Fuzzy logic Control Applications for Second Order Problems with Low Damping

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FUZZY LOGIC CONTROL APPLICATIONS FOR SECOND ORDER PROBLEMS WITH LOW DAMPING

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ABSTRACT

A general methodology has been developed for the design of a robust control law for a family of lightly damped second order problems. In this research effort, the passivity approach has been extended to systems having non-collocated input/output pairs by introducing an observer that incorporates the nominal dynamical model of the plant. The developed passive observer-based control law emulates numerous dynamic vibration absorbers which are tuned to a targeted frequency using classical methods and the tuning ratios are time-invariant. However, the uniqueness of this approach is that the damping parameters of the emulated absorbers are continuously varied by means of a fuzzy logic control algorithm to provide near minimum-time suppression of vibration. The developed approach is applied to both several benchmarks in the field of structural dynamics as well as experiments using piezo-ceramic sensors and actuators. Results show that this methodology provides stability and performance robustness on the one hand as well as requiring relatively low amount of actuation authority for desired nominal plant close-loop behavior.

INTRODUCTION

In the field of structural dynamics many problems may be represented by a second-order dynamic system. For such a class of dynamic systems, Juang and Phan [1] presented a robust controller which is a passive design based on virtual second-order dynamic system comprising of virtual mass, spring and dashpot elements. The virtual mechanisms incorporated into the passive design serve only to transfer and dissipate the energy of the system thereby maintaining the stability of the system. In addition, Juang and Phan [1] showed that overall closed-loop stability was guaranteed, independently of the system structural uncertainty and perturbations in the temporal plant dynamics.

These second-order controllers may also be termed "collocated" and they consist of compatible pairs of actuators and sensors, which may be distributed throughout the structure. However, in many real-life situations involving the control of flexible structures, because of physical placement and hardware limitations, absolute collocation may sometimes be impossible [2]. Furthermore, for the case of non-collocated actuator and sensor pairs strictly passive feedback no longer guarantees stability. To circumvent this problem, Hughes and Wu[3] presented an observer-based extension of the passive controller design for the above non-collocated case. This approach, based on the nominal dynamical model of the system, is a direct generalization of the dissipative controller, whereby the passive output is synthesized using an observer as opposed to the availability of physical measurement as required. This generalization, which includes application to the non-collocated case, is however at the expense of two of the inherent characteristics of passive controllers, the sacrifice of model independence; and the taking of stability robustness for granted.

In this paper, a second-order passive controller is applied to several benchmark problems whereby the control force emulates a virtual dynamic vibration absorber. The springs and mass elements of the controller are tuned using Den Hartog's classical method [4]. Furthermore, a control law, which is based on the principles of fuzzy logic control is introduced, to continuously tunes the damping parameter of the above-described passive controller.

The main advantages of using a fuzzy approach are the relative ease and simplicity of implementation and the robustness characteristics. The parameters of the above absorber may be adapted to provide fairly fast control for large deviations, of the measured state of the plant from the desired state, and a minor amount of control for small deviations. The successful implementation of a fuzzy logic controller depends, among other design aspects, on the heuristic rule base from which control actions are derived. In order to obtain the required heuristic physically-based insight, a single DOF system based on optimal control theory was analytically examined, to observe the characteristics of a minimum time solution [5]. Based on this analysis, Cohen, Weller and Ben-Asher [5] introduced a fuzzy logic non-linear mapping function, which has the potential of being a universal approximator[6] to emulate the above minimum time solution. The resulting rule base is the core of the control law that is applied to all the applications presented herein.

The passive observer-based control is first applied to the two-mass-spring ACC (Active Control Conference) benchmark problem [17], whereby the control force emulates a dynamic vibration absorber attached to a virtual wall by means of a virtual spring. For this benchmark, we examine whether the closed-loop system should provide satisfactory stability and performance characteristics based on Stengel and Marrison's [7] evaluation criteria which are based on "Stochastic Robustness Analysis". The next benchmark involves the vibration suppression of a flexible structure represented by a ten-bar, two-bay truss. The developed approach is also applied for the active suppression of aircraft cabin noise that is induced by structure borne vibration. Another application using the above methodology includes fuzzy logic control of NASA Langley's benchmark for active flutter suppression (BACT) of a wing segment for a wide spectrum of dynamic pressures. The resulting closed-loop response compare favorably to those published using conventional robust control approaches. Finally, experimental verification of the effectiveness of the above control algorithm for active vibration control, in the presence of transient disturbances, is conducted on a cantilever beam equipped with piezoceramic sensors and actuators. It is experimentally demonstrated that application of this methodology provides relatively quick settling times in the closed-loop.

FUZZY LOGIC CONTROL

Fuzzy logic, which is the logic on which fuzzy control is based, is a convenient way to map an input space into an output space [7]. The logical system that captures the spirit of our approximate, imprecise world was introduced by Lotfi Zadeh [8] as the theory of fuzzy sets, which in time proved to be a very powerful tool for dealing quickly and efficiently with imprecision and non-linearity. The experience of the past decade, with the successful marketing of a wide variety of products based on the FLC [7], has shown that for certain applications, use of FLC can lead to lower development costs, superior features, and better end product performance. One of the inherent properties of fuzzy logic systems is that it has the capability of being a universal approximator. This implies that by using adequate inputs, a number of rules and a number of fuzzy sets for each input variable, a fuzzy based system can approximate any real continuous nonlinear function to an arbitrary degree of accuracy [7]. The implementation of a variable damping strategy requires such a universal approximator that can emulate the bang-bang type of minimum-time control.

