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Hydroelastic response of marine risers subjected to internal slug-flow

Ioannis K. Chatjigeorgiou [a,b]

[a] School of Naval Architecture and Marine Engineering, National Technical University of Athens, Greece
[b] School of Mathematics, University of East Anglia, Norwich, UK

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ABSTRACT

It is the purpose of this study to investigate the dynamic behaviour of catenary pipelines for marine applications, assuming the combined effect of harmonic motions imposed at the top, and the internal slug-flow. The analysis is based on the assumption of a steady slug-flow inside the pipe that results in a relatively simplified model for the formulation of the internal flow. The slug-flow model is described using several assumptions and empirical correlations which attempt to reveal the ill-understood and concealed properties of the slug-flow. The pipeline dynamics are investigated in the two dimensional space omitting the out-of-plane vibrations. The system of differential equations is generic and accounts for the steady effect of the internal liquid as is conveyed through the structure.

The two models, those of the internal slug-flow and the pipeline's dynamical model, are properly combined through the internal flow terms of the dynamic equilibrium system. The solution provided is achieved using a frequency domain technique which is applied to the linearized governing set. The effect of the slug-flow is assessed through comparative computations with and without internal flow effects. The conclusions are drawn having the structure excited under axial and normal motions paying particular attention to the variation of the dynamic components along the complete length of the pipeline.

1. Introduction

Marine risers are long pipelines which are used to convey liquids from the source located at the sea bottom, up to the floating host facility. Due to the hostility of the environment, in which they operate, they should be considered continuously moving. The dynamic behaviour is a major concern for their structural integrity and it is influenced by i) the motions induced at their top due to the displacements of the floating structure, which is continuously subjected to external excitations (wind, waves and currents), ii) wave and current loading on the immersed pipelines, iii) strongly non-linear phenomena such as high frequency oscillations induced by vortex shedding effects or compression loading at the touch down zone and iv) the internal flow effects.

For long pipelines for marine applications, such as risers, the internal flow is typically formulated using the so-called *plug-flow* model, which considers that the velocity profile of the conveyed liquid is constant throughout the pipe [1,2]. When the subject of investigation is the coupled dynamic behaviour of the structure subjected to imposed motions and the effects of the internal flow, the plug-flow concept significantly simplifies the combined formulation as the internal flow terms are directly incorporated into the structural dynamic model [3,4].

Aside from the very simplified plug-flow model, there have been studies that complicate the problem assuming more sophisticated formulations to describe the internal stream, such as assuming a flow that relies on the potential theory [4–8] or a fully turbulent behaviour [9]. Chatjigeorgiou [4] showed that the effects of a potential flow model that assumes inviscid, incompressible fluid and irrotational flow are literarily similar to those due to the plug-flow approximation. The same holds for the turbulent model that assumes fully turbulent behaviour inside the pipe as well [9]. Hence, it could be safely claimed that the plug-flow approach is a good and robust engineering approximation, which, in addition, allows fast computations. Nevertheless, it should be noted that the aforementioned remarks assume a single phase flow, that of the liquid, that occupies the whole internal space of the pipeline throughout its length. Under this condition, the effect of the internal flow on typical riser configurations is limited as it does not change significantly the particulars of the response when the structure is subjected to top imposed excitations. In fact, the major source that amplifies the internal loading components comes from the forced motions. Chatjigeorgiou [4] reported that the dynamic behaviour in the plane of reference (in-plane vibrations) remain literarily unchanged, while only the out-of-plane behaviour is practically

E-mail address: chatzi@naval.ntua.gr

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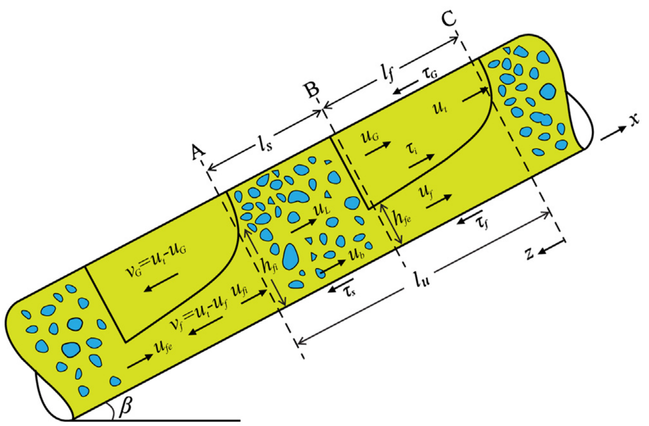

Fig. 1. The geometry of the slug-flow.

affected due to the Coriolis effects that introduce an additional damping component into the system.

In contrast, it has been reported that a two-phase internal flow model could lead to significant variations as regards the dynamics of marine pipelines. Analogous flow patterns can generate rapid changes of the mass distribution and pressure fluctuations along a riser, which may lead to vibrations. These vibrations combined with vibrations generated by other environmental loads will produce time varying stresses and consequently lead to accumulation of fatigue damage, excessive bending or even local buckling. Moreover, vibrations induced due to the internal flow could start resonating with the vibrations of the structural system itself. Slug-flow models are now being incorporated into the features of respected commercial software dealing with the dynamics of risers and pipelines [10].

