Effect of Corrugated Pipe Bending on Internal Flow Induced Acoustics

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***Abstract*—Internal flow induced acoustics is commonly noticed in corrugated pipes that provide both flexibility and strength in offshore flexible riser system. This phenomenon is commonly known as whistling when flow passes through the corrugated pipe at high pressure and high velocity. This paper evaluates the effect of corrugated pipe bending on the whistling behavior using 2D numerical simulation. It is found that the bending angle will have an effect on the peak-whistling Strouhal number (Sr_{p-w}). By incorporating the bending effect $A = \frac{360^o}{360^o - \theta}$ in characteristic dimension, such that $A(W + r_{up})$ rather than ($W + r_{up}$) which was proposed in literature resulted in smaller variation of Strouhal Number, Sr_{p-w}. Hence, provide more accurate prediction of the phenomena and further enhance the practicality of the modified characteristics length in predicting the peak whistling Strouhal Number.**

***Index Terms*—computational fluid dynamics, acoustics, sound generation, noise, whistling, riser, corrugated pipe, flow induced acoustics, pipe bending, vibration**

I. Introduction

Internal flow induced acoustics is the study of the acoustic behavior; such as noise and whistling when the flow passes through a pipe at high pressure and high velocity. This acoustic behavior is commonly noticed in corrugated pipe that provides both local stiffness and global flexibility in facilitating fluid flows [1].

In the industry, corrugated pipes are commonly used in offshore flexible riser system to aid the transportation of natural gas from the seafloor to floating drilling facilities above the sea. Under uneven seabed conditions, the flexibility of the corrugated pipes eliminates the needs to install complicated rigid pipeline. Nevertheless, one of the issues arise is the severe noise problem when fluid flows through these pipes. This phenomenon is commonly known as whistling. Whistling is an environmental nuisance and it can cause side effects to the health of the personnel working on the oil platform.

Besides of severe environmental noise problem, flow-acoustic coupling observed in corrugated pipes can cause a significant structural vibration due to flow-acoustic-structure interaction. Vibrations thus induced would result in severe damage to machinery and offshore pipelines that use corrugated pipes [2].

Over the years, researches have been carried out to investigate the design parameters of corrugated pipe towards its flow induced acoustics phenomenon. This paper extends the research into evaluating the effect of bending on whistling behavior induced in corrugated pipe.

II. Literature Review

Generally, the whistling behavior of the corrugated pipe is due to the vortex shedding around its cavities. The viscous forces of fluid are negligible in the main flow, but become significant within thin boundary near to the pipe wall. This results in the formation of shear layers that separate the high speed and low speed flow region. These shear layers are unstable and sensitive to acoustic perturbations. These perturbations trigger the roll-up of the shear layer into vortices [1]. As shown in Fig. 1 below, the unsteady vortex shedding exerts an unsteady force on the wall of the pipe. This unsteady force acting on the wall will then create a reaction force, which is identified to be the source of sound for the whistling phenomenon [3].

In describing the whistling phenomenon, Strouhal number is the most commonly used dimensionless parameter that is defined as

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$$Sr = \frac{fL_C}{U} \tag{1}$$

where f is the frequency of oscillation, L_c is the characteristic length and U is the average flow velocity inside the corrugated pipe. The most suitable L_c for Strouhal number calculation in corrugated pipe is given by the summation of cavity width (W) and the upstream edge radius (r_{up}), as illustrated in Fig. 2 below [3]. Experiments have proven that characteristic length composed of (W + r_{up}) has the smallest scatter of peak-whistling Strouhal number ($Sr_{p\text{-}w}$) that reflects the maximum fluctuation in sound pressure level generated [4]. Currently, researchers still working on defining and refining the characteristics length in the Strouhal Number. As mentioned by Matevž Dular1 and Rudolf Bachert, there are many interpretations of the parameters that are included in its definition, which leads to a confusion and, as this study shows, to its uselessness [8].

In an experiment conducted earlier, it is found that a mild bending does not have significant effect on the noise production. This is applicable when the bending radius is much larger than the diameter of the corrugated pipe [5]. Therefore, further analysis on the corrugated pipe bending will be performed to analyze the whistling behavior generated. This allows a prediction of the changes in Strouhal number to avoid the critical flow velocity range that can cause whistling issue.

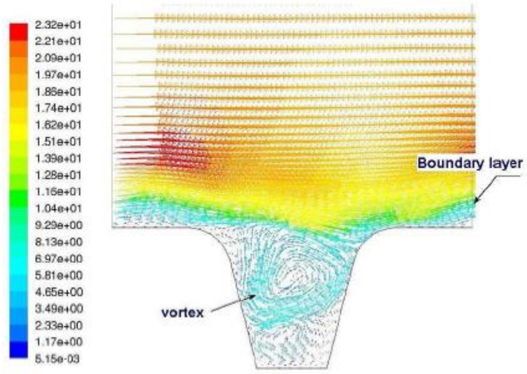

Figure 1. Vortex shedding around the cavity of corrugated pipe.

