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Review

Two-phase flow induced vibration in piping systems

Shuichiro Miwa [a,*], Michitsugu Mori [a], Takashi Hibiki [b]

[a] Graduate School of Engineering, Hokkaido University, Kita 13 Nishi 8, Kita-ku, Sapporo 060-8628, Japan
[b] School of Nuclear Engineering, Purdue University, 400 Central Drive, West Lafayette, IN 47907-2017, USA

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ABSTRACT

Hydrodynamic force acting on the structures, pipes and various forms of objects can generate destructive vibrations, and could cause acoustic and noise problems in industrial machineries. Such phenomenon is known as Flow-Induced Vibration (FIV), and it can obstruct smooth operation of engineering devices and could potentially cause serious consequences like system failures. The subject has become increasingly important problem in engineering industry in recent years for both single-phase and multi-phase flow cases, as well as for various flow orientations including external and internal flows. Present review paper summarizes the historical background of FIV research and how the phenomenon has been classified in both industrial and academic fields, particularly focusing on the progress of two-phase FIV research. Special attention was paid to the subject of internal two-phase FIV generated at industrial piping systems two-phase flow regimes. Based on the extensive and comprehensive literature survey, most up-to-date progress of the research in the area of two-phase flow induced vibration in piping system are thoroughly reviewed and presented in this article.

1. Introduction

In recent years, two-phase flow induced vibration (FIV) has been given increasing attention in various engineering fields including petroleum pipelines, power and processing plants, heat exchangers, as well as in the nuclear power plant components (Altstadt et al., 1995; Anagnostopolous, P., 2002; Blevins, 1979, 1990; Cong et al., 2014; Fujita, 1990; Hara, 1975; JSME, 2003; Konno and Saito, 1985; Laggiard et al., 1995; Miwa et al., 2014a; Pettigrew and Taylor, 1994; Weaver et al., 2000). In these applications, knowledge of gas–liquid two-phase flow induced force fluctuation magnitudes and its predominant frequency is paramount for designing the safely operable engineering systems and avoiding structural damage that may be caused by fluid–solid interaction.

The terminology, “FIV”, was first introduced by Robert Blevins in 1977. He was the first to classify the phenomena according to hydrodynamic and structural dynamics, and has developed a fundamental road map to analyze the problem (Blevins, 1990). Based on his classification, fluid dynamic mechanisms responsible for FIVs are categorized according to steady and unsteady conditions (Fig. 1). The categories of FIV phenomena are coupled with structural dynamics through hydrodynamic force acting on the structure. When the hydrodynamic force is acted on the structure surface, it will undergo deformation. The deformed structure will then react and apply the opposite force against fluid based on its material properties, such as elasticity, natural frequency, damping parameters, and so on. During the process, flow is disturbed and direction and magnitude of the hydrodynamic force may change considerably. Consequently, FIV is generated due to the linkage of force fluctuations between these two dynamic forces (Blevins, 1990).

In order to predict FIV phenomena, separate models for fluid and structural dynamics can be developed, and they are coupled with hydrodynamic and structural force terms. Models available for structural dynamics are near-linear for most cases and can be modeled as linear-oscillator. In contrast, fluid dynamic models can be more complicated in general since it possesses inherently nonlinear and multi-degree-of-freedom behaviors. Due to such reason, fluid dynamic models of FIV must be always verified by the experiment. Models for structural response to fluid flow can be developed from the database of physical law and experimental data.

Contrary to the single phase flow case, mechanisms of two-phase flow-induced vibration can be quite different due to complex motions/interactions at phase boundary, differences in material properties (density, surface tension, viscosity etc.), and phase change process via energy transfer/generation. General

* Corresponding author.
E-mail address: smiwa@eng.hokudai.ac.jp (S. Miwa).