The capability of FLC to emulate time-optimal bang-bang control was attributed, by Thomas and Armstrong-Hélouvry [9], to what is termed as the *generalized damping* benefit of FLC, thereby providing fast and effective system responses. For large values of system error, the damping effect of the error derivative control is blocked as full control authority is used to quickly drive the system to zero. On the other hand, as the system error tends to zero a progressively greater damping effect is introduced. This nonlinear approach is in complete contrast to the trade-off required between the rise time, overshoot, and control effort seen in linear control. Another shortcoming of linear control is that it is far from time-optimal when control authority is bounded [10].

The controller proposed by Cohen, Weller and Ben-Asher [11] provided continuous tuning of the damping parameter of the above-described emulated absorber. Its parameters could be adapted to provide fairly fast control for large deviations, of the measured state of the plant from the desired state, and a minor amount of control for small deviations. Thus, non-linear control actions, corresponding to a *lightly* damped absorber, which fully utilize the range of actuator displacements, send the Plant State hurtling towards the desired state. On the other hand, in the vicinity of this desired state, the absorber is *heavily* damped. Heuristic rules, based on well-experienced structural engineering insight, coupled with fuzzy reasoning provide crisp values for *lightly* and *heavily* damped absorber [11]. The main advantages of using a fuzzy approach are the relative ease and simplicity of implementation and the robustness characteristics. Cohen [12] applied the above methodology to several benchmark problems using MATLAB® simulations.

The major mechanisms of the fuzzy logic controller (FLC) are: a set of if-then statements called linguistic control rules; and a fuzzy inference system that *interprets* the values in the input vector and, based on the linguistic rules, *assigns* values to the output vector. The structure of a fuzzy logic controller is depicted in Fig. 1.

The first stage in building the fuzzy part of the controller, which emulates a virtual dynamic vibration absorber, is referred to as *Fuzzification* of the input/output parameters. The inputs of the algorithm are the displacement, x(t), and the velocity, dx(t)/dt, of the structure at which point the external force is applied. The output of the fuzzy logic based algorithm is the damping coefficient of the virtual dynamic vibration absorber.

Five membership functions are used to describe each of the input parameters, namely, *POSITIVE, SMALL POSITIVE, ZERO, SMALL NEGATIVE* and *NEGATIVE*. In addition, the output parameter is also described using five membership functions, namely, **VERY LARGE, LARGE, MEDIUM, SMALL,** and **VERY SMALL**. The respective membership functions for the inputs / output parameters are obtained after a tuning process as described in Cohen [12]. The fuzzy adaptation strategy, presented in this effort, is based on rules of the form:

" **if...** premise, **then...**consequence "

that converts inputs (normalized transverse displacement and velocity) to a single output (actuation command), i.e. conversion of one fuzzy set into another.

