Sensors and Actuators A 147 (2008) 607–612

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

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

Coupled piezoelectric fans with two degree of freedom motion for the application of flapping wing micro aerial vehicles

Hsien-Chun Chung [a], K. Lal Kummari [a], S.J. Croucher [b], N.J. Lawson [b], S. Guo [b], Z. Huang [a,*]

[a] Department of Materials, School of Applied Sciences, Cranfield University, Bedford MK43 0AL, UK
[b] Department of Aerospace Engineering, School of Engineering, Cranfield University, Bedford MK43 0AL, UK

ARTICLE INFO

Article history:
Received 17 April 2008
Received in revised form 3 June 2008
Accepted 17 June 2008
Available online 26 June 2008

Keywords:
Piezoelectric fan
Flapping
Twisting
Resonance
FEM
MAV

ABSTRACT

Piezoelectric fans consisting of a piezoelectric layer and an elastic metal layer were prepared by epoxy bonding and a coupled flexible wing was formed by a pair of carbon fibre reinforced plastic wing spars and polymer skin attached to two piezoelectric fans. Two sinusoidal voltages with phase differences were then used to drive the coupled piezoelectric fans. High speed digital cameras were used to characterize the two degree of freedom (DOF) motion of the wing and these results were compared to finite element model of the wing and the coupled piezoelectric fans. It has been observed that the phase delay between the driving voltages applied to the coupled piezoelectric fans plays an important role in the control of the flapping and twisting motions of the wing and this set-up has the potential for application to the control of flapping wings for micro aerial vehicles.

1. Introduction

The interest in flapping wing micro aerial vehicles (MAV) has resulted in substantial work in recent years [1–3]. A MAV is defined as a semiautonomous airborne vehicle, measuring less than 15 cm in any dimension, weighing not more than 140 g, which can fly up to 2 h for a range of 10 km [1]. As demonstrated by flying birds and insects, flapping flight is advantageous for its superior manoeuvrability and lifting capability at low flight speeds [3,4]. Flapping wing systems as inspired by insect flight generally involve the wing completing pitching, yawing and sweeping components of motion over a flapping cycle [5]. Different mechanisms such as pneumatic and motor-driven actuators have been applied to mimic this complex flapping motion, but these mechanisms often suffer from heavy weight and mechanical system complexity [5].

Piezoelectric materials especially lead zirconate titanate (PZT) are widely used in smart structures as sensors and actuators due to their high bandwidth, high output force, compact size, and high power density [6]. However, the piezoelectric effect is intrinsically very small and only a small deflection can be expected directly from the bending piezoelectric unimorph/bimorph. Therefore some kind of motion amplification mechanisms are required to achieve large deflection. Fearing et al. [7–9] developed piezoelectrically actuated four-bar mechanisms for micromechanical flying insect thorax. Cox et al. [10] reported three piezoelectrically activated four-bar and five-bar linkage systems for the electromechanical emulation of mesoscale flapping flight. Park et al. [11] developed a four-bar linkage system driven by lightweight piezo-composite actuator to mimicking the flapping wing system of insects.

A simpler motion amplification mechanism is a piezoelectric fan (piezofan) which couples a piezoelectric unimorph to an attached flexible blade and is capable of producing large deflections especially at resonance. Piezofans were first investigated in the late seventies [12]. In the last few years the demand for portable electronic devices has brought interest in the use of piezofans as a compact, low power, noiseless air cooling technology for applications such as laptop computers and DVD players [13,14]. We have investigated the optimization and characterization of individual piezofan structure at quasi-static and dynamic operations in a separate report [15]. In this paper we report the investigation on using two coupled piezofans in parallel driven by sinusoidal voltages with different phase delays between them to realise the flapping and twisting movements of the wing structure. The main purpose of using piezofan as actuators is to facilitate this simple actuation mechanism to obtain two degree of freedom motion (2DOF), namely the flapping and twisting, of the wing and to develop meth-

* Corresponding author at: Department of Materials, School of Applied Sciences, Cranfield University, Building 70, Bedford MK43 0AL, UK. Tel.: +44 1234 750111; fax: +44 1234 751346.
E-mail address: Z.Huang@Cranfield.ac.uk (Z. Huang).

0924-4247/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2008.06.017

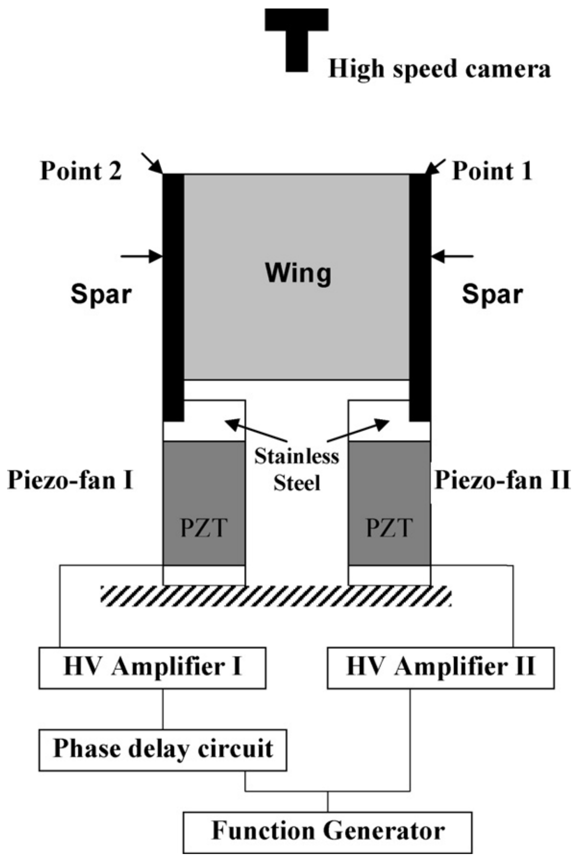

Fig. 1. The schematic set-up for the coupled piezoelectric fans with the attached wing and their vibration measurement by high speed camera photography.

ods for the control of its 2DOF motion. The experimental and finite element analysis and the effect of phase delay to the flapping and twisting of the wings attached to the coupled piezofans will be presented.

