Robust Control of Flapping-Wing in Micro Aerial Vehicle to have a Smooth Flapping Motion

Bahram Tarvirdizadeh Aghil Yousefi-Koma Esmaeel Khanmirza

***Abstract*—This paper in first sections, will give a brief overview of both the purpose and the challenges facing the actuator and structure of Micromechanical Flying Insects (MFIs) and, in the last sections, an appropriate controller will developed for flapping motion. A hierarchical architecture that divides the control unit into three main levels is introduced. This approach break a complex control problem into a multi-level set of smaller control schemes, each of which is responsible for a clearly defined task. Also, the controller at each level can be designed independently of those in other levels. A fourbar mechanism for the wing displacement amplification, and a new system for fourbar mechanism actuation (wing actuation) is developed. We will develop a flexible beam with piezoelectric actuators and sensor (called Smart Beam) that will used to excite the fourbar mechanism for flapping mode of flight. The Frequency Response Function (FRF) of the smart beam was obtained from a Finite Element (FE) model and experimental system identification. The corresponding transfer function was derived from the mu synthesis and several robust controllers were then designed to control the beam to reach a smooth flapping motion. Besides excitation of the fourbar mechanism, the Smart beam will be used to control of noise and disturbance in the structure of the wing system.**

Index Terms—Actuator Challenging, Flapping Flight, H∞ Control, Micro Aerial Vehicles, Structure, Wing Actuation

I. INTRODUCTION

The development of Unmanned Aerial Vehicles (UAVs) has been an active area of research during the past several decades because they are indispensable for various applications where human intervention is considered difficult or dangerous. UAVs are remotely controlled or autopilot aircraft that can carry cameras, sensors, communications equipment or other payloads. They have been used mainly in military operations, such as reconnaissance, communications relay, and intelligence-gathering missions, since the 1950's [1].

Although UAVs have been proven to be a safe means to carry out many missions, their use in some tasks is limited by their size and maneuverability. Additionally, enabling technologies in the recent past allow the creation of many small scale devices which have performance comparable to that of their large scale counterparts. These have motivated the development of miniaturized UAVs, termed Micro Aerial Vehicles (MAVs).

According to the requirement specified by the U.S. Defense Advanced Research Projects Agency (DARPA), the size of an MAV can not exceed 15*cm* in any dimension [2]. Because of the small size, MAVs offer the advantages of being able to move through small passage and operate in small space, greater agility in flight, and portability. Also they have low cost of fabrication and can be operated with limited resources. Therefore, MAVs may be deployed in a large quantity in an operation and they are generally considered expendable. The applications envisioned for MAVs include search and rescue within collapsed buildings, inspection of sites containing hazardous material, and security monitoring in addition to many of the applications identified for UAVs [1].

Despite the remarkable achievements obtained with the development of larger aircraft, the development of MAVs is still a challenging task. Directly scaling down the design of larger aircraft will not create an MAV because factors that are not of major concerns for the operation of macro-scale aircraft may have significant effects on the operation of microscale aircraft. For example, an important consideration in the design of MAVs is that they are operated in the aerodynamic regime of small Reynold's numbers (the Reynold's number is defined to be the ratio of inertial to viscous forces of a fluid flow). This means that the surrounding air feels like a viscous fluid to the wings of an MAV and drag forces from the air become more dominant players in affecting the aerodynamics of the MAV. In order to increase the lift-to-drag ratio, the wings of an MAV need to have a higher velocity relative to the air. This, in effect, puts greater demands on the propulsion system of the aircraft [1].

Since it is not possible to meet all of the design requirements of an MAV system with current technology, research is proceeding. To date, a number of prototyped MAVs has been developed and many of them have demonstrated stable flight for limited duration [3], [1].

The best solution to building even smaller MAVs may come from nature where many flyers of centimeter size exist. Throughout creation, animals that are capable of initiating lift-generating flight do so through the flapping of wings. The reason for wing flapping as a universal means of biological flight propulsion may be related to the scale. A flapping wing design relies on lift generated by airflow created by both vehicle speed and wing flapping to support the weight of the vehicle. If the scale is reduced, the frequency of wing flapping can be increased without affecting the minimum velocity of the vehicle. Thus, this design is inherently forgiving to scale changes. In an attempt to imitate the flight mechanisms used

Manuscript received November 27, 2013.

