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Active vibration control over the flexible structure of a kitchen hood

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ABSTRACT

This paper presents the full analysis and the complete development of a system for mechanical vibration reduction in a kitchen hood by using piezoelectric actuators. The control system is based on a feedback controller whose action depends on a single acceleration sensor collocated with the actuator. A model of the collocated actuator-sensor pair mounted on the hood and a model of the disturbance are provided. A Minimum Variance (MV) controller is able to provide the theoretically best performance in terms of noise reduction. A single-tones Minimum Variance controller (resonant controller) provides quasi-optimal performance while maintaining the stability of the system. Two different resonant control laws have been designed: the first one operates without the information of the hood motor velocity; the second one is a more sophisticated controller, which also exploits the velocity information. Both controllers are effective in reducing the mechanical vibration with performances that well approximate those achievable with an MV controller. Overall, through the motor velocity's information, the best performances are guaranteed with an 85% vibration reduction. The resonant control system without the motor velocity information provides the best compromise in terms of performances (75% of reduction) and complexity of the implemented system. Tests held in an anechoic chamber have shown the vibration reduction's influence upon the acoustic noise.

1. Introduction

Of many different types of actuators for active vibration suppression in flexible structures, piezoelectric (PZT) transducers are considered the best compromise among achievable performances, costs and reliability (see e.g. [5,7,11,31,13,27,34,1,29]).

Piezoelectric materials are sensitive to electric fields due to the permanent dipole of their crystal structure [22]. This kind of material strains when exposed to a voltage and provides a voltage when strained. So, in the first case, it can be used as an actuator, while in the second case it can be used as a sensor. The piezoelectric material is usually manufactured as a film and cut in small patches which can host both sensing and actuation on the same device.

The vast research activity of the last two decades devoted to piezoelectric materials can be divided into two mainstreams: the study of the material properties and behaviors (see e.g. [15,18,26]) and the research about control techniques and applications of devices based on piezoelectric materials (see e.g. [4,12,17,32,23,25]). This work belongs to the latter group.

For mechanical vibration reduction, piezoelectric patches can be used in either active control systems or passive ones. In a typical active control application, a piezoelectric patch actuates forces over a flexible structure while vibrations are measured by an appropriate sensor which is usually embedded in the actuator or collocated with it (see e.g. [10,2,36]). This approach is frequently used on a small flexible structure (the case of the present paper) where the problem of sensor/actuators placement is less critical than in the case of a large structure (for some example see [1,28]) The passive approach consists in the use of piezoelectric actuators shunted to a passive electric circuit that converts mechanical energy into electricity: so, the passive piezo-circuit system provides an extra-damping to the mechanical system (for some examples see [38,16]).

However, any passive framework can be emulated by an active control, which may also guarantee fine tuning on the vibration frequency, therefore achieving better performances. This is paid in terms of control design complexity, since only a passive framework is ensured to be stable with respect to any adopted configuration.

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This paper deals with a control application of piezoelectric actuators for mechanical vibration suppression using an active control scheme. In particular, this study is focused on the use of a collocated piezoelectric patch and an accelerometer sensor for vibration and noise reduction in a kitchen hood (Fig. 1). As a matter of fact, the vibration reduction in a kitchen hood is extremely important since it directly affects the perceived noise. Actually, a low noise level is probably the most significant quality factor in kitchen hoods, together with design.

Roughly speaking, the noise produced by the hood has two main sources:

- The electric motor, which generates a mechanical vibration (@50 Hz and multiples) that is directly transmitted to the hood structure and produces an annoying single tone noise with high intensity.
- The turbulent motion of the air flowing inside the chimney, which causes a broad-band aerodynamic noise with low intenstity.

