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Vibration-Based Leak Detection Approach in a 90-Degree Pipe Elbow: A Computational Study

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Abstract

The present paper numerically explores Vibration-Based Leak Detection (VBLD) method based on Fluid-Structure Interaction (FSI) to predict leakages in pipelines. Earlier studies primarily investigated the VBLD approach in a straight small-diameter water loop system pipes using laboratory experiments. The current work aims to extend these investigations combining Computational Fluid Dynamics (CFD) with Finite Element Analysis (FEA) in ANSYS™. The paper lays out a numerical approach of the VBLD method to predict the changes in vibration signals between normal operating conditions versus leakages. This is carried out for a 90-degree pipe elbow with applications in the oil and gas industry. Firstly, changes in forces experienced by pipe walls resulting from a leakage (modelled as an additional outlet) and consequently changes in fluid behaviour are predicted using CFD. Secondly, the CFD results are coupled to FEA to model structural responses of the pipe walls to the different forces and this in turn allows the changes in vibration signals to be measured. This numerical approach based on FSI and incorporating the VBLD method offers a cost-effective and complementary early-detection tool to use out in the field together with vibration monitoring devices.

Key words: *VBLD, CFD, Turbulence modelling, pipe flow, FEA, FSI*

1. Introduction

The VBLD method helps detect early signs of leakages in pipeline systems in the field by using accelerometers to measure changes in vibration signals resulting from changes in flow behaviour induced by leakages and other abnormalities. The vibration sensors are attached to the outer pipe walls and connected to computer software to record and analyse vibration data. The VBLD approach has been experimentally shown [1]–[5] to be reliable to detect onset of leakages and is popular because of its non-invasive nature.

There are limited numerical studies of the VBLD method [6], [7]. These focused on flows in straight pipes. The current study aims to add to the field of research body by investigating the application of VBLD to predict leakages in 90-degree pipe elbows where the flow regime is more complex and challenging compared to straight pipes. The fluid forces on the pipe wall and corresponding structural responses to various flow conditions (normal versus presence of leakage) are numerically predicted using FSI: coupling CFD with FEA. The structural responses generate vibration signals which could be used in conjunction with field monitoring devices for early detection of leakages. FSI simulations are very useful for modelling and understanding complex interactions between fluids and solids especially since analytical solutions are impossible to compute [8] and recent developments in numerical methods and increased computational power have made it easier to model FSI processes [9].

2. Fluid Structure Interaction (FSI) Strategy

In Part 1, Reynolds Stress Model (RSM) turbulence closure scheme is employed to model the turbulent pipe flow in order to predict the fluid forces exerted on the pipe walls. The CFD results are then exported and coupled with FEA in Part 2 to model the pipe wall structural response to the fluid forces in what is termed as Flow-Induced Vibration (FIV). The changes in vibration signal resulting from alterations in fluid behaviour due to the presence of a leakage, for example, is the principle behind the VBLD approach. The steps are captured in the research workflow illustrated in Figure 1.

