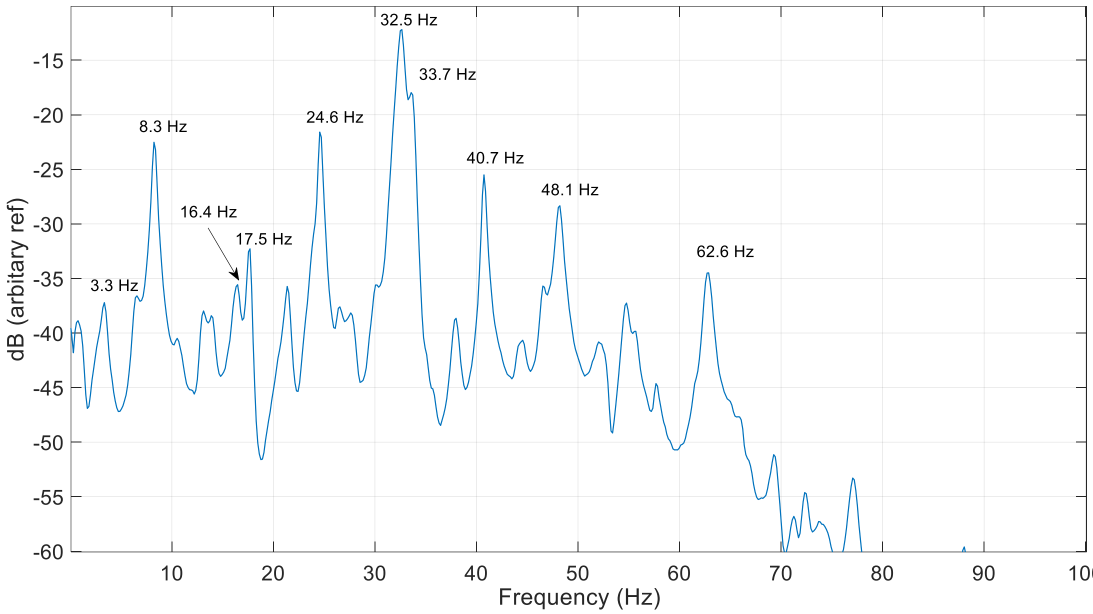

Figure 17: Spectrum at the duct B transducer with 20 m/s dual stream flow.

For the single stream flow the picture is more subtle. Figure 18 does show a good correspondence of peaks in the spectra as predicted by the CFD and dips in the spectra predicted by the FE model at the blocking frequency of the sidebranches. However, the full explanation of the phenomenon involved has required the aeroacoustic Rossiter feedback mechanism in the inlet header to be invoked, which preferentially drives harmonics of 10-12 Hz at source for the single stream case.

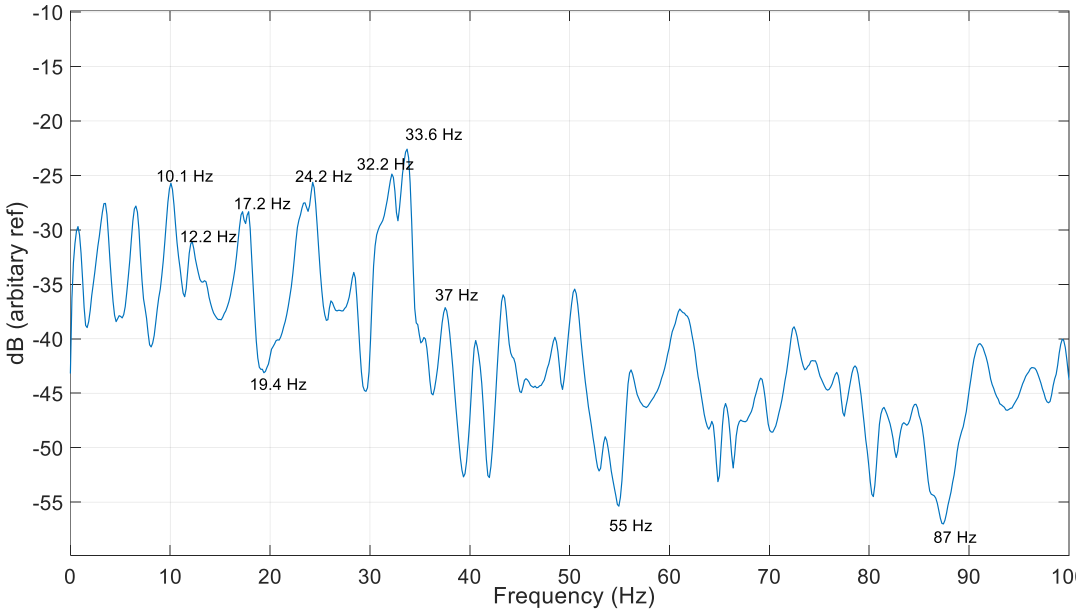

Figure 18: Spectrum at the duct A transducer with 20 m/s single stream flow.

5. CONCLUSIONS

A combined analysis of CFD and acoustic FEM has been used to model the aeroacoustic feedback mechanisms responsible of restriction of operations of a gas platform for several years. URANS has shown to be capable to predict the interaction between the fluid dynamics and acoustics which in turns interacting with the acoustic duct modes and the vibration modes of the pipeline has caused the high response on the platform.

For the dual stream configuration, it has been demonstrated that there is an oscillating flow into the inlet manifold with out of phase acoustic sources at the entry into the measurement ducts. This combination of sources couples to the acoustic modes of the entire measurement duct system, and these modal frequencies also align with the vortex shedding frequencies at flow speeds above 20 m/s.

With the single stream configuration the resonant frequencies of the ductwork are less evident. In particular the natural frequencies of the sidebranches have been shown to not be at frequencies that would explain a problem at 30-35 Hz. However, the flow generates aeroacoustic feedback on the vortex shedding process at multiples of about 10-12 Hz. Given the potential for frequencies locking-in, the 3rd harmonic of this feedback aligns reasonably well with the 2nd harmonic of the vortex shedding process and also with the frequency of a standing wave in the combined header and sidebranch cavity.

ACKNOWLEDGEMENTS

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