The aim of this work is the suppression of the most tiresome component of the noise, i.e. the one due to the mechanical vibration of the hood produced by the electric motor. To this aim, an active vibration control system has been designed using a piezoelectric actuator to contrast the hood wall vibration measured by a collocated accelerometer. The control design has been carried out according to the Generalized Minimum Variance (GMV) approach [39,40,8,14]. This method has been chosen for two main reasons: it can easily accommodate adaptive control strategies, and it can accomplish control action penalization. The first feature has been exploited to adaptively tune the controller parameters depending on the motor speed. The second one is very important in piezoelectric based control systems to avoid the use of excessive control energy. More specifically, a broad-band Minimum Variance controller is able to provide the theoretically best performance in terms of noise reduction, by deleting noise (no matter its source) over a given bandwidth. On the other side, a single-tone Minimum Variance controller (resonant controller) will provide noise cancellation only at given frequency values, selectively deleting only the noise due to the motor vibration. This approach is of particular interest in view of the use of soundproof materials to reduce aerodynamic noise. At the best of our knowledge, this paper contains the following innovative contributions:

- The topic of vibration reduction with PZT actuator in a kitchen hood has never been explored. To this aim a description of the experimental set-up and a control-oriented model of the system are provided.

Fig. 1. The kitchen hood object of this work.

- A vast experimental activity has been carried out and here reported in order to assess the effectiveness of the proposed control system. Final tests have also been held in an anechoic chamber to explore the relationship between the reduction in terms of vibration and in terms of noise.

The paper is organized as follows: the control system and the experimental set up are presented in Section 2. The model of the plant and the mathematical description of the disturbance are reported in Section 3. The control design and experimental tests of two active resonant control laws are described in Section 4, where some tests in an anechoic chamber are also reported. Finally, Section 5 contains some conclusive remarks.

2. Plant description

The kitchen hood used in this work is a prototype designed by Faber S.p.A. – Italy (Fig. 1). Such hood model is composed of two main parts, described in Fig. 2:

- The *external part*, including the chimney, the hood base and the air filters.
- The *internal part*, called "motor-box" (the grey part in Fig. 2), which is fixed to the back side of the external structure. The motor-box is made of a small fan and an electric motor encapsulated in a cubic box.

As commonly used in domestic appliances, the hood is equipped with a universal AC-motor fed by the public power network. As a consequence, the main rotation frequency of the motor is 50 Hz (European standard). The motor speed can be controlled by a triac, which saturates, at adjustable values, the input current to the motor. This way the modulation of the motor speed can easily be obtained. Unfortunately, current saturation introduces pure-tone disturbances (at frequencies in multiples of 100 Hz, such as 100 Hz, and 200 Hz) in the torque delivered by the electric motor. This disturbance is at the origin of the motor induced vibrations.

The control system uses a piezoelectric actuator to contrast the hood wall vibration on the basis of its measurement performed by an accelerometer. Notice that, for control purposes, the sensor is collocated with the actuator.

The piezoelectric actuator used in this project is a P876-A15 DuraAct Patch produced by PI Ceramic (Germany, Fig. 2). The actuator is characterized by the following features that make it appropriate for this kind of application: a maximum holding force of 775 N and a −250 V to +1000 V operating voltage. The patch is driven by a voltage amplifier designed by PI which is governed by a −5 V to +5 V analog voltage signal and delivers to the patch a control action in the −250 V to +750 V range over a bandwidth of 5 kHz with a power consumption up to 48 W.

Vibrations are measured by a ±50 g accelerometer designed and distributed by PCB Piezotronic and featuring a 0.2 Hz–20 kHz bandwidth.

The experimental final control loop is depicted in Fig. 3:

- The hood vibration $a(t)$ is measured by the acceleration transducer. The resulting voltage signal is then electronically conditioned (amplified and translated) as $a_c(t)$ and sampled by the ECU at a 10 kHz frequency.
- The ECU is a fast-prototyping system MicroAutobox by dSPACE, which runs at a control frequency of 10 kHz. The control unit computes the driving voltage $v^{\#}(t)$ according to the designed control law. The ECU is also responsible for the data logging.
- The sampled-and-hold output of the ECU is electronically conditioned and then amplified by the PI driver as the command signal $v_a(t)$.