Aerospace Science and Technology 49 (2016) 144–153

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

# A model reduction approach for the vibration analysis of hydraulic pipeline system in aircraft

Pei-xin Gao [a], Jing-yu Zhai [a], Yang-yang Yan [a], Qing-kai Han [a,*], Fu-zheng Qu [a], Xi-hong Chen [b]

[a] School of Mechanical Engineering, Dalian University of Technology, Dalian 116024, PR China
[b] North Heavy Industry Group Ltd, Shenyang 110004, PR China

ARTICLE INFO

*Article history:*
Received 8 August 2015
Received in revised form 9 November 2015
Accepted 5 December 2015
Available online 8 December 2015

*Keywords:*
Hydraulic pipeline
Model reduction
Component mode synthesis
Multi-supports with elasticity
Vibration analysis

ABSTRACT

This paper presents a developed model reduction approach for the vibration analysis of hydraulic pipeline with long distance and multi-supports with elasticity popularly used in aircraft. Based on the Euler–Bernoulli beam theory, the motion equations of the pipeline conveying fluid are established via the finite element method. An efficient solution procedure for the model reduction of pipeline is developed based on component mode synthesis, in which the artificial springs are imported to simulate the arbitrary boundary conditions. A pipeline with four elastic supports in wings is investigated as a numerical example to validate the present approach. The influence of the mode truncation numbers, stiffness of elastic supports and fluid velocity on natural frequencies are all discussed. The obtained results indicate that the current approach can reduce the computational cost significantly with sufficient accuracy, which may serve as an efficient guidance for the design of hydraulic pipeline in aircraft.



## 1. Introduction

The hydraulic pipeline system in aircraft is always configured using very long pipeline with multi-elastic-supports, compared with ordinary pipeline conveying fluid. For example, the pipelines of braking and landing gear system are up to 60 meters from oil tank to actuator in a certain type of aircraft. According to the aviation standard, the distance between two neighboring clamps (also known as hoops), which are used to support the pipeline, should be less than 0.4 m in aircraft. Thus, the long pipeline is always equipped with plenty of hoops, which can be considered as multi-supports with elasticity. Induced by the based excitation from the Aero-engine and the pressure fluctuation by the pump, the pipeline may undergo resonances in a wide frequency range (10–3000 Hz), which could damage the local section of pipeline through overload and fatigue. Therefore, in the design of the long pipeline in aircraft, it is essential to establish the dynamic model of pipeline and reduce the computational cost while obtaining sufficient accuracy in order to avoid the harmful resonances as much as possible.

The dynamic behavior of pipeline has received considerable attention in the past decades, and plenty of striking achievements have been gained (Païdoussis et al. [1–4]). Many methods have been published in the open literatures, such as Galerkin-type solution, transfer matrix method, the method of characteristics and the finite element method, etc. By taking into account the flexibly supports, Kheiri et al. [5] analyzed the dynamics and stability of a pipe conveying fluid via the Galerkin method, and the obtained natural frequencies had a good agreement with existing results. Liu et al. [6] proposed a transfer matrix method in frequency domain of pipelines, in which the fourteen frequency-domain equations were assembled into transfer matrix. Yu et al. [7] improved a new transfer matrix method to analyze the cantilevered pipeline conveying fluid. Tijsseling [8] obtained a solution for the four-equation model in time domain of pipeline conveying fluid by the method of characteristics, in which a set of coupled linear first-order partial differential equations were investigated. Li et al. [9] presented an analytical solution in time domain by the method of characteristics, and the experimental results verified the effectiveness of proposed method. Based on the finite element method, Lin et al. [10] investigated the influence of the fluid velocity on the nature characteristics of pipeline. Considering the effect of random excitation, Zhai et al. [11] analyzed the influences of fluid velocities on standard deviation of dynamic response for pipeline.

As mentioned above, most of the current strategies are excellent to handle the vibration behavior of pipeline conveying fluid availably and accurately. However, in engineer field, the hydraulic pipeline is configured long distance with multi-supports, it is thus

* Corresponding author. Tel.: +86 411 84706750; fax: +86 411 84706750.
*E-mail address:* hanqingkai@hotmail.com (Q. Han).