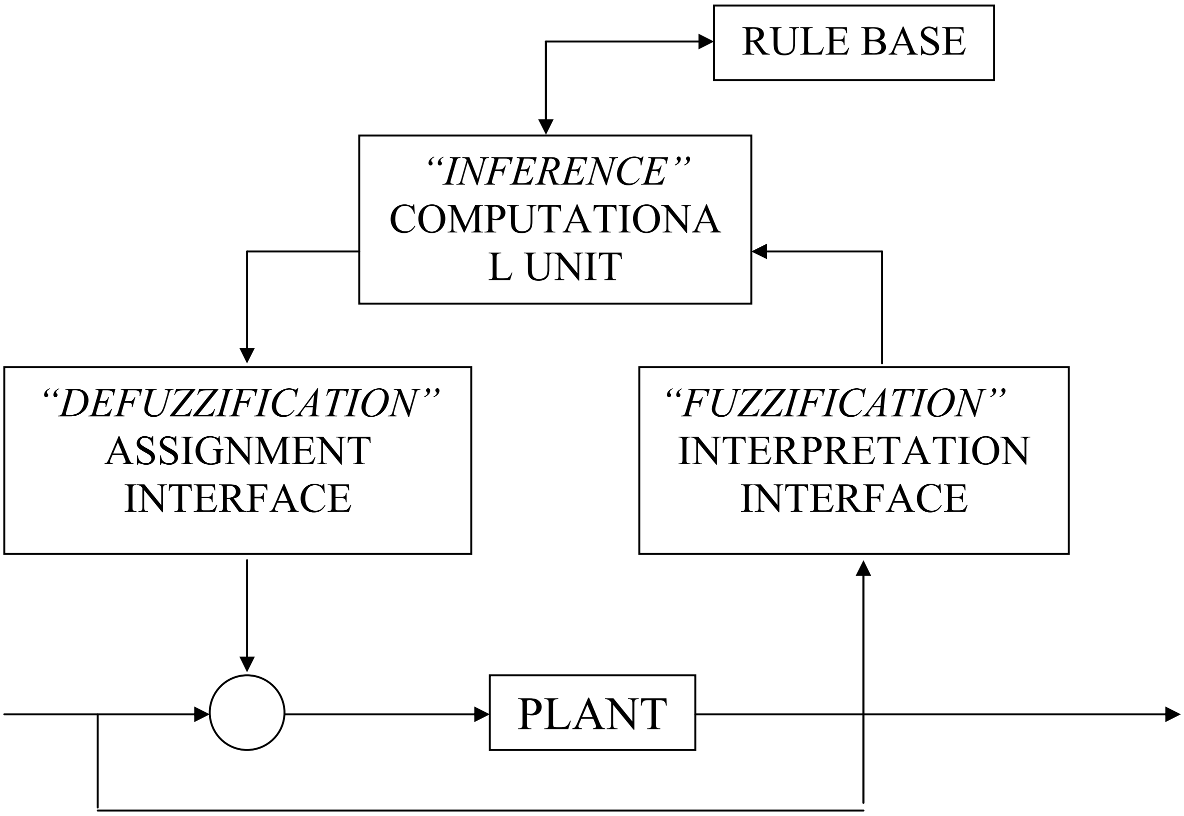

Figure 1: Fuzzy Logic Control System

	Negative x (t)	Small Negative x (t)	Zero x (t)	Small Positive x (t)	Positive x (t)
Positive dx (t)/dt	**Very Small**	**Small**	**Small**	**Small**	**Very Small**
Small Positive dx (t)/dt	**Very Small**	**Small**	**Large**	**Small**	**Very Small**
Zero dx (t)/dt	**Small**	**Medium**	**Very Large**	**Medium**	**Small**
Small Negative dx (t)/dt	**Very Small**	**Small**	**Large**	**Small**	**Very Small**
Negative dx (t)/dt	**Very Small**	**Small**	**Small**	**Small**	**Very Small**

Table 1: Fuzzy Logic Rule-Base

Heuristic rules based on well experienced structural insight are coupled with fuzzy reasoning whereby *large* values of the inputs require a *lightly* damped absorber, which would provide quick rise times. However, when the plant state is in the vicinity of the desired state, the damping factor is *large* to reduce the overshoot and steady state error. The Rule-Base, presented in Table 1, describes a set of 25 rules. A typical rule may be read as: "If $x_1(t)$ is *Negative* and $dx_1(t)/dt$ is *Positive*, then $c_2(t)$ is **Very Small".**

Abihana [13] defines inference as the process of applying the degree of membership, computed for a production rule premise, to the rule's conclusion to determine the action to be taken. The value assigned to the output may either be scaled (max-dot method) or clipped (max-min) to the degree of membership of the premise. Both of these methods provide similar results. The above inference methods are the most common methods used in fuzzy logic control. Nevertheless, several additional methods exist, as described by Wang [14].

As observed in Table 1, the Rule-Base contains quite a few rules relating to the same output variable. Therefore, to obtain an overall output in the fuzzy state, an inference method is applied. First, the degree of fulfillment of each and every rule is found by applying the fuzzy "AND" operation. In the next step, all the output values, obtained by clipping or scaling, are then brought together to form the final output membership function. After evaluation of the propositions, the output values represented are unified to produce a fuzzy set incorporating the solution variable. This unification of outputs of each rule, referred to as *aggregation*, occurs only once for each output variable. The aggregation process, always comprised of a commutative method, may be of the methods as described by Jang and Gulley [15]: *MAX* (maximum), *PROBOR* (probabilistc or), and *SUM* (simply the sum of each rule's output set). In this effort, the method applied is the *Bounded SUM* (simply the sum of each rule's output set having am upper bound of 1). Applying the *sum* to the rule base given Table 1, the union of the fuzzy sets for the same output variable is taken to reach the respective aggregation of the output. The rule-base, is usually not made to be part of the tuning process. However, the sensitivity of closed-loop performance to changes in the rule-base is examined and minor changes are made in order to ensure the desired performance.

Finally, in order to reach a practical controller a control action comprising of a single numerical value is required. Therefore, the space of the fuzzy damping factor, obtained using the method described in the previous section, is mapped into a non-fuzzy space (crisp) in a process known as defuzzification. There are various strategies aimed at producing a crisp value. Some of the commonly used strategies are the center of area (COA), the mean of maximum and the max criterion [16]. However, there is no accepted systematic methodology for selecting a defuzzification strategy. Herein, the COA scheme is adapted. This strategy was found to yield better steady-state performance when compared to the other above-mentioned strategies [16].

APPLICATION I: ACC BENCHMARK PROBLEM

During the years 1990-1992, certain benchmark problems for robust control design were presented at the American Control Conference (ACC). One of these problems, referred to by Wie and Bernstein [17] as ACC benchmark Problem 1, was concerned with vibration control of a two-mass system with an uncertain spring constant, k, in view of a transient disturbance (see Fig. 2). The simplicity of this problem provided a transparency that enabled it to be an interesting tool for comparison of a variety of robust control design methodologies. Nevertheless, this problem is nontrivial because it couples both rigid and flexible body modes with plant uncertainty and non-collocated sensor and actuator. In addition, sensor readings are contaminated by a high frequency sensor noise.

