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Qualification of Duct Resonator Array for Noise Reduction in Offshore Installations

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A compressor noise reducing device was investigated in connection with internal qualification of the technology for use in offshore installations in the Norwegian Continental Shelf. The acoustic performance of two duct resonator arrays consisting of a one-piece perforated tube applied to the inlet and discharge pipes as spool pieces was studied by means of sound insertion loss measurements. This array configuration minimizes the acoustical energy propagating to the inlet/discharge pipes and can be an optimal solution when retrofitting existing compressors in modification projects. The arrays are custom tuned to deliver maximum attenuation at the predominant tonal noise component (commonly at the blade passing frequency) of the corresponding compressor. Laboratory verification measurements demonstrated that the duct resonator array reduces 14-18 dB the noise level at designed frequency (2-3 kHz). Additionally, the correlation between insertion loss and effective length was found to be approximately linearly proportional. A comparative study carried out revealed no significant difference on whether the arrays are installed in series or separated 90° with a bend. Overall the investigation showed that this technology allows further flexibility of implementation often required in piping layouts with limited space.

1 Introduction

In recent years awareness has been raised on the consequences of noise exposure in offshore installations. Both authorities and the oil & gas industry are working on finding the means to reduce noise exposure and thus, prevent hearing damage, which can be permanent and irreversible. Excessive noise is also a safety concern as it can interfere with verbal communication and the audibility of the PA system. Traditionally, measures that treat the sound transmission path have been used, i.e. sound insulation, enclosures and ear protection. Latest trends, however, prioritize the use of low noise equipment and technical measures which act directly on the source.

It is well known that compressors are a major contributor of noise in offshore installations; hence targeting the noise emitted by turbo-machinery is a very effective way to reduce noise exposure. Since 2000, a centrifugal-compressor noise reducing technology, called Duct Resonator array, has been commissioned in over 220 compressors. This device is designed to attenuate the signature noise of a compressor, occurring at the blade passing frequency (BPF) and its harmonics. The BPF of an industrial turbo-compressor typically lies within 1200-4500Hz, a frequency range where human ear is most sensitive.

Duct resonator array can be applied to turbo compressors in two ways: installed internally in the diffuser region or externally, as a spool applied to the inlet/discharge pipes. For new compressor designs, installing a resonator array inside the compressor would be a preferred choice [3] for it is a highly efficient and easy to implement solution. On the other hand, the external application can be a more suitable option when retrofitting existing compressors. This paper will focus on the latter, which from here on will be designated as pipe array.

Pipe array minimizes the acoustical energy propagating to the inlet/discharge pipes that are a major noise radiation in a compressor system. This application provides noise attenuation in situations where it is not feasible (e.g. due to space limitations, design compatibility) or recommended to mount the device inside the compressor. And it does not require disassembling the compressor, hence reducing the machine down time [3]. All in all, it can be very helpful in addressing the challenging noise issues found in modification projects where, frequently, little might be done to the existing machinery. This approach, however, requires adding a pipe spool to the existing (and often limited) piping layout (see Figure 2 middle). Since it is preferable to install the spool closest to the compressor, the authors found it necessary to investigate new configurations that would allow further flexibility of implementation.

The present paper shows a study which was conducted in the context of internal qualification to promote the use of the technology in some installations on the Norwegian Continental Shelf (NCS). Laboratory noise measurements were performed on two pipe spools in order to verify noise attenuation, which includes a comparative study of the pipe arrays installed in series vs. the pipe arrays separated with a 90 degree bend and an investigation of the correlation between the insertion loss and the effective length of the array.

2 Pipe array design

Pipe array is a one-piece solid steel tube with acoustic chambers machined from the outer side that are connected to the flow path by a series of perforated openings, as represented in Figure 1.

Figure 1: close up of the perforations inside the pipe array

When the sound wave travels through the perforated holes, part of the acoustic energy is transformed into vorticity and consequently dissipated. The acoustic chambers are dead volume to the mean flow but are partially transparent to sound waves, resulting in reactive noise attenuation. The incident sound wave is reflected with phase shift and partially cancels the sound in the main gas flow.