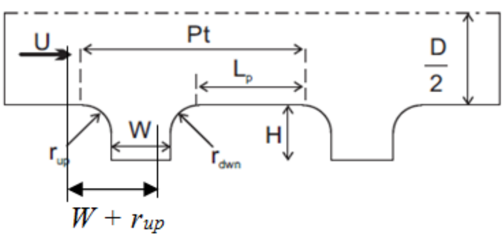

Figure 2. Characteristic length of strouhal number calculation using (W + r_{up}).

III. METHODOLOGY

This research will be carried out using 2-dimensional (2D) numerical simulation in computational fluid dynamics (CFD) software, which is Fluent 6.3. A single cavity corrugated pipe as shown in Fig. 3 is used to perform the simulation since whistling behavior is a local effect and thus, the interaction between cavities are assumed neglected.

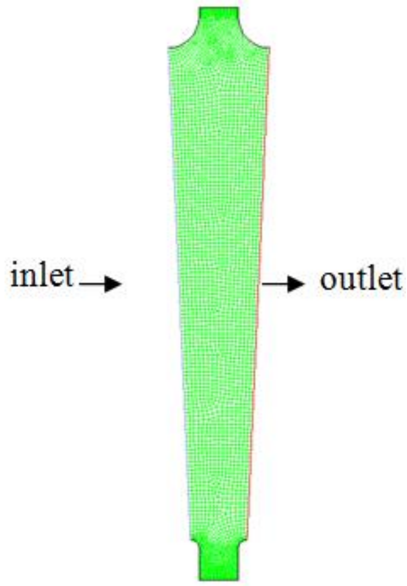

Figure 3. Single cavity of bent corrugated pipe with tension at the upside and compression at the downside.

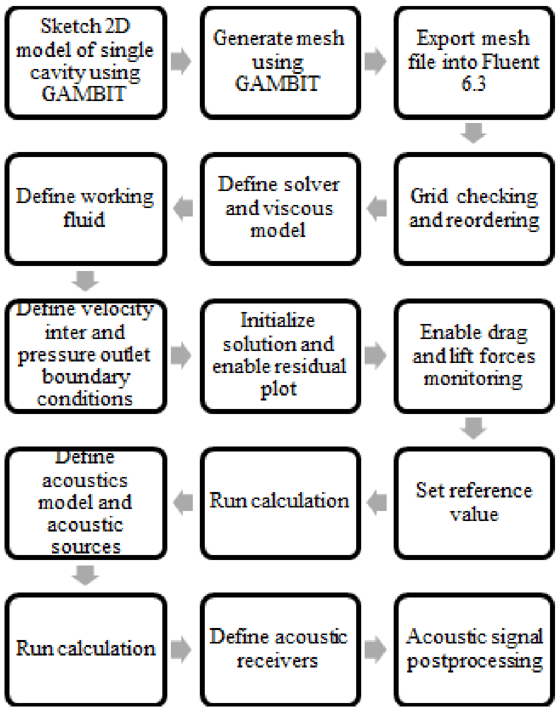

Figure 4. Process flow chart for 2D numerical simulation.

Fig. 4 summarizes the procedures in performing the numerical simulation. The simulation is performed using Large Eddy Simulation (LES) as the viscous model to simulate the turbulent flow under transient condition. As it is noted that turbulence modeling such as LES predicts [6], [7] the resonance frequencies reasonably well compared to measurements. The working fluid used is confined to air at 15°C.

Table I below summarizes the unbent corrugated pipe configurations applied in this research. In order to evaluate the bending effect, the upside and downside of the cavity are varied in a certain ratio to represent the pipe bending angle and tabulated in Table II below.

TABLE I. CORRUGATED PIPE CONFIGURATIONS

Cavity Width, W	4 mm
Cavity Depth, H	4 mm
Upstream Edge Radius, r_{up}	2 mm
Downstream Edge Radius, r_{dwn}	2 mm
Plateau Length, L_p	0 mm
Corrugated Pipe Diameter, D_p	49 mm
Fluid Density	1.225 kg/m^3
Fluid Viscosity	1.7894 ×10^{-5} kg/m.s
Fluid Velocity	13.61 m/s

TABLE II. CORRUGATED PIPE BENDING ANGLE AND COMPRESSION RATIO

Angle, θ [°]	Compression Ratio, CR
0	1.00
22.5	1.07
45	1.14
67.5	1.25
90	1.32
112.5	1.45
135	1.64
157.5	1.78

IV. RESULTS AND DISCUSSION

In order to avoid confusion on the characteristic length used in computing the peak-whistling Strouhal number (Sr_{p-w}), the subscript in Sr_{p-w} is replaced with the respective characteristic length.