A second-order passive controller is applied to the ACC benchmark problem whereby the control force emulates a virtual dynamic vibration absorber attached to a virtual wall by means of a virtual spring. The springs and mass elements of the controller are tuned to introduce two *virtual* low frequency flexible modes instead of the single rigid body mode. Furthermore, a control law, which is based on the principles of fuzzy logic control, presented in the previous section, is introduced, to continuously tune the damping parameter of the controller. Further details concerning the development of the controller are provided by Cohen, Weller and Ben-Asher[5].

Finally, we examine whether the closed-loop system should provide satisfactory stability and performance characteristics not only for the nominal plant but also over the range of values associated with parameter uncertainties. As mentioned by Wie and Bernstein[17], the feedback controller should display reasonable performance/stability robustness. To this end, Stengel and Marrison[7] presented some evaluation criteria, concerning the selection of appropriate measures of robustness of the ACC benchmark problem and demonstrate that the described evaluation criteria may be satisfied by the application of Stochastic Robustness Analysis (SRA).

The definitions and principles of the SRA adhered to in this effort are based on the approach, proposed by Stengel and Marrison[7], whereby Monte-Carlo evaluations are used to estimate the probabilities of stability/performance. The performance metrics are defined as follows:

P_I **: Probability of Instability** - portrays the likelihood that the variations in the uncertain plant parameter will force at least one closed-loop root into the right half plane.

P_{TS} : **Probability of Settling-Time Exceedance** - portrays the likelihood that the actual response of the targeted state variable will fall outside an arbitrarily chosen envelope.

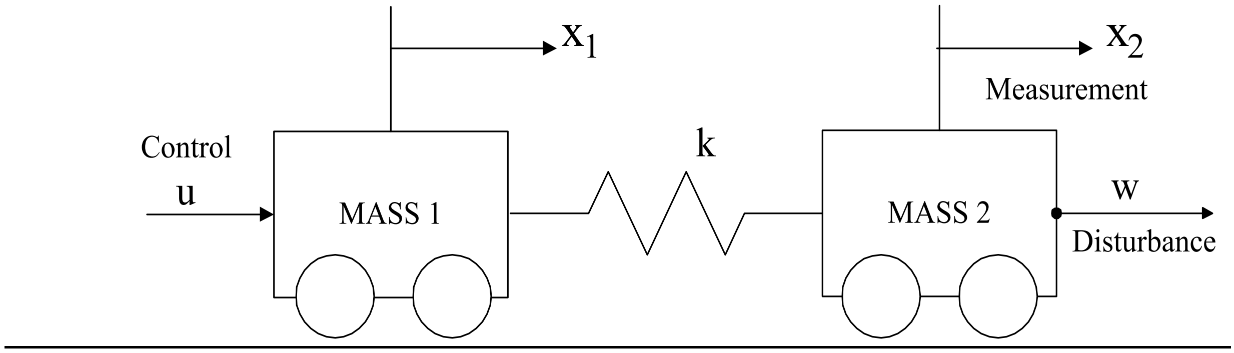

Figure 2: ACC Benchmark Problem (Wie and Bernstein [17])

Controller Description	**Design**	**Nominal Settling Time [s]**	**Nominal Control Effort**	P_I	P_{TS}	P_u
Fixed-order compensators achieving approximate loop-transfer recovery	A	21.0	0.514	0.160	0.971	0.160
Same basic design as A	B	19.5	0.469	0.023	1.000	0.023
Same basic design as A	C	19.7	0.468	0.021	1.000	0.021
H_∞	D	9.9	297.8	0.000	0.000	1.000
Nonlinear constrained optimization	E	18.2	0.884	0.000	1.000	0.000
Structured covariance terms added to linear quadratic Gaussian equations	F	13.7	2.397	0.000	0.633	1.000
Game theoretic controller based on linear exponential Gaussian and H_∞ concepts	G	31.3	1.458	0.000	1.000	1.000
H_∞ using the internal model principle.	H	14.9	0.574	0.000	0.742	0.000
Same basic design as H	I	17.8	0.416	0.000	0.756	0.000
Same basic design as H	J	43.2	1.047	0.039	1.000	0.857
Adaptive fuzzy passive observer based controller	K	8.8	0.53	0.000	0.468	0.042

Table 2: Comparison with other controllers (based on Stengel and Marrison [7])

P_U : **Probability of Control-Limit Exceedance** - portrays the likelihood that the peak actuator displacement will exceed the prescribed saturation limit of unity.

The Monte Carlo analysis is comprised of three steps, namely: generation of random spring stiffness; solution of the deterministic problem for a large number of realizations; statistical analysis of the results is described in detail by Cohen [12]. The number of Monte Carlo runs, m, was selected arbitrarily at 1000 and was found to be adequate. The results obtained using the developed fuzzy approach are compared to other strategies as presented by Stengel and Marrison [7] in Table 2. Table 2 indicates the substantial benefits obtained using an adaptive fuzzy passive observer-based controller. The confidence intervals of the probabilities for a confidence level of 95% are as follows:

a. The probability for instability for the adaptive fuzzy controller lies within the confidence interval [0, 0.0037].
b. The probability for settling-time exceedance for the adaptive fuzzy controller lies within the confidence interval [0.437, 0.499].
c. The probability for control-limit exceedance for the adaptive fuzzy controller lies within the confidence interval [0.030, 0.056].