Different types of two-phase flow in pipes are designated as "plug-flow with bubbles", "slug-flow", "churn-flow", "annular flow" and "wispy annular flow". The most important type of loading exerted on marine riser type structures due to internal two-phase flow arises from the *slug-flow* model [11,12]. In the two-phase slug-flow, the gas phase exist as elongated bubbles separated by the liquid phase, the slugs. The slugs occupy the whole cross sectional area of the pipe along the slug zone. Typically, the slugs contain bubbles as well in contrast with the liquid film, i.e. the liquid zone below the elongated gas bubble (see Fig. 1). As the liquid is transported through the pipe, the slugs are formed continuously and in the unsteady condition may change location and volume.

The two-phase slug-flow is typically correlated with applications involving heat and mass transfer in pipes, although the former is not an issue of concern in the present study. The majority of the existing studies concern fixed and straight pipes which may be inclined. One of the first studies on the subject that assumed a catenary configuration of the pipeline and tried to provide answers to its dynamic behaviour subjected to both external excitations and the internal slug-flow was that due to Patel and Seyed [13]. This study however, relied on an extremely simplified model for the internal slug-flow. The importance of the slug-flow on the dynamics of riser type structures for marine applications has been identified only recently (e.g. [11,12]) and there is an obvious lack on information on the subject.

Regarding the way slug-flow is approximated, irrespectively whether the pipe is excited externally or not, one may choose to assume the steady [14] or the unsteady formulation [15–18]. The latter is formulated via the continuity and momentum equations, separately for the liquid and the gas phases, which form a strongly nonlinear system that can be treated only in the time domain. An alternative and adequately accurate method to formulate the associated two-phase flow is to assume a steady slug-flow. For a thorough analysis on the particulars of the steady slug-flow the reader is referred to the seminal paper of Taitel and Barnea [14]. Regardless the model that is being considered, the problem of the slug-flow inside pipes is very complicated. Many issues are uncertain and therefore both concepts (steady and unsteady) rely practically on the same approximations which are frequently represented by empirical rules. The latter are based on the post-processing of measurements and observations. Relevant examples of concealed topics include, but not limited to, whether the flow is laminar or fully turbulent, the computation of the friction forces between the liquid and the wall, the gas and the wall and on the interface (the free-surface) between the liquid and the gas, the surface tension on the interface, the containment of bubbles in the slug zone (which accordingly defines the liquid hold-up in the zone) and the velocity of the bubbles, to mention a few. The aforementioned challenges must be properly addressed irrespectively whether the pipe is fixed or moving. Clearly, the situation is much more difficult when the latter condition occurs, such in marine risers, which perform continuous oscillations due to the motions imposed at their top by the host facility. In such a case, the structural dynamical system of the pipeline, which typically has a curved (catenary) configuration, must be combined with the slug-flow model, which constitutes itself a different dynamical system governed by a discrete set of differential equations.

Marine risers are subjected to a variety of impacts in their operational environment. Of paramount importance are the forced oscillations due to the displacements of the host facility. The axial components of the excitations in particular may lead to local buckling effects and parametric displacements associated with nonlinear resonances [19]. In this context, the task of the present study is to provide a solution of the combined dynamic problem of a catenary pipeline that conveys a slug-flow and in addition is excited by external factors which are represented by imposed motions applied at its top terminal point. The main goal is to reveal the details of the effect of the internal slug-flow on the dynamics of the pipeline and how it modifies its global dynamic behaviour. The structural dynamics problem is properly linearized in order to allow processing in the frequency domain, assuming harmonic imposed motions and alike responses. The linear dynamic equilibrium system of the pipeline is combined with a steady slug-flow model. To this end, the most complete formulation, that of Taitel and Barnea [14], was employed. In fact, most of the information and the assumptions used in the present were taken from reference [14]. The two models, those of the dynamics of the pipe and the slug-flow, are properly combined through the relevant terms of the inner flow components which are incorporated into the pipe's dynamical system. The global approach accounts for the variation of the liquid mass and its velocity inside the pipe, both in the liquid film and in the slug zones, as well as for variable inclination of the catenary.

The paper is organized as follows: Section 2 describes the steady slug-flow model that has been adopted, while the structural dynamic system of the catenary pipeline is outlined in Section 3. Information on how the two models are combined are given in Section 4. Relevant computations are shown in Section 5 followed by Discussion.

2. The model of the steady slug-flow

The geometry of the steady slug-flow is depicted in Fig. 1. The two phases of the flow, the liquid and the gas are propagating inside the curved pipe with constant inner diameter D along the generalized Lagrangian coordinate s that takes values along the curved configuration at static equilibrium. The densities of the two phases are denoted by ρ_G and ρ_L for the gas and the liquid respectively. In