http://dx.doi.org/10.1016/j.ast.2015.12.002
1270-9638/

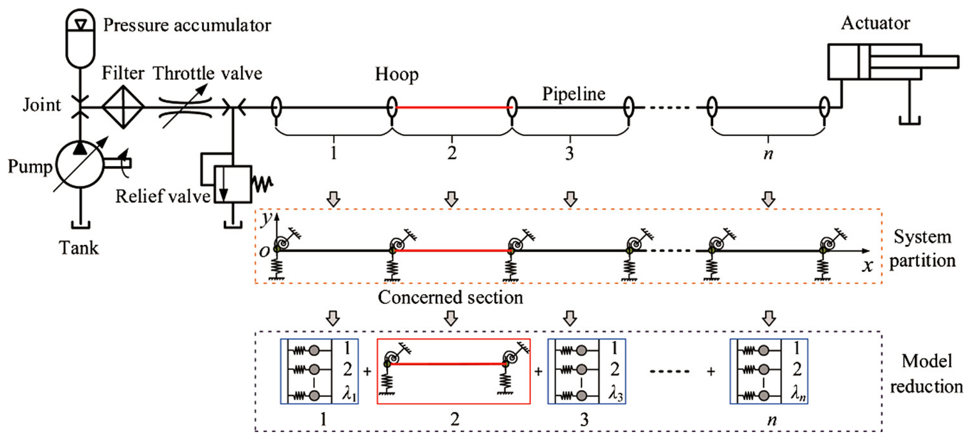


**Fig. 1.** The schematic diagram of hydraulic pipeline system for the model reduction in aircraft.

a complex and difficult work to calculate and verify the vibration model. In order to overcome these limitations, the component mode synthesis method has been widely used in finite element analyses, which refers to large system decomposed into different sub-systems. The model reduction method was firstly proposed by Guyan [12] to reduce the stiffness matrix of the structure. Hurty [13] presented a developed method for analyzing complex structural system that was divided into interconnected components separately. After that, a lot of improved modal synthesis methods were reviewed and summarized in reference [14]. Bathe et al. [15] investigated the calculation accuracy control of the structural parts using the modal synthesis method. Comparing with experimental investigation, Adam et al. [16] proposed a test verified component synthesis approach for the helicopter wing and fuselage applications. In recent years, the modal synthesis method has been applied to the structure optimization (Masson et al., [17]), the uncertainty analysis of structural parameters (Hinke et al., [18]), the nanometer structure (Li et al., [19]), the track bridge (Biondia et al., [20]) and the rotor system (Khulief et al., [21]; Stringer et al., [22]), the wind turbines (Holm-Jørgensen et al., [23]), and the multi-stage cyclic structures (Duc-Minh, [24]) etc. Recently, Curiel Sosa et al. [25] presented a developed finite element method to study the structural instability, and the delamination problem in fibre metal laminates [26]. Carneiro Molina et al. [27] proposed a novel multiscale finite element homogenization technique for modeling nonlinear deformation of multi-phase materials. From the reviewed works, the model reduction method is excellent applied to many industries, which has been motivated to develop a reduction method that can handle the vibration analysis of hydraulic pipeline. Therefore, it is of great challenging to reduce computational cost while obtaining sufficient accuracy.

This paper presents the model reduction for the vibration analysis of hydraulic pipeline in aircraft. Firstly, the principle of model reduction for hydraulic pipeline with long distance and multi-supports with elasticity is investigated. Then the motion equations of the pipeline conveying fluid are determined and the model reduction for a pipeline with four elastic supports in wings is conducted. Secondly, the proposed methodology is validated by a modal test, as well as the full FEM model. The effect of the mode truncation numbers, stiffness of elastic supports and fluid velocity on natural frequencies are all considered. Finally, the computational cost for full and reduced model is discussed comparatively.

## 2. The principle of model reduction for hydraulic pipeline

The pipeline, spanning from the pump to actuator for the delivery of fluid, is an important part of the hydraulic system in aircraft.

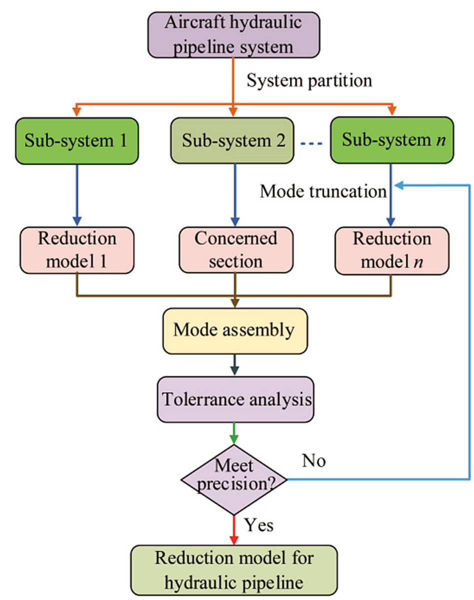


**Fig. 2.** The process of the model reduction of hydraulic pipeline system.

The hydraulic pipeline system consists of pump, pressure accumulator, oil filter, throttle valve, relief valve, actuator, pipeline, joints and clamps (also known as hoops), etc. as shown in Fig. 1. Some parts of hydraulic pipeline system can be simplified by the specific structural forms, such as the hoops used to support pipeline are commonly simplified as horizontal linear springs and torsion springs (Koutsawa et al., [28]).

Considering the long distance with elastic supports and the local resonance phenomenon in specific section of pipeline, the pipeline is divided into $n$ sub-systems. The concerned system refers to the most critical and vulnerable section of pipeline, in which the vibration characteristics need to further study with wide range of frequency. For example, the section of pipeline spanning from the pump to the filter can be set as concerned system. It is subjected to the excitation by aero-engine and the pump pulsation that could damage the pipeline easily. In this paper, the sub-system 2 is taken as the concerned section to illustrate the solution approach (see Fig. 1). The reduced model of the hydraulic pipeline is obtained by the assembly of sub-systems in which the mode truncation numbers $\lambda_n$ are selected for the other sections. The process of the model reduction method is plotted in Fig. 2. Further, the reduced model is confirmed by comparing the computational cost and accuracy with the full FEM model of the hydraulic pipeline system.