The results provided by Table 2 indicate that on the one hand, the adaptive fuzzy controller has the best results as far as the stability and settling times are concerned, while on the other hand the control effort required is within the required limit for most cases. For linear controllers, the improvement of settling times is directly associated with the payment of a huge penalty for the control effort. The most interesting result of this application is finding that the developed control strategy leads to *robust near time-optimal control* while requiring a relatively *small amount of control effort*. Comparative settling times, for a linear controller based on H_∞ (see Design D in Table 2), requires a larger maximum control force of about two orders of magnitude.

APPLICATION II: VIBRATION OF A TEN BAR TRUSS

In this application, the well-known ten bar truss benchmark (see Fig. 3), developed by AFWAL/FIB, was selected for the numerical analysis concerning vibration suppression of flexible space structures with several low natural frequencies and a high modal density. This benchmark serves as an ideal platform to demonstrate some of the important features of a control system design for a typical large space structure. Moreover, the main aim of the numerical exercise is pointing out the effectiveness of the fuzzy logic based controller in shortening the settling times. To this end, the results obtained are compared to those reached using LQG/LTR and H-infinity controllers, which serve as "universal" baselines. Further details are provided by Cohen, Weller, and Ben-Asher [18]. The different tasks involved in application of the developed controller to the ten bar truss were as follows:

a) The open-loop models were built on a MATLAB platform as follows: 2-mode reduced model for control design and a 8-mode truth model. Subsequently, the open-loop models were validated for persistent pulse disturbance by comparison with Parlos and Jayasuriya [19]. Furthermore, the open-loop models experiencing an initial condition were compared with Lynch and Banda [20].
b) The adaptive fuzzy passive control was applied, based on the strategy developed, for both types of disturbances.
c) The closed-loop performance for the nominal 2-mode design model was compared with that obtained a H_∞ controller [19] and a LQG/LTR controller [20].
d) The closed-loop performance for the nominal 8-mode truth model were evaluated for both types of disturbances and results obtained were compared with those using a H_∞ controller [19] and a LQG/LTR controller [20].
e) The stability and performance robustness for substantial perturbations in the plant was examined for persistent pulse disturbance and results obtained were compared with those using a H_∞ controller [19].

Results, presented by Cohen, Weller, and Ben-Asher [18], show that for the LQG/LTR controller [20], the initial vibrations are damped to within 0.1 percent of the initial amplitude in approximately 12 seconds. In comparison, for the adaptive fuzzy controller, the initial vibrations are damped to within 0.1 percent of the initial amplitude in less than 5 seconds (see Fig. 4). This remarkable improvement in the settling times is obtained without exceeding the specified control power limits. The robustness characteristics of the developed controller are examined for the 3 perturbed plants described in [18]. For all 3 cases, the fuzzy controller yielded satisfactory results.

APPLICATION III: AIRCRAFT CABIN NOISE

A major issue in the cabin design of commercial transport aircraft concerns the reduction of sound pressure level leading to improved passenger comfort. Cabin noise usually results from either airborne sources, such as prop-wash or engine whine, or from structure-borne sources such as spool imbalance and vibrations. In addition to cabin noise, the above disturbances can also cause material fatigue. The sound pressure level may be attenuated by the incorporation of structural acoustic control. In this application, the incorporation of the adaptive vibration absorber has been embraced with a few unique changes. The central theme of this approach is that it provides continuous tuning of the damping parameter of the vibration absorber based on the developed fuzzy logic control algorithm. The main objective of this application was to examine the

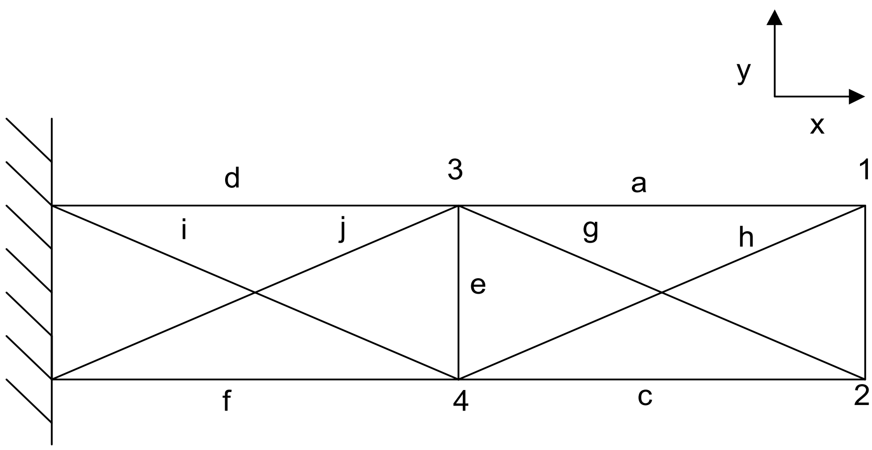

Figure 3: AFWAL/FIB Two Bay Model as presented by Lynch and Banda [20].