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DOI: 10.5176/0000-0004_1.1.3

by flying animals, several groups have worked on MAV platforms using flapping wings [4] [5] [6, 7] [8].

The authors have develop a nonlinear trajectory control of a flapping-wing micro aerial vehicle in [9], now in this paper a review of past studies will represent, and then a mechanism will be developed for a wing thorax structure. An appropriate fourbar mechanism will be introduced that will be explained in next sections. An appropriate structure for actuation of flapping wing will be introduced. At last the actuation and vibration control of this structure will be study and appropriate controller will be designed and implemented to have a smooth flapping motion.

II. MICROMECHANICAL FLYING INSECT (MFI) AND ITS ELECTROMECHANICAL STRUCTURE

The blowfly Calliphora erythrocephala (order Diptera) is used as a design target for the MFI since it is large enough for relatively easy assembly of actuators, thorax, wings, and on-board electronics (see Fig. 1). Wings of dipterous insects have three degrees of freedom: flapping, rotation, and out-of-stroke-plane motion. It is known that insect flight can not be explained by steady state aerodynamics, and this led to the elucidation of non-steady state aerodynamics which account for the large lift force generated by insect wings [10,11].

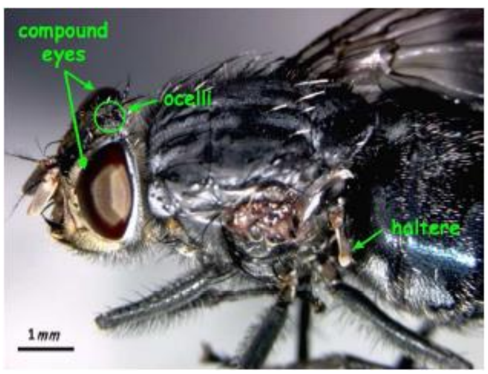

Fig. 1. Photo of the blowfly Calliphora. Shown are the three sensory systems: compound eyes, ocelli, and halteres [1]

Using a dynamically scaled model of Drosophila wings, known as the Robofly which can closely mimic the wing stroke kinematics of most flying insects, Dickinson et al. [10] were able to identify the three key aerodynamic mechanisms used by flying insects: delayed stall, rotational lift, and wake capture. The delayed stall occurs at the onsets of the translational phases (upstroke and downstroke) of the wing stroke and lasts for a distance of a few wing chord lengths. During this mode, large lift is produced at large angles of attack due to the growth of a leading edge vortex on the wing [11]. The rotational lift is the result of simultaneous wing translation and rotation. This mode is similar to the Magnus effect in which a spherical object simultaneously spinning and translating would experience a force perpendicular to both the velocity vector and the axis of rotation [12]. It occurs at the ends of upstroke and downstroke when the wing decelerates and rotates. The wake capture occurs during the stroke reversal when the wing collects the kinetic energy which was imparted to the fluid in the wake from the previous half stroke.

Since these three modes of force generation can be realized by wing flapping and rotation, the MFI wings will need only two degrees of freedom to exploit the unsteady aerodynamics. The out-of-stroke-plane motion does not appear to contribute much to the lift generation [13]. It may, however, have a significant effect on the maneuverability.

Fig. 2 illustrates the design architecture of the MFI. It is possible to identify five main units, each of which is responsible for a distinct task: the locomotory unit, the sensory system unit, the control unit, the communications unit, and the power supply unit. The locomotory unit of the MFI consists of piezoelectric bending actuators, thorax, and polymer wings [14]. The actuators are analogous to the flight muscles of real insects. However, the displacement generated by piezoelectric actuators is too small with respect to the desired MFI wing motion. In order to transform the small actuator deflection into large stroke amplitude and wing rotation, a flexural fourbar mechanism is used. The fourbar accepts a rotary input and yields an amplified rotary output. Furthermore, a slider-crank mechanism is used to convert the approximately linear motion of the actuator to a rotation at the input link of the fourbar mechanism.

