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A lumped element method for modeling the two-phase choking flow through hydraulic orifices

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ABSTRACT

A novel lumped element methodology for modeling the oil–gas two-phase flow through the hydraulic orifice has been presented, focus on the choking condition. The proposed approach consists of a gas cavitation model developed based on "Full Cavitation Model" and a formulation considering the homogenous fluid assumption for evaluating the mass flow rate. The two-phase choking flow occurring at extreme condition is characterized in detail by using the present method, in terms of the critical pressure, sound speed, filling ratio and the critical speed of pump operation in the hydraulic circuit. Mach number is found to be 1 and the critical speed is estimated by the inlet volumetric flow rate at choking condition of the two-phase flow. The effects of different parameters including the orifice diameter, the upstream pressure and the cavitation model coefficient are investigated to find possible ways of improving the operation of the pump circuit. Reducing the cavitation model coefficient is identified to be both advantageous for reducing the critical pressure and increasing the critical speed.

1. Introduction

In the discipline of system modeling and simulation, lumped element method is widely adapted to formulate the governing equations of the dynamic features of system behaviors, such as the study of mechanical multi-body systems and electrical circuits [1]. Generally in the philosophy of lumped element method, the spatially distributed physical parameters are simplified into a topology consisting of a certain number of components, without losing the major system characteristics [2]. Particularly only this approach allows a complete consideration of the interacting effects among the different components in the system and more significantly it can also be coupled with a distributed parameter submodel which is developed for a certain major component. For this reason, lumped element method has been applied in the simulation of hydraulic machines or systems [3–5] and much commercial software such as AMESim, EASY5 and DSHplus is also developed based on this methodology. Comparing to CFD method, lumped element approach can save much modeling effort and has a better numerical stability as well as computational swiftness, especially in the study of hydraulic circuits for which it is too costly to establish the full CFD model. Therefore, in this study the simplified approach is used in modeling the two-phase flow through hydraulic orifices which is placed at the inlet pipe of the pump circuit, focus on the choking phenomenon.

The two-phase flow through hydraulic orifice has been considered as the result of gaseous cavitation mainly caused by air release [6]. Fig. 1 illustrates a typical open pump circuit in hydraulic systems, which is usually employed in low-pressure lubricating systems or charge systems of closed-loop layouts. The pump is driven by a prime mover, and the variable orifice serves as a certain load. The pump inlet port is connected to a reservoir through an orifice, which is particularly introduced to generate cavitation to the pump circuit. Gas cavitation occurs when the localized pressure falls below the air separation pressure or even the vapor saturation pressure. In other cases, the downstream pressure can be fairly low to induce cavitation when the pump operates fast, resulting in a two-phase flow regime as covered by yellow in Fig. 1. The negative influence of gas cavitation in hydraulic orifice including the deterioration of flow capacity, structural erosion and increase of noise and vibration level brings a big challenge in the designing of the open hydraulic circuits [7,8]. In the past, researchers have broadly studied the cavitation problem from the interphase mass transfer to various types of applications, and several numerical models of describing multi-dimensional cavitating flow have been proposed in CFD domain, including the examples presented in [9–11]. However, these models are only suitable for

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Nomenclature

A	cross-sectional area m^2
C_f	filling ratio –
C_q	orifice flow coefficient –
E	fluid bulk modulus kPa
Q	flow rate m^3/s
T_0	constant temperature K
V_c	pump displacement volume cm^3
c	sound speed m/s
c_p	specific heat J/(kg K)
d	diameter m
f	mass fraction of air –
h	specific enthalpy J/kg
m	mass kg
$\dot{m}$	mass flow rate kg/s
n	shaft speed rpm
k	pressure ratio –
p	pressure kPa
p_b	air separation pressure kPa
t	time s
z	cavitation model coefficient $\sqrt{m/kg}$
α	volume fraction of air –
ρ	density kg/m^3
λ	polytrophic index of gas –