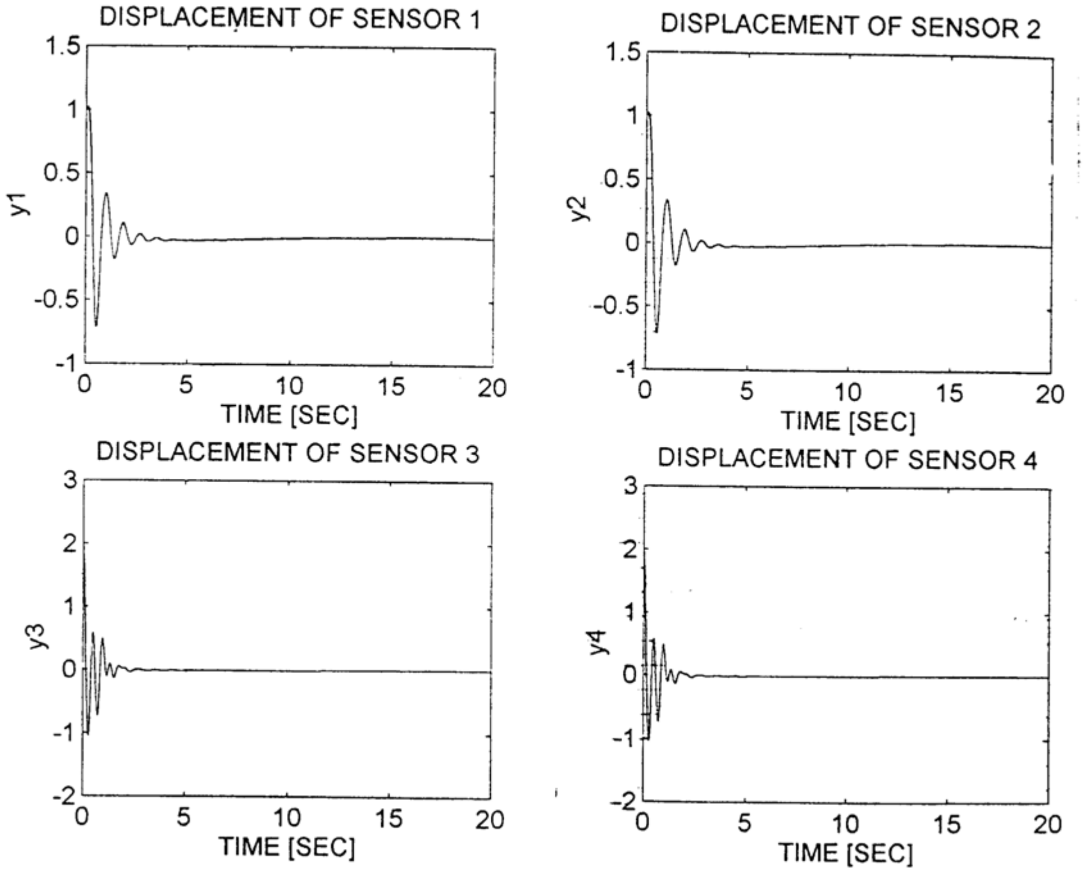

Figure 4: Closed-loop response using fuzzy based strategy.

effectiveness of the developed methodology, based on numerical simulations conducted on an experimental model used to test adaptive absorbers [21]. The performance robustness and the closed-loop performance of the developed approach were closely examined by comparing the results with those obtained using the approach suggested by Ryan [21]. Further details of the application are presented in a paper by Cohen, Weller, and Ben-Asher [22].

The results of the second set of simulations, based on the perturbed plants, is presented in Table 3:

CASE	RMS Displacement (m)	% Reduction from Passive Dynamic Vibration Absorber
Nominal Structure		
Ryan[1] [21]	0.0277	56.79 %
Fuzzy control[2] [22]	0.0275	57.10 %
Perturbed System A		
Ryan[1] [21]	0.0577	9.98 %
Fuzzy control[2] [22]	0.0263	58.97 %
Perturbed System B		
Ryan[1] [21]	0.0614	4.21 %
Fuzzy control[2] [22]	0.0288	55.07 %

Table 3: Results for Nominal and Perturbed Plants

In Table 3, "Ryan" refers to results reported, based on a conventional approach, by Ryan [21], whereas "Fuzzy control" refers to results obtained using the herein developed fuzzy logic based algorithm [22]. The salient observations made from Table 3 are as follows:

a) The algorithm, suggested by Ryan [21], is extremely sensitive to uncertainties in the dynamic model of the plant.

b) On the other hand, the fuzzy controller displays excellent robustness characteristics for both of the perturbed Systems, A and B, where the improvements are of an order of magnitude better than those demonstrated by Ryan [21].

It may be noted that an essential requirement from a flexible structure controller constitutes robustness [12]. Indeed, the controller, suggested by Ryan [21] performs well in an ideal situation (full knowledge of plant model and no measurement noise), however it is not a good choice at the real plant as shown in Table 3. Modeling uncertainties and noise lead to inaccurate switching of the absorber stiffness and this impairs the performance which is not only non-optimal, but also very close to that obtained with a passive controller. In such a case, the added cost of going from passive to active may not be justified.