The insert of a pipe array changes the pipe wall from acoustically rigid to acoustically absorptive. This acoustic boundary condition change at the pipe inner wall is represented by the acoustic impedance:

$$\frac{Z}{\rho c} = \frac{R}{\rho c} + i\frac{X}{\rho c} \tag{1}$$

where impedance Z is normalized with respect to the characteristic impedance ρc of the acoustic media. The real part R is called resistance and the imaginary part X is called reactance [1-2]. The noise attenuation performance of the pipe array is controlled by the above impedance.

Following (1), the volumes, cross-sectional areas and lengths of the perforations are custom designed to deliver maximum attenuation at the compressor's signature blade passing frequency and corresponding higher harmonics, i.e. at the predominant tonal noise component.

Manufacturer in-house experimental data has shown that the pipe arrays reduced the overall compressor noise level by about 10 dB (90% sound power reduction) without documented adverse effects on compressor and process performance [4]. Additionally, it can also have a positive effect on pipe vibration by reducing in-pipe pressure pulsation, and hence, help prevent fatigue damage [3].

Figure 2: Left, sketch of pipe spool with pipe array (illustration by [5]); Middle, 4D pipe-spool; Right, detail of pipe spool with pipe array inside

Figure 2 (left, right) illustrates the pipe spool inner wall lined with the pipe array. The pipe array is typically designed with an effective length of 4-diameter (4D). Because space limitations in a given piping layout could reduce the possibilities of implementing a pipe array of the above-mentioned length, a need to challenge the design criteria was identified with respect to the effect of having shorter pipe spools or dividing a 4D spool into two or more spool pieces.

3 Acoustic measurements

In order to verify the sound reduction of pipe arrays towards design, airborne sound insertion loss measurements were carried out on a 1st section inlet and a 2nd section discharge pipe arrays, originally designed for a specific re-injection compressor model. The pipe spools have an effective length of 4D each. The pipe arrays are tuned to target the compressor's BPF calculated to be around 2500 Hz, with a band width of 2-3 kHz. The arrays are tuned every 4-inch segment from low to high frequencies in the longitudinal direction. For ambient air test environment, the centre frequency of noise attenuation is about 2980 Hz for the inlet pipe array and 2580 Hz for the discharge pipe array, as predicted by the manufacturer (also see Figure 5). The difference in the – designed – centre frequency compensates for the lower temperature of the gas that flows in the inlet pipe, which causes a lower speed of sound, thus producing a shift in frequency.

3.1 Set up

Measurement set up is illustrated in Figure 3. Reduction of the sound pressure level due to the pipe array (insertion loss) is defined as the difference between the sound pressure levels measured before and after the attenuator, i.e. the array. A broad band acoustic signal (random noise) is generated and fed into a custom-made loudspeaker. A midrange loudspeaker with frequency response as in Figure 4 was used. A custom made enclosure was produced to fit the pipe opening. The sound pressure level generated inside the duct is measured by two microphones located upstream and downstream of the pipe array. Measurement data was acquired and processed using a B&K Pulse system driven by a laptop. The Pulse system was also used to drive the loudspeaker via a power amplifier.