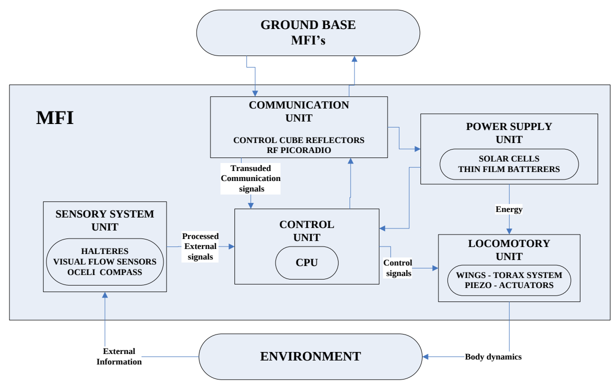

Fig. 2. The design architecture of the MFI

For each wing, two actuators, fourbars, and slider-cranks are used. Effectively, such a two-stage mechanical amplification technique can convert the $\pm 1^{\circ}$ motion range of the two actuators to the $\pm 45^{\circ}$ wing rotation and $\pm 60^{\circ}$ wing flapping. Moreover, the two fourbars drive a wing differential in such a way that one controls the leading edge while the other controls the trailing edge of the differential element [14, 16]. The wing has pure flapping when both fourbars move in phase, and the wing rotates when there is a phase difference between the two fourbars. Two of this compound kinematic mechanism are symmetrically arranged to form the thorax of the MFI. Fig. 3 shows the fourbar mechanism with piezoelectric actuator. In the next section we focous on piezoelectric actuators and robust control of them.

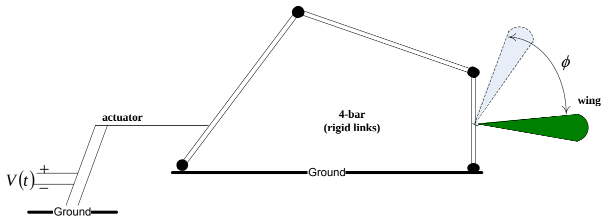

Fig. 3. Actuator, 4-bar, wing system

Inspired by the flight control scheme observed in real insects and that used in Berkeley UAV research, a hierarchical control architecture is proposed for the MFI control unit (see Fig. 4). This approach can break a complex control problem into a multi-level set of smaller control schemes, each of which is responsible for a clearly defined task. Also, the controller at each level can be designed independently of those in other levels, allowing the possibility to incrementally construct a more articulated control structure. For the MFI control unit, it is reasonable to define three levels: the trajectory planner, the flight controller, and the wing controller. This control architecture is built in a top-down fashion such that the controller at each level can interact only with the controller at the level directly below it, but not vice versa. The trajectory planner is voluntary and acts like a switcher, as it simply selects one flight mode at a time.

Nevertheless, the flight and wing controllers are more reactive. They continuously update the wing kinematics and track the wing trajectory in the presence of external disturbances to achieve the desired flight mode. Such a hierarchical control architecture presents a mixture of discrete events and continuous dynamics, making the MFI control unit a hybrid control system [15, 17, 18].