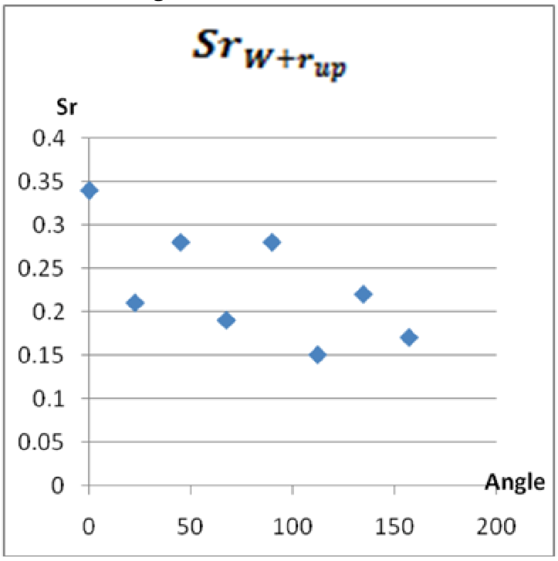

Figure 5. Graph of $Sr_{W+r_{up}}$ against bending angle

Fig. 5 shows the scattered plot of $Sr_{W+r_{up}}$ versus different bending angle. It is noticed that the bending angle has an effect on the Sr_{p-w} using $(W + r_{up})$ as characteristic length, such that it appears to be fluctuating within a large range between $0.15 \leq Sr_{W+r_{up}} \leq 0.34$.

Since it is known that the pipe bending will have an effect on the Srp-w, the compression ratio is taken into consideration in the characteristic dimension to define the whistling behavior. A constant (A) is proposed to be used as a factor to represent the compression ratio in the characteristic dimension, such that

$$A = \frac{360^o}{360^o - \theta} \tag{2}$$

where θ is the bending angle. This constant A also coincides with the compression ratio of each bending angle as shown in Table II above, thus it can be a good representation of the compression ratio in characteristic dimension.

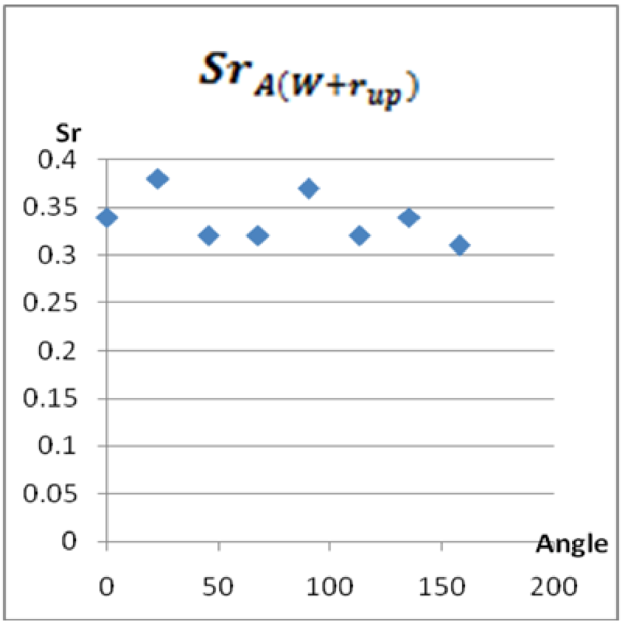

Figure 6. Graph of $Sr_{A(W+r_{up})}$ against bending angle

Fig. 6 shows the results obtained when the characteristic dimension is multiplied with constant A. The $Sr_{A(W+r_{up})}$ shows a smaller variation as compared to Fig. 5, which are within $0.31 \leq Sr_{A(W+r_{up})} \leq 0.38$. Therefore, the constant *A* can be a good representation of the bending effect in the characteristic dimension to describe the whistling behavior of corrugated pipe. Furthermore, the characteristic dimension remains as $(W + r_{up})$ when the pipe is not bent, since constant A is equal to 1. This eventually coincides with the previously established characteristic dimension [3].

V. CONCLUSION

Previous research works have only been carried out in straight pipe position where it does not meet the purpose of the function of the corrugated pipe. The corrugated pipe is supposed to serve the bend function as its global flexibility behavior. The previous proposed modified characteristics length was not able to obtain a consistent $Sr_{w+r_{up}}$ when it is applied to a bended corrugated pipe. Hence, the bending constant, **A** has been proposed to resolve this issue in this paper. As the bending of corrugated pipe is found to have a significant effect on the $Sr_{p\text{-}w}$ when $(W + r_{up})$ is used as the characteristic dimension. Therefore, The bending effect should be taken into consideration in the characteristic dimension by multiplying with a constant A:

$$A = \frac{360^o}{360^o - \theta} \tag{3}$$

It is proven that $A(W + r_{up})$ is a better characteristic dimension than $(W + r_{up})$ as the use of $A(W + r_{up})$ in the calculation of Strouhal number led to smaller variation. This allows a better design or selection of corrugated pipe to meet the specific flow condition in order to avoid the whistling phenomenon. The proposed characteristic length is not only applicable to the bended corrugated pipe but it is still applicable to apply on the straight corrugated pipe and the constant A will be equal to 1 if there is no bend on the pipe. Hence, this has enhance the usability of the modified characteristics length for the peak whistling Strouhal Number.

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