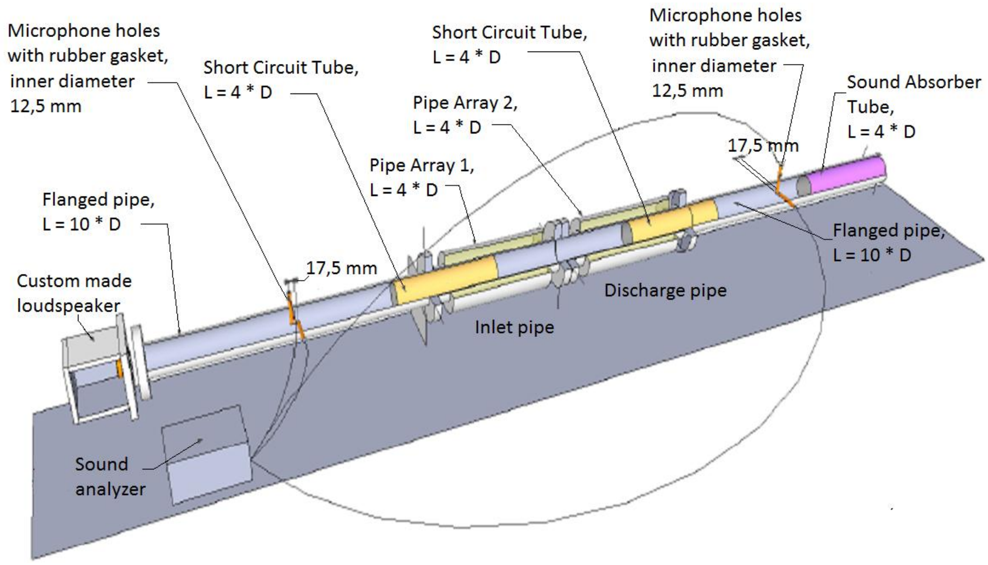

Figure 3: Measurement set up (illustration by [6])

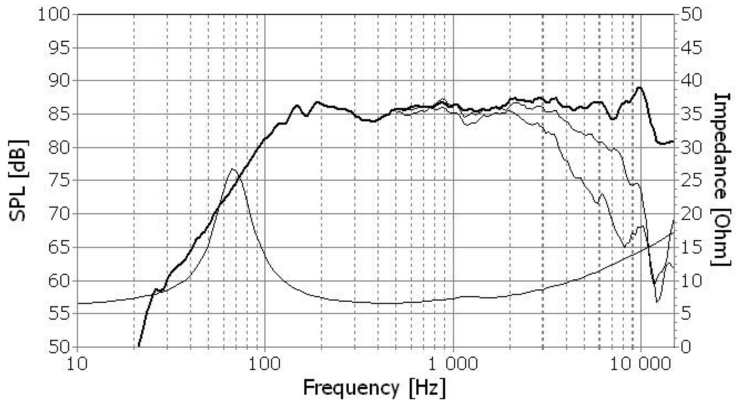

Figure 4: Loudspeaker frequency response (Seas H1304-08A12RC) [7]

The effective length of the pipe arrays was modified by inserting a thin metal plate cylinder with an outer diameter almost equal to the inner diameter of the pipe array (so-called "short circuit tube" in Figure 3). Four cylinders, each of 2D length, were used in order to cover partially (or totally) the two segments of each pipe array. In order to avoid unwanted reflections to disturb the measurements, the open end of the pipe was filled with wool with increasing density towards the end to create an anechoic termination (denoted as sound absorber tube in the set up illustration). This solution is a good approach for the purpose of the present measurement, although minor inaccuracies might be associated to it.

3.2 Results

Sound attenuation measured in the band of 2-3 kHz, i.e. the frequency range at which the compressor produces strong tonal noise, was ~14 dB in the case of the inlet pipe and ~18 dB for the discharge pipe (or approximately 97% sound power reduction). In both cases the effective length of the arrays is 4D. The discrepancy is explained by the slightly different tuning of each array (as observed in Figure 5) and previously introduced in this section. The inlet array's effective band (2.3-3.3 kHz) is slightly "off-tuned" with respect to the analysed band (2-3 kHz), hence the lower sound attenuation value. The A-weighted overall attenuation was additionally calculated to be about 7-8 dB (or ≈82% sound power reduction) based on the compressor's predicted octave band sound pressure level provided by the manufacturer.