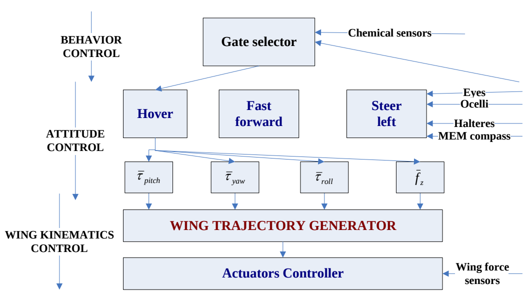

Fig. 4. Hierarchical control and sensory modality architecture

The sensory system unit contains various types of sensing devices that provide the necessary information to the control unit for navigation and flight stabilization. Due to the size constraint, conventional inertial navigation system (INS) and global positioning system (GPS) are not options for the MFI. Commercial off-the-shelf sensors such as silicon micromachined gyroscopes, accelerometers, and cameras used by MAVs are generally not suitable because of the limited computation and power available to the MFI. In addition, with a flapping frequency of 44*Hz*, the MFI needs sensors and processing algorithms with bandwidth and sensitivity much higher than those needed by fixed and rotary wing MAVs. To this end, a class of biologically inspired sensors, which exhibit advantages in terms of device structure, signal processing, and power consumption over existing commercial sensors to be used on the MFI, has been designed and fabricated: an optic flow sensor for obstacle avoidance, ocelli for angular position estimation, and halteres for angular velocity estimation [19, 21]. Other types of sensors, such as thermal and chemical sensors, may be carried depending on the mission of the MFI.

The communications unit of the MFI will use either a low-power RF transceiver or an optoelectronic transceiver, such as micro corner cube reflectors (CCRs) as described in [22]. The communications unit allows the MFI to exchange information with the ground station or with other communications platforms.

Currently, it is planned that the power required by the actuators, sensors, and other on-board electronics of the MFI will be supplied by a battery. However, for a robotic flyer as light-weight as the MFI, it is possible to be driven by solar cells [1].

III. DESIGN, MODELING AND ROBUST CONTROL OF MFI ACTUATOR

Each wing is moved by the thorax, a complex trapezoidal structure actuated by two piezoelectric actuators at its base, as shown in Fig. 5.

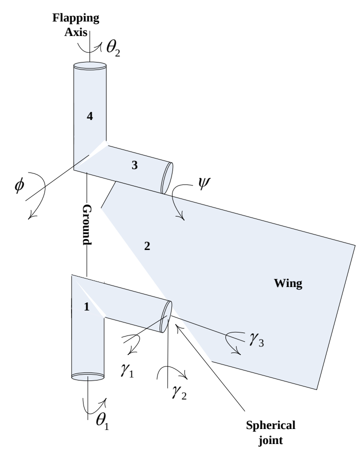

Fig. 5. Wing-Thorax structure [15]

This section presents the design, modeling and the control of piezoelectric actuators with embedded piezoelectric sensors which are meant to be used for the actuation of the MFI wings. First the design process of a piezoelectric bending actuator is described. Then the modeling and control of actuator is demonstrated. An experiment is carried out which validates the model for the actuator/sensor device under desired operating conditions.

Piezoelectric actuators are widely used in smart structure applications due to their high bandwidth, high output force, compact size, and high power density properties. For such reasons they are very appealing for mobile microrobotic applications such as the MFI where, because of strict size/weight constraints, smart structures capable of both actuating and sensing are preferred. Since the technology needed to fabricate PZT based bending actuators was already available, the possibility of integrating sensorial capabilities into the actuators themselves was investigated.

IV. DESIGN

The possibility of having the sensing section and the actuating section coexisting on the beam a layer of piezoelectric as an actuator is placed on the upper side of the beam and a layer of piezoelectric as a sensor is placed under the beam (at the opposite side of beam).

Since the publication of [24], several improvements have been made to the fabrication of PZT based actuators.

MFI [24] is a biomimetic project and a major design constraint is the wing beat resonance, determined to be at about 44Hz. The stiffness of the actuator is therefore designed to resonate, together with wing inertia reflected through an amplifying mechanism (4-bar mechanism), at this frequency. A rigid extension can be designed so that, by acting as a lever, it would provide larger free displacement at its tip together with lower blocking force, thus, leading to lower stiffness. In order to obtain the required stiffness, a rigid extension of appropriate length is needed. Rigidity of such an extension is a necessity.

Fig. 6. Piezoelectric actuator and beam

In this study, we use an Aluminum beam with two piezoelectric layers (one layer as actuator and another as a sensor). This structure is a model of a wing's actuator system.

The properties of Aluminum beam and piezoelectric layers are represented in table1.

V. MODELING OF ACTUATOR PLUS SENSOR

Due to the distributed nature and electromechanical coupling of piezoactuators, modeling is often a critical issue. For many applications, it is not easy to derive a mathematical model of the integrated smart structure directly from the partial differential equations defining the system thus, a Finite Element (FE) model is essential.

