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Two-phase damping for internal flow: Physical mechanism and effect of excitation parameters

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ABSTRACT

Two-phase flow induced-vibration is a major concern for the nuclear industry. This paper provides experimental data on two-phase damping that is crucial to predict vibration effects in steam generators. An original test section consisting of a tube subjected to internal two-phase flow was built. The tube is supported by linear bearings and compression springs allowing it to slide in the direction transverse to the flow. An excitation system provides external sinusoidal force. The frequency and magnitude of the force are controlled through extension springs. Damping is extracted from the frequency response function of the system. It is found that two-phase damping depends on flow pattern and is fairly proportional to volumetric fraction for bubbly flow. Measurements are completed by the processing of high-speed videos which allow to characterize the transverse relative motion of the gas phase with respect to the tube for bubbly flow. It is shown that the bubble drag forces play a significant role in the dissipation mechanism of two-phase damping.

1. Introduction

Two-phase flow induced vibration in steam generators is well documented in the literature (Pettigrew and Taylor, 1991; Weaver and Fitzpatrick, 1988; Au-Yang et al., 2000). Extensive experimentations have been carried out over the last forty years to get a better hand on the several excitation mechanisms involved, such as quasi-periodic forces or fluidelastic instability. Review and design guidelines for heat exchangers constructors have been proposed, improving nuclear power plant safety and reliability. The duality of two-phase flows from a vibration point-of-view lies in the fact that they bring about destructive phenomena while causing significant damping on the structure. Damping is a crucial input parameter to predict vibration effects in steam generators. However, the nature of the damping is not well understood. A better knowledge of the physical mechanism involved would lead to improved modeling of vibration effects in the near future.

The first experimental studies on two-phase damping were performed by Carlucci (1980) and Carlucci and Brown (1983). For a cylinder confined in axial two-phase flow, they found that total damping is strongly dependent on void fraction. Moreover, the two-phase damping component is much higher than the damping due to fluid viscosity for single-phase flow. It can reach up to 3% (Hara and Kohgo, 1985) derived an analytical model for a cylinder confined in axial-two-phase flow. They modeled the gas phase as columns having no mass nor stiffness. Cylinder and gas motions were described by beam equations, coupled by the fluid forces. Coupling coefficients were extracted from potential flow theory. The eigenvalue problem was solved to find the damping coefficients which compared well with the experiments. However, this approach does not provide a physical explanation for the mechanism. More recently, Uchiyama (2003) proposed a numerical

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simulation, also for a cylinder confined in two-phase flow, assuming a bubbly flow. Damping values of the same order of magnitude as in Carlucci and Brown (1983) were observed. However, the damping ratio goes down to zero for void fractions higher than 60%, which is not verified experimentally. This fact raises questions about the applicability of numerical codes for high void fraction. Indeed, these codes assume bubbly flow but usually do not take flow pattern transitions into account. Nevertheless, Uchiyama (2003) explains damping by “the phase lag of the drag force acting on the cylinder behind the cylinder displacement”. This introduces a notion of relative displacement inherent to the two-phase mixture.

Two-phase damping has also been measured for cross-flow. It is undoubtedly the most important flow configuration since most vibration mechanisms are critical in the U-bend region of the steam generator. Semi-empirical relations for design purposes are given by Pettigrew and Taylor (2004). They compiled a considerable amount of data to identify the most influent parameters. It was shown that flow velocity and tube frequency have minor influence, contrary to confinement and surface tension. Therefore, several phenomena are potential dissipative mechanisms that could be responsible for two-phase damping. Mainly, flow structure, relative motion of gas phase and liquid phase and coalescence/breakup of bubbles are suspected.

Other studies were steered towards the influence of fluid properties on two-phase damping at Ecole Polytechnique of Montreal. These were performed for internal axial flow on clamped–clamped tubes. This configuration is less interesting from a practical point-of-view since in CANDU nuclear plants, pressurized heavy water is supposed to be almost liquid inside steam generator tubes. Still, it is interesting to notice that two-phase damping vs void fraction curves are oddly the same for the three flow configurations reported: annular, internal axial and cross-flow (see Carlucci and Brown, 1983; Gravelle et al., 2007; Pettigrew and Taylor, 2004 respectively). This suggests that the mechanism involved is the same for each case. From a design point-of-view, internal axial flow configuration is the simplest. Gravelle et al. (2007) reported damping measurements in 20 mm tubes. The decrease of two-phase damping at the transition between bubbly and slug flow is explained by the decrease of interface surface area when slugs appear. This is somehow contradictory with Pettigrew and Knowles' (1977) observations: ζ was found to increase with surface tension σ. A possible explanation given was that bigger bubbles are more prompt to dissipate energy. This work was pursued by Béguin et al. (2009b) who tested several air–liquid mixtures, in order to assess the effect of viscosity and density on two-phase damping. Béguin et al. (2009a) also performed two-phase damping experiments with rigid spheres in sedimentation in stagnant liquids. It appeared that density difference between phases has a major effect, contrary to the viscosity. Damping values with rigid spheres were somehow smaller than in air–liquid mixtures by a factor 2, but proportionality with respect to interface surface area was confirmed. For large number of spheres, interaction occurring between spheres (e.g. onset of coalescence in case of a gas phase) seems to modify this trend. Béguin et al. (2009a) also presented a 2D model of a bubble in an oscillating tube filled with liquid, and solved the Navier–Stokes equations analytically. They showed that viscous dissipation due to the presence of a bubble can be related to the relative motion of the bubble with respect to the structure.

These conclusions motivated the design of a new test section which would not only allow damping measurements but also let us observe the gas phase behavior. Also, damping values have only been extracted at the natural frequency of the considered system so far. Thus, the objective of this project is to measure two-phase damping accurately, so as to relate it to the relative motion of the gas phase that we also measured.

In the next section, a new test rig is presented. It allows to command excitation parameters, such as frequency, on a structure subjected to internal two-phase flow. This leads to interesting information on the nature of the two-phase flow energy dissipation. Then, the experimental parameters involved in the system are described. In Section 4, the technique to extract the two-phase damping component of the oscillating structure is presented. Results on damping and the relation with flow patterns are described afterwards. Then, in Section 6, the motion of the gas phase is characterized with the processing of high-speed videos. It is related to the two-phase values through an analytical model of the forces exerting on the bubbles in Section 7.

2. Experimental setup

The experimental setup is composed of several features that will be described separately for the sake of clarity.

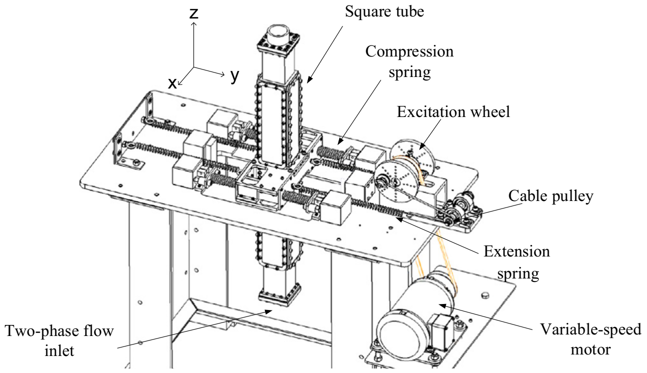

Fig. 1. Test section (pipe system not shown).