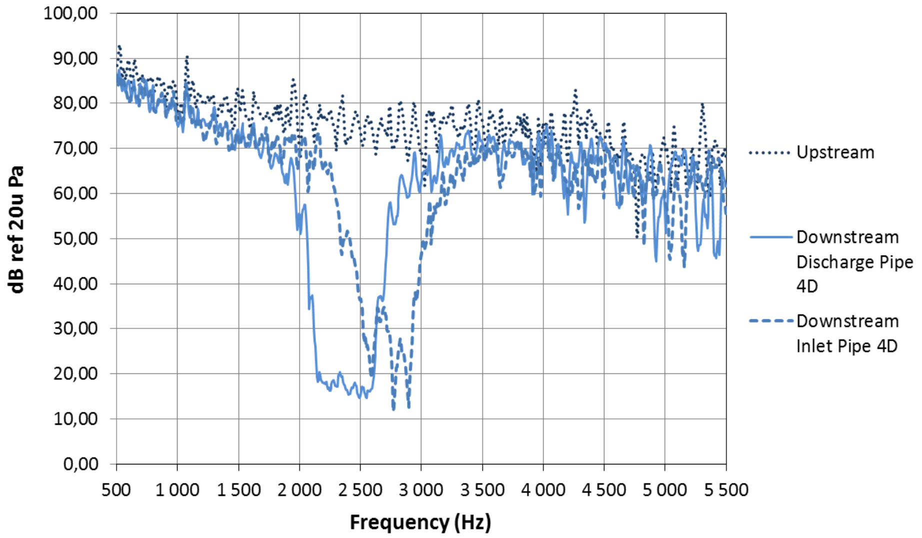

Figure 5: Measured sound pressure level (dB) downstream of discharge (solid line) and inlet (dotted line) pipe arrays. 4D effective length. Random noise

The results shown here represent airborne sound attenuation when the pipe array is driven with a broadband noise. Notice these results are based on a laboratory environment set up, i.e. there is no flow in the pipes.

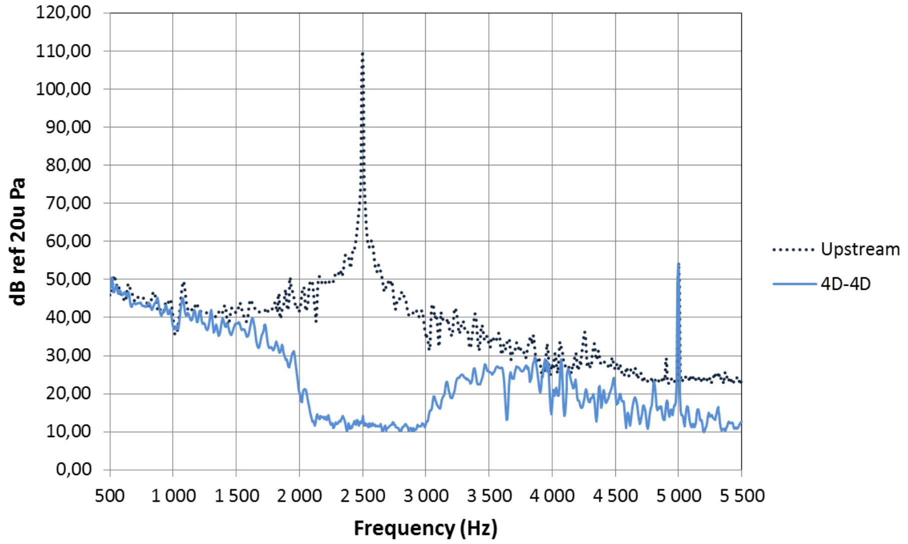

Figure 6: Measured sound pressure level (dB) of combined effect of both discharge and inlet pipe arrays in series. Effective length 8-diameter (8D). Tonal noise

Compressor noise is characterized by a tonal component, a strong peak at the BPF. A simulation of the noise spectrum of a compressor with discrete frequency at 2.5 kHz is shown in Figure 6, where the noise peak is attenuated by as much as 85 dB – with the combined action of the two pipe arrays, i.e. effective length 8-diameter (8D) –. Notice that structural noise has not been accounted for in the present test.

The correlation between insertion loss and effective length of the array was investigated by covering sections of the perforations with cylindrical tubes to vary the effective area. As more effective area of the array is “uncovered”, a wider frequency range (in the targeted 2-3 kHz band) is attenuated, as shown in Figure 7. This relation is defined by the particular characteristics of the array, which is tuned in the longitudinal direction. In the same way, the overall sound attenuation in the 2-3 kHz band increases. The correlation is clearly depicted in Figure 8. It can be seen that the insertion loss is approximately linearly proportional to the effective area. While in the interval 4D to 6D the insertion loss is about doubled, the increase from 6D to 8D is much smaller. Both situations could be explained by the array configuration that was chosen and, again, the slightly different tuning between the two devices. The 6D effective length is achieved as a combination of the full 4D discharge array plus the lower frequency half of the inlet array (2D length). Because the centre frequency of the inlet array is higher than that of the discharge pipe, more frequency bands in the upper limit of the 2-3 kHz band are being attenuated, which in turn produces a larger increase in the overall band attenuation.