Authors have worked on the effectiveness of the finite element code ANSYS in the modeling of the smart structures. In this work, the finite element method was proven to be a very effective tool for the analysis of the smart structures. However, due to the difficulties in the determination of an accurate finite element model for the smart structures, the experimental System Identification Technique is preferred. But a System Identification (ID) model that can be obtained from experiment is often a more costly method, particularly in the development and optimization stage of smart structures which may require several iterations in fabrication.

In this study, experimental system identification is performed to validate the FE system identification. The transfer function was then employed to develop an active control system for vibration suppression of a smart beam. So, structural modeling and controller development was based on an experimental system identification dynamic model of the smart beam.

TABLE 1
MECHANICAL PROPERTY OF ALUMINUM BEAM AND PIEZOELECTRIC

Beam	Piezoelectric Element	Notation	Property
------	7350	ρ	Density (Kg/m3)
0.271	-----	----	Mass per unit length (Kg/m)
72×10^9	71.4 $*10^9$	E	Elasticity Module (Pa)
27×10^9	-----	G	Shear Module (Pa)
	10^{-3}*0.3	t	Thickness
-----	10^{12}* 200	d31	Strain Constant
-----	10^{10}*150.4	ε	Electric permittivity
0.3	0.3	υ	Poisson's ratio

Authors were designed and implemented, Conventional Lead-Lag controller. LQG and mixed-sensitivity based controller and a H_∞ loop-shaping control systems also. Simulation and implementation results indicated the controller performance to be robust and stable. This confirmed the reliability of the simulation system identification and controller development of smart structures which is particularly important in the early stage of structural design and optimization which may require several iterations.

ANSYS was employed to create the FE model of the smart beam. Solid45 elements and Solid5 elements were used for modeling the beam and piezoelectric actuators respectively. The beam was fixed in all directions at the root and the damping ratio is considered to be 3%.

In order to design an active control system a dynamic model of the smart beam was required. Authors were used, two independent method for identification of the system, firset ANSYS as the FE solver and Experimental System Identification to perform frequency response analysis of the smart beam to obtain the Frequency Response Function (FRF) ([tip displacement]/[input voltage to all actuators]). In experimental system identification method, we use the XPC target of Matlab software. The chirp signal (in the interval of [0-60] Hz with 0.002sec sampling time) was used to excitation of the system. Fig. 7 shows the response of the system for this input. Because of existing of the noise in the recorded data a BJ (Box-Jenkins) model is used for this data.

Fig 9 shows the diagram of the final model of the system, Eq. 1 represent the mathematical model of this system. The first 3 mode shapes are shown in Fig. 8. The Bode plot of the FRF is illustrated in Fig. 9.

The transfer function is the final representation of the dynamic model of the smart beam as given in Eq. 1. This equation is later used for dynamic response evaluation as well as control design and implementation through simulation.

If we would like to have a pure flapping mode, we use a sinusoidal input with frequency of 44 Hz, but in practice we can't forget the disturbance and noise in the system. Therefore we must design appropriate control for vibration control of the system.

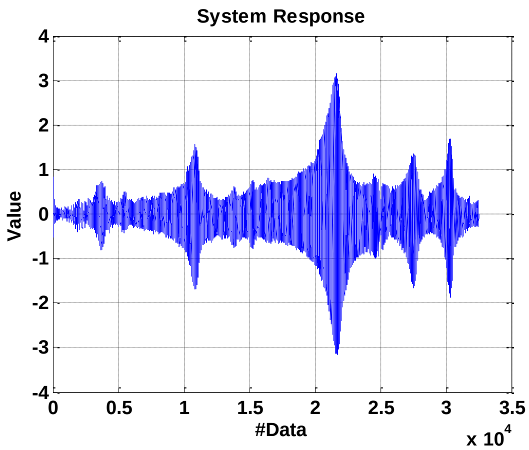

Fig.7. response of the system for chirp input

Now, an active control system will be developed. Controlling the vibration of the beam, the lead-lag regulator and LQG and mixed-sensitivity based controller and a H∞ loop-shaping based controller were designed.