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Nomenclature

a_i	Interfacial area concentration [m^{-1}]
a	Sound velocity [m/s]
A	Cross section area [m^2]
A_{eff}	Effective cross section area of liquid slug [m^2]
c	Speed of sound in liquid [m/s]
c_p	Specific heat at constant pressure [kJ/kg K]
c_v	Specific heat at constant volume [kJ/kg K]
C_0	Distribution parameter [−]
D	Pipe diameter [m]
D_H	Hydraulic diameter [m]
D_{Sm}	Sauter mean diameter [m]
f	Frequency [Hz]
f_α	Void propagation function
F	Fluctuating force [N]
Fr	Froude number [−]
G	Mass flux [$kg/s/m^2$]
g	Gravity [m/s^2]
i	Imaginary number
j	Superficial velocity [m/s]
l	Elbow length [m]
L_f	Liquid slug length [m]
L_g	Bubble length [m]
p	Pressure [Pa]
R	Curvature radius [m]
Re	Reynolds number [−]
t	Time [s]
u	Velocity [m/s]
We	Weber number [−]
x	x-axis
z	z-axis

Greek symbols

α	Void fraction [−]
β	Volumetric quality [−]
δ	Liquid film thickness [m]
θ	Elbow curvature angle [degree]
κ	Adiabatic index [−]
μ	Viscosity [−]
ξ	Fraction of liquid film thickness per pipe ID [−]
ρ	Density [kg/m^3]
τ	Shear stress [$kg/m\ s^2$]
σ	Surface tension [N/m]

Subscripts

f	Liquid phase
g	Gas phase
gs	Group-1 in liquid slug unit
k	k-th phase
in	Test section inlet
out	Test section outlet
t	Two-phase
1	Group-1
2	Group-2
2φ	Two-phase

classification of two-phase flow induced vibration, created based on JSME handbook (JSME, 2003) as well as available literature (Pettigrew and Taylor, 1994), is shown in Fig. 2.

The first category, "momentum fluctuation", includes FIV caused by the density difference between two phases, and large FIV is generated due to the change in flow direction and the impact force of two-phase mixture acted on piping component structure such as elbows and T-junctions (JSME, 2003). The second category, "thermal-hydraulic vibration associated with phase change", induced from the nature of two-phase flow which involves phase change due to the energy transfer through interfacial boundary and/or energy generation within the phase. Such phenomena, including boiling and condensation, involve highly unstable and oscillatory behaviors, and easily promote FIV within two-phase flow systems. The third category, "bubble-induced vibration" is due to the dynamics of various shapes and sizes of bubbles that

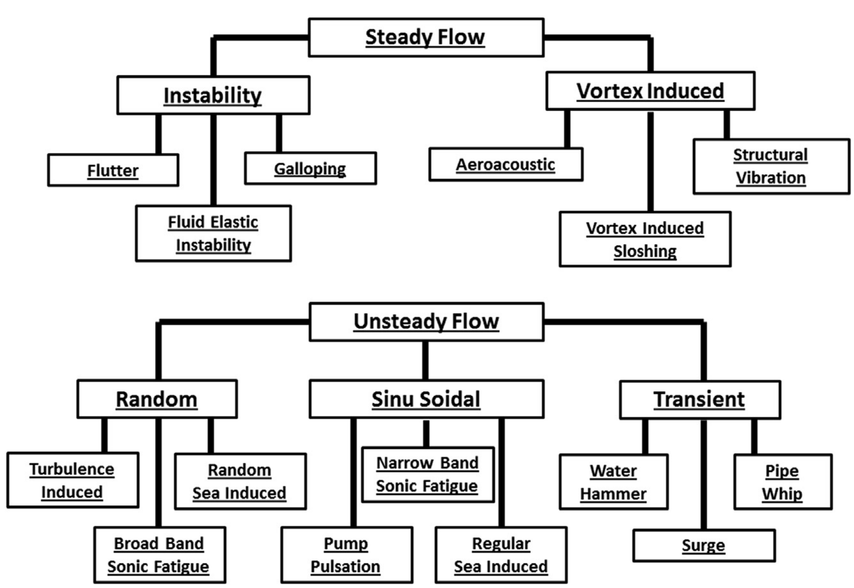

Fig. 1. Classification of flow induced vibration (Blevins, 1990).