Another question that crosses the mind is whether the added effort associated with the implementation of fuzzy controller is justified, i.e. the effectiveness of the variable damping strategy. These questions were addressed by running several simulations of the nominal and perturbed plants for different values of fixed damping for the absorber. Examination of the results, presented in [22], emphasizes the merits of the proposed approach based on the fuzzy logic algorithm. It is noticed that there is a trade-off between the result for the nominal plant and robustness for perturbed plants. A variable damping approach seems to exhibit excellent robustness characteristics without sacrificing nominal plant performance.

APPLICATION IV: ACTIVE FLUTTER SUPPRESSION

The problem of flutter instability may be treated by using a rapidly responding control system to produce stabilizing control-surface aerodynamic forces. The closed-loop system, which functions independently of the pilot and termed as an active control system, may be actuated by the motion of the main surface and leads to an appropriate deflection of the control surface. The favorable modification of the aeroelastic response, using active control, utilizes increased wing flexibility and multiple control surfaces in the design of wings such that smaller control deflections are required to initiate increasingly agile maneuvers. These features may result in substantial improvements in airplane performance and stability while reducing drag, actuation power, and structural loads. In order to realize the desired active control system an appropriate control system is required. A preferred controller will exhibit performance and stability robustness characteristics without having to pay a high price in control effort.

Recently, NASA Langley Research Center, as part of the Benchmarks Models Program, developed a Benchmark Active Control Technology (BACT) Wind-Tunnel Model [23-25]. Among other objectives, the BACT system provides an active controls testbed for evaluating new and innovative control algorithms for flutter suppression and gust load alleviation. Several control approaches were developed including classical Nyquist methods, linear quadratic Gaussian (LQG), H-infinity, μ-synthesis, generalized predictive control, neural networks and minimax approaches, based on the steady state differential game theory [23,25].

The BACT wind tunnel model is a rigid rectangular wing with an NACA 0012 airfoil section [26]. In this numerical analysis, the wing is equipped with a trailing edge control surface that can be controlled independently. A single accelerometer is the primary sensor for feedback control and is located at the wing-shear center.

In this application, seven working points have been considered with different dynamic pressures. The robustness requirement of the desired controller corresponds to acceptable settling times and control effort for each of the working points. The fuzzy logic controller, which is time variant and non-linear in nature, is compared to a reduced order linear quadratic Gaussian, LQG. The development of these two controllers is detailed in Adin et al. [27]. In order to compare the results of the two above controllers, the following definitions are made:

Settling Time – is the time, in seconds, after which the response, y, is contained within an envelope having a width of 50 i.e. less than 3% than the maximum response. This measure is used for both off-design and on-design cases and indicates the time taken to overcome the input step. In the open-loop, for the minimum dynamic pressure, the settling time is fairly large. Furthermore, as the dynamic pressure increases, the settling time also increases considerably until it reaches a point where the response becomes unstable.

RMS_{CE} - The root mean square of the controlled effort is defined as follows:

$$RMS_{CE} = \sqrt{\frac{\sum_{i=1}^{N} u_i^2}{N}}$$

where u_i is the value of the control input at the i^{th} time step and N is the number of the time steps in the simulation. The measure RMS_{CE} is used to compare the control effort required by the above two controllers at the design point (maximum dynamic pressure).

Having defined the measuring parameters, attention is now paid to the response obtained by the above two approaches for the design point (maximum dynamic pressure). These results, summarized in Table 4, illuminate the advantages of using the controller based on the fuzzy logic based design. The fuzzy logic controller brings the plant to the settling envelope in a mere 2.62 seconds, which is about a third to the time required by the reduced order LQG. Furthermore, the above performance is reached with a smaller amount of control effort.

When considering the off-design cases, it was evident that the fuzzy logic controller provides superior robustness characteristics [27]. The off-design cases represent six, additional working points with different dynamic pressures. The settling times of the fuzzy logic controller varies from 1.63 seconds to 2.62 seconds. On the other hand, the settling times for the reduced LQG controller varies from 2.59 seconds to 7.80 seconds. In addition, the closed-loop response of the reduced order LQG was found to be more sensitive to variations in the dynamic pressure of the system. The equivalent viscous damping factor of the fuzzy logic controlled response was always lower for the fuzzy logic design.

MEASURE OF COMPARISION	REDUCED ORDER CONTROLLER	FUZZY LOGIC CONTROLER
SETTLING TIME (SEC)	7.80	2.62
RMS_{CE} FOR FIRST 5 SEC	1.00120	1.00045
RMS_{CE} FOR FIRST 10 SEC	1.00058	1.00022

Table 4: Comparison between results obtained using a reduced LQG and a Fuzzy Logic Controller for the design case

APPLICATION V: SMART STRUCTURE EXPERIMENT

In this application, the experimental verification of the effectiveness of the developed fuzzy logic control algorithm for active vibration control, in the presence of transient disturbances, was conducted on a two dimensional model of the cantilever beam, "LFS1-P", which represents the characteristics of an orthogonal tetrahedral space truss. Active control of the beam was provided by one, two or three identical patches of piezo-ceramic material collocated with a single sensor. The experimental studies on "LFS1-P", conducted at the Aircraft Structures Laboratory, Faculty of Aerospace Engineering, Technion, observed the behavior of "LFS1-P" as reflected by the following characteristics:

a. Closed-loop response including rise time, overshoot, settling time, logarithmic decrement, steady-state error and actuator input required.
b. Sensitivity of the closed-loop performance and control voltage to the length of the actuating piezoceramic patch.
c. Robustness of the control system to an externally initiated change in the temporal dynamics of closed-loop model. This perturbation will be introduced by the addition of a discrete mass.