Subscripts

IT	internal transport
G	gas (air)
L	liquid
H	fluid mixture
in	inlet port
out	outlet port
u	upstream
d	downstream
0	initial condition

Superscripts

*	critical condition

Acronyms

CFD	computational fluid dynamics
CV	control volume

CFD modeling of hydraulic components as done in [8,12], but not applicable for lumped element models of fluid power circuits. For lumped element models, the homogenous fluid assumption is adapted to account for gas cavitation, as outlined by Gholizadeh et al. [13]. Recently, a novel fluid model which takes the dynamic features of air release/absorption into account has been proposed by the author in [14]. This model is successfully validated for predicting of fluid properties in a closed control volume and further utilized in the performance study of gear pumps [15].

Choking flow (also called critical flow) is essentially a compressible flow effect, saying that the mass flow rate passing through a restriction will not increase with a decreasing downstream pressure. A fairly amount of literature has been published on the two-phase choking flow field (for the classical work, see Refs. [16–19], but mainly focuses on the topic of water-stream mixture [20,21], with very few on the gas–oil case [4,22]. There are “equilibrium” and “non-equilibrium” models for water-stream case between which the difference is whether the interphase heat transfer is considered. This is essentially different to the gas–oil flow in which the mechanical equilibrium driven by low pressure is the main consideration. Therefore, the gas evolution equation is utilized to determine the gas fraction in gas–oil flow instead of the thermodynamic equation in water-steam flow. Furthermore, from the engineering point of view, the occurrence of choking flow at inlet orifice means that the pump has reached its maximum flow discharge capacity. Due to the limitation of mass flow rate of hydraulic pump, it is possible to predict the critical speed from the choking condition of the inlet orifice. Therefore, this will be helpful for the designing of the high speed pumps or relevant circuits.

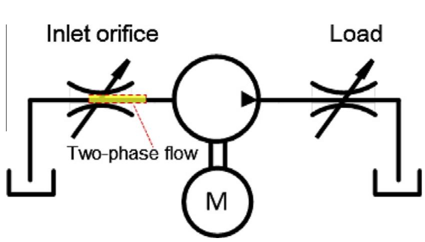

Fig. 1. Simplified diagram of studied system.

In this paper, Section 2 presents a detailed description of the lumped element two-phase flow model for the hydraulic orifice, which uniquely consists of a novel gas cavitation module and an equation for calculating mass flow rate derived from energy view. Section 3 gives an investigation of the two-phase choking flow associated with extreme condition. Especially the critical pressure, sound speed, filling ratio and critical speed is determined for the given case. In Section 4, the impact of various parameters in terms of orifice diameter, upstream pressure and cavitation coefficient on the critical pressure and the critical speed is demonstrated. In the end, the major conclusions of this research are summarized in Section 5.

2. Lumped element modeling of two-phase flow

There are two significant aspects in modeling the two-phase flow, including how to evaluate the gas generation and how to predict the mass flow rate, need to be considered in this section. First, the gas cavitation particularly indicating air release in this study is investigated using a lumped element approach presented in [15]. Second, the calculation of the mass flow rate is formulated using the gas fraction, according to the homogenous fluid method. Although the lumped element model is presented taking the studied orifice as reference, it is worth mentioning this methodology has a general applicability to other hydraulic applications.

2.1. Gas cavitation in hydraulic orifice

Lumped element approach for modeling hydraulic systems is on the basis of control volume (CV), in which fluid properties are considered as uniform. For this study, the main structure of a hydraulic orifice is illustrated in Fig. 2, including three CVs: the upstream region, the throat region (CV) and the downstream region. Where, p_u and p_d indicate the upstream and downstream pressure respectively; the subscripts “in” and “out” indicate the inlet port and the outlet port respectively.

The first significant step of modeling two-phase cavitating orifice flow is to predict the air content (mass fraction) in the throat CV. To achieve this goal, a generalized formulation of governing the air mass fraction in the open control volume presented in Ref. [15] has been employed, as written in Eq. (1).