2. Experimental

Piezofans were prepared by bonding together a stainless steel metal shim with a piezoelectric PZT patch using epoxy glue EPOTEK 301-2 (Epoxy Technology, USA). The PZT wafers (PSI-5H4E) and stainless steel foils (Fe/Cr15/Ni7/Mo2.25) were purchased from commercial sources [15]. The schematic set-up for the 2DOF motion is shown in Fig. 1. The two piezoelectric fans were of the unimorph type, with the PZT patch of the dimensions 30 mm × 10 mm × 127 μm, and the elastic stainless steel layer of the dimensions 43 mm × 10 mm × 125 μm, so the total length of the piezoelectric fan was 43 mm. A 3 mm gap existed between the clamping and the start of the PZT patch in order to prevent the ceramic layer from broken during vibration. A pair of spars made of carbon fibre reinforced plastic (CFRP) connected with a flexible polymer skin formed the wing and the wing was attached to the two piezoelectric fans clamped in parallel to form the coupled fans. The gap between the two fans, therefore also the gap between the two spars, was varied from 10 mm to 2 mm.

The same wave (usually sinusoidal) signal from a function generator was split and supplied to two high voltage amplifiers. One of the split signals was then amplified and applied to one piezofan directly whilst the second signal was connected to an in-house made phase delay circuit (which can achieve 0° to 180° phase delay) before being connected to the other amplifier and then the other piezofan. The piezofans were clamped perpendicularly in parallel and both the flapping and twisting motions are in the horizontal direction. This enabled a high speed camera (Photron APX) fixed above the piezofans to record both the flapping and the twisting motions of the wing. A frame rate of 2000 frames/s was used with an area of interest of 61.25 mm × 61.25 mm, which corresponded to a mean resolution of 67 μm per pixel. The camera was controlled by a computer system to record 1 s of data corresponding to 2000 images. The 2000 images covered several full cycles of the vibration (the frequency was usually between 10 to 100 Hz). The displacement data was then obtained by comparing images over a full cycle and directly analysing the image showing the largest displacement. ANSYS finite element modelling (FEM) was used to model the behaviours of the coupled piezofans and the wing attached to it.

3. Results and discussion

3.1. Characterization of the dynamic motions for the coupled piezofans

Fig. 2 shows the results of the FEM modal analysis. The first mode was pure bending or flapping, at 23.7 Hz (a). The second mode was pure twisting (b), at 58 Hz and the third mode contained both bending and twisting at 62.9 Hz. The material parameters used in the FEM are listed in Table 1.

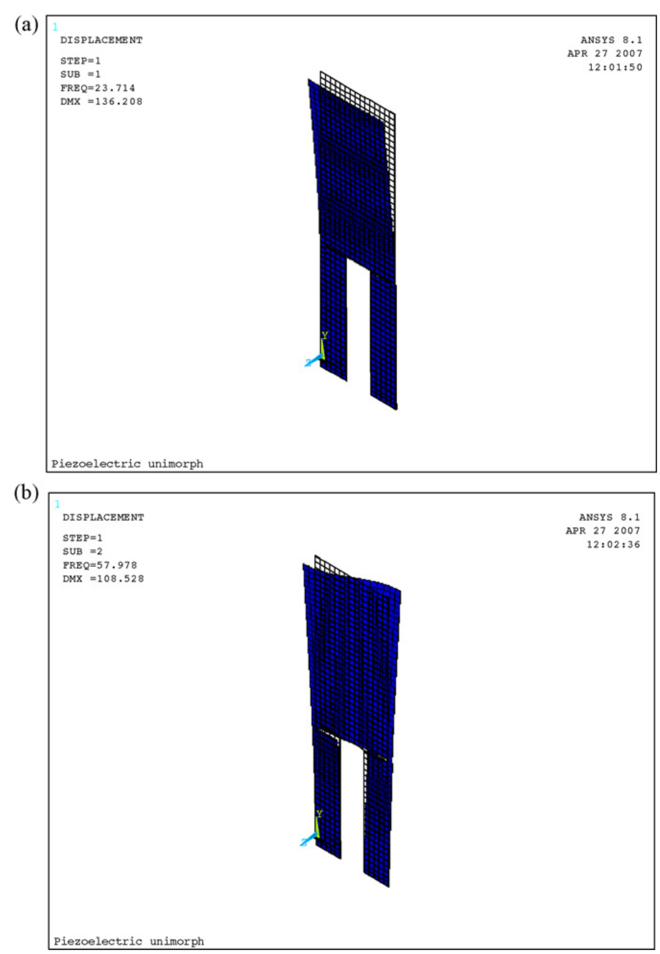

Fig. 2. The finite element modelling modal analysis for the coupled piezoelectric fans systems as shown in Fig. 1: (a) first mode bending, 23.7 Hz; (b) second mode twisting, 58 Hz.