Control Engineering Practice 51 (2016) 108–120

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Vibration control of a Stirling engine with an electromagnetic active tuned mass damper

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ARTICLE INFO

Article history:
Received 11 August 2015
Received in revised form
22 December 2015
Accepted 20 March 2016
Available online 6 April 2016

Keywords:
ATMD
Active control
System modeling
Voice coil actuator
Real time
FPGA implementation
Relative and absolute feedback

ABSTRACT

Active tuned mass damper (ATMD) systems have been used extensively to reduce vibrations in machines. The motivation of this study is attenuating the vibrations in a Free-Piston Stirling Engine/Linear Alternator (FPSE/LA) for a frequency band of 47–53 Hz using an electromagnetic ATMD that employs a linear Voice Coil Motor (VCM) for periodic excitation rejection. To the authors' knowledge, however several approaches to minimize vibrations in Stirling machines have been patented, the technique proposed in this research differs from other patented work by the simplicity of the proposed control law which aims to attenuate the engine vibrations at the fundamental operating frequency. The proposed control system features a zero-placement technique that utilizes both relative or absolute position and velocity feedback from the system response as well as a feedthrough measurement of the disturbance frequency that is used to determine the position gain online. The performance of the control system with the ATMD was evaluated both theoretically and experimentally. A test rig emulating the vibration behavior of the Stirling engine, featuring an electrodynamic shaker and an ATMD was developed and a model of the rig is presented and validated. A novel experimental procedure of identifying unknown stiffness and unknown dynamic mass of a spring–mass system is also presented. Similarly, another experimental procedure of determining the damping coefficient in the electromagnetic ATMD is shown. The implementation findings illustrate that the proposed active controller succeeds in broadening the attenuation band from 50 ± 0.5 Hz to between 45 Hz and 55 Hz.

1. Introduction

Free Piston Stirling Engine Generators are synchronous grid-connected machines fitted with a linear alternator that generate electricity by utilizing a heat source (FPSE/LA). Commercially available FPSE/LAs for Micro Combine Heat and Power (MCHP) systems have a single phase linear alternator (Harrison, 2004). A Free Piston in the Stirling engine operates on gas springs and holds the permanent magnets used for generation in the linear alternator. The piston moves with simple harmonic motion at grid frequency and voltage generating very clean electrical power (ENTSO, 2015a). This motion results in a reaction force according to Lorentz' law which acts on the alternator coil. The alternator coil is attached to the engine's case and hence this reaction force is the main cause of vibrations.

From an operational point of view, these machines are always subjected to vibrations due to the reciprocating motion of the permanent magnets attached to the power piston. From an engineering and economic perspective, the cheapest and most reliable implementation is currently based on a passive absorber tuned to operate within a frequency range of frequency 50 ± 0.5 Hz in Europe. Recently, the European Network of Transmission System Operators for Electricity (ENTSO) has brought new regulations for grid connection and disconnection of low power generators imposing a wider frequency bandwidth 47 Hz–52 Hz (ENTSO, 2015b). Operation at grid frequencies outside of 50 ± 0.5 Hz would move the piston and displacer frequencies far away from their resonant frequencies resulting in Piston/displacer crashing.

While passive devices could provide a simple and a reliable way to tackle many vibration problems, there is distinct performance limitations associated with the use of only passive devices. Hence in its current form, the engine cannot comply with the new regulations since its passive absorber is not suitable with wider frequency bandwidth operation. The principle of a vibration absorber or a tuned mass damper (TMD) has been widely known as a passive vibration control technique for many years (den Hartog, 1956; Harris & Crede, 1961). Active damping techniques can achieve far better performance than simple passive ones by employing adjustable actuators such as hydraulic pistons,

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http://dx.doi.org/10.1016/j.conengprac.2016.03.014
0967-0661/

piezoelectric device, electric motor, etc. that require external power as well as complex control systems (Liu, Waters, & Brennan, 2005). The concept of the active tuned-mass absorber was first flagged in 1972 by Yao (1972) whereby the concept of structural control was presented as an alternative approach to the safety problems of structural engineering. Morison and Karnopp (1973) theoretically investigated an active vibration control approach as compared with a conventional passive TMD. The work done by Morison and Karnopp is considered the first theoretical attempt to improve control performance of the passive tuned-mass damper by means of an active device supplement. Chang and Soong (1980) studied the method of using an ATMD based on a pneumatic spring and an actuator in which they followed a linear quadratic control law to determine the appropriate feedback gain of the ATMD. De Roeck, Degrande, Lombaert, and Müller (2011) presented an active tuned mass damper that could be used to control lateral vibrations induced by pedestrians on a bridge deck. In recent years, there has been a growing interest in using electromagnetic actuators instead of piezoelectric actuators. Chen, Fuh, and Tung (2005) evaluated the performance of an active vibration absorber using a VCM by both simulation and experiments. Park et al. (2008) developed a four-mount active vibration isolation system using voice coil actuators. Liu and Wu (2013) used a voice coil actuator with absolute velocity feedback control for highly sensitive instruments by producing a sky-hook damper at low frequencies (2–6 Hz).

