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Modal testing of hydraulic pipeline systems

Gudrun Mikota [a,*], Bernhard Manhartsgruber [a], Helmut Kogler [b], Franz Hammerle [a]

[a] Institute of Machine Design and Hydraulic Drives, Johannes Kepler University Linz, Altenbergerstrasse 69, A-4040 Linz, Austria
[b] Linz Center of Mechatronics GmbH, Altenbergerstrasse 69, A-4040 Linz, Austria

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ABSTRACT

Dynamic models of fluid power systems require accurate descriptions of hydraulic pipeline systems. For laminar flow in a rigid pipeline, modal approximations of transcendental transfer functions lead to a multi-degrees-of-freedom description. This suggests the application of experimental modal analysis to investigate fluid dynamics in hydraulic pipeline systems. The concept of modal testing is adapted accordingly and demonstrated for a straight pipeline, the same pipeline with a single side branch, and a pipeline system with three side branches. Frequency response functions are determined by injecting a defined flow rate excitation and measuring pressure responses along the pipelines. The underlying theory is confirmed by comparisons between calculated transcendental, measured, and estimated rational frequency response functions. Natural frequencies, damping ratios, and pressure mode shapes are identified. Although the experiments are made for low flow rates and stiff pipeline walls, they indicate the way to perform modal testing in practical applications of fluid power.

1. Introduction

Hydraulic pipelines in fluid power systems serve as connections between pumps, valves, and motors; they are realized by bores in metal blocks, metal pipes, or reinforced rubber hoses, and connected by suitable fittings. The resulting pipeline systems receive periodic and transient excitations which originate from the attached components. These excitations can be modelled as time-dependent relations between hydraulic states and may often be approximated by flow rate boundary conditions. Pressure response along the pipelines will influence noise emissions and may be crucial with respect to structural safety and cavitation. To address these issues, accurate models of hydraulic pipeline systems are required.

For laminar flow conditions and sufficient stiffness of the surrounding structure, the dynamic response of hydraulic pipeline systems can be derived from the transcendental transfer functions of the individual pipelines [1]. According to [2], special modal approximations of these transfer functions enable a multi-degrees-of-freedom description of pipelines and pipeline systems. Fluid dynamics in hydraulic pipeline systems can therefore be investigated by experimental modal analysis to estimate natural frequencies, damping ratios, and one-dimensional mode shapes of pressure. In this paper, the concept of modal testing shall be demonstrated for three examples of hydraulic pipeline systems.

Finite Element modal analyses and modal tests of pipelines have considered fluid-structure interaction with a focus on mechanical vibrations. Li et al. [3] calculated vibration mode shapes of fluid-filled pipes in aircraft hydraulic systems;

* Corresponding author.
E-mail address: gudrun.mikota@jku.at (G. Mikota).

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individual natural frequencies were determined from vibration responses to pump excitation and compared with Finite Element results. Makaryants et al. [4] used Finite Elements to investigate the coupled hydraulic-mechanical modes of a press forge unit drain pipeline system; spectra of pressure and velocity were measured under operating conditions and indicated the dominant mode. Modal tests of fluid-filled pipelines are reported from the context of reactor components. Yigang et al. [5] tested straight pipes with different mechanical boundary conditions and emphasized the asymmetry of the underlying model; however, the model did not contain pressure state variables, and only mechanical vibration responses were measured. Nurkkala et al. [6] tested a feed-water pipeline by hydraulic shaker excitation; although the pipeline was filled with water, they only measured mechanical vibrations.

Under harmonic flow rate excitation, Fanelli et al. [7] performed spatially distributed pressure and flow rate measurements on a straight water-filled pump suction line made of acrylic glass. They compared measured frequency responses with results from a transfer matrix model that considered a complex frequency dependent compliance of acrylic glass and linearized friction losses from turbulent flow; for the first two hydraulic modes of the pipeline, excellent agreement was achieved.