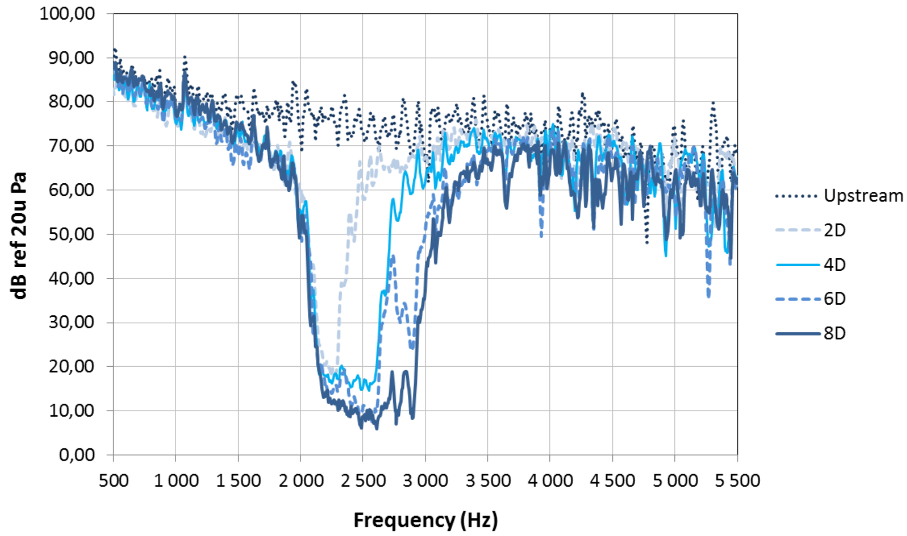

Figure 7: Measured sound pressure level (dB) with variable effective length of the pipe array (2D to 8D)

Under field operating conditions, i.e. with gas flow of different temperature and pressure in the pipes, both arrays will have the same centre frequency (about 2500 Hz) and the correlation would be expected to follow a more linear trend in the interval 4D-6D. The maximum sound attenuation in the 2-3 kHz band is limited to about 42-43 dB with an 8D pipe array configuration.

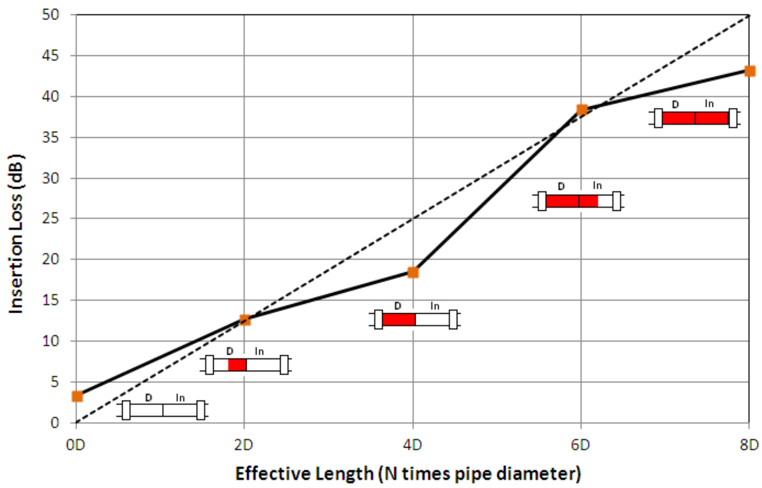

Figure 8: Sound insertion loss (dB) function of effective length of the pipe array (0D to 8D). The drawings illustrate the corresponding pipe array configuration where red colour indicates the active area of the array. Discharge pipe is designated with a “D”; inlet pipe is labelled “In”

A comparative study revealed no diminished performance due to the pipe arrays being separated with a 90º bend compared to the in series configuration (Figure 9). Similarly, dividing a pipe array into 2 spools (with effective length of 2D each, i.e. combined total length 4D) and connecting them either in series or with a 90 degree bend, has no negative effect on its performance. It is recommended, however, the arrays be installed as close to the source as possible for maximum noise level attenuation. Likewise the distance between the two spools should also be as short as practically possible.