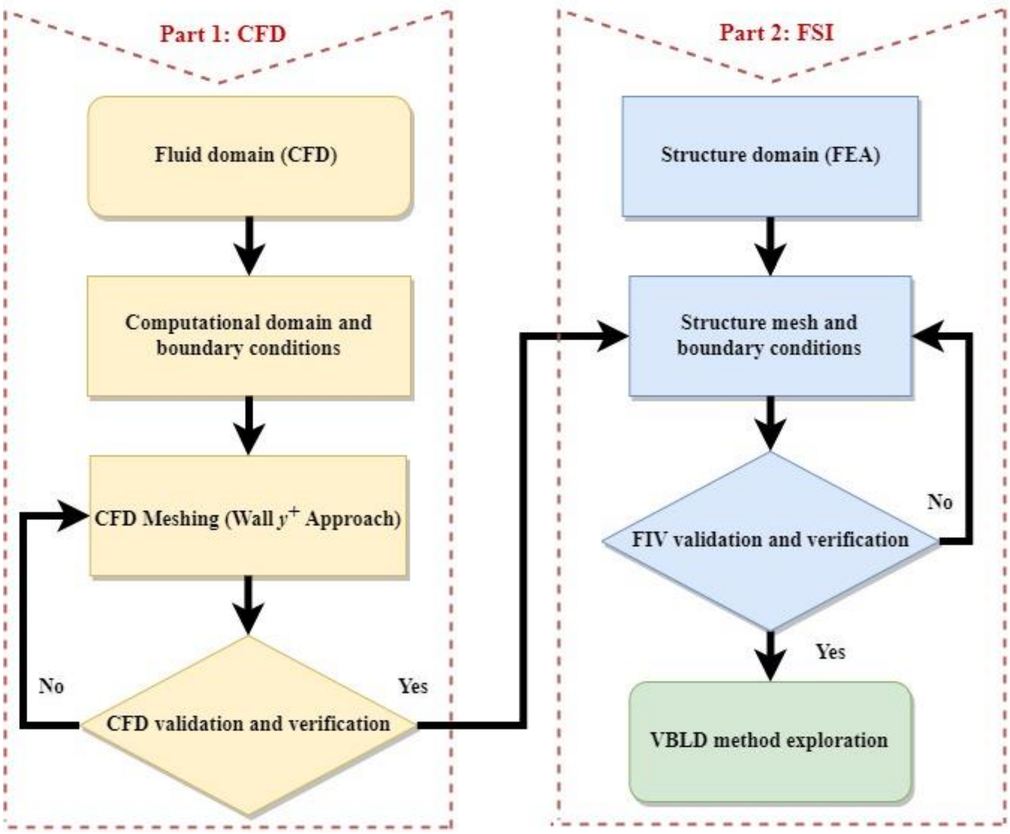


Figure 1: The research workflow

The CFD study is detailed in a recently published paper by the same authors [10] which discusses the wall y^+ approach to guide selection of appropriate mesh and turbulence closure schemes, balancing computational cost and accuracy.

One-way FSI coupling approach is employed due to negligible deformations expected in the pipe walls. This is discussed in previous works [11]–[13]. The pressure field is computed from CFD and transferred to the structural domain to carry out FEA simulations.

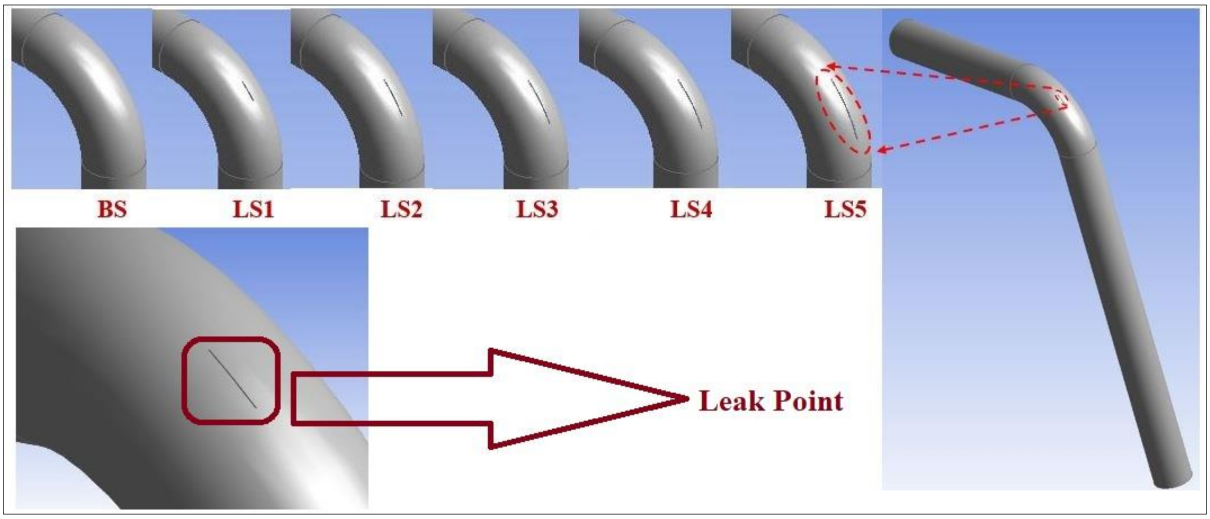


Figure 2: Leak points and sizes including case IDs.