"LFS1-P", is a slender aluminum alloy (7075-T6) cantilever beam of rectangular cross-section whose dynamic characteristics represent a flexible structure. A variety of transient disturbances is introduced to excite the first few modes. The basic properties of this proof-of-concept model are:

a. Length - 1145 mm.
b. Width - 60 mm.
c. Thickness - Varies 1.27-1.95 mm.
d. Material - Aluminum alloy (7075-T6).
e. Boundary Condition - Fixed-Free (Cantilever).

The experimental structure is equipped with a piezosensor /piezoactuator pair. The transducers comprise of one or more rectangular (54.6 mm × 54.6 mm) PZT patches attached as close as possible to the clamped end of the cantilever. These patches, designated as PSI-5A-S3, are piezoceramic sheets manufactured by Piezo Systems, Inc., Massachusetts, USA. The first four measured open loop frequencies of "LFS1-P" are as follows: 0.65 Hz., 4.8 Hz., 14.0 Hz., and 27.0 Hz. "LFS1-P" is subject to a wide variety of transient disturbances in the form of arbitrary "hits" or "flicks" at different locations along the structure. Even though there is no self-imposed requirement to simulate any particular type of disturbance, the "flicks" were primarily aimed at exciting as many modes as possible. In addition, the closed-loop response was observed for many different initial conditions to ensure that the quality of the resulting performance is not noticeably dependent on the type of disturbance. Cohen [12] describes the experimental set-up used for the testing of "LFS1-P" and other details of experimental procedures.

The electro-mechanical equations that govern the behavior of a PZT patch, as described by Cohen, Yaffe, Weller and Ben-Asher [28], point to the relationship between the length of the actuator patch and the applied voltage command required to produce an equivalent point force. Experiments on structural vibration control, using PZT transducers, conducted by Yousefi-Koma and Vukovich [29] show the effect of actuator patch on the closed-loop performance. Furthermore, for a longer piezoceramic patch, a smaller control voltage was required to achieve greater damping. To examine the effectiveness of the developed AFCA to the length of the piezo-actuator, three cases of actuators made of square (54.6^2 mm^2) PZT patches are considered, namely:

CASE 1: A single patch attached at a distance of 15mm from the clamped end of the cantilever, is collocated with a similar PZT patch sensor bonded to the opposite face of the beam.

CASE 2: Two square patches attached together, to form a patch twice as long, at a distance of 15mm from the clamped end. The PZT sensor patch is identical to CASE 1.

CASE 3: Three square patches attached together, to form a patch three times as long, at a distance of 15mm from the clamped end. The PZT sensor patch is identical to CASE 1.

The application of AFCA to the nominal "LFS1-P", provides damping augmentation in view of the transient disturbance leading to improved settling times with respect to the open-loop response. When the control force is turned off a little after the dying out of the vibrations, almost all the vibrational energy is dissipated as the beam returns to its undisturbed state throughout its length. In addition, the performance of the AFCA was found to be insensitive to the type of transient disturbance.

The effectiveness of the developed controller to the length of the piezo-actuator is examined. In comparison to the results obtained in CASE 1 and CASE 2 substantial improvement in the damping is obtained for CASE 3. The controller suppresses the flexural vibration quickly and the greater damping is at the expense of smaller control voltage. This result is similar to that reached by Yousefi-Koma and Vukovich [29].

To demonstrate the robustness of the control system to changes in the temporal dynamics of "LFS1-P", CASE 2, the transient disturbance response to a perturbed plant is experimentally obtained. A discrete, non-structural weight of approximately 50 gm. is attached to the free end of the beam, reducing the fundamental frequency of vibration by about 10% as well as increasing modal density and altering mode shapes as detailed in Cohen, Yaffe, Weller and Ben-Asher [28]. For the perturbed structure, the developed controller provides similar settling times and rates of vibrational energy dissipation [12].

CONCLUSIONS

In this paper, a novel approach using a fuzzy logic based algorithm, is presented for the control of linear second-order systems, having low inherent damping. It was demonstrated that the developed approach yielded in performance and stability robustness in view of plant uncertainties, sensor noise and sensitivity to actuator/sensor non-collocation. The providing of fast and effective system responses demonstrated during the numerical investigations are primarily due to the capability of a fuzzy logic controller to emulate time-optimal bang-bang control.

The central idea, which drives the developed control law, implies that for large values of system error, the damping effect of the error derivative control is blocked as full control authority is used to quickly drive the system to zero. On the other hand, as the system error tends to zero a progressively greater damping effect is introduced. The developed control strategy leads to robust near time-optimal control while requiring a relatively small amount of control effort.

Pursue of current research involves the application of the developed fuzzy logic methodology for a wider range of applications such as flight control systems and active flow control systems. In addition, studies should be pursued to further develop and test the controller presented herein for the vibration suppression of structures like beams, plates and shells and possessing very high modal densities at the lower frequencies, and suppression of buckling problems. Future research plans should include further comparisons with other linear and non-linear control laws.

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