For applications with limited space where the 4D effective length requirement might be a restriction, the results depicted in Figures 8 and 10 are of particular interest. These alternative configurations illustrate a potential for greater flexibility of use and the relation to maximum sound attenuation.

Figure 9: left, in series configuration; right, pipe arrays separated by a 90° bend.

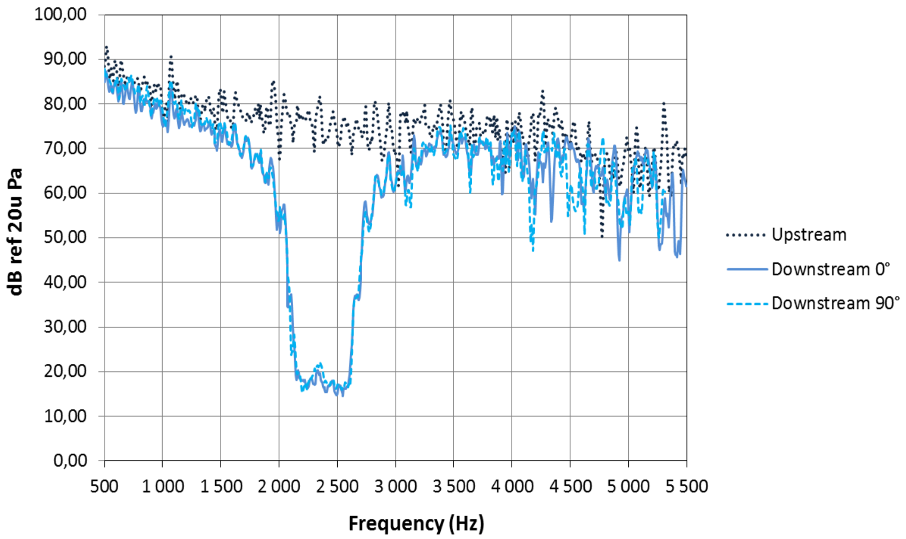

Figure 10: Comparison of sound pressure level (dB) between spool configurations in-series (solid line) and separated with a 90° bend (dotted). Effective length 4D

The combined effect of two pipe arrays (4D+4D, or 8D, total effective length) aimed to simulate the combined action of one array installed in the compressor diffuser area plus a second array installed as a spool piece. This solution could be relevant for those applications which would benefit from additional noise level reduction in order to comply with regulations, and when practically possible, could use both array systems. The combined solution (which is depicted both in Figures 6 and 7) adds on average an extra 60% sound attenuation to that of a single array. Measurements also reveal up to 31 dB reduction at the BPF (2500 kHz), confirming the large potential of this technology.

4 Conclusion

Laboratory verification measurements demonstrated that the pipe duct resonator array reduces significantly the noise level at the designed frequency, that is, the frequency at which the compressor produces a strong noise or so-called blade passing frequency. Overall sound pressure level attenuation in the range of 7-8 dB (80-85% reduction of the sound power of the source) was reported, with 14-18 dB reduction (97% less sound power) in the frequency band containing the BPF (2500 Hz).

The effective area of the arrays was varied using cylindrical tubes that covered partially the array perforations. Measured insertion loss values (in dB) are found to be approximately linearly proportional to the effective length, with discrepancies explained by the particular nature of the array tuning. Comparative study revealed no detriment in the performance when the spool is installed after a 90° bend (rather than in series) or when divided into two spools of 2D length separated with a 90° bend. These two findings together demonstrate the flexibility this technology potentially allows; the applications with layout limitations, generally found in offshore installations and particularly in modification projects, can benefit from the use of these alternative configurations. Nevertheless, it is recommended that the pipe array is placed as close to the source as possible. The combined effect of two pipe arrays was also recorded, the results showing that adding a second array provides an extra 60% of the total performance (in general, about +6 dB reduction). The investigation finalized with the internal qualification of the technology to possibly be used in infrastructure in the North Sea.

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