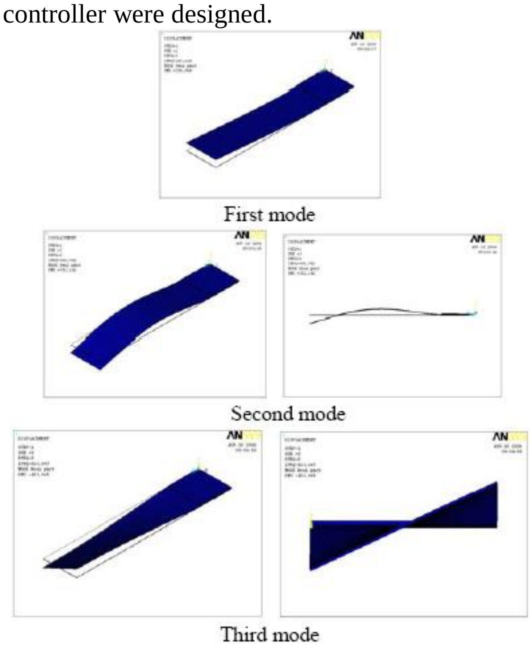

Fig. 8. First 3 modes of the smart beam

$$G_{Act}(s)=\frac{-9.322\times 10^{-8}s^{6}-4.672\times 10^{-5}s^{5}+0.07449s^{4}-9.024s^{3}}{s^{6}+70.63s^{5}+7.206\times 10^{-7}s^{4}+1.741\times 10^{-7}s^{3}+5.48\times 10^{10}s^{2}}\rightarrow$$
$$\frac{-4.317\times 10^{4}s^{2}-6.289\times 10^{5}+1.234\times 10^{9}}{+1.863\times 10^{11}s+1.204\times 10^{14}} \tag{1}$$

It must be mentioned that Linear-quadratic-Gaussian (LQG) control is a modern state-space technique for designing optimal dynamic regulators. It enables designer to trade off regulation performance and control effort, and to take into account process disturbances and measurement noise.

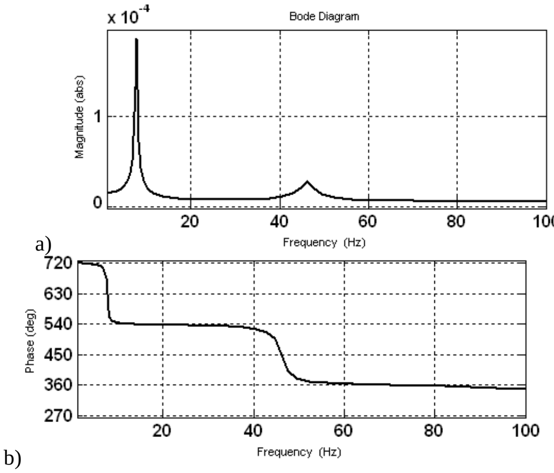

Fig. 9. FRF from the FEM, a) Amplitude versus Frequency, b) Phase versus Frequency

Mixed-sensitivity is the name given to transfer function shaping problem in which the sensitivity function $S=(I+GK)^{-1}$ is shaped along with one or more other closed loop transfer function such as KS or the complementary sensitivity function $T=I-S$.

The loop-shaping design procedure described in this paper is based on H∞ robust stabilization combined with classical loop shaping, as proposed by McFarlane and Glover (1990) [32]. It is essentially a two stage design process. First, the open-loop plant is augmented by pre and post-compensators to give a desired shape to the singular values of the open-loop frequency response. Then the resulting shaped plant is robustly stabilized with respect to coprime factor uncertainty using H∞ optimization. An important advantage is that no problem-dependent uncertainty modelling, or weight selection, is required in this second step. H∞ robust stabilization problem is described in [32, 33] (Glover and McFarlane, 1989). This is a particularly nice problem because it does not require γ-iteration for its solution, and explicit formulas for the corresponding controllers are available [32].

The simulation of control systems for Lead-Lag, LQG, mixed-sensitivity based controller and H∞ loop-shaping based controller are done in Matlab software in which the continuous state space model block was similar to dynamic model obtained from the FEM (Eq. 1). That transfer function has not unstable pole but it have three zeros in right half plane. So the system is nonminimum phase.