A transfer matrix method for the vibration analysis of branched pipelines was developed by Liu et al. [8]. It includes frictionless fluid flow and was validated against experiments. Assuming external force excitation, calculated pressure frequency responses were compared between rigid and flexible pipes. The results demonstrate that metal pipes do not constitute rigid walls and the dynamic behaviour of the fluid in such pipes usually couples with the dynamics of the surrounding structure.

Modal testing of the fluid in hydraulic networks was attempted by Mikota [9,10]. The first test case consisted of two accumulators and three pipelines including a number of bends. The prestressed network was excited by the step response of a servovalve closing the connection to a tank; pressure responses were measured by four pressure sensors and approximated from fifteen circumferential strain measurements. Frequency response functions between flow rate excitation and pressure response were obviously influenced by structural vibrations. Nevertheless, identified natural frequencies and pressure mode shapes showed fair agreement with results from a hydraulic Finite Element model. The network was modified by attaching an additional piece of pipeline; modal testing confirmed the expected tuning effect. Despite the practical success of the method, the underlying model was only based on the lumped parameter duality between one-dimensional hydraulic and mechanical systems [11]. A reliable justification would have required an adequate description of dynamic flow in pipelines.

Bends and junctions in hydraulic pipeline systems are often treated as Kirchhoff nodes, which stands for the simple assumption that the sum of incoming and outgoing flow rates are equal. For a 90° bend, Manhartsgruber [12] introduced a frequency dependent flow resistance with variable lengths of the adjacent pipeline sections. Under pulse excitation with a servovalve, pressure was measured in three points before and two points after the bend. System identification was performed for various orders of the resistance transfer function. To avoid fluid-structure interaction, pipeline bores were contained in aluminium blocks.

Returning to Kirchhoff nodes, Mikota [2] found a multi-degrees-of-freedom approximation for dynamic laminar flow in pipeline systems. Rational fraction approximations of the transfer functions between flow rate excitation and pressure response lead to multi-degrees-of-freedom descriptions of the individual pipelines, which were assembled into an overall pipeline system model with flow rates as forcing functions and pressures as response degrees of freedom. Within the accuracy of the approximation, this provided the justification missing in [9] and [10].

Augusztinovicz and Sas [13] discussed model formulations in acoustic modal analysis. Due to the available sensors, volume velocities are preferred as forcing functions and sound pressures as response degrees of freedom. This formulation agrees with the above description of laminar pipeline flow. Although the velocity distribution within the pipeline depends on the radial position [14], the overall dynamic behaviour of hydraulic pipelines can be approximated by one-dimensional acoustic models.

Acoustic modal tests have been published by several authors. Nieter and Singh [15] investigated tubes with closed and open end as well as one-dimensional lumped parameter systems; Kung and Singh [16] extended the technique to three-dimensional axially symmetric systems. Byrne [17] reconstructed the velocity field from differentiable approximating functions for the sound pressure modes of a rectangular enclosure. Zhang [18] applied acoustic modal analysis to the passenger's compartment of a car. Rossetto et al. [19] determined the particle displacement mode shapes of a rectangular cavity using spatial Discrete Fourier Transform. Yoshimura et al. [20] identified highly damped acoustic modes of an automotive cabin with excitations in up to eight points. Peeters et al. [21] treated a similar problem and used four excitation points to test an aircraft interior. In most of these publications, the excitation was applied by loudspeakers, although some experiments were made with moving pistons. Random noise volume velocities were used as forcing functions, and sound pressure responses were measured by microphones. Zhang [18] performed a second modal test in which vibro-acoustical coupling was taken into account. Wyckaert et al. [22] summarized vibro-acoustical modal analysis theory and presented modal tests of a cavity with a flexible bottom plate.

In this paper, modal testing is applied to the fluid dynamics of hydraulic pipeline systems; effects from structural vibrations are avoided. This is realized by adopting the aluminium block system from [12], which also allows for pressure measurement with minimal disturbance of the pipeline system bores. Servovalve excitation is used like in [9] and [10], but with burst chirp as a second type of excitation. Flow rates are kept low so that bends and junctions can be treated as Kirchhoff nodes. Three different pipeline system setups are investigated. In contrast to [9] and [10], the excitation is always