Stirling engine technology has come a long way in the past several decades with new designs and concepts continuing to appear (Ross, 1995). Among these, the domestic-scale Stirling electric power generator is particularly of great potential (Berchowitz, 1983). The improvement of the engine can only be carried out in a relatively high-cost time-consuming trial-and-error process. In this regard, modeling the engine is expected to be one of the alternative solutions to these issues. Cheng and Yu (2010) reviewed some numerical models that have been developed for different types of Stirling engines and also proposed a numerical model for a beta-type Stirling engine with a rhombic-drive mechanism.

Research within the area of active vibration control for free piston Stirling machines has been mainly industry-led. As a result, there is not much academic research available within this topic. Nevertheless, there have been some attempts made to find a solution for the vibration problem of the engine for wider frequency bandwidths. Rauch (1983) claimed the conceptual design of a low-cost and low-maintenance absorber that self-adjusts its gas spring constants to tune its natural frequency at all engine frequencies. While this method is theoretically ideal and low cost for reducing the vibration of the engine for different operating frequencies, this concept has never become a working product. More recently, few patents in this area still continue to come out. Some of them require control of the amplitude and phase of the piston or displacer and the engine case motion such as the control algorithm in Qiu, Augenblick, Peterson, and White (2005). Latest patented solution in Holliday (2014) uses the concept of adaptive filtering to balance the vibrating machine at the fundamental operating frequency of the machine and at selected harmonics of that operating frequency. A motion sensor that measures the amplitude and phase of the vibration is required. In terms of other Stirling-type applications, Ross (2003) provided an overview of the vibration characteristics of typical linear-drive space cryo-coolers outlining the history of development and typical performance of the various active and passive vibration suppression systems being used. Ross considers that work done by Sievers and von Flotow (1992) and others on active vibration control in 1990 became visible to the cooler community. Recently, Johnson, Long, Nelson, and Mascarenas (2012) worked on developing embedded active vibration cancellation of a Piston-Driven cryo-cooler or nuclear spectroscopy applications.

This study is a continuation of the work done in Hassan, Torres-Perez, Kaczmarczyk, and Picton (2015) in which a zero-placement control law with position and velocity feedback, and disturbance frequency feedthrough, is proposed for the mitigation of the vibration in the FPSE/LA and tested using a test rig that emulates the vibration response of the Stirling engine under study by integrating a VCM with a TMD and a controller.

1.1. Organization

Section 1 presents the introduction and reasoning for this work. Section 2 of this paper considers the modeling, simulation, and model validation of the Stirling engine under study. Section 3 presents the derivation of the proposed control law alongside the simulation predictions of the engine vibration under the effect of the control action. In Section 4 a detailed description of the test rig structure that emulates the behavior of the engine-absorber system is presented. Furthermore, a model of the rig is derived, simulated, validated, and then used to study the performance of the control law in the test rig model. In addition to that, we show the procedure of determining the helical unknown spring stiffness/dynamic mass values. Section 5 is dedicated for the implementation of the control system. It also addresses the procedure for determining the damping coefficient in the ATMD. Finally, conclusion is drawn in Section 6.

2. The FPSE/LA analysis: modeling, simulation, and validation

2.1. Modeling

A Stirling engine is a complex machine and its behavioral description requires a multidisciplinary approach. An accurate FPSE/LA dynamic model involves a complex multiphysics problem that couples thermodynamics, electromagnetism and mechanics. However, this type of modeling could be cumbersome to handle (Chen & Griffin, 1983). Therefore, the use of simpler models is required from a dynamic point of view. Fig. 1 shows a schematic of the proposed vibration model of the Stirling engine under study.

The subsystem (a) of Fig. 1 represents the casing of the Stirling engine which forms the main structure that contains a displacer and a piston modeled as spring–mass–damper system. Subsystem

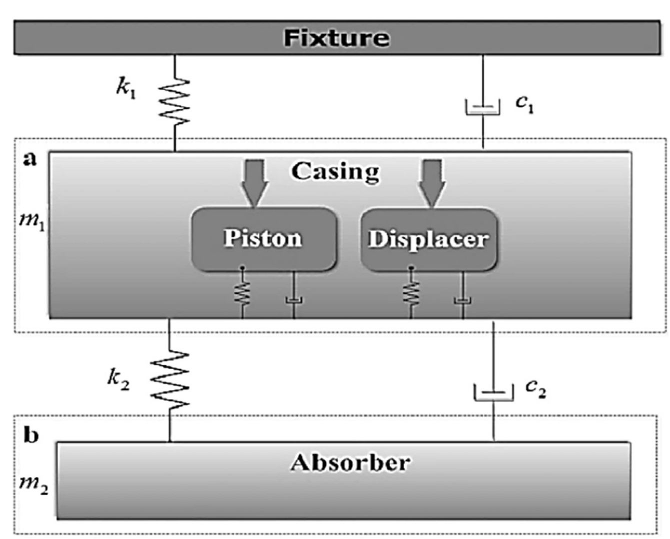

Fig. 1. Dynamic model of the β-type Stirling engine showing a casing.