VI. Result

A Lead-Lag controller given by Eq. (11) was developed and implement. The controller transfer function is given by:

$$C(s)=12547111286232\times\frac{(s^{2}+41.35s+3781)}{s(s^{2}+633.1s+1.261\times 10^{5})}\,\frac{(s^{2}+36.95s+1.189\times 10^{5})}{(s^{2}+1007s+3.485\times 10^{5})} \tag{2}$$

we have following results for H∞ loop-shaping controller:

$$K_{\infty} = 8.0602 \times \frac{(s+24)(s^2+91.04s+2111)}{(s+40)^3(s+1.004)} \frac{(s^2+56.74s+900.6)}{(s^2+48s+576)} \tag{3}$$

Time histories of the tip accelerometer output for step excitation with and without the controller are shown Fig. 10. LQG and LQ regulators have almost the same treatment as shown in Fig. 11. It seems that LQG followed the commands quickly and more accurately than LQR.

In order to investigate the broadband control performance, a sine sweep excitation between 1-130Hz was applied to the beam. The open and closed loop tip accelerations are presented in Fig. 12. The output of controllers, the voltage that was applied to piezoelectric actuators (control effort), were shown in (Fig. 13).

Fig. 14 shows the bode plot of G for open loop, and bode plot of $L = KG$ for mixed sensitivity controller and loop shaping controller.

In order to test the robustness of the H∞-controller the structural singular value (μ) of the system is calculated across the frequency range of interest. A closed loop system is said to have the robust performance if the stability and the performance specifications are satisfied in the presence of the uncertainties defined if μ value is less that 1 within the frequency range of interest. The closed loop system designed for the smart beam demonstrated robust stability and robust performance (it is clear from Fig. 14).

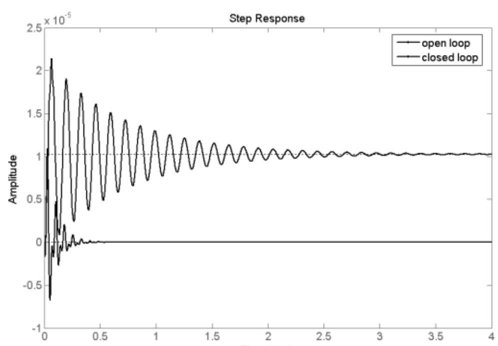

Fig. 10. step response of classical controller

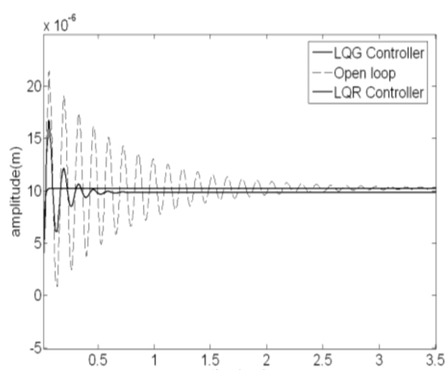

Fig. 11. step response of optimal controller

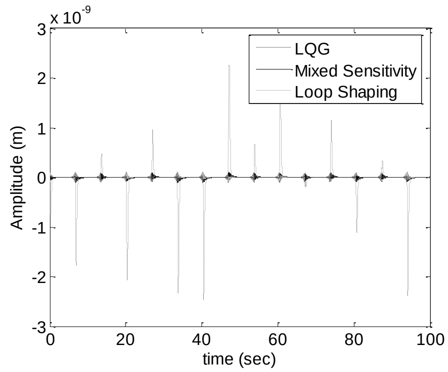

Fig. 12. sine sweep

In Fig.s 15, 16 and 17 we exert a noise of $\pm\%10mg$ in magnitude to the system. The results show that the Mixed sensitivity and loop shaped systems have enough robustness in noise rejection.

VII. Conclusion

In this paper, flapping flight as an effective form of locomotion for robotic insects was analyzed. We gave a brief overview of both the purpose and the challenges facing the actuator and structure of MFIs. Taking our cues from real insects, we propose a hierarchical architecture that divides the control unit into three main levels: the lowest level is designed to track a desired wing trajectory, the middle level is designed to stabilize flight modes in the event of external disturbances and the top level is designed to allow the insect to navigate in varying environments.