Figure 2 illustrates the six different leak cases investigated in the present study starting with no leak (BS case) and moving through increasing leak sizes: LS1 - LS5. These are also listed in Table 1 below. The leak points are modelled as outlets in the computational domain and their corresponding mass flow rates obtained using CFD simulations.

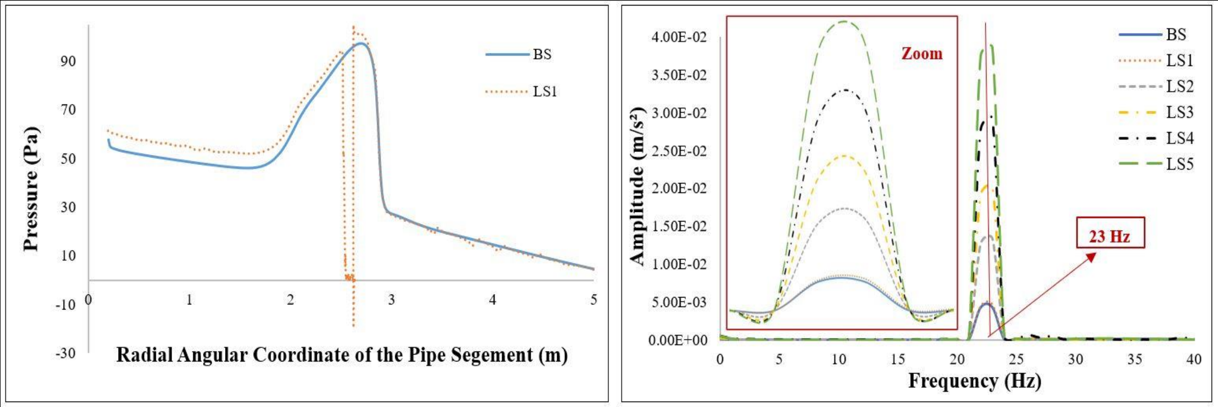
Table 1: All pipe state simulation cases (free leak and leaks occurrence).

Case ID	Leak Size	Leak Mass Flow Rate (Kg/s)
BS	No Leak	0.000
LS1	0.002m X 0.1m	0.051
LS2	0.002m X 0.2m	0.148
LS3	0.002m X 0.25m	0.175
LS4	0.002m X 0.30m	0.206
LS5	0.002m X 0.35m	0.245

As expected, the mass flow rate increases as the leak size grows. Literature [14] reports that leakages are more likely to occur at the centre of the elbow due to drops in pressure, centrifugal forces, and changes in flow field behaviour in that region.

3. Numerical results

Figure 3 (a) compares the pressure distribution along the pipe wall for a normal operating condition (BS) versus a leak case (LS1). A significant and localised pressure drop is observed around the mid-point of the pipe elbow segment where the leak is situated. The sudden fluctuation in pressure induces a noticeable change in the vibration signal as can be seen in Figure 3 (b) and explains the term FIV. Figure 3 (b) also plots the vibration signals of the remaining cases investigated and this shows that the vibration amplitude increases with increasing leak sizes. For instance, although the first leak (LS1) is very small, an alteration in the vibration signal is detectable when compared with the normal operating condition (BS). The changes in vibration signal for the remained cases are clearer due to fact of larger leak sizes combined with greater pressure drop magnitudes (vibration force). The vibration peaks that represent all scenarios occurred in the same frequency (23 Hz) because there was no change in flow field behaviour or the structure features (pipe segment) apart from the leak point which is assumed in the same place for all cases.



(a) Fluid domain in a form of pressure (CFD)

(b) Structure domain in a form of vibration (FEA)

Figure 3: (a) Pressure distribution in the pipe wall for normal operating condition (BS) versus a leak case (LS1). (b) the vibration signals of the remaining cases.

4. Conclusions

The current research uses FSI in conjunction with the VBLD method to investigate leakages in 90-degree pipe elbows. A noticeable pressure drop is observed at leak points and these manifests as changes in vibration signal which can easily be monitored externally using vibration sensors offering a cost-effective early detection tool in the field.

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