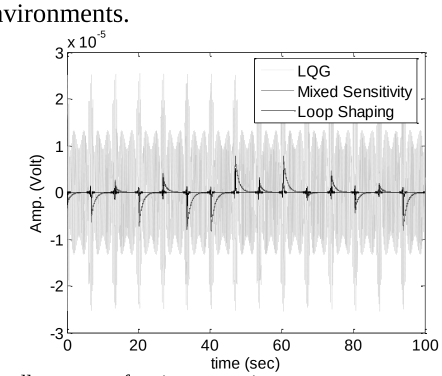

Fig. 13. Controllers output for sine sweep input

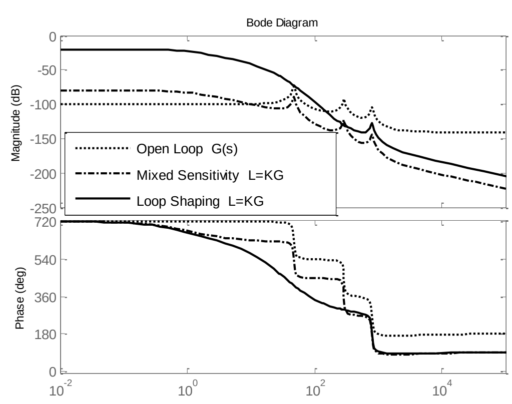

Fig. 14. bode plot of open loop and closed loop

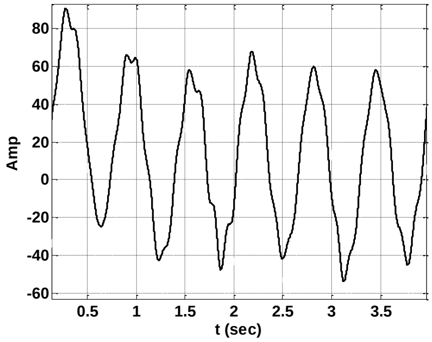

Fig. 15. LQG system response for distributed sinusoidal input

The structural problems such as mechanism and actuator were described and appropriate approach was investigated. Authors represented an appropriate fourbar mechanism for wing displacement amplification. They developed a new system (Smart Beam) to actuate the fourbar mechanism, also. They extract a transfer function (using experimental and FE system identification) and appropriate robust controllers for smart beam to have smooth and controlled flapping motion. The robust controller was designed based on extracted transfer function from experimental system identification. The robust control system developed for wing actuator control was successfully simulated and implemented. Results indicated that the controllers were effective for the desired vibration mode as well as for broadband vibration without causing spillover effects to the other modes. To have smooth flapping motion, in contrast with Lead Lag compensator, LQG and H_∞ optimal controller (such as H_∞ Loop shaping and Mixed sensitivity controllers) have sufficient performance.

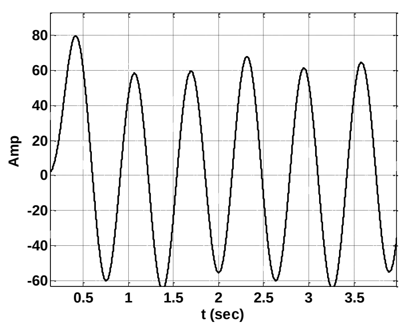

Fig. 16. Mixed sensitivity system response for distributed sinusoidal input

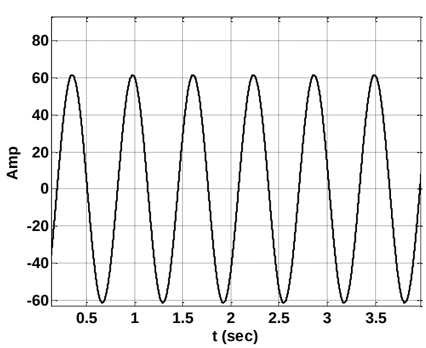

Fig. 17. Loop shaped system response for distributed sinusoidal input

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